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Lotfi A. Zadeh, inventor of Fuzzy Logic, dies at 96, but Fuzzy Logic is alive!

On November 23, 2017, his pioneering paper "Fuzzy Sets" now reaches almost 100,000 citations in Google Scholar and all Zadeh's works were cited over 185,000 times.

Lotfi A. Zadeh (Feb. 4, 1921 - Sept. 6, 2017)

World-renowned computer scientist Lotfi A. Zadeh, father of Fuzzy Sets and Fuzzy Logic, was a member in Editorial Board of our International Journal of Computers Communications & Control (IJCCC), since 2008.

In 2008 Lotfi A. Zadeh was a keynote speaker at International Conference on Computers Communications and Control (ICCCC 2008), organized by Agora University.

Program Committee of ICCCC and the Editorial Board of IJCCC, we were very honored that a famous scientist Lotfi A. Zadeh was our collaborator.

R.I.P., Dear Professor Zadeh!

BRIEF DESCRIPTION OF JOURNAL

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To differentiate from other similar journals, the editorial policy of IJCCC encourages the submission of original scientific papers that focus on the integration of the 3 "C" (Computing, Communication, Control).

In particular the following topics are expected to be addressed by authors: (1) Integrated solutions in computer-based control and communications; (2) Computational intelligence methods (with particular emphasis on fuzzy logic-based methods, ANN, evolutionary computing, collective/swarm intelligence); (3) Advanced decision support systems (with particular emphasis on the usage of combined solvers and/or web technologies).

Editorial Address:
Agora University/ R&D Agora Ltd. / S.C. Cercetare Dezvoltare Agora S.R.L.
Piata Tineretului 8, Oradea, jud. Bihor, Romania, Zip Code 410526
Tel./ Fax: +40 359101032
E-mail: ijccc@univagora.ro, rd.agora@univagora.ro, ccc.journal@gmail.com
Journal website: http://univagora.ro/jour/index.php/ijccc/

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Fuzzy Logic Is Not Fuzzy: World-renowned Computer Scientist Lotfi A. Zadeh

I. Dzitac, F.G. Filip, M.J. Manolescu

Lotfi A. Zadeh (1921-2017)

Ioan Dzitac[1,2], Florin Gheorghe Filip[3], Misu-Jan Manolescu[2,*]
1. Aurel Vlaicu University of Arad
310330 Arad, Elena Dragoi, 2, Romania, ioan.dzitac@uav.ro
2. Agora University of Oradea
410526 Oradea, P-ta Tineretului 8, Romania
*Corresponding author: mmj@univagora.ro
3. Romanian Academy
Calea Victoriei 125, Sector 1,
010071 Bucharest, Romania, ffilip@acad.ro

Abstract: In 1965 Lotfi A. Zadeh published "Fuzzy Sets", his pioneering and controversial paper, that now reaches almost 100,000 citations. All Zadeh's papers were cited over 185,000 times. Starting from the ideas presented in that paper, Zadeh founded later the Fuzzy Logic theory, that proved to have useful applications, from consumer to industrial intelligent products. We are presenting general aspects of Zadeh's contributions to the development of Soft Computing(SC) and Artificial Intelligence(AI), and also his important and early influence in the world and in Romania. Several early contributions in fuzzy sets theory were published by Romanian scientists, such as: Grigore C. Moisil (1968), Constantin V. Negoita & Dan A. Ralescu (1974), Dan Butnariu (1978). In this review we refer the papers published in "From Natural Language to Soft Computing: New Paradigms in Artificial Intelligence" (2008, Eds.: L.A. Zadeh, D. Tufis, F.G. Filip, I. Dzitac), and also from the two special issues (SI) of the International Journal of Computers Communications & Control (IJCCC, founded in 2006 by I. Dzitac, F.G. Filip & M.J. Manolescu; L.A. Zadeh joined in 2008 to editorial board). In these two SI, dedicated to the 90th birthday of Lotfi A. Zadeh (2011), and to the 50th anniversary of "Fuzzy Sets" (2015), were published some papers authored by scientists from Algeria, Belgium, Canada, Chile, China, Hungary, Greece, Germany, Japan, Lithuania, Mexico, Pakistan, Romania, Saudi Arabia, Serbia, Spain, Taiwan, UK and USA.
Keywords: fuzzy sets, fuzzy languages, fuzzy logic, Romanian early contributions, SC, AI, IJCCC.

1 Introduction

"Fuzzy logic is not fuzzy. Basically, fuzzy logic is a precise logic of imprecision and approximate reasoning." (L.A. Zadeh [139])

In 2008, Professor Lotfi A. Zadeh was a keynote speaker at the International Conference on Computers Communications and Control (ICCCC), organized by Agora University of Oradea, Romania (ICCCC2008).

Under the umbrella of the ICCCC2008, on the occasion of an exploratory workshop we co-edited the volume "From Natural Language to Soft Computing: New Paradigms in Artificial Intelligence" (Editors: Lotfi A. Zadeh, Dan Tufis, Florin Gheorghe Filip, Ioan Dzitac) [145][1]

I. Dzitac, M.J. Manolescu, L.A. Zadeh and F.G. Filip (ICCCC2008)

The members of the Agora University and the Editorial Team of the IJCCC[2], were very honoured that a world-famous computer scientist, Lotfi A. Zadeh, was their collaborator and they are dedicating to his memory this work.

We have made a literature review in the fields of fuzzy sets, fuzzy logic and their applications, consisting in main papers of Lotfi A. Zadeh, and also of the several important international followers and Romanian contributors [1-151].

[1]"Dear Professor Dzitac: I received copies of the Proceedings and the Journal. I was highly impressed in all respects.You and your colleagues have done an outstanding job. I was very pleased with the inclusion of my powerpoint presentation in the Appendix of the Proceedings. Please accept my compliments and congratulations. I should like to take this opportunity to thank you again for the very warm welcome which you extended to me. Participation in your Conference was a very stimulating as well as pleasant experience. With my warm regards. Sincerely, Lotfi Zadeh." (From: Lotfi A. Zadeh [zadeh@eecs.berkeley.edu]; Sent: Thursday, May 07, 2009 9:51 AM, To: Ioan Dzitac; Subject: Congratulations/Dzitac).

[2]`http://univagora.ro/jour/index.php/ijccc/`

2 Lotfi A. Zadeh (1921 - 2017): A brief biographical note

"The question really isn't whether I'm American, Russian, Iranian, Azerbaijani, or anything else. I've been shaped by all these people and cultures and I feel quite comfortable among all of them."
(Lotfi A. Zadeh [15])

Lotfi A. Zadeh, inventor of fuzzy logic, multidisciplinary and interdisciplinary scientist (engineer, mathematician, computer scientist, logician, scientist in artificial intelligence), was born on February 4, 1921, in Baku, Azerbaijan, as Lotfi Aliaskerzadeh[3]. Lotfi enrolled the elementary school no.16 in Baku.

In 1905, Lotfi's mother, Fanya Korenman, with her family moved from Russia to Baku and settled there. She graduated from Tbilisi (Georgia) Women Gymnasium in 1918, and after she graduated from Azerbaijan State University, Faculty of Medicine, Pediatric Department. Lotfi's father, Rahim Aleskerzade, was from Ardabil (South Azerbaijan, Iranian Azerbaijani ethnicity) graduated from Azerbaijan State University, faculty of Journalism. They met each other during university time and married in 1920 in Baku.

When Lotfi turned 10, in 1931, Zadeh's family moved from Azerbaijan to Tehran, Iran. Here Zadeh was enrolled in Alborz College, which was a Presbyterian missionary school, where he was educated for the next eight years, and where he met his future wife, Fay.

In 1942, Zadeh graduated from the University of Tehran with a degree in Electrical Engineering.

In 1943 he emigrated to the US and obtained his Master in the famous Massachusetts Institute of Technology (MIT) and his Ph.D. at Columbia University in 1949, where he lectured for a year, then becoming a professor at the University of California, Berkeley.

Zadeh taught for ten years at Columbia University, was promoted to Full Professor in 1957, and has taught at the University of California, Berkeley since 1959. He was also director of the Berkeley Initiative in Soft Computing (BISC) from 1991 to his death. His research was supported by Omron Grant, Tekes Grant, The Ministry of Communications and Information Technologies of Azerbaijan Republic, Grant from Azerbaijan University and BISC grant.

He was lucid and active almost until the last minute. Lotfi A. Zadeh, father of Fuzzy Sets, Fuzzy Logic and Fuzzy Mathematics, dies at 96, on September 6, 2017, in Berkeley, California, USA. On September 29, the Azerbaijan National Academy of Sciences hosted a worldwide famous Azerbaijani scientist, Lotfi Zadeh's funeral. Lotfi A. Zadeh was laid to rest in the 1st Alley of Honor in Baku, Azerbaijan. President of Azerbaijan Republic Ilham Aliyev participated at this ceremony.

Professor Shahnaz Shahbazova, a very good friend of the Zadeh's family, was legal granted by Norman Zadeh, Lotfi Zadeh's son, for transfer from USA the Lotfi's body to be buried in Baku. Both daughters of Shahnaz Shahbazova (Chimnaz and Sabina) worked with Professor Zadeh since 2012 at Berkeley. There it is some memories about Zadeh's family: "I have visited Lotfi and Fay every week and was with them until their last days. I also assisted him with his research and with every need they had. I loved visiting them and spending time with both Lotfi and Fay, listening to their life stories and experience." (Chimnaz); "He always pleased to receive emails from colleagues and friends and tried to answer to them at the same day. He also appreciated to friends who contacted him via phone as well."(Sabina).

[3]While in the United States, he changed his name to Lotfi Asker Zadeh.

Lotfi Zadeh's funeral:

Prof. Shahnaz Shahbazova[4], Prof. Vadim L. Stefanuk[5], and Prof. Valentina E. Balas[6] at the 1st Alley of Honor in Baku.

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[4] Dr. Shahnaz Shahbazova is a Professor at Azerbaijan Technical University. She is an academician of the International Academy of Sciences named after Lotfi A. Zadeh, 2002 and vice president of the same academy, 2014. Her research interests include Artificial Intelligence, Soft Computing, Intelligent System, Machine Learning Techniques to Decision Making and Fuzzy Neural Network. She is a member of Berkeley Initiative in Soft Computing group (BISC), New York Academy of Sciences, member of "Defined Candidate Dissertation" Society and member of the Board of Directors of North American Fuzzy Information Processing Society (NAFIPS), International Women Club, Azerbaijan [1]. In 2007, Professor Shahbazova won Fulbright Visiting Scholar Grant and had conducted her research at the University of California, Berkeley, in Computer Science Department under the supervision of Prof. Lotfi Zadeh. They worked on several projects together which were great success. Since then, she became very close to Zadeh and his family. Being treated as daughter, she visited them often and was with Fey Zadeh and Prof. Lotfi A.Zadeh until his last days. Per Shahnaz's initiative, the World Conference on Soft Computing has launched, and was held every year worldwide. Her daughters Chimnaz and Sabina, who are both in the US since 2012, were very close to Lotfi Zadeh, and were with him until his last day.

[5] Dr. Vadim Stefanuk is a Full Professor of Russian University for People's Friendship and a Full member of Russian Academy for Natural Sciences. He authored over 250 papers. He is interested in scientific fields, such as: Man-Machine Systems, Artificial Intelligence, Fuzzy Sets, Collective Behavior of Learning Automata, Information Theory, Information Safety. He is well known in literature for "Markov - Stefanuk chain". Vadim L. Stefanuk translated about 25 books into Russian language, including very second paper on Fuzzy Sets by L.A. Zadeh.

[6] Dr. Valentina E. Balas is currently Professor at the University Aurel Vlaicu of Arad, Romania. She is author of more than 250 research papers in refereed journals and International Conferences. Her research interests are in Intelligent Systems, Fuzzy Control, Soft Computing, Smart Sensors, Information Fusion, Modeling and Simulation. She is Editor-in Chief to International Journal of Advanced Intelligence Paradigms (IJAIP) and International Journal of Computational Systems Engineering (IJCSysE), member in Editorial Boards for national and international journals, serves as reviewer for many International Journals. She is General Co-Chair to seven editions of International Workshop Soft Computing Applications (SOFA) starting from 2005. As Honorary Chair of SOFA Conferences, Prof. Lotfi A. Zadeh participated to the 2005 and 2007 editions in Arad and Oradea. Dr. Balas was editor for more than 20 books in Springer and Elsevier. She is series editor for the work entitled Elsevier Biomedical Engineering from October 2017. She was Vice-president (Awards) of IFSA International Fuzzy Systems Association Council (2013-2015), responsible with recruiting to European Society for Fuzzy Logic and Technology - EUSFLAT (2011-2013), Senior member IEEE, etc. Dr. Balas invited Prof. Lotfi A. Zadeh to Arad in July 2003 when he was awarded the title of Doctor Honoris Causa at Aurel Vlaicu University of Arad, Romania. She was very good friend of Lotfi A. Zadeh and Fay Zadeh.

Zadeh's daughter, Stella (1947-2006)[7], and his wife, Fay[8] (1920-2017), died before him. Lotfi A. Zadeh is survived by his son, Norman Zadeh.[9]

Lotfi Zadeh's funeral at the Azerbaijan National Academy of Sciences

2.1 Awards

"The "Grigore Moisil" Prize in Fuzzy Systems comes to give a new encouragement to fuzzy system and artificial intelligence scientific community in the name of one of the greatest mathematicians and logicians of this century. It also provides once again a recognition of fuzzy logic, and of Zadeh's work, by the followers of Grigore Moisil."[10]

Lotfi A. Zadeh received many awards and medals, such as: the IEEE Education Medal, the IEEE Richard W. Hamming Medal, the IEEE Medal of Honor, the ASME Rufus Oldenburger Medal, the B. Bolzano Medal of the Czech Academy of Sciences, the Kampe de Feriet Medal, the AACC Richard E. Bellman Control Heritage Award, the Honda Prize, the Okawa Prize, the AIM Information Science Award, the IEEE-SMC J.P. Wohl Career Achievement Award, the SOFT Scientific Contribution Memorial Award of the Japan Society for Fuzzy Theory, the IEEE Millennium Medal, the ACM 2001 Allen Newell Award, the Norbert Wiener Award of the IEEE Systems, Man and Cybernetics Society, the Civitate Honoris Causa by Budapest Tech Polytechnical Institution, the V. Kaufmann Prize (International Association for Fuzzy-Set Management and Economy), the Nicolaus Copernicus Medal of the Polish Academy of Sciences, the J. Keith

[7]Stella Zadeh graduated in 1969 from Radcliffe College and earned a master's degree in journalism in 1971 from the University of California, Los Angeles.

[8]Fay Zadeh authored the book: "My Life and Travels with the Father of Fuzzy Logic", Hardcover, 1998. [128]

[9]Today he is know as Norman Zada and is founder of Perfect 10. "Prior to starting Perfect 10, Zada obtained a doctorate in operations research at the University of California, Berkeley and worked at IBM and was an adjunct mathematics professor at Stanford University, Columbia University, UCLA and University of California, Irvine, writing articles on applied mathematics as well as the 1974 book Winning Poker Systems. After teaching, he won both backgammon and sports handicapping championships. He later became a money manager, and in the 1980s ran a number of financial competitions, including the U.S. Investing Championship. Zada made headlines in 1996 when he offered 400,000 US dollars for anyone successfully refuting his claim that balancing the United States federal budget over a multi-year period without an accompanying substantial trade surplus would be effectively mathematically impossible." Source: `https://en.wikipedia.org/wiki/Norman_Zada`

[10]Lotfi Zadeh was a recipient of a prize awarded by the Romanian Academy: Historical note by I. Bogdan, Al.P. Tacu, H.-N. Teodorescu, E. Sofron, presented at Kyushu Institute of Technology Iizuka, Fukuoka, Japan, 3 AUG 1994 and published in "Fuzzy Sets and Systems", 8, p.367, 1994).

Brimacombe IPMM Award, the Silicon Valley Engineering Hall of Fame, the Heinz Nixdorf Museums Forum Wall of Fame, the Egleston Medal, the Franklin Institute Medal, the Medal of the Foundation by the Trust of the Foundation for the Advancement of Soft Computing, the High State Award "Friendship Order" (from the President of the Republic of Azerbaijan), the Transdisciplinary Award and Medal of the Society for Design and Process Sciences, the BBVA Foundation Frontiers of Knowledge Award in the Information and Communication Technologies[11], the Nizami Gancavi Gold Medal (Azerbaijan, 2016), Golden Goose Award (USA, 2017), and other awards and twenty-four honorary doctorates.[12]

In 2003 Lotfi A. Zadeh became a Doctor Honoris Causa of the Aurel Vlaicu University in Arad, Romania, at the suggestion of prof. V.E. Balas. In 2007 Lotfi Zadeh was elected as a member of the Academy of Technical Sciences of Romania (in the same day as one of co-authors of this paper - F.G. Filip), at the proposal of prof. M. Petrescu.

2.2 Lotfi A. Zadeh: The inventor of fuzzy sets and fuzzy logic

"I believe that my paper would have been rejected if I were not on the Editorial Board. In large measure, comments of my paper were skeptical or hostile. An exception was Japan." (L.A. Zadeh [143])

Lotfi A. Zadeh published his seminal work on fuzzy sets in 1965, in which he detailed the mathematics of fuzzy set theory. In 1973 he proposed his theory of fuzzy logic.

In [143] Lotfi A. Zadeh said about the birth of fuzzy sets: "In July of 1964, I was attending a conference in New York and was staying at the home of my parents. They were away. I had a dinner engagement but it had to be canceled. I was alone in the apartment. My thoughts turned to the unsharpness of class boundaries. It was at that point that the simple concept of a fuzzy set occurred to me. It did not take me long to put my thoughts together and write a paper on the subject. This was the genesis of fuzzy set theory.
I knew that the word "fuzzy" would make the theory controversial. Knowing how the real world functions, I submitted my paper to Information and Control because I was a member of the Editorial Board. There was just one review-which was very lukewarm. I believe that my paper would have been rejected if I were not on the Editorial Board. [...] My paper was a turning point in my research. Since 1965, almost all of my papers relate to fuzzy set theory and fuzzy logic. As I expected, my 1965 paper drew a mixed reaction, partly because the word "fuzzy" is generally used in a pejorative sense, but, more substantively, because unsharpness of class boundaries was not considered in science and engineering. In large measure, comments of my paper were skeptical or hostile. An exception was Japan. In 1968, I began to receive letters from Japan expressing interest in application of fuzzy set theory to pattern recognition. In the years which followed, in Japan fuzzy set theory and fuzzy logic became objects of extensive research and wide-ranging application, especially in the realm of consumer products. A very visible application was the subway system in the city of Sendai - a fuzzy logic based system designed by Hitachi and Kawasaki Heavy Industry. The system began to operate in 1987 and is considered to be a great success."

The departure of fuzzy logic from the classical Aristotelian logic, with a tradition of over two millennia, several mathematicians and scientists has made fuzzy logic an object of controversy, skepticism and hostility. In [116] E. Trillas said: "... important aspect of Zadeh's life is his way

[11]This category has been granted in this fifth edition to the electrical engineer Lotfi A. Zadeh, "for the invention and development of fuzzy logic." This "revolutionary" breakthrough, affirms the jury in its citation, has enabled machines to work with imprecise concepts, in the same way humans do, and thus secure more efficient results more aligned with reality. In the last fifty years, this methodology has generated over 50,000 patents in Japan and the U.S. alone (2013).

[12]https://www2.eecs.berkeley.edu/Faculty/Homepages/zadeh.html

of confronting criticism. Not only did he never avoid criticism of his work, but always encouraged people to criticize his idea; and he did it in a very polite and gentle form. It should be recalled that since Zadeh's first ideas on fuzzy logic fell down the wall of crisp bivalent logic and the mystics of precision, by introducing contextual and purpose driven representations of imprecise concepts, he received strong criticism coming from prestigious researchers. Nevertheless, forty years later, it can be said that Zadeh's ideas not only resisted criticism but imposed on them."

In [139] Lotfi A. Zadeh said about mathematical rigour of fuzzy logic theory:
"Fuzzy logic is not fuzzy. Basically, fuzzy logic is a precise logic of imprecision and approximate reasoning. More specifically, fuzzy logic may be viewed as an attempt at formalization/mechanization of two remarkable human capabilities. First, the capability to converse, reason and make rational decisions in an environment of imprecision, uncertainty, incompleteness of information, conflicting information, partiality of truth and partiality of possibility - in short, in an environment of imperfect information. And second, the capability to perform a wide variety of physical and mental tasks without any measurements and any computations [137, 138].

In fact, one of the principal contributions of fuzzy logic - a contribution which is widely unrecognized - is its high power of precisiation. Fuzzy logic is much more than a logical system. It has many facets. The principal facets are: logical, fuzzy-set-theoretic, epistemic and relational. Most of the practical applications of fuzzy logic are associated with its relational facet".

Since then many authors have developed the theory of fuzzy set and its applications. Especially, many mathematicians tried to extend in fuzzy context classical mathematics results.

The success of the research undertaken has been demonstrated in a variety of areas such as: artificial intelligence, computer science, quantum particle physics, control engineering, robotics and many more. Perhaps the main reason for this rapid development is that the world that surrounds us is full of uncertainty, the data we collect from the environment are, in general, vague and incorrect. So the notion of fuzzy set allows us to study the degree of uncertainty mentioned above in a purely mathematical way [36].

Nowadays, in Quantum computing is used Quantum Logic. Similarities and differences between Fuzzy and Quantum Logic are presented in [105]: "Quantum logic was developed in the context of quantum mechanics. In contrast to fuzzy logic, the logic is not based on membership values but on vector subspaces identified by projectors. The lattice of all projectors provides us with a lattice operations interpreted as conjunction and disjunction. Interestingly, there are relations between both theories. The interaction of a projector with a normalized vector produces a value which can be interpreted directly as fuzzy membership value. This paper shows, that under some circumstances the conjunction of projectors directly corresponds to the t-norm algebraic product in fuzzy logic. However, in contrast to fuzzy logic which is defined on fuzzy sets, quantum logic takes the producing projectors into consideration. As result, we are able to overcome the problem of idempotence for the algebraic product. Furthermore, if we restrict projectors to be mutually commuting we obtain a logic obeying the rules of the Boolean algebra. Thus, quantum logic gives us more insights into the semantics behind the fuzzy norms algebraic product and algebraic sum."

3 Zadeh's visits in Romania

"Zadeh has been a friend of Romanian science, which he prized publicly several times. Zadeh dedicated a single paper to the memory of a scientist -namely, to Grigore C. Moisil, whom he named his friend and supporter. The topic he chose for the paper, approximate reasoning, was cherished by both of them." (H.-N. Teodorescu [113]).

Professor Ioana Moisil[13] let us know that she met Zadeh in 1967 on a visit he had made in Bucharest to her uncle Grigore C. Moisil. This visit was amazing and productive. Zadeh was in Romania at the invitation of Prof. Mircea Stelian Petrescu.[14]

Grigore C. Moisil (1906-1973)[15] himself, on 1968 in the paper "Lukasiewiczian Algebras" [68] writes the following:
Acknowledgment: "During professor L. Zadeh visit to Bucharest, in the autumn 1967, I became acquainted with his work about "fuzzy sets" as a set theory in a logic with totaly ordered set of logical values. The present work exposes the logic of propositions with a totaly ordered set of logical values. The models of this logic of propositions uses an algebraic technic very closed to that given by us in the study of models for propositional logic with a finite number of logic values". (This preprint of the Gr. C. Moisil was reprinted in his book [69], 311-324. His paper [67] was also reprinted in [69], 195-232).

Several Romanian scientists started to study fuzzy theory and their applications, obtaining valuable results, the best performers in the field were Constantin Virgil Negoita[16] and Dan Ralescu[17], who published in collaboration two books, in 1974 [76] (in Romanian), and in 1975 [77](in English). "The first published book ever, specifically devoted to fuzzy sets is the one (in French) by Kaufmann (1973), translated into English in 1975 ([55]), closely followed by a mathematical treatise by Negoita and Ralescu (1975, [77]), based on a 1974 monograph in Romanian ([76])."(Dubois and Prade [34]).

Since 1978, Dan Butnariu[18] published some early papers in fuzzy mathematics field: [19–22].

Anca L. Ralescu[19] and Dan A.Ralescu have many papers published in the field, more quoted being [95](1984), and [96] (1997).

[13]Dr. Ioana I. Moisil is a Professor Honoris Causa of Agora University. She obtained the M.Sc. in mathematics-mechanics at the University of Bucharest, and the Ph.D. in mathematics-statistics and probabilities at the Romanian Academy. She has, as a second specialisation, informatics, and she obtained the scientific degree from the School of Public Health-Universite Libre de Bruxelles, Belgium. She started her career at the Institute for Research in Informatics - ICI Bucharest, then moved on to the Carol Davila University of Medicine, the Ministry of Health and since 1999 at the Lucian Blaga University of Sibiu. She was a full professor at the Lucian Blaga University of Sibiu.

[14]Dr. Mircea S. Petrescu (born 1933) is an Emeritus Professor of the University Politehnica of Bucharest, Romania. He is a honor member of the Romanian Academy. He was a visiting professor at the University of California, Berkeley (1969-1990). He was a very good friend of Lotfi A. Zadeh.

[15]In 1996, Grigore C. Moisil received posthumously the IEEE Computer Pioneer Award for the development of polyvalent logic switching circuits, the Romanian School of Computing, and support of the first Romanian computer. Moisil, one of the greatest Romanian intellectuals, was first of all a gifted mathematician. [70]

[16]Dr. Constantin Virgil Negoita (born 1936 in Bucharest, Romania) is a Romanian computer scientist and writer. He published the first in the world monograph inspired from Zadeh's pioneering work: "Fuzzy Sets and Their Applications" (in Romanian, with Dan Ralescu, Bucharest, 1974) [76]. Since 1982 he served as a professor in Mexico and USA. Since 2009 he is a Professor Emeritus at Department of Computer Science, Hunter College, City University of New York. Other referential books authored by C.V. Negoita are [77–80].

[17]Dr. Dan Ralescu (graduated from University of Bucharest, Romania, 1972) is a Professor at the Department of Mathematical Sciences, University of Cincinnati, Ohio, USA. He is the coauthor of the first comprehensive monograph on fuzzy sets and systems, published in the early 1970s. He has authored and coauthored more than 60 papers in scientific Journals. In the late 1970s he has initiated the theory of fuzzy random variables and mixed models of uncertainty. His recent interests are in statistical decision making under various kinds of uncertainty. He was awarded the IFSA Fuzzy Pioneer in 2003.

[18]Dr. Dan Butnariu (1951-2008) was born in Romania and in 1984 he emigrated to Israel. He received his PhD from A.I. Cuza University of Iasi, Romania and was a post-doctoral fellow at the Weizmann Institute of Science. He was a professor at the University of Haifa and visiting professor in Linz, Texas, Rio, and CUNY. He published over 70 papers in approximation theory, fuzzy game theory, fuzzy topology, etc.

[19]Dr. Anca Ralescu (graduated from University of Bucharest, Romania, 1972) is a Professor at the Department of Mathematical Sciences, University of Cincinnati, Ohio, USA. During 1990-1995 she worked in Japan in the area of Fuzzy Engineering, in connection with the Laboratory for International Fuzzy Engineering (LIFE), including holding the LIFE Endowed Chair of Fuzzy Theory in the Systems Science Department at the Tokyo Institute of Technology.

After 2000 has been published lots of papers and books in fuzzy theory and applications fields, (co)authored by several Romanian scientists. We can enumerate some contributions quoted in this work: Alina Alb-Lupas [2], Razvan Andonie [3], Marius Balas [6–8], Valentina E. Balas [6–8, 58], Adrian I. Ban [9], Boldur E. Barbat [38], Barnabas Bede [11,12], Lucian Coroianu [9], Otilia Dragomir [30], Ioan Dzitac [22,36–41,73,88,107,118,119,145], Simona Dzitac [22,39–41,118,119], Ioan Felea [39–41, 118], Sorin G. Gal [12], George Georgescu [44], Vasile Lupulescu [59], Dorel Mihet [65], Sorin Nadaban [22,71–74], Georgia I. Oros [86,87], Gheorghe Oros [2,86,87], Bogdana Pop-Stanojevic [88, 106, 107], Emil M. Petriu [90], Radu-Emil Precup [89–91], Stefan Preitl [89], Ioan M. Stancu-Minasian [106], Sergiu Rudeanu [100], Horia-Nicolai L. Tedorescu [111–113], Marius L. Tomescu [91], Tiberiu Vesselenyi [39–41, 118, 119] etc.

In 2003, Lotfi A. Zadeh became Doctor Honoris Causa of Aurel Vlaicu University in Arad at the suggestion of professor Valentina E. Balas, who met him at the IMPU 2002 conference in Annecy (France), was due to come to Arad in 2005 (SOFA2005) and to Oradea (SOFA2007), where Ioan Dzitac was very fortunate to meet him through prof. Balas. Lotfi A. Zadeh accepted to be a guest of Agora University in Oradea at ICCCC2008.

3.1 Remembering the beginnings

"The admiration of his followers is well known, but the picture which the critics drew of him was not always a pleasing one." (C.V. Negoita [81])

The following appreciations, authored by Constantin V. Negoita, are reprinted from [81], partially.

"[...] We know Zadeh as we know no other eminent man who have made the last half of the last century memorable in science history. A mere glance at the materials to which we have access still suffice to show that our information regarding him is of such a kind as to leave scarcely anything to be desired. In the first place we have his papers. They are written with talent. He has not only left a minute record of his research during a space of nearly five decades but he found real pleasure in communicating on paper.

As a scientist, he was consistent. His memoir of himself remains unfortunately a fragment, but enough was completed to illustrate that portion of his career during which fuzzy sets were promoted. But if we owe much to the communicativeness of Zadeh himself, we owe much also to the communicativeness of his peers. The admiration of his followers is well known, but the picture which the critics drew of him was not always a pleasing one. They saw him not as he presented himself to the fascinated eye of friendship.

It should be remembered that they knew him only from a vivid immediacy that derives from the speech of witnesses, full of slang of the moment yet extremely serious because the fuzzy set seemed of the utmost cultural significance. What they painted was what they understood, and what they understood was very little.

It is common for logicians to give truth conditions for predicates in terms of set theory. "John is tall" is defined to be true just in case the individual John is in the set of tall men. Zadeh used the same path and said that "tall men" is a fuzzy set when the membership is a matter of degree.

In presenting the theory of fuzzy sets, we hoped to break through the bars of the prison of set theory. To understand a fuzzy set, imagine a two-dimensional world called Flatland. Each Flatlander is incarcerated in a flat set. We can peel him off and place him back somewhere else. If we fling a Flatlander into our three-dimensional world, he can see only two-dimensional cross sections of our world, a family of crisp sets. Simply put, by adding another dimension, we can capture more features. This is what a fuzzy set does. It adds a new dimension: our evaluation of the membership. Using classical flat mathematics, a fuzzy set can be represented by a family of crisp sets, projected on the Flatland.

The classical rules of logic are represented by operations on the set with only two elements: true and false (0 and 1). In the universe of all sets - call it the category of sets - this important set is called classifier. When we tried to investigate the category of fuzzy sets, it was impossible to find a similar classifier. In fact in fuzzy set theory there is no fuzzy set of fuzzy subsets of a fuzzy set. The point is that there are two predicates in set theory: membership and equality. In the category of generalized sets, both can be fuzzy, but in fuzzy set theory only membership is allowed to be. This fact puzzled a lot of people.

Some critics bordered on the vituperative, and the tenets of fuzzy logic were dismissed as comical. Its arguments were declared frivolous and idle exercises in irrelevance and blasphemy. In 1977 Arbib wrote bad reviews for the periodicals, and in 1984 Zeleny published a paper on the (ir)relevancy of fuzzy set theory. That, no doubt, explains why Herbert Toth, in 1987, in his PhD Thesis at the University of Vienna suspected that probably something has gone wrong in the development and interpretation of the theory.

Toth didn't deny Zadeh's original definition to be natural, immediate and elegant. This assertion was sufficiently justified by the vast amount of literature in an epidemically growing number of papers and books.

Perhaps to deter us fuzzy people from further abuse, or perhaps only to improve our connection, Jim Bezdeck established our annual meetings. These are the origins of the international meetings that have today become pilgrimages, where all controversies were clarified when fuzzy sets were represented as families of crisp sets, and the Japanese started to implement fuzzy comptrollers, and, later, fuzzy systems were implemented as neural networks. But, still then, some mathematicians never understood fuzziness, because, for them, the precise specification of a set could be given only by binary logic.

The anatomy of a boom is simple. Over time, most ideas will rise in value. As this happens, people are attracted to them and this causes the ideas to rise more. This further gain attracts more people and gradually, perhaps over a period of a century, the number of people looking for this increase in value comes to determine what ideas are worth. The knowledgeable man, as he unwisely considers himself, is now concerned with the way an idea is attracting interest. That, rightly for the moment, determines its value.

The binary logic, beautiful, useful, and promising, determined the modern era, obsessed with mathematical models. Scientific truths became the pillars of progress. Zadeh, speaking of degrees of truth, shocked the foundation of modernity, and became the postmodern of information sciences. More than that, he defined postmodernity as a return to premodernity.

Why do postmodern scientists, in their advancing years, when love for precision survives, but only barely, cleave to the fluid vagueness as though it were cable for rappelling and not a tightrope any longer?

To embrace the whole from one point of view. The remarks made are less detailed, but more sure. You perceive each object less distinctly, but you describe the facts with more certainty. The details of the immense picture are lost in the shade, but you conceive a clear idea of the entire object.

In the philosophy of science this fact has been known for a long time. In the sixth century, Leontius from Bizantium observed that our impression of the world is vague, not revealing the details. If we attempt to particularize by division into species and individuals, the general view is lost: we are heading not towards truth but towards an infinite regress. In 1906, in France, Pierre Duhem, in a book about physics, its object and structure, distinguished between practical facts expressed in vague, ordinary language and theoretical facts expressed in precise, quantitative language. He argued that confidence in the truth of a vague assertion may be justified just because of its vagueness, which makes the assertion compatible with a whole range of observed facts. There is a balance between precision and certainty: one is increased only to the detriment of the other. [...]

Berkeley was the place where Zadeh was preaching his gospel, but his onslaughts were mercy compared with those terrible philippics in which, at Vanderbilt University in Nashville, Georgescu Roegen gave vent to his rage against arithmomorphism, the worship of numbers. In 1971, in an extraordinary book, The Entropy Law and the Economic Process, among the thesis that he defends is the claim that concepts are not arithmomorphic. They do not overlap. Concepts like "good" or "tall" have no boundaries. Instead they are surrounded by a penumbra within which they overlap with their opposites. At a particular historical moment, he notes, a nation may be both a democracy and a dictatorship just as there is an age when a man is both young and old. To the category of concepts we cannot apply the fundamental law of the binary logic, the principle of excluded middle (X cannot be both A and non-A). [...]

Basically, fuzzy logic is based on the same feeling, and its applications allow engineers to create machines that approach human responses to stimuli, working with incomplete and unclear data to generate positive actions. Using fuzzy logic, Japanese washing machines are able to decide how dirty clothes are, how much water and soap should be used to wash them, and how long it should take to get them clean, all things an experienced launderer would know how to do instinctively. To me, the most impressive accomplishment was a fuzzy system built by Michio Sugeno, in 1985, at the Tokyo Institute of Technology, when he stabilized a helicopter that lost a rotor blade. No human pilot can manage that, and no mathematical model either.

Fuzzy systems, linguistically inspired, are a direct consequence of the seminal papers of Zadeh, published in the 1970s.

In 1975 classical fuzzy set theory had reached its apogee, since solutions of its basic problems were now at hand. Classical fuzzy set theory then changed from an heroic phase, in which we addressed ourselves to hitherto unfathomable questions, to an academic phase, in which a wealth of detail, albeit most important detail, was worked on by an army of competent scholars and technologists following well-established lines. The period of trail blazing was over, though most of the practical benefits were yet to be reaped."

3.2 On the meaning of approximate reasoning: An unassuming subsidiary to Lotfi Zadeh's paper dedicated to the memory of Grigore Moisil

"As Grigore Moisil has also did, Zadeh emphasized in all his work how much language is fundamentally creative." (H.-N. Teodorescu [111])

The following text, authored by H.-N. Teodorescu[20], is reprinted from [111], partially.

"The concept of "approximate reasoning" is central to Zadeh's contributions in logic. Standard fuzzy logic as we use today is only one potential interpretation of Zadeh's concept. I discuss various meanings for the syntagme "approximate reasoning" as intuitively presented in the paper Zadeh dedicated to the memory of Grigore C. Moisil in 1975 [134].

I perceive three central ideas in Zadeh's wide conceptual construction in his work until now. The first one is that words and propositions in natural languages, consequently human thoughts are not representable by standard sets and standard binary predicates. The second central idea in many of Zadeh's papers is that humans perform computations in an approximate manner that

[20]Dr. Horia-Nicolai L. Teodorescu is a Romanian computer scientist, full member of the Romanian Academy. He is a member in editorial board of IJCCC. He have several important contributions in fuzzy/neuro-fuzzy systems, and also he publish many applications of fuzzy methods in engineering, medicine, social sciences and artificial life. He has authored or co-authored over 300 journal and conference papers, holds 24 national and international patents and has received numerous national and international awards and prizes.

real numbers can not represent well. The third idea, which Zadeh presented in his more recent works, is that of granularity of human mental representations and reasoning. These three strong points were represented by Zadeh in various forms and synthesized in the title of his paper on "computing with words" [136].

Most frequently - and Zadeh himself is doing no exception - authors cite as the initial paper clearly stating the approximate reasoning model the one published in the journal Information Sciences, July 1975 [133]. However, another paper published in Synthese [134], during the same year, deals with the main ideas in approximate reasoning, not to mention a conference paper published in 1974.

The paper published in Synthese is important in several ways. First, it offers clear explanations of the meanings associated by Zadeh to the syntagme "approximate reasoning". Second, the paper was published in a well-established journal that "spans the topics of Epistemology, Methodology and Philosophy of Science", thus boldly reaching to a large audience in a set of fundamental disciplines and daringly affirming the importance of the new concepts. Third, the paper is important for the Romanian scientists because it re-enforces the understanding of Grigore Moisil's contributions and the deep connections between Zadeh and Moisil. [...]

Zadeh starts the paper [134] from the common-sense remark that "It is a truism that much of human reasoning is approximate rather than precise in nature." From that remark, he builds a broad program for research.

The program that Zadeh establishes remains, in my opinion, unfinished. In the abstract of the paper discussed here, Zadeh states "Since T [the truth-value set] is not closed under the operations of negation, conjunction, disjunction and implication, the results of an operation on truth-values in T requires, in general, a linguistic approximation by a truth value in T." With this clarification, classic fuzzy logic as we know today is not a proper representation of Zadeh's original ideas.

There are two ways to interpret the above quotation. The first interpretation is in the frame of the classic thinking and runs as follows. Because language is a set of propositions (we restrict the discussion to truth-valuable propositions only), under whatever logic, all simple and composed propositions have a truth value. Denoting the set of truth values by T, the above remark by Zadeh has no effect. Moreover, when defining the truth-valuation function we already need to know the set of truth values, which again makes ineffective Zadeh's remark. Standard fuzzy logic pursue this direction of thinking, as it starts with. Under this approach, as T is given, what is needed is to define the logic operators for the respective logic.

The second interpretation is constructive. It may start with the assumption that language is not predetermined and must be constructed as a recursive, dynamic process, as poets, writers, other language professionals, and laymen do every day. Whenever a new proposition is invented, it is assigned a meaning. The meaning includes what we conveniently name "truth", a coverage degree of the reality that we need for making inferences. The *truth* may or may not be numerically representable. Moreover, the truth of a composed proposition may not be representable by the truth of each of the initial propositions. Therefore, the "set of truth values" evolves continuously. That, in turn, creates a stumbling block. Because we are supposed to know the truth of the original sentences, but not of the result, how are we supposed to infer? The answer proposed by Zadeh is that we still have an approximate truth in the initial set of truth values, approximating the truth of the new proposition. He hypothesizes that there is always an inverse application, which I will name *projection*, from the new truth set to the original one, indicating a truth degree in the original set that approximates the truth degree of the composed proposition. That makes our reasoning possible, if approximate.

This way of thinking, more or less directly suggested by Zadeh, opens the door to several formal descriptions. I sketch below a loose formalism for the recursive approach.

Consider a language $L = (\{p\}, c_1, c_2, \cdots c_r)$, where p denotes extant propositions and c_k logic operators (either unary or binary). Notice that L is an initial language, meaning that the initial set $\{p\}$ is evolvable, that is, it is recursively increased by adding propositions correctly formed from the initial ones through logic operations. Assume that any proposition has a characteristic named truth value. Thus, there is some set T of truth values (I use for this set the same notation as Zadeh's), as well as an application such that for any proposition p there is a truth value in T. Also assume that any propositions can be concatenated to produce a new or extant proposition. Whenever such proposition is new in the language, it has a characteristic truth value which is not necessarily in T. We can regard the creation of new propositions (including those used for reasoning) as producing an application $T \to T\prime$, as for the negation operator, or $T \times T \times \cdots \to T\prime$, as for the connectives. The new $T-$set which includes the original one. Moreover, for satisfying Zadeh's hypothesis, there is a projection operation ϑ. Notice that whenever a new proposition is produced, L is modified.[...]

The main requirements for the T^*-set are: i) The truth-attribute of a proposition is represented by an application $\theta : L \to T$, where T is measurable. ii) For any two extant propositions p_1 and p_2 and for any connective c, the new proposition p_1cp_2 has a truth degree such that $T \cup \{\theta(p_1cp_2)\}$ is measurable and includes the measurable space T. iii) For any valid linguistic construction that uses logic operators, there is an application $\vartheta : T\prime \to T\prime$, named back-projection. iv) For any connective c, there is a formula f_c such that $\vartheta(\theta(p_1cp_2))$ and $f_c(\theta(p_1), \theta(p_2))$ are two points close enough in T.

Standard fuzzy logic obviously satisfies the above conditions, with $T = T\prime$. Replacing the measurable space with a metric one, we obtain another construction, which may be closer to Zadeh's intuition in [134]. Using distances $d : T \to T$, the conditions to satisfy are:

$$d(\vartheta(\neg p), 1 - \theta(p)) < \varepsilon$$

$$d(\vartheta(p \bigwedge q), min(\theta(p), \theta(q)) < \varepsilon$$

$$d(\vartheta(p \bigvee q), max(\theta(p), \theta(q)) < \varepsilon,$$

where ε is the allowed approximation error.

As Grigore Moisil has also did, Zadeh emphasized in all his work how much language is fundamentally creative. By stating that "$T \cdots$ is not closed under the logic operations", he highlights that there is always generation of new meaning, or at least an evolution of the meaning, whenever a sentence is uttered. I believe that this is one of the fundamental contributions made by Zadeh's work until now.

Understanding the creative process in languages and in reasoning was significantly elucidated by Zadeh's work, yet much remains to be done for deriving conclusions and theoretical developments in the directions pointed to by his works. The developments informally suggested above may indicate several such directions, yet others may be put forward in a more formal manner during the years to come."

4 Visit of Lotfi A. Zadeh at the Agora University

In 2008 L.A. Zadeh was a keynote speaker at the International Conference on Computers Communications and Control (ICCCC2008)[21], organized by the Agora University of Oradea, Romania.

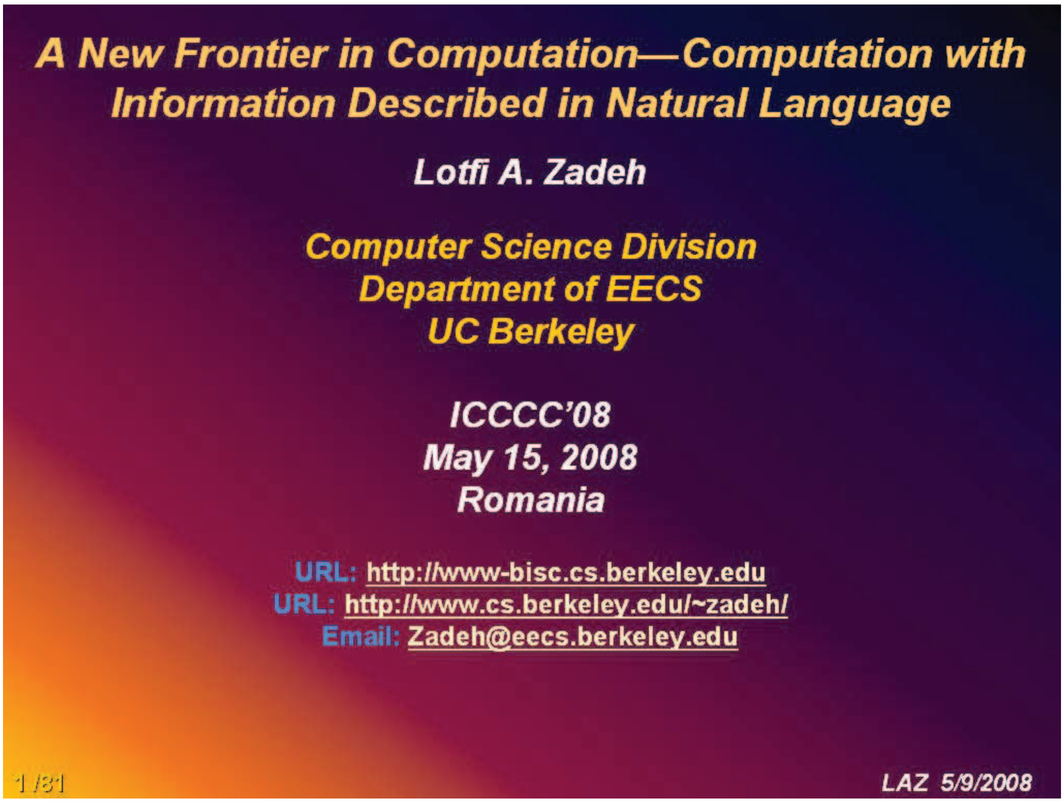
D. Tufis, I. Dzitac, L.A. Zadeh, M.J. Manolescu and F.G. Filip
(ICCCC2008, Agora University)

After ICCCC2008 we published in vol. 3 of IJCCC/2008, in a supplementary issue, several papers on topics related to fuzzy theory and its applications, authored by: I. Dzitac [37]; L.A. Zadeh [140]; M.M. Balas, and V.E. Balas [6]; D.G. Radojevic [92]; A. Bazoula , M.S Djouadi., and H. Maaref [10]; G.C.Crisan, and E. Nechita [25]; O. Dragomir, R. Gouriveau, and N. Zerhouni [30]; S. Dzitac , I. Felea, I. Dzitac, and T. Vesselenyi [40]; N. Nikolova, S. Ahmed, K. Tenekedjiev [82].

Under the umbrella of the ICCCC2008, on the occasion of an exploratory workshop, we edited the volume "From Natural Language to Soft Computing: New Paradigms in Artificial Intelligence", co-edited by Lotfi A. Zadeh, Dan Tufis, Florin Gheorghe Filip, Ioan Dzitac [145]. In this volume there were published 14 papers and one appendix, by authors from Bulgaria, Chile, Hungary, Romania, Serbia and Spain: Marius M. Balas, and Valentina E. Balas [7, 8]; Ioan Buciu, and Ioan Nafornita [18]; Camelia Chira, Camelia M. Pintea, and D. Dumitrescu [27]; Felisa M. Cordova, and Luis E. Quezada [28]; Simona Dzitac, Ioan Felea, Ioan Dzitac and Tiberiu Vesselenyi [41]; Gaston Lefranc [57]; Natalia Nikolova, Daniela Toneva, Sevda Ahmed, and Kiril

[21] "Dear Professor Dzitac, Please accept my apology for not writing to you earlier. I was away on travel much of the time during the past three weeks. With regard to sending you a paper for publication in your book, I do not have a written version of my presentation. I have other papers, which are attached, which are scheduled for publication in journals. Currently, I am working on a paper but it is on a subject different from the one that I presented in your Conference. I appreciate your including my name as a co-editor of your book "From Natural Language to Soft Computing: New Paradigms in Artificial Intelligence." However, be sure to list my name after the names of Professor Tufis, Filip and yourself. I should like to take this opportunity again to extend to you, Professor Tufis, Professor Filip and your associates my great appreciation for the very warm welcome which was extended to me in Oradea. With my warmest regards, Sincerely, Lotfi Zadeh." (From: Lotfi A. Zadeh, Sent: Wednesday, July 23, 2008 2:21 AM; To: Ioan Dzitac).

Volume co-edited by L.A. Zadeh, D. Tufis, F.G. Filip and I. Dzitac
(2008, Romanian Academy) [145]



First slide of the plenary lecture of Lotfi A. Zadeh
at ICCCC2008, Agora University of Oradea, Romania

Tenekedjiev [83]; Dragan G. Radojevic [93]; Emilio del Rosal, Rafael Nunez, Carlos Castaneda, and Alfonso Ortega, [94]; Imre J. Rudas, and Janos Fodor [97]; Gheorghe Stefanescu, and Camelia Chira, [108]; Dan Tufis [115] and Lotfi A. Zadeh [141], [142].

Also since 2008, he accepted to join the editorial board of our IJCCC.

IJCCC has published in Zadeh's honour two special issues:

1. *Special Issue on Fuzzy Sets and Systems Dedicated to the 90th Birthday of Prof. Lotfi A. Zadeh*, Guest Editors: Valentina Emilia Balas, Ioan Dzitac and Horia-Nicolai Teodorescu (IJCCC, Year: 2011, Volume: 6, Number: 3).

In the first special issue papers have been published by the following authors: L.A. Zadeh [144]; H. Benitez-Perez, F. Cardenas-Flores, F. Garcia-Nocetti [14]; I. Dzitac, T. Vesselenyi, R.C. Tarca [39]; T.C. Lin, C.H. Kuo, V.E. Balas [58]; A. Meyer, H.-J. Zimmermann [63]; G.I. Molnarka, L.T. Koczy [66]; C.V. Negoita [81]; C.N. Nyirenda, F. Dong, K. Hirota [84]; M.Z. Reformat, R.R. Yager, Z. Li, N. Alajlan [98]; N. Sahab, H. Hagras [101]; R. Seising [104]; D.E. Tamir, A. Kandel [109]; H.-N.L. Teodorescu [111].

2. *Special Issue on Fuzzy Sets and Applications Dedicated to the 50th Anniversary of "Fuzzy Sets" Published by Lotfi A. Zadeh in 1965* (Year: 2015, Volume: 10, Issue: 6).

In this second special issue the following authors have published articles: R.R. Yager [127]; I. Dzitac [36]; S. Ashraf, A. Rehman, E.E. Kerre [4]; O. Bologa, R.E. Breaz, S.G. Racz [16]; Z.-B. Du, T.-C. Lin, T.-B. Zhao [31]; V. Kreinovich, C. Stylios [56]; S. Nadaban [71]); R.-E. Precup, M.L. Tomescu, E.M. Petriu [91]; X. Tang, L. Shu [110]; H.-N.L. Teodorescu [112]; Z. Turskis, E.K. Zavadskas, J. Antucheviciene, N. Kosareva [117]; H.-D. Wang, S.-C. Guo, S.M. Hosseini Bamakan, Y. Shi [120]; T. Wang, G. Zhang, M.J. Perez-Jimenez [121]; H. Xu, R. Vilanova [126].

IJCCC also published several papers on applications of fuzzy methods, such as [118], and [119].

4.1 Lotfi A. Zadeh: Foreword (IJCCC, Issue 3, 2011)

"In the early nineties, a thought that began to crystallize in my mind was that in most of the applications of fuzzy logic linguistic concepts play an important, if not very visible role." (L.A. Zadeh [144])

The following text, authored by Lotfi A. Zadeh, is reprinted integral from [144].

"I feel honored by the dedication of the Special Issue of IJCCC to me. I should like to express my deep appreciation to the distinguished Co-Editors and my good friends, Professors Balas, Dzitac and Teodorescu, and to distinguished contributors, for honoring me. The subjects which are addressed in the Special Issue are on the frontiers of fuzzy logic.

The Foreword gives me an opportunity to share with the readers of the Journal my recent thoughts regarding a subject which I have been pondering about for many years - fuzzy logic and natural languages. The first step toward linking fuzzy logic and natural languages was my 1973 paper," Outline of a New Approach to the Analysis of Complex Systems and Decision Processes." Two key concepts were introduced in that paper. First, the concept of a linguistic variable - a variable which takes words as values; and second, the concept of a fuzzy if- then rule - a rule in which the antecedent and consequent involve linguistic variables. Today, close to forty years later, these concepts are widely used in most applications of fuzzy logic.

The second step was my 1978 paper, "PRUF - a Meaning Representation Language for Natural Languages." This paper laid the foundation for a series of papers in the eighties in which a fairly complete theory of fuzzy - logic-based semantics of natural languages was developed. My theory did not attract many followers either within the fuzzy logic community or within the linguistics and philosophy of languages communities. There is a reason. The fuzzy logic community is largely a community of engineers, computer scientists and mathematicians - a community which has always shied away from semantics of natural languages. Symmetrically, the linguistics and philosophy of languages communities have shied away from fuzzy logic.

In the early nineties, a thought that began to crystallize in my mind was that in most of the applications of fuzzy logic linguistic concepts play an important, if not very visible role. It is this thought that motivated the concept of Computing with Words (CW or CWW), introduced in my 1996 paper "Fuzzy Logic = Computing with Words." In essence, Computing with Words is a system of computation in which the objects of computation are words, phrases and propositions drawn from a natural language. The same can be said about Natural Language Processing (NLP.) In fact, CW and NLP have little in common and have altogether different agendas.

In large measure, CW is concerned with solution of computational problems which are stated in a natural language. Simple example. Given: Probably John is tall. What is the probability that John is short? What is the probability that John is very short? What is the probability that John is not very tall? A less simple example. Given: Usually Robert leaves office at about 5 pm. Typically it takes Robert about an hour to get home from work. What is the probability that Robert is home at 6:l5 pm.? What should be noted is that CW is the only system of computation which has the capability to deal with problems of this kind. The problem-solving capability of CW rests on two key ideas. First, employment of so-called restriction-based semantics (RS) for translation of a natural language into a mathematical language in which the concept of a restriction plays a pivotal role; and second, employment of a calculus of restrictions - a calculus which is centered on the Extension Principle of fuzzy logic.

What is thought-provoking is that neither traditional mathematics nor standard probability theory has the capability to deal with computational problems which are stated in a natural language. Not having this capability, it is traditional to dismiss such problems as ill-posed. In this perspective, perhaps the most remarkable contribution of CW is that it opens the door to empowering of mathematics with a fascinating capability - the capability to construct mathematical solutions of computational problems which are stated in a natural language. The basic importance of this capability derives from the fact that much of human knowledge, and especially world knowledge, is described in natural language.

In conclusion, only recently did I begin to realize that the formalism of CW suggests a new and challenging direction in mathematics - mathematical solution of computational problems which are stated in a natural language. For mathematics, this is an unexplored territory."

4.2 Ronald R. Yager: Foreword (IJCCC, Issue 6, 2015)

"Interestingly a number of researchers from Romania, the home of this journal, were among the early supporters of ideas presented by Zadeh." (R.R. Yager [127])

Following text, authored by Ronald R. Yager[22], is reprinted integral from [127].

"Here we are celebrating the fiftieth anniversary of Lotfi Zadeh's pioneering paper Fuzzy Sets that appeared in Information and Control in 1965. While the paper was clear, direct and easy to understand the ideas presented were revolutionary and ground breaking. This article now has close to sixty thousand citations as noted in Google Scholar. Clarity and simplicity are the hallmark of the writing of Zadeh. This has always reminded me of the writings of Sigmund Freud. One rarely needs to draw on complex mathematics to read Zadeh's papers.

The capacity of fuzzy sets to represent and manage imprecise linguistic concepts has proven to

[22]Ronald R. Yager is a Professor of Information Systems and Director of the Machine Intelligence Institute at Iona College. He is among the world's most highly cited researchers with over 61,000 citations to his work in Google Scholar. He has published over 500 papers and edited over 30 books in areas related to fuzzy sets, human behavioral modeling, decision-making under uncertainty and the fusion of information.

be of great use in the modern technological world where there is now a great interest in building intelligent systems that can model human reasoning but take advantage of the vast amount of information available on the Internet. If the idea of fuzzy sets was not introduced in Zadeh's ground breaking paper in the 1960's it would have naturally arisen in early 2000's as we moved into intelligent systems. However the early reception of fuzzy sets was not very promising both the Artificial Intelligence community and the probabilistic community were very dubious of the worth of this new field.

Interestingly a number of researchers from Romania, the home of this journal, were among the early supporters of ideas presented by Zadeh. Zadeh persevered in the face of adversity, describing himself as thick skinned, until mid 1980's when the Japanese engineers provided significant applications of fuzzy sets in control systems. Particularly notable among these applications was the use of fuzzy control to the Sendai subway. These applications brought a new appreciation to the possibilities of fuzzy sets and clearly changed its history.

The editors of this Special Issue of the International Journal of Computers Communications & Control dedicated to the 50th anniversary of the publication of Lotfi Zadeh's pioneering paper Fuzzy Sets have provided a collection of papers representative of the current state of the field of fuzzy sets. Included in this issue are papers investigating some current theoretical issues and applied papers in domains in which fuzzy sets has introduced some benefits.

The editorial team is to be congratulated for providing a wonderful anniversary gift to Professor Zadeh and a useful collection of articles for the community."

5 Several concepts of fuzzy mathematics

Following concepts and results are partial reprinted from papers [36], [73], [71], [74], and [107] (authored/co-authored by I. Dzitac, S. Dzitac, S. Nadaban and B. Stanojevic).

5.1 Fuzzy sets

Definition 1. [129] A fuzzy set in X is a function $\mu : X \to [0,1]$. We denote by $\mathcal{F}(X)$ the family of all fuzzy sets in X.

Remark 2. In fact μ is the membership function of a fuzzy set A of X and the value $\mu(x)$ represents "the grade of membership" of x to fuzzy set A. But, in this paper, we adopt the convention to identify fuzzy sets with their membership functions. This identification was first used by J.A. Goguen [46].

Remark 3. As any subset of X can be identified with its characteristic function we remark that fuzzy sets generalize subsets.

Definition 4. [129] Let μ, ν be fuzzy sets in X. The union of fuzzy sets μ şi ν, denoted $\mu \vee \nu$, the intersection of fuzzy sets μ şi ν, denoted $\mu \wedge \nu$, the complement of fuzzy set μ, denoted $1-\mu$, are fuzzy sets in X, defined by

$$(\mu \vee \nu)(x) = \max\{\mu(x), \nu(x)\} \tag{1}$$

$$(\mu \wedge \nu)(x) = \min\{\mu(x), \nu(x)\} \tag{2}$$

$$\mathcal{C}(\mu)(x) = 1 - \mu(x) \tag{3}$$

Definition 5. The union of the fuzzy sets $\{\mu_i\}_{i \in I}$ is defined by

$$\left(\bigvee_{i \in I} \mu_i\right)(x) = \sup\{\mu_i(x) \ : \ i \in I\} \ .$$

The intersection of the fuzzy sets $\{\mu_i\}_{i\in I}$ is defined by

$$\left(\bigwedge_{i\in I}\mu_i\right)(x) = \inf\{\mu_i(x)\ :\ i \in I\}\ .$$

Definition 6. Let $\alpha \in (0,1]$, and let μ be a fuzzy set in X. The α-level set $[\mu]_\alpha$ is defined by

$$[\mu]_\alpha := \{x \in X\ :\ \mu(x) \geq \alpha\}\ .$$

The support of μ is

$$\text{supp}\ \mu := \{x \in X\ :\ \mu(x) > 0\}\ .$$

Definition 7. [129] Let X be a vector space over a field $\mathbb{K}$ (where $\mathbb{K}$ is $\mathbb{R}$ or $\mathbb{C}$). A fuzzy set μ is called convex if

$$\mu(\lambda x_1 + (1-\lambda)x_2) \geq \min\{\mu(x_1), \mu(x_2)\}\ ,\ (\forall)x_1, x_2 \in X, (\forall)\lambda \in [0,1]\ .$$

The extension principle is undoubtedly one of the most important of Zadeh's contribution in fuzzy set theory, allowing to extend in a fuzzy context almost any mathematical concept. The extension principle was introduced by Zadeh [129] in 1965, and then it suffered many changes: Zadeh [133]; Jain [52]; Dubois & Prade [32]. [...]

Let $X = X_1 \times X_2 \times \cdots \times X_r$ and $\mu_1, \mu_2, \cdots, \mu_r$ be fuzzy sets in $X_1, X_2, \cdots, X_r$, respectively. Let $f : X \to Y$. The extension principle allows us to define a fuzzy set in Y by

$$\mu(y) = \begin{cases} \sup\limits_{(x_1,\cdots,x_r)\in f^{-1}(y)} \min\{\mu_1(x_1), \cdots, \mu_r(x_r)\} & \text{if} \quad f^{-1}(y) \neq \emptyset \\ 0 & \text{if} \quad f^{-1}(y) = \emptyset \end{cases}\ .$$

5.2 Fuzzy relations

It is well known that the fuzzy relations play an important role in fuzzy modeling and fuzzy control and they also have important applications in relational databases, approximate reasoning, preference modeling, medical diagnosis.

The concept of fuzzy relation was introduced by L.A. Zadeh:

A fuzzy relation T between two nonempty sets X and Y is a fuzzy set in $X \times Y$, i.e. it is a mapping $T : X \times Y \to [0,1]$. We denote by $FR(X,Y)$ the family of all fuzzy relations between X and Y.

For $x \in X$ we denote by T_x the fuzzy set in Y defined by $T_x(y) = T(x,y)$. Thus, a fuzzy relation can be seen as a mapping $X \ni x \mapsto T_x \in \mathcal{F}(Y)$, where $\mathcal{F}(Y)$ represents the family of all fuzzy sets in Y. [36]

5.3 Fuzzy real numbers and fuzzy interval

Definition 8. A fuzzy set in $\mathbb{R}$, namely a mapping $x : \mathbb{R} \to [0,1]$, with the following properties:

1. x is convex, i.e. $x(t) \geq \min\{x(s), x(r)\}$, for $s \leq t \leq r$;

2. x is normal, i.e. $(\exists)t_0 \in \mathbb{R}\ :\ x(t_0) = 1$;

3. x is upper semicontinuous, i.e.

$$(\forall)t \in \mathbb{R}, (\forall)\alpha \in (0,1]\ :\ x(t) < \alpha,$$

$$(\exists)\delta > 0 \text{ such that } |s-t| < \delta \Rightarrow x(s) < \alpha$$

is called a fuzzy real number. We will denote by $\mathbb{R}(I)$ the set of all fuzzy real numbers.

Remark 9. Let $x \in \mathbb{R}(I)$. For all $\alpha \in (0,1]$, the α-level sets $[x]_\alpha = \{t : x(t) \geq \alpha\}$ are closed intervals $[a_\alpha, b_\alpha]$, where the values $a_\alpha = -\infty$ and $b_\alpha = \infty$ are admissible. When $a_\alpha = -\infty$, the interval $[a_\alpha, b_\alpha]$ will be denoted by $(-\infty, b_\alpha]$.

Definition 10. A fuzzy real number x is called non-negative if $x(t) = 0, (\forall)t < 0$. The set of all non-negative real numbers will be denoted by $\mathbb{R}^*(I)$.

Remark 11. For each $r \in \mathbb{R}$ we can consider the fuzzy real number $\overline{r}$ defined by

$$\overline{r}(t) = \begin{cases} 1 & \text{if} \quad t = r \\ 0 & \text{if} \quad t \neq r \end{cases} .$$

These fuzzy numbers are called crisp. Thus $\mathbb{R}$ can be embedded in $\mathbb{R}(I)$.

Definition 12. [64] The arithmetic operations $+, -, \cdot, /$ on $\mathbb{R}(I)$, are defined by:

$$(x+y)(t) = \bigvee_{s \in \mathbb{R}} \min\{x(s), y(t-s)\}, \ (\forall)t \in \mathbb{R} \tag{4}$$

$$(x-y)(t) = \bigvee_{s \in \mathbb{R}} \min\{x(s), y(s-t)\}, \ (\forall)t \in \mathbb{R} \tag{5}$$

$$(xy)(t) = \bigvee_{s \in \mathbb{R}^*} \min\{x(s), y(t/s)\}, \ (\forall)t \in \mathbb{R} \tag{6}$$

$$(x/y)(t) = \bigvee_{s \in \mathbb{R}} \min\{x(ts), y(s)\}, \ (\forall)t \in \mathbb{R} \tag{7}$$

Remark 13. Previous definitions are special cases of Zadeh's extension principle.

Remark 14. The additive and multiplicative operations are associative and commutative with the identities $\overline{0}$ and $\overline{1}$, where

$$\overline{0}(t) = \begin{cases} 1 & \text{if} \quad t = 0 \\ 0 & \text{if} \quad t \neq 0 \end{cases}, \ \overline{1}(t) = \begin{cases} 1 & \text{if} \quad t = 1 \\ 0 & \text{if} \quad t \neq 1 \end{cases} .$$

Remark 15. It is obvious that

1. $-x = \overline{0} - x$;
2. $(-x)(t) = x(-t)$;
3. $x - y = x + (-y)$;
4. $-(x+y) = (-x) + (-y)$.

Definition 16. The absolute value $|x|$ of $x \in \mathbb{R}(I)$ is defined by

$$|x|(t) = \begin{cases} \max\{x(t), x(-t)\} & \text{if} \quad t \geq 0 \\ 0 & \text{if} \quad t < 0 \end{cases} .$$

Proposition 17. [54] The equations $a + x = \overline{0}$ and $ax = \overline{1}$ have unique solutions if and only if a is crisp.

Definition 18. [42] A partial ordering on $\mathbb{R}(I)$ is defined by

$$x \leq y \text{ if } a^1_\alpha \leq a^2_\alpha \text{ and } b^1_\alpha \leq b^2_\alpha \ , \ (\forall)\alpha \in (0,1] \ ,$$

where $[x]_\alpha = [a^1_\alpha, b^1_\alpha]$ and $[y]_\alpha = [a^2_\alpha, b^2_\alpha]$.

Proposition 19. [54] If $[a_\alpha, b_\alpha]$, $0 < \alpha \leq 1$, are the α-level sets of a fuzzy real number x, then:

1. $[a_{\alpha_1}, b_{\alpha_1}] \supseteq [a_{\alpha_2}, b_{\alpha_2}]$, $(\forall) 0 < \alpha_1 \leq \alpha_2$;

2. $[\lim_{k\to\infty} a_{\alpha_k}, \lim_{k\to\infty} b_{\alpha_k}] = [a_\alpha, b_\alpha]$, where $\{\alpha_k\}$ is an increasing sequence in $(0, 1]$ converging to α.

Conversely, if $[a_\alpha, b_\alpha]$, $0 < \alpha \leq 1$, is a family of non-empty intervals which satisfy the conditions (1) and (2), then the family $[a_\alpha, b_\alpha]$ represents the α-level sets of a fuzzy real number.

Remark 20. As α-level sets of a fuzzy real number is an interval, there is a debate in the nomenclature of fuzzy real numbers. D. Dubois and H. Prade [32] suggested to call this *fuzzy interval*.

6 Fuzzy logic and fuzzy languages

The following subsections, authored by Rudolf Seising[23] in 2011, are reprinted from [104], partially.

6.1 From logic of inexact concepts to fuzzy logic

"It should be noted that a membership function may be regarded as a predicate in a multivalued logic in which the truth values range over [0, 1]." (L.A. Zadeh)

To understand what happened from coming from Fuzzy Sets and Systems to the idea of the computational theory of perceptions (CTP) we have go once again back to the roots.

In the 1960s Zadeh looked for applying fuzzy sets in linguistics. This idea led to interdisciplinary scientific exchange on the campus of the University of California at Berkeley between him and the mathematician Joseph Goguen (1941-2006) - who was a Ph. D. student of his, his Berkeley-colleague Hans-Joachim Bremermann (1926-1996), who was then in the mathematics department on the one hand and between the psychologist Eleanor Rosch (Heider) (born 1938) and the Berkeley-linguist George Lakoff (born 1941) on the other.

Zadeh had served as first reviewer for Goguens's Ph.D. thesis "Categories of Fuzzy Sets" [45] and Bremermann served as the second.

In this work, Goguen generalized the fuzzy sets to so-called "L-sets" [47]. An L-set is a function that maps the fuzzy set carrier X into a partially ordered set $L : A : X \to L$.

The partially ordered set L Goguen called the "truth set" of A. The elements of L can thus be interpreted as "truth values"; in this respect, Goguen then also referred to a *Logic of Inexact Concepts* [48].

Since Zadeh's earlier definition had established this truth set as the unit interval, Fuzzy Set Theory was very soon associated with multi-valued logics, and also Lotfi Zadeh mentioned this in later papers, e.g.: "It should be noted that a membership function may be regarded as a predicate in a multivalued logic in which the truth values range over [0, 1]."

Goguen's generalization of the set of values to a set L for which the only condition was to be partially ordered cleared up these misunderstandings. Goguen's work was laid out in terms of

[23]Rudolf Seising received his MS degree in mathematics from the Ruhr University of Bochum in 1986, and PhD from the Ludwig Maximilians University (LMU) of Munich in 1995. In 2008 and from 2014 to 2016 he was acting as a professor for the history of science at the Friedrich-Schiller-University Jena. In 2010 he was acting as a professor for science history at the Ludwig-Maximilians-University Munich. He has been Visiting Scholar at the University of California at Berkeley in 2000, 2001 and 2002 and at the University of Turku, Finland in 2008. From 2009 to 2014 he was Adjoint Researcher at the European Centre for Soft Computing in Mieres, Spain.

logical algebra and category theory, and his proof of a representation theorem for L-sets within category theory justified Fuzzy Set Theory as an expansion of set theory.

6.2 Fuzziness for biology and computer science. Fuzzy algorithms

Also in 1969 Zadeh gave a talk on "Biological Applications of the Theory of Fuzzy Sets and Systems" [130] where he proposed his new mathematical theory to the life scientists, when he wrote:

"The great complexity of biological systems may well prove to be an insuperable block to the achievement of a significant measure of success in the application of conventional mathematical techniques to the analysis of systems [130]".

"By 'conventional mathematical techniques' in this statement, we mean mathematical approaches for which we expect that precise answers to well-chosen precise questions concerning a biological system should have a high degree of relevance to its observed behavior. Indeed, the complexity of biological systems may force us to alter in radical ways our traditional approaches to the analysis of such systems. Thus, we may have to accept as unavoidable a substantial degree of fuzziness in the description of the behavior of biological systems as well as in their characterization." [130]

In the same year he wrote more generally:

"What we still lack, and lack rather acutely, are methods for dealing with systems which are too complex or too ill-defined to admit of precise analysis. Such systems pervade life sciences, social sciences, philosophy, economics, psychology and many other 'soft' fields."

Since that time, Zadeh is inspired by the "remarkable human capability to perform a wide variety of physical and mental tasks without any measurements and any computations", e. g. parking a car, playing golf, deciphering sloppy handwriting, and summarizing a story.

However, in 1970, 20 years after later then his first paper on "Thinking machines", Zadeh was aware of Turing's philosophical article when he presented his paper "Fuzzy Languages and their Relations to Human and Machine Intelligence" at the conference "Man and Computer" in Bordeaux, France: "The question of whether or not machines can think has been the subject of many discussions and debates during the past two decades."
He continued:

"As computers become more powerful and thus more influential in human affairs, the philosophical aspects of this question become increasingly overshadowed by the practical need to develop an operational understanding of the limitations of the machine judgment and decision making ability. Can computers be relied upon to match people, decide on promotions and dismissals, make medical diagnoses, prescribe treatments, act as teachers, formulate business, political and military strategies, and, more generally, perform intellectual tasks of high complexity which in the past required expert human judgment? Clearly, this is already a pressing issue which is certain to grow in importance in the years ahead."

He called it a paradox that the human brain is always solving problems by manipulating "fuzzy concepts" and "multidimensional fuzzy sensory inputs" whereas "the computing power of the most powerful, the most sophisticated digital computer in existence is not able to do this". Therefore, he stated that "in many instances, the solution to a problem need not be exact, so that a considerable measure of fuzziness in its formulation and results may be tolerable. The human brain is designed to take advantage of this tolerance for imprecision whereas a digital computer, with its need for precise data and instructions, is not."

One year later these arguments should culminate in Zadeh's *Principle of Incompatibility* whereas here he intended to push his theory of fuzzy sets to model the imprecise concepts and directives:

"Indeed, it may be argued that much, perhaps most, of human thinking and interaction with the outside world involves classes without sharp boundaries in which the transition from membership to non-membership is gradual rather than abrupt."

He stated:

"Although present-day computers are not designed to accept fuzzy data or execute fuzzy instructions, they can be programmed to do so indirectly by treating a fuzzy set as a data-type which can be encoded as an array [...]."

Granted that this is not a fully satisfactory approach to the endowment of a computer with an ability to manipulate fuzzy concepts, it is at least a step in the direction of enhancing the ability of machines to emulate human thought processes. It is quite possible, however, that truly significant advances in artificial intelligence will have to await the development of machines that can reason in fuzzy and non-quantitative terms in much the same manner as a human being."

In August 1967, the Filipino electrical engineer William Go Wee (born 1937) at Purdue University in Indiana had submitted his dissertation "On Generalizations of Adaptive Algorithms and Application of the Fuzzy Sets Concept to Pattern Classification" that he had written under King Sun Fu, one of the pioneers in the field of pattern recognition.

Wee had applied the fuzzy sets to iterative learning procedures for pattern classification and had defined a finite automaton based on Zadeh's concept of the fuzzy relation as a model for nonsupervised learning systems:

"The decision maker operates deterministically. The learning section is a fuzzy automaton. The performance evaluator serves as an unreliable "teacher" who tries to teach the "student" to make right decisions."

The fuzzy automaton representing the learning section implemented a "nonsupervised" learning fuzzy algorithm and converged monotonously. Wee showed that this fuzzy algorithm could not only be used in the area of pattern classification but could also be translated to control and regulation problems. He also demonstrated that the fuzzy automaton he had defined contained the concepts of deterministic and non-deterministic automata as special cases: "Based on the concept of fuzzy relation defined by Zadeh, a class of fuzzy automata is formulated similar to that of Mealy's definition. A fuzzy automaton behaves in a deterministic fashion. However, it has many properties similar to that of a probabilistic automaton."

Working with his doctoral advisor, Wee presented his findings in the article "A Formulation of Fuzzy Automata and its Applications as a Model of Learning Systems".

At the end of the same year the Chinese student Chin-Liang Chang completed his dissertation "Fuzzy Sets and Pattern Recognition" that was an advancement of Zadeh's thoughts on the separation problem in pattern recognition. This was the first Ph D dissertation on Fuzzy Sets that was supervised by Lotfi Zadeh. Chang had also had contact with Professor King Sun Fu to whom he expresses gratitude for the conversations they shared.

Two years later, in "Towards a Theory of Fuzzy Systems" that was first printed as a report in 1969, Zadeh's goal was a theory for all systems - including those that were too complex or poorly defined to be accessible to a precise analysis. Alongside the systems of the "soft" fields, the "non-soft" fields were replete with systems that were only "unsharply" defined, namely "when the complexity of a system rules out the possibility of analyzing it by conventional mathematical means, whether with or without the computers".

As he would also do in the same year in Bordeaux, Zadeh was already pointing out here the usefulness of fuzzy sets in computer science: In describing their fields of application, he enumerated the problems that would be solved by future computers. Alongside pattern recognition, these included traffic control systems, machine translation, information processing, neuronal networks and games like chess and checkers. We had lost sight of the fact that the class of non-trivial problems for which one could find a precise solution algorithm was very limited, he wrote. Most real problems were much too complex and thus either completely unsolvable algorithmically or – if they could be solved in principle – not arithmetically feasible. In chess, for instance, there was in principle an optimal playing strategy for each stage of the game; in reality, however, no computer was capable of sifting through the entire tree of decisions for all of the possible moves with forward and backward repetitions in order to then decide what move would be the best in each phase of the game. The set of good strategies for playing chess had fuzzy limits similar to the set of tall men - these were fuzzy sets. By far the most systems that remained to be solved were fuzzy systems, and in a footnote Zadeh remarks that the automata proposed by Wee and his supervisor Eugene Santos were also considered examples of fuzzy systems.

To make fuzziness a part of system theory, Zadeh presented in 1968 "fuzzy algorithms". With that, he had fuzzified the central concept of computer sciences. "The concept in question will be called a fuzzy algorithm because it may be viewed as a generalization, through the process of fuzzification, of the conventional (nonfuzzy) conception of an algorithm."

Algorithms depend upon precision. An algorithm must be completely unambiguous and error-free in order to result in a solution. The path to a solution amounts to a series of commands which must be executed in succession. Algorithms formulated mathematically or in a programming language are based on set theory. Each constant and variable is precisely defined, every function and procedure has a definition set and a value set. Each command builds upon them. Successfully running a series of commands requires that each result (output) of the execution of a command lies in the definition range of the following command, that it is, in other words, an element of the input set for the series. Not even the smallest inaccuracies may occur when defining these coordinated definition and value ranges.

After 1965, when Zadeh had fuzzified input, output and state in system theory and had thus founded a theory of fuzzy systems, it was obvious to him how to go about fuzzifying algorithms. The commands needed to be fuzzified and so, of course, did their relations!

"I began to see that in real life situations people think certain things. They thought like algorithms but not precisely defined algorithms."

Inspired by this idea, he wrote the article "Fuzzy Algorithms" for *Information and Control* in 1968 which uncharacteristically contained neither theorems nor proofs. Many years later he said that "it is not really a mathematical paper. And the reason why it appeared there is because, again, I was on the editorial board. So it could be published quickly. And I do say it's not a mathematical paper but the idea. But then other people who were mathematicians have developed that and added more mathematical and so forth. So, my function was not that of coming up with very precise. It's just an idea. That's little bit like a composer who just hums something, a sort of orchestrazing." [...]

To illustrate, fuzzy algorithms may contain fuzzy instructions such as: (a) "Set y approximately equal to 10 if x is <u>approximately equal</u> to 5," or (b) "If x is <u>large</u>, increase y by <u>several</u> units," or (c) "If x is <u>large</u>, increase y by <u>several</u> units; if x is <u>small</u>, decrease y by <u>several</u> units; otherwise keep y unchanged." The sources of fuzziness in these instructions are fuzzy sets which are identified by their underlined names.

All people function according to fuzzy algorithms in their daily life, Zadeh wrote – they use recipes for cooking, consult the instruction manual to fix a TV, follow prescriptions to treat illnesses or heed the appropriate guidance to park a car. Even though activities like this are not normally called algorithms: "For our point of view, however, they may be regarded as very crude forms of fuzzy algorithms".

In that time Zadeh wrote also a paper with the title "Toward Fuzziness in Computer Systems. Fuzzy Algorithms and Languages". [...]

Therefore this paper was not written before 1969. The next section in this article is titled "Fuzzy Languages". It has also just two pages and a footnote says:

"A more detailed discussion of fuzzy languages appears in a forthcoming paper by E. T. Lee and the writer." [...]

However, the association of fuzziness and computers in the title of this paper must have sounded surprisingly in the late 1960s and referring to that Zadeh set in the introduction to this paper: "At first glance, it may appear highly incongruous to mention computers and fuzziness in the same breath, since fuzziness connotes imprecision whereas precision is a major desideratum in computer design."

In the following paragraphs Zadeh justified this with arguing that the future computer systems will have to perform many more complex information processing tasks than that kind of computers that he and his contemporaries in the 1960s knew. He expected that the future computers have to process more and more imprecise information! "Fuzziness, then, is a concomitant of complexity. This implies that as the complexity of a task, or a system for performing that task, exceeds a certain threshold, the system must necessarily become fuzzy in nature. Thus, with the rapid increase in the complexity of the information processing tasks which the computers are called upon to perform, a point is likely to be reached – perhaps within the next decade - when the computers will have to be designed for processing of information in fuzzy form. In fact, it is this capability - a capability which present-day computers do not possess - that distinguishes human intelligence from machine intelligence. Without such capability we cannot build computers that can summarize written text, translate well from one natural language to another, or perform many other tasks that humans can do with ease because of their ability to manipulate fuzzy concepts."

For that purpose, Zadeh pointed out, "intriguing possibilities for computer systems" are offered by fuzzy algorithms and fuzzy languages!

6.3 Fuzzy algoritm and fuzzy languages

"Roughly speaking, a fuzzy algorithm is an ordered set of instruction containing names of fuzzy sets. An example of such an instruction is "If x *is large, set* y *equal to 2. Otherwise, set* y *equal to 1. All languages, whether natural of artificial, tend to evolve and rise in level through the addition of new words to their vocabulary. These new words are, in effect, names for ordered subsets of names in the vocabulary to which they are added".* (L.A. Zadeh)

Real world phenomena are very complex and rich of members. To characterize or picture these phenomena in terms of our natural languages we use our vocabulary and because this set of words is restricted, Zadeh argued that this process leads to fuzziness: "Consequently, when we are presented with a class of very high cardinality, we tend to group its elements together into subclasses in such a way as to reduce the complexity of the information processing task involved. When a point is reached where the cardinality of the class of subclasses exceeds the information handling capacity of the human brain, the boundaries of the subclasses are forced to become imprecise and fuzziness becomes a manifestation of this imprecision. This is the reason why the limited vocabulary we have for the description of colors makes it necessary that the names of colors such as red, green, bleu, purple, etc. be, in effect, names of fuzzy rather than non-fuzzy sets. This is why natural languages, which are much higher in level than programming languages, are fuzzy whereas programming languages are not."

Here, Zadeh argued explicitly for programming languages that are - because of missing rigidness and preciseness and because of their fuzziness – more like natural languages. He mentioned the concept of *stochastic languages* that was published by the Finnish mathematician Paavo Turakainen in *Information and Control* in the foregoing year, being such an approximation to our human languages using randomizations in the productions, but however, he preferred fuzzy productions to achieve a formal fuzzy language. Then, he presented a short sketch of his program to extend non-fuzzy formal languages to fuzzy languages which he published in elaborated form with the co-author Edward T.-Z. Lee in "Note on Fuzzy Languages."

His definition in these early papers was given in the terminology of the American computer scientists John Edward Hopcroft and Jeffrey David Ullman that was published in the same year.

L is a *fuzzy language* if it is a fuzzy set in the set V_T^* (V_T^* is called the Kleene closure of V_T, named after the American mathematician Stephen Kleene (1909-1994)) of all finite strings composed of elements of the finite set of terminals V_T, e.g. $V_T = \{a, b, c, ..., z\}$.
The membership function $\mu_L(x) : V_T^* \to [0, 1]$ associates with each finite string x, composed of elements in V_T, its grade of membership in L. Here is one of the simple examples that he gave in the early article ([131], p. 16): "Assume that $V_T = \{0,\ 1\}$, and take L to be the fuzzy set $L = \{(0, 0.9), (1, 0.2), (00, 0.8), (01, 0.6), (10, 0.7), (11, 0.3)\}$ with the understanding that all the other strings in V_T^* do not belong to L (i.e., have grade of membership equal to zero)."

In general the language L has high cardinality and therefore it is not usual to define it by a listing of its elements but by a finite set of rules for generating them. Thus, in analogy to the case of non-fuzzy languages Zadeh defined a *fuzzy grammar* as "a quadruple $G = (V_N, V_T, P, S)$, where V_N is a set of variables (non-terminals) disjoint from V_T, P is a set of [fuzzy] productions and S is an element of V_N. The elements of V_N (called *[fuzzy] syntactic categories*) and S is an abbreviation for the syntactic category "sentence". The elements of P define conditioned fuzzy sets in $(V_T \cup V_N)^*$."

7 Fuzzy control

"One special moment of the 7th European Congress on Intelligent Techniques & Soft Computing EUFIT'99, Aachen, Germany, September 13-16, 1999, was a Debate on Fuzzy versus Conventional Control. This debate has been organized as one of the plenary sessions. The debate featured Prof. Lotfi A. Zadeh of the University of California at Berkeley taking the side of fuzzy control, and Prof. Michael Athans of the MIT taking the side of conventional control. Prof. Zadeh has argued the merits of fuzzy control, and his opinions have represented a serious step forward towards continuing the research in fuzzy control." (Radu-Emil Precup)[24]

The following text, co-authored by A. Meyer[25] and H.-J. Zimmermann[26], is reprinted from

[24] Dr. Radu-Emil Precup is a Professor at the Politehnica University of Timisoara, Romania. He was the recipient of the "Grigore Moisil" Prize from the Romanian Academy, two times, in 2005 and 2016, for his contribution on fuzzy control and the optimization of fuzzy systems. He was listed as one of the top 10 researchers in Artificial Intelligence and Automation (according to IIoT World as of July 2017). He wrote a valuable survey about fuzzy control applications in industry [90].

[25] Andreas Meyer: After his studies of Computer Science at "Saarland University" and "Darmstadt University of Technology", Andreas Meyer started his career in 1997 as product manager in an IT Security company. Being in charge of the development of IT products to secure internet banking as Director for Research and Development since 2003, he became two years later Vice President for Sales and Marketing with world-wide responsibility. Working as an executive, he received in parallel his PhD in Public Key Cryptography at Darmstadt University of Technology. In 2008 he joined INFORM as the Director of the Risk & Fraud Division and a member of the executive board.

[26] Hans-Jürgen Zimmermann: He studied in Frankfurt, Darmstadt, Berlin and Oxford, received his masters in engineering and his PhD in Operations Research and Management Science from the Technical University of Berlin. He received honorary doctors from universities in Belgium and Finland. He spent appr. 10 years in industry in different companies such as Siemens, IT&T Europe (SEL), Caterpillar International etc. and became Assoc. Professor of Operations Research and Industrial Administration at the University of Illinois in Urbana in 1964. 1967 he accepted the chair for Operations Research of the Aachen Institute of Technology. He was founding president of IFSA, editor of Fuzzy Sets and Systems and the European Journal for Operational Research and Assoc. Editor of 10 other international journals. He founded INFORM in 1969 and published 260 papers and 35

[63], partially.

"In his first paper on Fuzzy Sets L.A. Zadeh [129] already mentioned as one motivation of his Theory of Fuzzy Sets: "The fact remains that such imprecisely defined 'classes' play an important role in human thinking, particularly in the domains of pattern recognition, communication of information, and abstraction." This statement has become even more true in the meantime since we have moved from a time of scarce data into the period of data warehouses etc., i.e., into a world of abundance of data, in which people try hard to extract useful information from masses of data ([142]).

From the point of view of applications we still consider as some of the most important goals of fuzzy set theory to extract information from data and model it visually or otherwise in such a way, that people can understand it, communicate it and to model problems adequately. They can use it to solve their problems better than by a purely dichotomous modeling language. In doing this professionally, they can combine the high computing power of EDP with human experience and creativity.

Extremely successful fuzzy models were first used in engineering intelligence in areas such as Fuzzy Control ([60, 142, 147, 149]). Controlling cranes, cement kilns, video cameras, washing machines, ABS, and even subway systems by fuzzy control turned out to be almost sensational. Most of these applications had one feature in common: These were manmade systems, the control of which was often nonlinear (and therefore difficult to model traditionally). However the controls could be decomposed into linear systems by modeling human experience by fuzzy technology ([148]) and one could then determine the adequate parameters, operators ([33]) and membership functions, as well as the defuzzification models, by trial and error. Practitioners loved these controllers because they used predominantly rather basic fuzzy set theory and operators as well as membership functions could be defined rather than determined on the basis of human knowledge. Many of these models have become regular teaching material in control engineering courses.

In the meantime fuzzy set theory was further developed, it became more powerful mathematically and it became more strenuous to learn and understand it. When one started to apply it to business intelligence and to human decision making another problem became visible: Many applications do not permit a trial and error calibration as in fuzzy control because the results of a fuzzy model cannot easily be compared with the results or the behavior of the real system.

Think of strategic decisions, of evaluations of long term vulnerability of companies or persons, the determination of the creditworthiness ([151]) of persons or institutions. Here the human knowledge that goes into the fuzzy model has to be modeled properly in advance. That means, that operators ([99]), membership functions, inference methods ([148]) etc. have to properly map the counterparts in the human mind, in which they are very often very context dependent. This is no longer only a mathematical problem but predominantly a problem of psycho-linguistics or similar disciplines ([146]). Unluckily this part of science is much less developed than the mathematics of fuzzy set theory. Hence, in applications one often has to rely again on assumptions rather than on scientific results when modeling operators ([114, 150]), membership functions ([29, 50]) and other parts of fuzzy models. The justification of assumptions, of course, also depends on whether one wants to build descriptive or prescriptive models."

8 Fuzzy logic systems

"The Fuzzy Logic Systems are general knowledge base systems with linguistic rules that can be constructed using the knowledge of experts in a given field."(D. Wu & W.W. Tan [122])

books in different areas. In 2011 he received the IEEE Fuzzy Systems Pioneer Award.

This part is co-authored by Nazanin Sahab and Hani Hagras[27], and is reprinted from [101], partially.

"Professor Lotfi Zadeh introduced fuzzy sets in 1965. He has written several papers since then, but his comprehensive paper on the concept of linguistic variables became very famous as a reference on fuzzy logic theory. He introduced fuzzy logic for the application of approximate reasoning and mentioned the need of a humanistic system whose behavior is strongly influenced by human judgment, perception or emotion for the purpose of computing with words to solve the problems of human-oriented fields such as philosophy, psychology, politics, law, sociology and literature. Professor Zadeh also described the use of his fuzzy logic approach in [132] in describing the behaviors of too complex or too ill-defined systems. This has inspired control engineers from over the world to investigate the power of fuzzy logic to control applications which are difficult to mathematically model.

In 1975, the first Fuzzy Logic Controller (FLC) was developed by Mamdani and Assilian for controlling a steam engine [61]. Since then Fuzzy Logic Systems (FLSs) have been applied with great success to many real world applications. It was reported in 1995 that over the last two decades, the number of applications of FLSs have dramatically increased. Several industrial applications of fuzzy logic were reported from which we can mention cement kilns [43], steel furnaces [43], aircraft engine control, steam turbines, power supply controllers, etc [17]. FLSs have also been used domestically in elevators, washing machines [17], fridges [24], air conditioners, automobiles [43], automatic transmission, camera autofocus control, etc [17]. [...]

According to the John Lewis website about a top brand washing machine from AEG and reporting about the fuzzy logic washing machine, the website mentions "fuzzy logic circuit detects when the laundry is out of balance and rejig it accordingly, ensuring minimum wear and tear to the drum bearings. The fuzzy logic also detects half loads, if too much detergent has been added and adds extra rinses if required" [123]. Hence, for the past thirty years fuzzy logic and its applications became embedded in our everyday environments.

Fuzzy logic laid the basis for a successful method to model uncertainty, vagueness, and imprecision [53]. The FLSs are general knowledge base systems [122] with linguistic rules that can be constructed using the knowledge of experts in a given field. During more than four decades from the invention of fuzzy logic, great progress in using FLS has been achieved. While traditionally type-1 FLSs have been widely employed in real world applications, recent years have shown a rapidly growing interest in the research and application of type-2 FLSs. This is because, it has become apparent that type-1 FLSs cannot fully handle the large amounts of uncertainties encountered in real world environments and applications. Interval type-2 FLSs have shown to provide better performance when compared to type-1 FLSs in applications with high levels of uncertainty. The difference in performance has been attributed to the nature of interval type-2 fuzzy sets which can better account for the uncertainties as they incorporate a Footprint of Uncertainty (FOU) and they can be assumed to embed a large number of type-1 fuzzy sets. However, the majority of the type-2 FLSs [102] handle the linguistic and input numerical uncertainties using singleton interval type-2 FLSs that mix the numerical and linguistic uncertainties to be handled only by the linguistic labels type-2 fuzzy sets. Input numerical uncertainties are associated with the noise, imprecision and uncertainty associated with sensors and input devices. However, the linguistic uncertainties are associated with human words and perceptions. Hence, it seems paradoxical to use singleton type-2 FLSs to handle the input numerical uncertainties, as this ignores the fact that if input numerical uncertainties were present,

[27]Professor Hani Hagras is a Director of the Computational Intelligence Centre, Head of the Intelligent Environments Research Group, Head of the Fuzzy Systems Research GroupSchool of Computer Science and Electronic Engineering, University of Essex, UK.

they should affect the incoming inputs to the FLS. Thus we cannot treat the incoming FLS inputs as perfect signals as in the case of singleton FLSs. Hence, there is a need to employ non-singleton FLSs to handle the input numerical uncertainties by modeling the inputs as fuzzy inputs rather than crisp values.

[...] The work done so far in (type-1 and type-2) non-singleton FLSs use predefined shapes for the uncertainty distribution affecting the FLSs inputs (mainly Gaussian and triangular) which might not reflect the real uncertainty distribution associated with the given sensor. For example in the case of a sonar sensor, the numerical input uncertainties depend on many factors such as the shape and type of objects reflecting the sonar signal as well as wind speed, humidity and temperature. Moreover, the uncertainty distribution also varies with the measured values where for the case of a sonar sensor, the amount of uncertainty affecting measurement readings at 20cm distance could be much less than the uncertainties affecting the measurement at large distances such as 3m. Hence, it is not fair to consider that there is specific shape for the uncertainty distribution (triangular, Gaussian, etc.) with fixed parameters (average, standard deviation, etc.) for all the measured values. [102]"

8.1 Fuzzy logic based applications in communication networks

"The application of fuzzy technology is widely known as a technological revolution." (K. Hirota [51])

Following text is reprinted from [84] (co-authored by C.N. Nyirenda, F. Dong, and K. Hirota), partialy.

"The number of fuzzy logic based applications in communication networks is increasing rapidly. This development is motivated by the difficulties experienced when modeling communication networks by using conventional analytical methods. Some of the fuzzy applications include power control [23] in cellular systems; congestion control in IP networks [26], [85]; routing [5] and data fusion [62] in wireless sensor networks; and Quality of Service management in wireless sensor and actuator networks [125]. Input parameters are, generally, sampled at a fixed rate and the fuzzy system is triggered accordingly. In some cases, an external signal is used in order to trigger the systems. The fuzzy computations are invoked even when there are no significant differences between the subsequent input parameters, at the expense of precious CPU and memory resources. Furthermore, for systems that employ a sampling rate, the rate is chosen by trial and error such that it is difficult to tell if it is optimal."

Kaoru Hirota[28] has coauthored many papers in this field within scientists from Canada, China, Japan and Romania.

[28]Prof. Kaoru Hirota, a member of the editorial board of IJCCC, was born in Japan (1950). He received the B.E., M.E., and Dr.Eng. degrees in electronics from Tokyo Institute of Technology, Tokyo, Japan, in 1974, 1976, and 1979, respectively. From 1979 to 1982, he was with Sagami Institute of Technology, Fujisawa, Japan. From 1982 to 1995, he was with the College of Engineering, Hosei University, Tokyo. Since 1995, he has been with the Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology. Dr. Hirota is a member of the International Fuzzy Systems Association and the Japan Society for Fuzzy Theory and Systems. In present he is a head of the Beijing Representative Office at Japan Society for the Promotion of Science (Beijing Institute of Technology; JSPS Beijing Office), and an editor in chief of Int. J. of Advanced Computational Intelligence and Intelligent Informatics. His research interests include fuzzy systems, intelligent robot, image understanding, expert systems, hardware implementation and multimedia intelligent communication. Kaoru Hirota was a good fiend of Lotfi Zadeh.

9 Artificial intelligence, soft computing, and decision making

9.1 Artificial intelligence

In the near future Artificial Intelligence (AI) will surpass human intelligence in more and more domains. Indeed, based on soft computing, fuzzy control, bio-inspired computing, computational theory of perceptions and computation in natural language, Artificial Intelligent computers can write their own programs as they encounter situations and try different ways to achieve a goal. In the near future Artificial Intelligent machines (net-centric automobiles, intelligent aircraft, intelligent home utilities, intelligent learn labs, entertainment devices, military defense arms, health applications), will be a commonplace. Humans have a remarkable capability to reason and make decisions in an environment of imprecision, uncertainty and partiality of knowledge, truth and class membership. It is this capability that is needed to achieve human-level machine intelligence. Achievement of human-level machine intelligence is beyond the reach of existing AI techniques and more of these are based on fuzzy sets theory and fuzzy logic.

AI has made slow but steady advances in all its subfields, overcoming unexpected obstacles and taking advantage of a long period of exponentially increasing computer power. AI problems that had begun to seem impossible in 1970 have been solved and the solutions are now used in successful commercial usually products. Experts are divided on whether it is possible even in theory to build an AI system with a human-level of intelligence.

We can see today many examples already increasing to strong AI, such as: robot Sophia (a humanoid robot developed by Hong Kong-based company Hanson Robotics); self-driving car (The Google project Waymo); AlphaGo (a computer program that plays the board game Go, developed by Alphabet Inc.'s Google DeepMind in London), etc.

9.2 Soft computing

In accordance with Zadeh's definition, *Soft Computing* (SC) consist of computational techniques in computer science, machine learning and some engineering disciplines, which study, model, and analyze very complex reality: those for which more traditional methods have unusable or inefficiently.

SC uses soft techniques, contrasting it with classical artificial intelligence, *Hard Computing* (HC) techniques), and includes: Fuzzy Logic, Neural Computing, Evolutionary Computation, Machine Learning, and Probabilistic Reasoning.

HC is bound by a Computer Science (CS) concept called *NP-Complete*, which means that there is a direct connection between the size of a problem and the amount of resources needed to solve that called "grand challenge problem". SC aids to surmount NP-complete problems by using inexact methods to give useful but inexact answers to intractable problems.

SC became a formal CS area of study in the early 1990's. Earlier computational approaches could model and precisely analyze only relatively simple systems. More complex systems arising in biology, medicine, the humanities, management sciences, and similar fields often remained intractable to HC. It should be pointed out that simplicity and complexity of systems are relative, and many conventional mathematical models have been both challenging and very productive. SC techniques resemble biological processes more closely than traditional techniques, which are largely based on formal logical systems, such as Boolean logic, or rely heavily on computer-aided numerical analysis (as in finite element analysis).

SC techniques are intended to complement HC techniques. Unlike HC schemes, which strive for exactness and full truth, soft computing techniques exploit the given tolerance of imprecision, partial truth, and uncertainty for a particular problem. The inductive reasoning plays a larger role in SC than in HC. SC and HC can be used together in certain fusion techniques.

Table 1: Hard Computing vs. Soft Computing

Hard Computing	**Soft Computing**
Deterministic environment (closed, static, known)	*Nondeterministic* environment (open, dynamic, uncertain)
Well-defined *problem* (quantity, precision, certainty)	Fuzzy-defined *Situation* (quality, imprecision, uncertainty)
Solving accurately problems (imperative, firm, reliable)	*Managing* "Just In Time" situations (descriptive, flexible, robust)
Optimal, lasting, *solution* (algorithmic, apodictic, general)	Suboptimal, temporary, *answer* (non-algorithmic, revisable, local)
Technocentric design Software entity: *PROGRAM* (*object devised as tool*)	*Anthropocentric* design Software entity: *AGENT* (*process devised as interactant*)
Client-Server paradigm (object-oriented, sequential)	*"Computing as Interaction"* paradigm (agent-oriented, parallel)

Soft Computing can deal with ambiguous or noisy data and is tolerant of imprecision, uncertainty, partial truth, and approximation. In effect, the role model for SC is the human mind. Artificial Intelligence and Computational Intelligence based on SC provide the background for the development of smart management systems and decisions in case of ill-posed problems.

In Table 1 we present the summarized conclusions of the Hard Computing paradigm versus Soft Computing paradigm, adapted from [38].

9.3 Decision making in fuzzy environments

In many real-world situations, the problems of decision making are subjected to some constraints, objectives and consequences that are not accurately known. After Bellman and Zadeh [13] introduced for the first time (1970) fuzzy sets within multiple-criteria decision-making (MCDM), many researchers have been preoccupied by decision making in fuzzy environments. The fusion between MCDM and fuzzy set theory has led to a new decision theory, known today as fuzzy multi-criteria decision making (FMCDM), where we have decision-maker models that can deal with incomplete and uncertain knowledge and information [22, 35].

The most important thing is that, when we want to assess, judge or decide we usually use a natural language in which the words do not have a clear, definite meaning. As a result, we need fuzzy numbers to express linguistic variables, to describe the subjective judgement of a decision maker in a quantitative manner. Fuzzy numbers (FN) most often used are triangular FN, trapezoidal FN and Gaussian FN [36], [107].

We highlight that the concept of linguistic variable introduced by Lotfi A. Zadeh in 1975 allows computation with words instead of numbers and thus linguistic terms defined by fuzzy sets are intensely used in problems of decision theory for modelling uncertain information.

10 Conclusion

Several key notions in Zadeh's thinking that are worth mentioning, namely optimality, uncertainty, reasoning, and meaning; also, the concept of discrete variables and its tension with the concept of continuum plays a central part in his work. Lotfi A. Zadeh has been a system theorist, a computer scientist, a physicist, and an engineer. He published the vast majority of his papers as single author, but he has also worked together with John R. Ragazzini (1912-1988), Richard E. Bellman (1920-1984), Charles A. Desoer (1926-2010), and a few other scientists [113].

A number of researchers from Romania were among the early supporters and followers of ideas presented by Lotfi A. Zadeh, such as: Grigore C. Moisil (1906-1973), Constantin V. Negoita (born 1936), Dan A. Ralescu (born 1949), Dan Butnariu (1951-2008), and many others.

His seminal paper "Fuzzy Sets" has already about 100,000 citations in Google Scholar and all Zadeh's papers have over 185,000 citations (Dec. 1, 2017).

Fuzzy Logic have nowadays many useful applications, from consumer smart products to industrial intelligent products, such as: washing machines, air conditioners, cameras, camcorders, fuzzy/neuro-fuzzy expert systems, fuzzy data/information mining, fuzzy search engines, microcontrollers, microprocessors, signal processing, fuzzy/neuro-fuzzy controllers, edge detectors, speech recognition, fuzzy decision making in economy/medecine, knowledge management, fuzzy thinking, etc.

Lotfi A. Zadeh, the inventor of Fuzzy Logic, dies at 96, but Fuzzy Logic is alive and is in progress through his followers.

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Time Series Clustering Based on Singularity

D. Chang, Y.F. Ma, X.L. Ding

Dan Chang, Yunfang Ma*, Xueling Ding
School of Economic and Management,
Beijing Jiaotong University,
Beijing, 100044, China
dchang@bjtu.edu.cn
*Corresponding author: yunfangm@bjtu.edu.cn
dingxueli@boe.com.cn

Abstract: With relevant theories on time series clustering, the thesis makes research into similarity clustering process of time series from the perspective of singularity and proposes the time series clustering based on singularity applying K-means and DBScan clustering algorithms according to the shortage of traditional clustering algorithm. In accordance with the general clustering process of time series, time series clustering based on singularity and K-means are made respectively to get different clustering results and make a comparison, thus proving that similarity clustering research of time series from the perspective of singularity can better find out people's concern on time series.
Keywords: time series, clustering, singularity, DBScan, Kmeans.

1 Introduction

Time series is a high dimensional data type, a random variable which is strictly arranged by time order and correlated with each other. As an important data type in the economic field, it plays a significant role in people's analysis on market trend and their decision-making. As some time series data increase at the magnitude of several billion per day or even per minute, how to find the data correlation in time series and analyze such huge data with timely and fast response, thus figuring out similar or regular changing pattern, tendency, mutation with obvious change and distribution of outliers, has become an increasingly important and challenging hot topic.

During the last decades, a societal focus on the work of university faculty as a measure of return on the public's investment in higher education stimulated a reevaluation of how faculty performance ought to be measured and assessed. The development of workable assessment systems is difficult largely due to the fact that the value of assessment is often controversial:Clustering analysis is one of the important tasks in data mining. It is a process in which data set is divided into several groups or classes, making the data objects in the same group or class have high similarity and those in different groups or classes different. Differing from traditional clustering analysis, data processed in the clustering analysis of time series are changing over time with features of high-dimension, complexity, dynamism and high noise, which are easy to reach large-scale. Variable clustering approach usually is used to handle the high-dimensional variable [12]. Time series clustering refers to cluster time series with similar change into one class, and time series in different classes have obvious different changes [6]. How to cluster the mass time series which is closely related to daily life has aroused concern among many scholars in the field of data mining. Most of current classic similarity analysis is based on mathematical model, which considering the overall features of time series. However, for the mass data and the special time series with high-dimension, high noise and high complexity, traditional similarity searching based on mathematical model does not consider that user requirement and concern vary in different situations in real life, which means the importance of singularity in time series differs for different users, in spite of the shortening processing time caused by relative technology and more accurate results.

There are many definitions for singularity without a formal and standard one that is generally accepted. The definition in the thesis is the data that is obviously diverged from most sample data, namely data points different from most sample data which do not meet the general model of sample data. That is to say the data points taking up very small data volume in the clustering result.

The thesis aims to analyze through time series data mining algorithm with theories related to clustering such as DBScan and Kmeans, figuring out the existing problems in traditional time series data mining clustering algorithm, confirming the factors which should be comprehensively analyzed during the time series clustering analysis such as the influence of major events or accidental events on time series, and finishing the time series clustering research based on singularity. The case study at the end of the thesis demonstrates the application of time series clustering proposed by the thesis in detailed container port transportation.

2 Literature review

2.1 Time series

Basic Concept of Time Series

Time series is a series composed of data that change over time, which is also called dynamic series. Time series metrics or features that can be used for time series classification or regression analysis [7]. Time series are used in statistics, pattern recognition, econometrics, mathematical finance, weather forecasting, intelligent transport and trajectory forecasting [14], container shipping freight rate forecasting [8], etc. Different from static data, time series is a data object of high complexity and high noise that describes the changing process of things over time. Time series exists widely in various fields of daily life. For example, the grain yield of a certain place changes every year; stock price keeps fluctuating over time; the traffic flow of a certain road changes in different time periods.

Data of time series change over time. According to this feature, every data unit of time series is abstracted to a binary array (t, x) composed of time and corresponding time value, in which t represents time variable and x represents data variable.

Similarity of time series

Suppose that there are time series Q and time series C, $Q = \{q_1, q_2, ...q_n\}$, $C = \{c_1, c_2, ...c_n\}$, if the distance between Q and C satisfies dist$(Q, C) \leq \epsilon$ (given similar threshold value which is used to adjust the level of similarity), Q and C is similar. Besides, dist(Q,C) is a distance function, and the most typical one is Euclidean distance. However, Euclidean distance is not sensitive to noise data and can hardly recognize time series with displacement or stretch.

Similarity based on Euclidean distance regards time series as points in multi-dimensional space and measure the similarity of time series with the distance between points. Because of the advantages of fast calculation and low complexity, Euclidean distance becomes the most commonly used measurement method. For example, for time series Q and time series C of the same length, $Q = \{q_1, q_2, ...q_n\}$, $C = \{c_1, c_2, ...c_n\}$, then $Q, C \in R_n$; Q and C are regarded as two points q_i and c_i in N-dimensional space, and the distance between them is:

$$d = \sqrt{\sum_{k=1}^{n} (q_2 - c_k)^2}$$

2.2 Time series clustering algorithm

Data in real life have features such as huge amount, high-dimension and high noise etc., especially for time series data. And data are expanding and becoming more complicated [1]. So far there is no clustering algorithm that can be applied to data of any type. Many scholars have built many clustering algorithms in order to solve the clustering for multi-type data.

K-means algorithm

K-means has been successfully used in various areas, such as market segmentation, computer vision, geostatistics, astronomy and agriculture [4]. K-means by default considers that cluster comprises all objects within close distance and the ultimate goal is to obtain a compact and independent cluster. In a complete iteration, K-means will calculate the distance between the cluster center and every remaining object and distribute the object to the nearest cluster. Iteration is finished after all data objects are detected, and then new clustering center is figured out.

Description of detailed algorithm is as follows:

Given data set $X = \{x_1, x_2, x_3, ...x_n\}$, in which data object x_i has m-dimension variable, x_i=$\{x_{i1}, x_{i2}, x_{i3}, ...x_{im}\}$. K represents the number of needed cluster; data set X is divided into K classes; according to the requirement of high similarity inside the cluster and low similarity between clusters, square-sum-of-error criteria function E should be minimum in order to obtain the optimal clustering effect. E represents the sum of distance between each object and its located cluster center [5].

It can be seen from the experimental study of square-sum-of-error function E that when data objects in a data set are intensive and the differentiation between types is obvious, the criteria function of square sum of error is more effective, thus enabling K-means to get a better clustering effect. The algorithm has converged when the assignments no longer change. There is no guarantee that the optimum is found using this algorithm [3].

DBScan algorithm

DBSCAN (Density-Based Spatial Clustering of Applications with Noise) is a spatial clustering algorithm based on density [2]. It requires two parameters: distance (radius of the detection region) and the minimum sample points (minPts). DBSCAN can be used with any distance function [2] [10] (as well as similarity functions or other predicates) [9].

Description of detailed algorithm [10]:

(1)Search for object p that is not detected in the data set. If p is not processed, then the number of object in the field is no less than MinPts. Build new cluster C, and add all objects in C to candidate set N;

(2)Detect object q that is not processed in candidate set N. If the number of object in its neighborhood is greater than or equal to MinPts, then add these objects to N; if q does not belong to any cluster, add q to C;

(3)Repeat 2); keep Detecting objects remaining unprocessed in N until N is empty. Repeat 1) 3) until all objects are processed. Clustering process is demonstrated in (Fig. 1).

DBScan defines cluster as the biggest set of points that are density-reachable, which means dividing areas of high density into clusters, so it can recognize the noise point, which is different from partition clustering and hierarchical clustering. Compared with K-means clustering, it does not need to know K in advance, and can find out cluster of any shape.

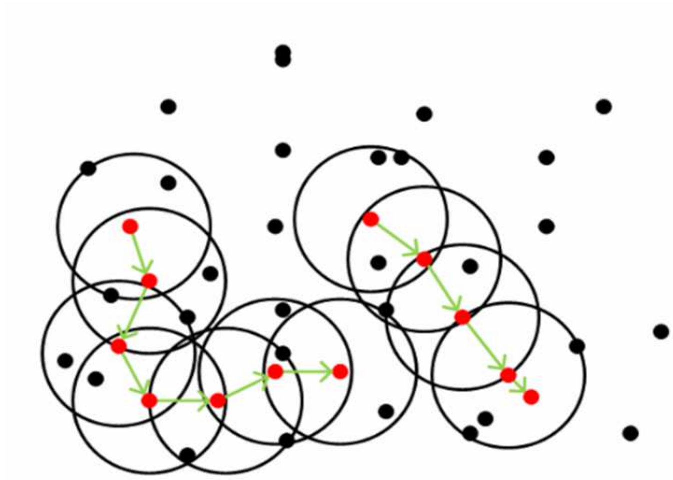

Figure 1: DBScan clustering process diagram

Advantages and disadvantages of the algorithm

As a mountain-climbing search algorithm, K-means algorithm has certain disadvantages: (1) K should be provided externally and the accuracy of K is closely related to the clustering result, but it is not easy to confirm K, which forms one of the disadvantages of K-means. (2) The clustering result is related to the initial center. If the choice of initial center fails, then it is impossible to get ideal clustering result. (3) K-means should keep iterating on classification adjustment and calculating new cluster until meeting the condition. Therefore, the time cost of K-means algorithm is huge for mass data. In spite of many disadvantages, K-means algorithm become one of the most commonly used algorithm in clustering research because of the features of simplicity, high intelligibility, high convergence rate and high scalability. Obviously there are many clustering algorithms. According to the brief introduction and analysis of the two algorithms above we can obtain the comparison result of the two clustering algorithms as showed in (Tab. 1).

Table 1: Comparison of the DBScan and K-means algorithms

Feature / Algorithm	K-means	DBScan
Data type	Symbolic type and numeric type	Numeric type
High dimension	Normal	Normal
Sensitivity to data order	Normal	Sensitive
Sensitivity to noise	Sensitive	Insensitive
Scalability	Good	Good
Efficiency	Normal	Normal
Algorithm implementation feature	Mathematical description; easy to understand and implement; repeated scan for the optimal result; but sensitive to the initial condition; number of clusters confirmed by man; all data put in internal storage.	One-time scan; able to recognize noise; clustering result independent of parameter; not very ideal clustering effect for data object with uneven density; not high degree of support for high-dimension data.

The above two algorithms for similarity measurement figure out the series which is similar to given series through various relative technology at certain target efficiency. Target efficiency means that the implement of similarity analysis algorithm is of high efficiency and low complexity. Most of current classic similarity analysis is based on mathematical model, which considers the overall features of time series. However, for the mass data and the special time series with high-dimension, high noise and high complexity, traditional similarity searching based on mathematical model does not consider that user requirement and concern vary in different situations in real life, in spite of the shortening processing time caused by relative technology and more accurate results. For example, people pay more attention to the place, time and probability of earthquake in the earthquake prediction; investors put special emphasis on the fluctuation of stock price in the stock market forecast. Therefore, it is essential to introduce the influence of key events such as major events and accidental events on time series during the time series analysis.

3 Clustering algorithm based on singularity

In light of the shortage of traditional algorithm that it does not consider that user requirement and concern vary in different situations in real life, the thesis made further optimization of the traditional algorithm by taking different concerns, namely singularity, of users in real life into consideration.

3.1 Basic thought of singularity clustering

Based on the distance-based K-means algorithm, cluster total sample data N to get K class; then with the density-based DBScan clustering algorithm, successively get the data volume m_i in every class of K_i, and then figure out $\rho_i = m_i/N$, given threshold value ϵ (defined according to user requirement):

When $\rho_i \geq \epsilon$,i type is density-reachable at ϵ;

When $\rho\_i <\epsilon$, i type is not density-reachable at ϵ. Then i is regarded as the data class diverged from most data sample, namely singular class, which refers to the data class including singularity.

3.2 Clustering based on singularity

Current time series clustering is made with every series as a whole. For example, if we cluster n time series with current time series clustering algorithm, n time series are regarded as data objects while clustering. What we consider is the whole similarity of n time series, but ignoring the possible similarity of data objects at certain time periods. Therefore, the thesis takes the data of n time series at the whole time period $(t_i - t_j, i \in N, j \in N)$ as data object, which means making similarity clustering with $n * (j - i)$ data objects, thus not only considering the similarity showed by different ports at the same year, but also comprehensively considering the similarity demonstrated by different ports at different years and that by the same port at different years.

Description of detailed process:

(1) Data labeling. Label data after preprocessing. Data of n at t is expressed as (t, n).

(2) DBScan clustering. Choose radius r as density in DBScan algorithm and get K class results.

(3) Decide discrete class, namely singular class. Figure out data volume m_i in every K_i successively and then figure out $\rho_i = m_i/N$; given threshold value ϵ. When $\rho_i \geq \epsilon$, i class is

density reachable at ϵ; when $\rho_i<\epsilon$, i class is density unreachable, then it is called the data class that deviates from most data sample, namely singular class.

(4) Combine with expert advice and accidental events to get reasonable clustering result.

3.3 Singularity detection

The important feature of singularity in time series carries important information. For example, according to the data from Census and Statistics Department of Hong Kong, several scholars summarized some irregular events through text mining technology based on webpage, and then integrated these events through Delphi Technique combining expert advice, figured out the influence direction of these events on the throughput respectively, and searched on International Maritime Information Website for the events that influenced throughput of container in recent years, thus drawing the influence direction of irregular events on port throughput as showed in (Tab. 2), which can be used to judge the influence on throughput when irregular events happen. Of course, data in the table should be updated and adjusted according to the actual situation in order to keep flexibility.

Table 2: Effect of irregular events on port throughput

Class	Important Event	Direction
Industry Factor	Container cost reduction	Up
	Container vacancy rate decline	Up
	Barge cost reduction	Up
Economic Factor	Economic crisis	Down
	Foreign exchange rate	Uncertain
	Crude oil price rise/Fall	Down/Up
Related Policy	Pallet carrier cross-border license fee reduction	Up
	Wharf occupation rate decline	Up
Natural Disaster	Typhoon/tsunami/earthquake	Down
Regional Competition	Port merger	Up
	Operating efficiency rise of other ports	Down
Political Factor	Port labor strike	Down
	Direct Flight for cross-strait trade	Down
	Terrorist attack	Down
Other Factor	Wharf construction	Up
	Berth number increase	Up
	Shipping company and wharf company reach related agreement	Uncertain

4 Experimental comparison-taking China's container port clustering as an example

Ports have become a significant strategic resource for the development of national economy and regional economy in China. They act as the nodes connecting water transport with land transport and play pivotal roles in logistics network [13]. As the development of port cities and hinterland economy relies on the development of ports, a series of research on ports is of great significance for not only the development of hinterland cities, but also the development of ports themselves [11].

4.1 Choice of representative ports

The thesis takes the clustering research of China's container ports as an example, during which the choice of container ports data is the basis for research. Coastal ports mainly spread at coastal areas such as Yangtze River delta, Pearl River delta, Shandong Peninsula and west coast of Bohai Sea etc., which are the optimal objects of clustering research. Ports at Yangtze River delta mainly include Shanghai Port and Ningbo-Zhoushan Port, froming a container transportation system consisting of ports such as Lianyungang Port; with an emphasis on Ningbo-Zhoushan Port and Lianyungang Port, imported mineral, handling of crude oil and transfer system of ports of Shanghai, Suzhou, Zhenjiang and Nanjing etc. should be developed correspondingly; Shanghai Port and Ningbo-Zhoushan Port form the major coal transfer system. Therefore, the thesis chooses Shanghai Port, Ningbo-Zhoushan Port and Liangyungang Port as the representatives of ports at Yangtze River delta.

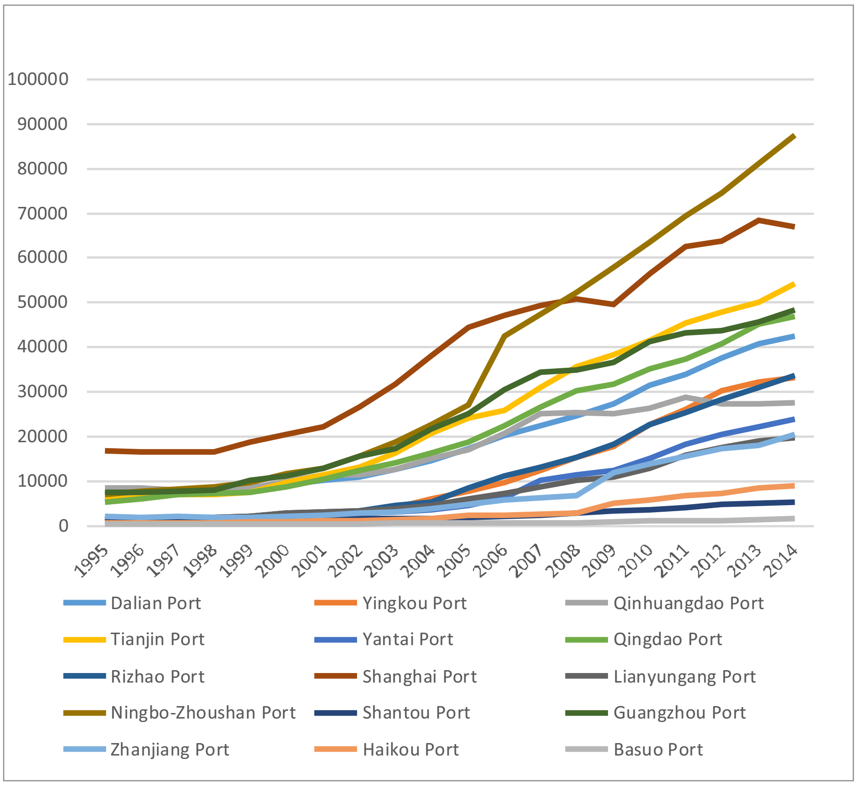

Figure 2: Comparison of the DBScan and K-means algorithms 1995- 2014 throughput of coastal container port above designated size in China

First of all, we choose throughput of 15 coastal container ports above designated size in China from 1995- 2014 as the time series data to analyze different variation trend demonstrated by different ports. Without any process on the original data, it can be seen from (Fig. 2) that although all ports largely demonstrate an upward trend as time goes by, some ports show different changing trend at certain stages. For example, from 2008 to 2009, Shanghai Port and Qinhuangdao Port showed downward trend while other ports went upward. Therefore, we assume that whether there was a big event in 2008 which had great influence on only Shanghai Port and Qinhuangdao Port while having no influence or little influence on other ports. In order to better describe various features of different time series at different stages, indicators representing tendency of every stage are clustered as attributes. Therefore, the thesis takes throughput growth rate as the attribute of clustering analysis calculation.

4.2 Ports clustering based on singularity

The time series clustering algorithm that can recognize singularity in 3.3 is adopted in this part in order to figure out the influence of accidental events on every port in port market.

Current time series clustering is all made with each series as a whole. For example, if we use current time series algorithm to cluster ports, it is made with 15 time series as data objects. Therefore, what is considered is the overall similarity of 15 time series, but ignoring the possible similarity of data objects at certain stage. The thesis takes the throughput data of every port from 1995 to 2014 as data objects. Taking the port data in each year as one time series data set, so total 19 years between 1995 to 2014 with 15 ports lead to $19 * 15 = 285$ data sets. To make similarity clustering, not only considering the similarity showed by different ports at the same year, but also comprehensively considering the similarity demonstrated by different ports at different years and that by the same port at different years.

Ports clustering based on singularity clustering process of throughput time series

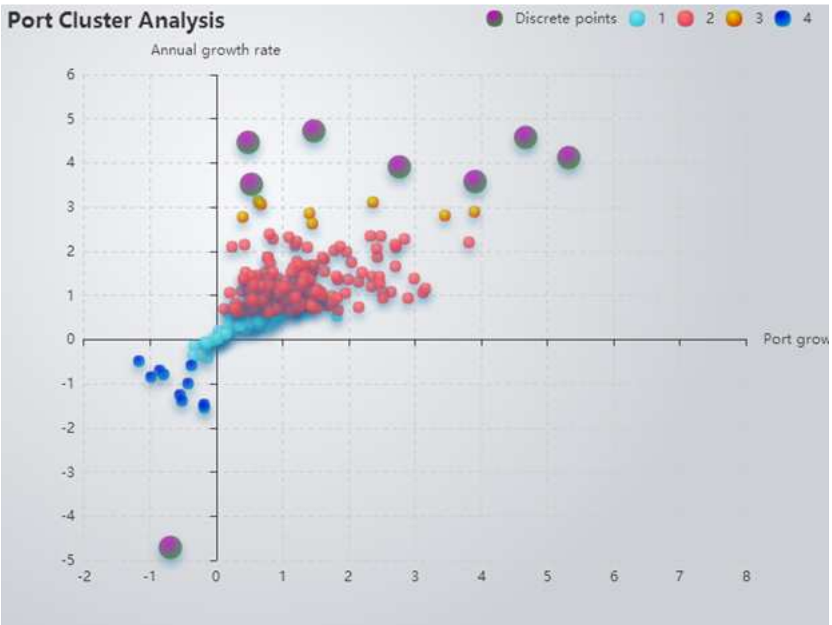

Figure 3: Cluster distribution of coastal container ports above designated size in China

According to the detailed process in 3.2, the discrete class results figured out are as follows (please note that the number for this year demonstrates the situation of last year):

[1.474297, 4.726063, 100, "1996-Yingkou Port"],
[0.482091, 4.467265, 100, "1998- Yingkou Port"],
[3.906951, 3.579445, 100, "2007-Yantai Port"],
[0.530989, 3.517523, 100, "1998-Lianyungang Port"],
[-0.693107, -4.709108, 100, "1998-Zhanjiang Port"],
[5.322229, 4.122826, 100, "2009-Zhanjiang Port"],
[4.670751, 4.580626, 100, "2009-Haikou Port"],
[2.764757, 3.911730, 100, "1997-Basuo Port"].

Clustering effect picture is showed in (Fig. 3).

Singularity detection of throughput time series

Take Ningbo-Zhoushan Port as an example, as showed in the table. It demonstrated a continuous upward trend on the whole, but changed greatly in 2006. We have found that the reason is the merger of Ningbo Port and Zhoushan Port, and based on the exploration of related records and expert interviews we have also found that it is the period of financial crisis. (Tab. 3) demonstrates the final turning point formed according to singularity detection, expert experience and major events taking place during the period. As mentioned before, throughput of different ports have different responses to a given event. We can see that in 1998 and 2009, some ports showed distinct turning trend because of the financial crisis, while others kept steady tendency.

Table 3: Turning point of Chinese port market

Time	Event or Major Change in Policy
1997	National key construction project: finishing the infrastructure of coastal ports
Latter half of 1997-1998	Asian financial crisis: leading to financial crisis in Southeast Asia
2006	Ningbo Port and Zhoushan Port merged as Ningbo-Zhoushan Port
2008	Shanghai financial crisis
2009	Administrative Regulations of Port Operation
2013	Official establishment of China (Shanghai) free trade pilot zone

According to the irregular influential factors and the clustering bubble diagram, singularity is figured out through comprehensive analysis of social events or expert experience.

(1) 1996-Yingkou Port. Yingkou Zhongyuan International Container Wharf Limited Liability Company, a container wharf company jointly operated and managed by Yingkou Port Office and China Ocean Shipping Group Company, was set up. The company owns a wharf coastline of 309 meters, a container yard of 150,000 square meters, 2 container unloading bridges, a CFS warehouse of 3000 square meters and other related infrastructure. It can berth one 15,000-tons container ship or two 5000-tons container ships, enabling Yingkou Port achieved container quantity of 14,900 standard containers in 1996.

(2) 1997-Basuo Port. Major coastal ports construction and operation, a national key construction project was finished in 1997 with 22 berths were completed and put into use, among which there are one in 200,000-tones mineral transfer wharf second-stage project in Beilun harbor district of Ningbo Port, five in the second-stage project in Bayuquan harbor district of Yingkou Port, six in the second-stage project in west basin of Yantai Port, three in the second-stage project in front bay of Qingdao Port, and one in the first-stage project in Xiahai of Zhanjiang Port. Throughput of most ports showed an obvious growing trend in this year.

(3) Because of the financial crisis in Southeast Asia from the latter half of 1997 to 1998, most ports showed a distinct deviation, especially Zhanjiang Port, Yingkou Port, Lianyungang Port, which experienced dramatic decline in terms of growth rate, indicating the relatively great influence of the financial crisis on the three ports compared with other ports.

(4) China's container transportation kept high-speed increase in 1999 with an obvious trend of concentrating on major hub ports, thus forming Yangtze River delta regional ports with Shanghai Port being the center, Pearl River delta regional ports represented by Shenzhen including

Shenzhen Port, Shantou Port, Guangzhou Port and Haikou Port, as well as circum-Bohai-Sea regional ports including Dalian Port, Qingdao Port and Yantai Port.

(5) 2007-Yantai Port. Based on repeated port integration, 30 new port projects were constructed in Yantai Port in 2007 with four already existing harbor districts including West district, Penglai district and Longkou district, leading to a throughput of over 100 million tons in 2007.

(6) The international financial crisis resulted in an obvious decline in terms of growth rate of ports, which was closely related to the insufficient supply of goods caused by the financial crisis.

(7) In 2009, ports largely stayed in the condition of insufficient supply of goods because of the international financial crisis in 2008. Although the throughput of most ports kept increasing, the growth rate showed a downward trend. Facing such situation, related administrative department in Zhanjiang and port companies jointly kept going forward by striving for supply of goods and took them to the port, thus leading to a throughput of over 100 million tons again in 2009, exceeding the expected target. In addition, *Some Opinions Concerning Promoting the Construction and Development of Hainan International Tourism Island* put forward by the State Council clearly proposed "implementing supporting policy for business related to international shipping, improving supporting policy for the development of modern logistics industry, forging a shipping hub and logistics center facing Southeast Asia while relying on the hinterland of southern part of China". Therefore, Haikou Port smoothly went through the crisis in 2009 caused by the financial crisis in 2008 and showed a distinct upward trend.

(8) In addition, it can be seen from the growth curve of throughput that the throughput of Shanghai Port reached its max at 2014. Throughput transferred from Shanghai Port to Taicang Port actually indicated the fact that the throughput growth space of Shainghai Port was increasingly narrow.

4.3 Port clustering based on K-means

In order to verify that the port clustering based on singularity can better detect the influence of accidental events on different port throughput time series, and to contrast the deficiency of current frequently-used K-means clustering algorithm, K-means clustering algorithm is adopted to cluster the port throughput time series again, thus making a comparison with the time series based on singularity.

After standardization of original data, it can be seen in (Fig. 4) that the throughput changing trend of the fifteen ports can be largely divided into three classes: fluctuate increase, steady increase, and accelerated increase. To be more specific, it can be divided into five classes. Therefore, we assume it is divided into five classes and choose K-means clustering with the max $K = 5$ in the SPSS statistical analysis software.

(Tab. 4) demonstrates the cluster class and the members in every class. According to the table, the first class: Ningbo-Zhoushan Port; the second class: Shanghai Port; the third class: Yingkou Port, Qinghuangdao Port, Rizhao Port; the forth class: Guangzhou Port, Tianjin Port, Qingdao Port, Dalian Port; the fifth class: Shantou Port, Lianyungang Port, Zhanjiang Port, Yantai Port, Haikou Port, Basuo Port.

4.4 Contrastive analysis of clustering results

It can be seen from the two clustering results in 4.2 and 4.3 that the clustering results obtained through two clustering algorithms are quite different.

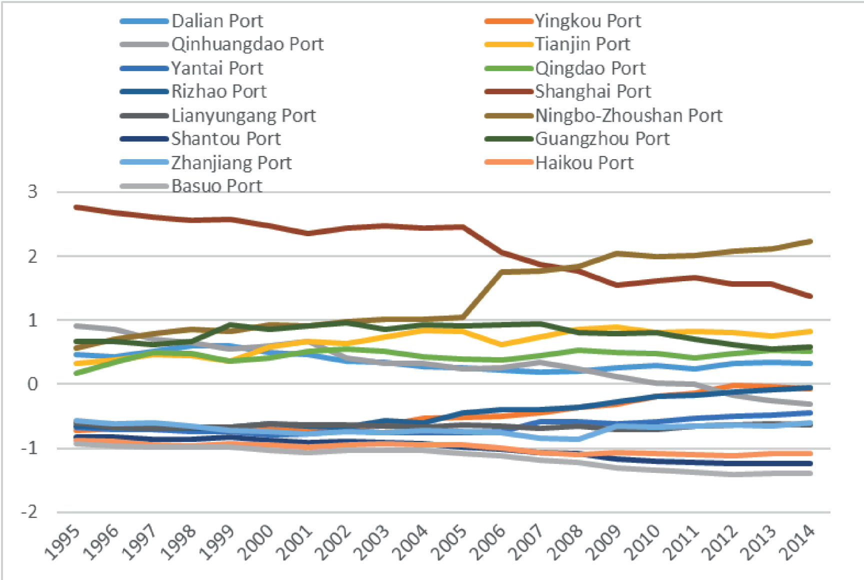

Figure 4: Trends of throughput of major ports along the Coast of China in 1995-2014 (after standardization)

Table 4: Cluster members

No.	Throughput of Port (Unit: ten thousand tons)	Cluster	Distance
1	Dalian Port	4	18180.566
2	Yingkou Port	3	11999.398
3	Qinhuangdao Port	3	22396.025
4	Tianjin Port	4	14222.241
5	Yantai Port	5	22071.565
6	Qingdao Port	4	6685.459
7	Rizhao Port	3	10612.377
8	Shanghai Port	2	.000
9	Lianyungang Port	5	15698.608
10	Ningbo-Zhoushan Port	1	.000
11	Shantou Port	5	16305.687
12	Guangzhou Port	4	12746.441
13	Zhanjiang Port	5	14322.937
14	Haikou Port	5	10183.355
15	Basuo Port	5	25108.685

The clustering result based on singularity is as follows:

"1996-Yingkou Port", "1998-Yingkou Port", "2007-Yantai Port", "1998-Lianyungang Port", "1998-Zhanjiang Port", "2009-Zhanjiang Port", "2009-Haikou Port", "1997-Basuo Port".

K-means clustering results are as follows:

The first class: Ningbo-Zhoushan Port;

The second class: Shanghai Port;

The third class: Yingkou Port, Qinhuangdao Port, Rizhao Port;

The forth class: Guangzhou Port, Tianjin Port, Qingdao Port, Dalian Port;

The fifth class: Shantou Port, Lianyungang Port, Zhanjiang Port, Yantai Port, Haikou Port, Basuo Port.

It can be seen that K-means algorithm can detect the similarity of overall feature variation trend of time series, but is not good at detecting different features of every time series at different stages and does not take into account different demands and concerns of users in real life under different situations. Times series clustering based on singularity just complement such aspect, which not only considers the similarity of different time series at the same time, but also fully considers the possible similarity of different time series at different times and that of a certain time series at different times; that is to say to take different demands and concerns of users in real life under different situations into consideration.

5 Conclusion

The thesis proposes the time series clustering based on singularity according to the shortage of traditional clustering algorithm. As users have different demands and concerns in real life under different situations, researches into similarity clustering process of time series are carried forward from the perspective of singularity, which make choice among trend indicators of time series at every stage and optimize the original data. Different clustering results are obtained through time series clustering based on singularity and K-means respectively. By the comparison of the clustering results, it can be figured out that time series similarity clustering research from the perspective of singularity can better find out the important point of time series.

However, during the singularity detection part, there are some subjective factors to some extent in only the event exploration in relative records and expert interview. If such factors could be quantified, it would be more convincing. Finally, as for the time series that are not involved in the research except ports, the clustering algorithm in the thesis can be adopted to figure out the sensitivity of time series to different major events, thus making precautions to the predicted events with the discrimination theory and prediction model.

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Intelligent Decision Support Algorithm Based on Self-Adaption Reasoning

G. Chen, Y. Jin, H. Wang, S. Cao

Guomin Chen, Yingwei Jin,
Huili Wang*, Shuo Cao
Dalian University of Technology
dr.chen@vip.126.com, jinyw67@dlut.edu.cn
*Corresponding author: huiliw@dlut.edu.cn
caoshuo@dlut.edu.cn

Abstract: This paper analyzes the logic deduction and reasoning techniques used in several intelligent decision support algorithms, and proposes a flexible planning method *GARIv* using fuzzy descriptive logic in media enterprise management. Combined with experiments, the above methods are illustrated in terms of effectiveness and feasibility. In the end, the challenges and possible solutions of intelligent decision support algorithms with self-adaption reasoning are discussed.
Keywords: intelligent decision support, propositional logic, non-monotonic logic, descriptive logic, fuzzy logic, automatic reasoning.

1 Introduction

Intelligent decision support (artificial intelligence planning), also known as automated planning (automated planning), is an important area of artificial intelligence research, and covers a knowledge representation, automatic reasoning, non-monotonic logic, human-computer interaction and cognition science and other areas of cross-disciplinary [6]. The first intelligent decision support research, which originated from the automatic reasoning and knowledge representation, in the 20th century, 90 years ago, has been the use of logical deduction method to be solved, with the focus on classical logic of reasoning. Mahmood [9]solves the problem of exponential space explosion in the process of knowledge representation, which draws the field of intelligent decision support more and more attention from researchers.

Intelligent decision support technology has been widely used in aerospace, robot control, logistics scheduling, game character design and system modeling. The results are obvious [8]. The US military forces in the Gulf War dynamic analysis and re-planning Tools DART is used in automated logistics planning and transportation scheduling, so that the scheduling work, which used to take a few weeks, now can be completed within a few hours. Intelligent decision support technology in the field of production scheduling and Mars Rover, Hubble Space Telescope and other aerospace fields. The application also shows its huge application prospects [11]. Especially in recent years, this huge application has also been demonstrated in the field of on-line education, such as Dalian Dragon Stone Internet EDU Service co, who employs the knowledge-based system for learning performance analysis and evaluation [7].

The International Planning Competition (IPC) has made great progress in the field of intelligent decision support technology, for which 5 sessions have been held continuously since 1998 [12]. The planning system of the previous three competitions mainly deals with the system performance, with the handling time of planning problems being the only criterion to measure the pros and cons of the system. In IPC-4 the consideration of complexity of the problem processing capacity is added to the probabilistic programming problem. In IPC-5 the Conformant planning problem is added. In the IPC development process, the scale of problem which needs to dealt with is gradually increased, so that the difficulty is gradually increased. The standard problem can describe the complicated and objective world more closely, enabling the intelligent decision support research to deal with complex practical problems.

The existing planning methods are divided into two main categories: fusion planning and fusion state space heuristic search planning [14]. By convergence transformation planning method, planning problems are converted into a number of classic problems (such as Propositional satisfiability problem, model checking problem, constraint satisfying problem, linear programming problem, theorem proving problem of non-classical logic, *etc.*), and solving the original programming problem indirectly through solving the transformed objective problem efficiently. In various fusion transformations planning, the logical deduction and reasoning techniques are used, more or less. The planning of the first class predicate logic is the source of these phenomena. It is very important to improve the efficiency of the planning method by using logical deduction and reasoning techniques.

This paper mainly studies the planning method and planning system of fusion logical deduction and reasoning technology. Firstly, the relevant concepts and problem description of intelligent decision support are introduced. Then the planning methods, which combine fusion logic deduction and reasoning technology are described, with a focus on the famous international planning system: flexible programming method of fusion fuzzy description logic. Finally, based on fuzzy descriptive logic, a flexible planning method is proposed and experimentally proved effective and feasible in the operation and management of media enterprises.

1.1 Intelligent decision support and fusion self-adaptive reasoning programming method

At present, intelligent decision support has not yet been defined uniformly, but it is generally believed that intelligent decision support is the process of finding the sequence of actions from the initial state to the target. According to Aleksander [1], intelligent decision support is defined as the "understanding and analysis of the surrounding environment. The goal of the realization of a number of alternative actions and the resources provided by the reasoning to develop a comprehensive action to achieve the goal sequence. Most of the media companies have witnessed an increasing online application, despite the combination of online and paper, which therefore leads to the wider use of computer-based adaptive technology.

1.2 Intelligent decision support problem

The description of the planning problem, usually based on the common planning domain description language (PDDL) [5], is similar to the representation of the first-order predicate logic, which adds conditional effects to the requirements of IPC, Numerical effects, probability effects, etc., leading to more detailed descriptions of the planning problem to be handled. Now the most common is PDDL3.2, which contains a description of the predicate and soft constraints and the description of the various logical relations.

And the abstract description of the planning problem is restricted to classical programming problems and non-classical programming problems. Non-classical programming problems mainly refer to conformant programming problems and flexible programming problems as related to this paper.

The problem of programming includes the domain definition and problem definition, which define the operation of the planning problem and the initial / target state respectively. A classical programming problem P is a triad (I, O, G), where I is the initial state, O is the operation set, and G is the target state set. The preconditions and the effects of each operation $o \in O$ are deterministic. Fusing the closed world hypothesis, all the propositions that I describe a state are explicitly depicted, and the true value of the proposition that is not present in the statement

I is false. That is the condition to be satisfied to describe the target state G. Example 1 is a partial description of a classical programming problem that fuses PDDL.

Example 1. (Logistics Planning Problem): The Logistics Planning Problem describes a logistical problem in which multiple parcels are transported to a designated location by loading, shipping, and unloading for multiple trucks and packages in several cities for a logistics package that contains two packages A, B , two locations L, P , and a truck R planning problem, the domain description and problem description is as follows:

Domain description:

$$\begin{aligned} &load(X,Y,Z) : PRE : at(X,Z), at(Y,Z); ADD : in(X,Y) : DEL : at(X,Z) \\ &unload(X,Y,Z) : PRE : in(X,Y), at(Y,Z); ADD : at(X,Z); DEL : in(X,Y) \\ &move(X,Y,Z) : PRE : at(X,Y), fuel(X); ADD : at(X,Z); DEL : at(X,Y), fuel(X) \end{aligned} \tag{1}$$

Problem description:

$$\begin{aligned} &Init : at(A,L), at(B,L), at(R,L), fuel(R) \\ &Goal : at(A,P), at(B,P) \end{aligned} \tag{2}$$

Conformant programming problem is a triad , in which is the initial state set, is the operation set, and is the target state set. Here it is no longer a state, but a state set consisting of all possible initial states. The effect of each operation is uncertain. Conformant planning problem to solve is the initial state and the effect of action is uncertain circumstances, to find a certain plan to reach the target solution.

Flexible planning problem is a triad , in which is the initial state set, the set of operations, the target state set. Here, each operation for a specific action with a different degree of satisfaction. Some researchers define it as a four-tuple, Contains a measure of satisfaction. Flexible planning problem is to solve is the satisfaction of different actions (or preferences) measure, choose one of the most satisfactory or satisfactory enough efficient planning solution.

The above two kinds of non-classical planning problems, as the expansion of the classical planning problem from the uncertainty of the initial state and the action effect, are more in line with the needs of practical problems and suit the cognitive needs more consistently .

1.3 Convergence transformation planning method and fusion self-adaptive reasoning planning method

The convergent-transform programming method transforms the planning problem into other types of knowledge representations and is solved accordingly. The planning problem of the fusion logic representation only relies on the logical deductive method to be solved before 1992. Logical deductions need to be implemented under conditions that ensure reliability and completeness, which is not efficient. In 1992, Neumann [10] proposed the transformation of the planning problem to the propositional satisfiablility (referred to as SAT) to solve the problem of fusion to meet the satisfaction of the planning method. Ever since then, there have been many researches which have attempted to convert planning problem into model detection problem and linear programming problem. The corresponding planning systems Alt [2], MIPS [3], SGPlan [13] have displayed good performances.

In the narrow sense, it relies on the logical semantics of the planning problem itself, transforming it into some theorem proving problem of some logical representation, which calls for the corresponding adaptive reasoning programming method. Logic theorem proves that the system is to be solved, and the solution of the transformed problem can be reduced to the original solution to the original planning problem. The generally- accepted explanation is: logical deduction and reasoning technology are used, directly or indirectly, to verify the planning process; the former focuses on the transformation of knowledge representation, that is, the coding process, while the latter focuses on the use of reasoning technique to prove the process.

The transformation of planning problems to other types of knowledge representation is called encoding, and the new knowledge representation is called encode. Coding may be a specific kind of storage structure, relational structure, clause set, axiom or axioms, etc. For the convenience of description, the coding here only takes into account the representation of the axiomatic hierarchy and has not yet been converted into a conjunctive normal form (CNF) or a set of clauses.

Definition 2. (coding of the planning problem). For a particular coding scheme, the coding of a programming problem is a knowledge representation that can be characterized, either explicitly or implicitly, with respect to a given programming problem: (1) Prerequisites of operation (the coding of a planning problem) , the intrinsic relationship between effects; (2) the relationship between the operation; (3) the initial state and target conditions; 4) (optional) on the action and state constraints.

Definition 3. (coding combination of planning problems) For a particular coding scheme, the coding combination of planning problems is a knowledge representation that can explicitly or implicitly describe the following characteristics about a given planning problem: (1) the relationship between the operations; (2) the initial state and target conditions; (3) (optional) on the action and state constraints.

The coding combination is a kind of coding scheme which is converted into a logical representation. Coding and coding combination are two different concepts, with the former being the planning problem, which corresponds to a suitable overall knowledge representation, and does not distinguish between coding and coding combinations without causing confusion. Cresswell [4] transformed the planning problem into model detection problem.

2 Flexible programming method based on fusion fuzzy description logic

The flexible planning problem (also known as flexible programming problem) introduced introduces a measure of satisfaction to the operation in the planning problem, which is a relaxation of the classical programming. The flexible graph plan system is also the first planning system which addresses such problems.

Since the description of such problems has been difficult to unify, it is necessary to impose a fuzzy characterization on the operation, or a measure of the state preference, which is worth considering and measuring. The description logic ALC* was extended, and a fusion of fuzzy description logic (fuzzy description logic), fuzzy description of the state of the fuzzy description logic, FALC* (fuzzy ALC*) is proposed, which uses FALC* to express the state attributes, and the actions with the relation, which makes the attributes closer to the reality and the actions unique in preference. In addition, the problem definition is transformed into the inclusive relation of the fuzzy concept, and the action definition is transformed into the implicating relation of the fuzzy concept.

2.1 Fuzzy description logic problem representation

According to Badea's design method of fusion description logic frame, FALC* is used to code the planning problem as follows:

According to the standard semantics of fuzzy explanation I, it is interpreted as mapping $C(s)$ a truth value between $[0, 1]$ them. Then we call the subjective C truth degree of the attribute in the state to be n; $R(s, s')$ mapped to a truth value between $[0, 1]$, and then we call it from state s to state s', this action has preference l.

With the implication of fuzzy concept to express the dynamic axiom $DA : \langle C, n\rangle \to \exists\langle R, l\rangle.\{s'\} \wedge \forall\langle R, l\rangle.\langle D, m\rangle$ which, C and D represent that the concept in FALC *, R is FALC * in the relationship. The formula represents: the state s to meet the premise C, and the truth degree of C is $C(s)$, trigger preferences $R(s, s')$ for the action, so that the state s transferred to another state s', and the state s' to meet the true degree $D(s')$ of the property D.

For the knowledge base that needs to be described, the following type descriptions are included:

$$Pkg_2 < pkg \quad \text{etc;}$$

status description:

$$\begin{aligned}&ConnectCitywithMainR < MainRoad \wedge \exists\, forwardCity.\\&T \wedge \exists\, nextCity.\\&T \wedge \forall\, forwardCity.\\&City \wedge \exists\, nextCity.\\&City;\end{aligned}$$

action description:

$$\begin{aligned}&atTruckCity \wedge atPkgCity \wedge \neg onGuardTruck \wedge \langle ValuableP, k_2\rangle \to \exists\,(LoadTruck_3, l_2).\\&\{x(\neg atPkgCity \wedge onPkgTruck)\} \wedge \forall\,(LoadTruck_3, l_2).\\&(\neg atPkgCity \wedge onPkgTruck)\\&\text{coding etc.}\end{aligned}$$

2.2 Reasoning ability of fuzzy description logic

The post-transformation theory needs to assert the goal of deriving satisfaction degree n from the fuzzy knowledge base,$\sum | =\langle goal, n\rangle, i.e.$

$$\{\Gamma_S \cup \Gamma_D, \langle S(init), n\rangle\}| = ((\exists\,\langle plan, l\rangle.\{xgoal\}) \wedge (\forall\,\langle Plan, l\rangle.\langle goal, m\rangle))\,(init) \tag{3}$$

Among them, Γ_S is the static axiom set, it Γ_D is the dynamic axiom set; $init$ for the initial state, it $S(init), n\rangle$ means satisfying the attribute S, and its subjective truth degree is n .$(\exists\langle plan, l\rangle.\{xgoal\}) \wedge (\forall\langle Plan, l\rangle.\langle goal, m\rangle)$, indicating that there is a satisfaction degree l satisfying the target state, and satisfying the satisfaction degree m.

Since the pruning strategy is not adopted, the FPExp algorithm designed to find the optimal solution satisfies the requirements, but it needs to consider the appropriate pruning strategy to compress the search scale.

For planning solutions with satisfaction below a given limit, even if the length of the solution is very small, it is not considered as an effective solution. For the trade-off between length and satisfaction, the length of the solution is given priority.

2.3 Flexible programming method based on fusion fuzzy description logic

We design a flexible programming method which integrates fuzzy descriptive logic and solve the flexible programming problem by transforming the flexible programming problem into the knowledge representation problem of fuzzy description logic. This is a new attempt which corresponds to the complex planning problem to the non-classical logic problem, and use the inference technology of non-classical logic to deal with the transformed problem. Despite the far-from-expectation result , there is much to be developed with this method, such as adding pruning strategies and other heuristic search strategies.

3 Experiment and analysis

Currently, the enterprise decision-making method for the media enterprise data run features are not fully considered which led to no data on the steady-state decision to determine the enterprise decision-making. In this case, there is not enough clarity of case partitioning, resulting in poor comparability between the final information mining result and the actual data. In this paper, combined with the main features of the production mode of the media enterprise, the steady state judgment is carried out on the data. On this basis, a classification model is constructed to ensure the accuracy of the classification results and evaluate the effectiveness of the algorithm.

3.1 Experimental data

In this study, a media enterprise reasoning data was used, and the data of the first half of 2012 was selected as the research object. There are 427 attributes of the integrated data, besides the set key number and the data retention time automatically generated by the system, there are 425 condition attributes in total, all of which maintain the numerical characteristics. The steady-state, unsteady-state annotation of the operating data is obtained by referring to the steady-state operating parameters, and the decision-making attributes are obtained. And in order to better test the algorithm 3 (GARIv) and maintain the original data of each system unchanged, the original database of the same decision attributes is added.

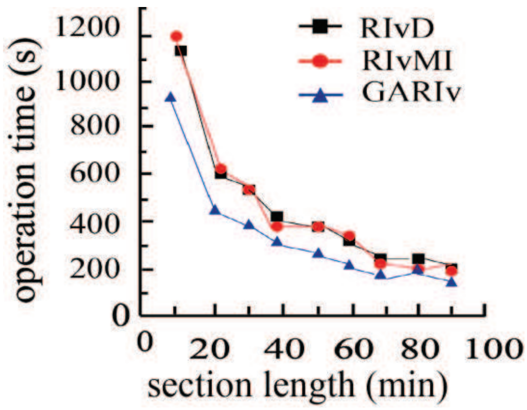
In addition, in order to evaluate the performance of the algorithm synthetically, a variety of partitioning methods are employed to design the data interval. If there is a decision class corresponding to a certain interval in the interval division, the data belonging to the same decision class are divided; it is classified into the same small interval, starting from the next interval starting from the different decision classes in turn.

The experiment is implemented on the workstation Intel Xeon(R) Processor (Four Core, 2.5GHz, 16GRAM). The algorithm is mainly realized by JAVA writing. In the calculation of the GARIv algorithm, two virtual machines are constructed to form two sites. In the experiment, the accuracy of classification can be confirmed, which can effectively guarantee the fairness of the experiment.

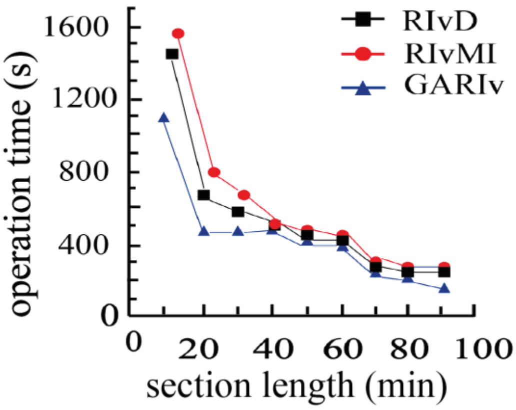
3.2 Experimental comparison

First, the experiment data of algorithm 1, algorithm 2 and algorithm 3 are combined with the selected experimental data. The time of the algorithm is determined by the interval length of the algorithm. Fig.1 (a) to Fig.1 (d) show $\lambda = 0.7$, the running time chart when the interval length is 10minutes, 20minutes, ..., 90minutes, respectively, when the number of attributes is different.

Fig. (a) To Fig. 2 (b), represents when $\lambda = 0.5, 0.7$ the running time required for selecting two attributes under different section lengths.



(a) Select 1 attribute



(b) Select 2 attributes

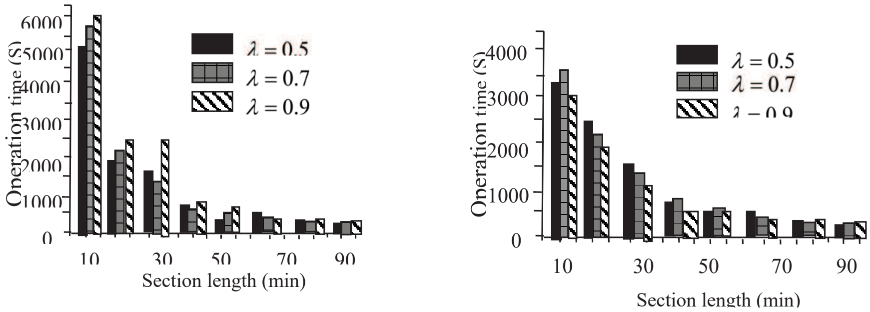
Figure 1: $\lambda = 0.7$, the running time of different decision algorithms

As can be seen from Figure 1:

- the length of the interval is increasing, the data object will be reduced by a factor of two, and the time required for the algorithm to run will decrease;

- When the length of the interval increases, the coincidence degree between the intervals will increase, which will increase the number of $\lambda-$ compatible class elements. If an attribute is added, the computation amount will increase. Therefore, the running time of the algorithm shows a nonlinear trend. The number of objects decreases, but the running time does not decrease with the interval length, but it shows an increasing state. Analysis of this situation may be due to it that although the length of the interval is increasing, but based on the number of $\lambda-$ compatible elements in an increasing number of state, thereby extending the running time;

- Compared with the algorithm RIvD and algorithm RIvMI, the two maintain relatively similar running times for a relatively small number of attributes, but the similarity decreases with the increase of the number of attributes, and the running time of the former will be longer. The reason is that the number of compatible classes increases with the increase of the number of attributes. However, it is necessary to judge whether the compatibility class is classified as positive domain when calculating the domain. It leads the algorithm RIvD to take longer time for the calculation, and for this algorithm RIvMI, the number of compatible class will increase with the property; however, its new conditional entropy, the combination of the original conditional entropy expansion can be achieved, and, therefore, the latter requires a shorter time.



(a) RIvD Select 3 attribute (b) GARIv Select 3 attributes

Figure 2: the running time required of the two algorithms when λ is different

Analysis of Figure 1, the required minimum run time is the GARIv algorithm, which is, theroretically, the algorithm running time for the basic half of the algorithm RIvMI. However, because the compatibility class is calculated, it is related to the transmission of partially compatible classes, and overall, the configuration of the virtual machine is difficult to match with the workstation, so that the actual time required for the algorithm GARIv exceeds its theoretical time; however, in terms of overall time, the algorithm is relatively low, and with the increase in the number of sites, this time advantage will be more prominent.

As shown in Fig.2, because the λ values are more irregular and more consistent, λ increases continuously. Their compatible classes are more refined and the number of compatible elements decreases. For the algorithm GARIv, the amount of compatible class traffic that needs to be done is larger, which results in a longer run time.

Experimental average classification accuracy and the traditional average classification accuracy were compared to evaluate the effectiveness of the three algorithms. The results are as follows:

Table 1: The average accuracies of classification

algorithm		Section length (unit:minutes)								
		10	20	30	40	50	60	70	80	90
RIvD	$\lambda = 0.5$	78.8%	80.3%	81.4%	80.2%	80.4%	80.3%	71.2%	70.9%	69.5%
	$\lambda = 0.7$	78.8%	84.4%	81.3%	82.4%	81.2%	79.4%	76.3%	70.5%	67.3%
	$\lambda = 0.9$	80.1%	81.5%	85.0%	81.9%	78.5%	79.3%	70.3%	66.9%	69.9%
RIvMI	$\lambda = 0.5$	85.2%	84.6%	86.6%	85.6%	82.6%	88.3%	79.6%	72.6%	67.9%
	$\lambda = 0.7$	84.5%	94.6%	89.6%	90.3%	92.3%	92.6%	79.2%	73.6%	62.6%
	$\lambda = 0.9$	83.5%	90.2%	88.3%	92.6%	88.3%	92.3%	84.2%	79.3%	72.5%
GARIv	$\lambda = 0.5$	77.3%	91.6%	86.3%	89.6%	86.3%	86.3%	80.3%	72.3%	67.5%
	$\lambda = 0.7$	81.2%	93.4%	84.3%	82.5%	85.5%	92.2%	82.5%	81.0%	72.9%
	$\lambda = 0.9$	78.2%	91.1%	88.3%	83.5%	82.7%	84.5%	75.2%	80.5%	71.2%

After analysis of the table above, in many traditional analysis methods, the classification effect of kNN is the best; and RBF, REPTree have a relatively low accuracy, because the multi-source information in the steady-state judgment calls for a certain interval of data to judge, which is difficult to achieve through only one stream of data. The reason why the kNN accuracy in the classification is better is that it takes the data value of the same sub-section for the same paragraph of its decision-making class. Thus, when a neighbor k is computed, the corresponding decision class is as likely as the adjacent test result, and if the value k keeps increasing, a cross-class phenomenon is most likely to occur. This approach effectively reduces the information dimension and enhances the accuracy and efficiency of multi-source information decision making.

The three algorithms proposed in this paper are implemented on the basis of interval division, and are easier to satisfy the requirements of the decision-making stability, and thus have better accuracy than the traditional methods.

4 Conclusion and outlook

With the demand of problem representation, the programming method of the deductive logic and reasoning technology has been paid more and more attention to by the researchers of the related fields. A variety of non-classical logic calls for the need of the fusion knowledge representation, adding the description of modal, time and ambiguity etc. Many researchers use various techniques such as satisfiability judgment technique, first-order predicate lifting technique, fuzzy descriptive logic to express satisfaction degree of planning, and fusion modal logic representation and deduction reasoning technology to deal with various complicated planning problems, which has achieved a recognized outstanding recognition, promoting the intelligent decision support and self-adaptive reasoning of mutual promotion and integration. The uniqueness of media enterprises does not allow the one-sided decision-making system to fully meet the needs of its development, which means that in the future research the features of media enterprises should be taken into consideration so that an exclusive decision-making system can be devised and developed to meet the requirements of this industry in terms of operation and management.

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A Rapid Recognition of Impassable Terrain for Mobile Robots with Low Cost Range Finder Based on Hypotheses Testing Theory

Y. Gao, X.Y. Wu, Y. Liu, J. M. Li, J. H. Liu

Yang Gao*
School of Automobile,
Chang'an University,
Xi'an, Shaanxi Province, 710061,China
*Corresponding author: nchygy@chd.edu.cn

Xueyi Wu, Yu Liu, Jian Ming Li, Jia Hao Liu
School of Automobile,
Chang'an University,
Xi'an, Shaanxi Province, 710061,China

Abstract: The recognition of impassable terrain plays a vital role in the motion planning of a mobile robot, which generally relies on expensive sensors such as stereo vision cameras. This paper proposes a rapid impassable terrain recognition algorithm based on hypotheses testing theory using low-cost range finders with different diffusion angles. In this algorithm, a slope estimation model using two range finders mounted on different heights is first established, where the influence of the diffusion angle of the range sensor is considered. To deal with inaccurate measuring from low cost range finders, the hypothesis testing theory is then applied to judge whether there is an impassible terrain approaching, where the historical slope estimation results are treated as a sample set of the same slope, and the judgement of impassible terrain is then made based on the sampling set rather than the concurrent slope estimation. So the robot is only required to count the number of slope estimation that support the determination of a terrain as being impassible, and the judgement is confirmed only when that number is larger than a precisely designed threshold value. Then the stable recognition for impassable terrain would be acquired while the risk of wrong judgement is limited. The experiments' results indicate that this algorithm can provide a reliable recognition of impassable terrain using lower cost range finders with different diffusion angles with minimal computation.
Keywords: Impassable terrain, range finder, slope, hypothesis testing.

1 Introduction

Recognition of impassable terrain, which generally includes rapid vertical variations, is a critical and fundamental issue for mobile robots. Over the previous few decades, techniques and theories for terrain recognition of intelligent automatic vehicles or robots have achieved many successes. [8] presented a three-dimensional (3-D) vision technique for incrementally building an accurate 3-D representation of rugged terrain using multiple sensors. This technique demonstrated the desired accuracy for self localization tasks but is too complex for rapid recognition of impassable terrain . [17] proposed a method for the retrieval of 3-D surface models of the earth using optical and radar imaging sensors. However, this requires 3-D sensor and is difficult to fulfill the efficiency requirement. [2] proposed a method for building a 3-D world model for a mobile robot through sensory data derived from outdoor images using a camera. [21] proposed a method for terrain recognition using a 3-D reconstruction technique that requires 3-D sensors and shows poor efficiency. [11] proposed an overview of stereo vision, stereo image processing as well as a method of obstacle avoidance and navigation based on stereo vision for a mobile robot. [4] proposed a novel navigation framework for autonomous vehicles where a stereo camera is used for both slope estimation and obstacle detection. [12] proposed an approach for obstacle detection in a greenhouse environment, where the depth data provided by the Kinect 3D sensor are used for slope estimation. [16] proposed a novel method for analyzing a mobile robot's ability to travers rough terrain where the roughness and the slope are calculated using an elevation map built by a laser range finder. [9] proposed a hierarchical, decentralized and networked controled system for mobile robots where the slope of terrain is detected using a laser range finder. This approach shows good robustness for various environments but needs much more computational resources. [15] proposed a terrain recognizer where a database consisting of five terrain classes is generated, then depth images are enhanced using confidence map based filtering technology. This approach classifies the terrain into five types, but expensive depth sensing and much computational resources are required. [10] proposed a survey of the distribution of slope angles in the Alishan area using airborne Lidar and aerial digital camera. [20] proposed a novel approach for obstacle detection using optical flow without recovering range information. This approach shows good efficiency but is not reliable without recovering range information. [18] proposed a collision-free area detection algorithm for an autonomous mobile robot, using a depth camera. However, depth cameras are expensive and may lead to much computational capacity, while the accuracy would gradually decrease with increasing distance. [7] proposed a multisensory data-fusion system for driving an autonomous earthwork vehicle operating in a sanitary landfill, using ultrasonic sensors, a laser range finder, and several charge-coupled device cameras. [13] proposed a method for recognition of uneven terrain using 3D laser scanner. [23] proposed a novel but complex method for real-time obstacle detection and recognition, where several key obstacle characteristics are identified based on image information and geometric information using support vector machine (SVM). [14] proposed a novel algorithm to qualitatively categorize the terrain type in real-time, using high fidelity sensors. [11] proposed an application of an image registration method for a mobile manipulator, where the range image may be interpreted for object recognition using ultrasonic range finders. [5] proposed a real time terrain recognition method for a mobile robot moving on uneven terrain to capture a terrain depth image using a RGB-D sensor, which may result in poor performance as the environment changes. [1] proposed a probabilistic framework in which the visual information and the mechanical supervision interact to learn the terrain types.

It may be concluded that most existing research rely on sensors generally including: 2D sensors such as vision sensors, range finders, laser range finders, ultrasonic range finders, etc; 3D sensors such as 3D vision sensors, 3D laser range finders, etc. The 3D sensor is generally expensive but provides abundant information for the task. As to the 2D sensors, the laser range finder can provide precise angle measuring but is much more expensive. The ultrasonic range finder, on the other hand, is widely used due to its lower cost and can acquire distance measuring along the wave propagation direction of the ultrasonic range which causes a diffusion angle and provides only slightly less accurate measuring in respect of both distance and angle. So, for these lower cost 2D range finders which may come up with different diffusion angles, such as the ultrasonic and infrared range finders, it is important to develop an algorithm for the reliable recognition of the impassable terrain, provide a good conditions for path planning [19], [6], [3].

2 Mathematical model of recognition

In this paper, descent terrain is not discussed because of the limited sensor ability. We can define the impassable terrain as a terrain with a slope angle larger than a threshold value of θ_T, which is set according to the travel capability of the robot. So, impassable terrain may be recognized according to the slope estimation result.

2.1 Slope estimation based on range finder with various diffusion angles

As the slope estimation algorithm will be proposed in another paper, a brief introduction is proposed as follows.

A robot coordinate system is mounted on the mobile robot as shown in Figure 1, where the orientation of the robot is the X axis, the origin point is settled on the floor under the wheels, and the Y axis is settled along the height of the robot. Assume there are two range finders mounted on the robot at different heights, as shown in Figure 1, whose positions are $O_A(X_A, Y_A)$ and $O_B(Y_B, Y_B)$ respectively and the vertical difference is $O_AO_B = h$. Assume the measurement of sensor A is D_A(mm), whose diffusion angle is Φ_A, the measurement of sensor B is D_B(mm), whose diffusion angle is Φ_B. Sensor A for instance detects a sector such as a spreading beam as shown as Figure 1. Let points a and b denote the two boundary contact points of the spreading beam and the obstacle, among which the lower one is a, and the upper one is b. For an obstacle whose slope is θ, the beams of the two sensors are shown in Figure 2. So, for sensor A, the horizontal and vertical distances between sensor A and contact point a, respectively denoted as DX_A(mm) and DY_A, is expresses as formula (1).

$$\begin{aligned} DX_A &= |D_A| \cos\left(\frac{\Phi_A}{2}\right) \\ DY_A &= |D_A| \sin\left(\frac{\Phi_A}{2}\right) \end{aligned} \tag{1}$$

Similarly, sensor B forms the two boundary contact points c and d, where the horizontal and vertical distances between sensor B and the lower contact point c is expressed as formula (2).

$$\begin{aligned} DX_B &= |D_B| \cos\left(\frac{\Phi_B}{2}\right) \\ DY_B &= |D_B| \sin\left(\frac{\Phi_B}{2}\right) \end{aligned} \tag{2}$$

Let Δx,Δy denote the difference between the two boundary contact points a and c along the X axis and Y axis respectively. Then, formula (3) can easily be obtained, where X_a, X_c, Y_a, Y_c, are the X and Y coordinates of the two boundary contact points a and c respectively.

$$\begin{aligned} \Delta x &= X_a - X_c = X_A + DX_A - X_B - DX_B \\ \Delta y &= Y_a - Y_c = Y_A - DY_A - Y_B + DY_B \end{aligned} \tag{3}$$

Accordingly, the slope of the obstacle θ can be obtained through formula (4).

$$\theta = \arctan\left(\frac{\Delta y}{\Delta x}\right) \tag{4}$$

2.2 Impassable terrain recognition based on hypothesis testing theory using unreliable slope estimation

It is generally the case that sensors can only provide inaccurate measurements, resulting in inaccurate estimations of the slope. To address this problem, Gaussian noise is used to describe the inaccurate nature, whose distribution can be expressed by formula (5), where μ and δ denote the expectation and the variance respectively. In this paper, μ is supposed to be the estimation

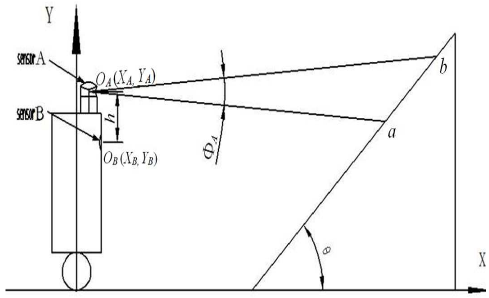

Figure 1: One sensor diffusion angle

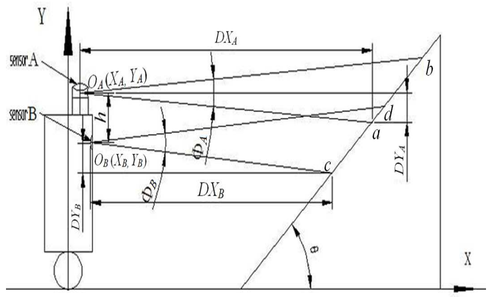

Figure 2: Two sensors diffusion angles

of the slope by using the algorithm described above, implying that the estimation results most likely reflect the actual slope, while δ implies the possible distribution of the actual slope.

$$N(\mu,\sigma)=\frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{(X-\mu)^2}{2\sigma^2}} \tag{5}$$

$$P_{hit}(r,r^*)=\begin{cases}\eta_1 N(r,r^*,\delta_{hit}) & 0\le r\le r_{\max}\\ 0 & otherwise\end{cases} \tag{6}$$

$$\eta_1=(\textstyle\int_0^{r_{\max}} N(r,r^*,\delta_{hit})dr)^{-1} \tag{7}$$

$$N(r,r^*,\delta_{hit})=\int_0^r \frac{1}{\sqrt{2\pi\delta_{hit}^2}}e^{-\frac{(r-r^*)^2}{2\delta_{hit}^2}}dr \tag{8}$$

So, the inaccurate sensor information can be modeled by adding a Gaussian noise. Let $P_{hit}(r,r^*)$ denote the possibility that r is a noisy observation to r^* (r^* represents the actual value of the sensor, $r_{\max}$ represents the maximum measured value of the sensor, r^* and δ_{hit} denote the expectation and the variance respectively of the sensor), which can be obtained by formula (6). The normalizer η_1 is expressed as formula (7). The Gaussian observed noise $N(r,r^*,\delta_{hit})$, as expressed by formula (8), shows that the further r is from r^*, the less P_{hit} is.

Let the wave line superscript denote a Gaussian distributed random variable, while the subscript k denotes the time step. Then, $(\tilde{\theta}_k - N(\theta_k,\delta))$ denotes the possible distribution of the correct slope on time k affected by the Gaussian noise, as shown in formula (5), whose expectation is the slope estimation value θ_k.

Assume there are n independent historical slope estimations for the same terrain, while the terrain is supposed to be static. These estimations can then be treated as n estimation samples $(\{\tilde{\theta}_k \big| k=0...n\})$ of the same one terrain confronting the robot.

For each observation of the same terrain, applying formulas (1) to (4) to estimate its slope can yield only two opposite results; the terrain with a slope that is passable or impassable. Let p denote the probability that the estimation result $\tilde{\theta}_k$ indicates an impassable terrain. Let M denote the number of estimation results that indicates it is an impassable terrain. Then, the probability, that all the n samples are found to indicate an impassable terrain, conforms to a binomial distribution $B(n,p)$.

Considering the inaccurate nature of the estimation process, if p is smaller than a threshold value P_u, a passable terrain can be confirmed. So, formula (9) is applied to judge whether there is an impassable terrain. Here the threshold value P_u being approximate to 0 implies a low likelihood of misrecognition. The hypothesis testing theory can then be applied for a reliable recognition of the terrain type based on the n estimation samples as follows.

$$p\le P_u \tag{9}$$

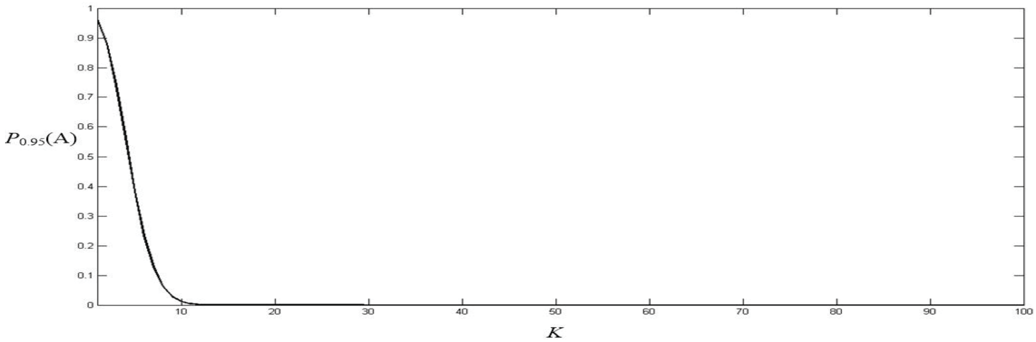

Figure 3: Relationship between K and $P_{0.05}(A)$

Let hypothesis H_0 be: a passable terrain is detected ($p \leq P_u$). Let event A be: the number of the estimation samples that have proved to indicate an impassable terrain ($\tilde{\theta}_k \leq \theta_T$), is larger than the threshold value K. Let $\overline{A}$ be the opposite event of A. Let $P_p(A)$ denote the probability of A with p given. Then formulas (10) to (12) can be induced where C_n^j denotes the extraction of j samples from n samples.

According to the hypothesis testing theory, $P_p(A)$ also denotes the probability of rejecting H_0 and A happening while p is given. Similarly, $P_p(\overline{A})$ denotes the probability of accepting H_0 and $\overline{A}$ happening while p is given.

$$P_p(A) = \sum_{j=K+1}^{n} C_n^j (1-p)^{n-j} p^j \tag{10}$$

$$P_p(\overline{A}) = \sum_{j=0}^{K} C_n^j (1-p)^{n-j} p^j \tag{11}$$

$$\sup_{p \leq P_u} P_p(A) \leq \alpha \tag{12}$$

There are two types of error that may occur. The first type is H_0 may be rejected and A has happened while H_0 is in fact true ($p \leq P_u$). The second type is H_0 may be accepted and $\overline{A}$ has happened while H_0 is in fact untrue ($p > P_u$). The hypothesis testing theory has proved that the probability of the both types of error cannot be decreased simultaneously, and the decreasing of the probability of the first type should be guaranteed. Thus, we can confine the probability of the first type under a manually selected level α as expressed by formula (12). As $P_p(A)$ is in proportion to p, let $P_{p_u} = \alpha$, then formula (12) is fulfilled. Let $p = P_u$, then K can be obtained from formula (10).

As a result, it can be concluded that, with the given α if $M \leq K$, then a passible terrain is confirmed to be detected; otherwise an impassable terrain is confirmed. For instance, if $n = 100$,$P_u = 0.05$,$\alpha = 0.01$, then $K = 10$ would result (Figure 3 shows the relationship between K and $P_{0.05}(A)$. So an impassable terrain could be confirmed only if M is larger than K.

3 Experimental study

To validate the algorithm, several experiments are described in this section. All these experiments were carried out in our laboratory, which is a typical indoor environment. A Pioneer 3-DX Mobile robot (Figure 4), equipped with six ultrasonic range finders (Figure 5) and a HOKUYO UTM-30LX laser range finder (Figure 6), are used in the experiments. The laser range finders are mounted on the top of the robot, which is capable of providing a long maximum measuring range (about 30m) with very limited deviation (up to 50mm). Meanwhile, the maximum sensing range of the ultrasonic range finder is about 5m. The diffusion angle of the laser range finder is so limited that it could be considered as zero, while that of the ultrasonic range finder is 4.6 Â°. In the following experiment, the number 3 ultrasonic range finder, as shown in Figure 5, and the measuring data of the laser range finders, along the orientation of that ultrasonic sensor, are used. Both of the two range finders are mounted along the Y axis with a height difference of 60mm. The principle of laser and ultrasonic ranging is expressed by formula (13).

$$D = \nu t/2 \tag{13}$$

Where D represents the distance value, v represents the speed of light propagation or sound wave propagation, t represent the time of light propagation or sound wave propagation.

Figure 4: Mobile robot

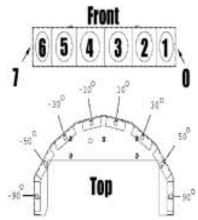

Figure 5: Ultrasonic range finder

Figure 6: Laser range finder

4 Results and discussion

4.1 Slope Estimation Experiments

Figure 7 shows an example of the inaccurate measuring of the ultrasonic range finder where an object is located in front of the robot at a distance about 500mm. The horizontal ordinate of Figure 7 denotes the elapsed time, while the vertical ordinate denotes the range measuring. The blue line shows the measuring of the ultrasonic sensor where a large deviation appears.

Table 1: Objects with different slopes

object index	1	2	3	4	5	6	7	8	9
slope(^{o})	6	7	8	9	10	11	12	13	14

Table 2: Different distance between the robot and the objects

distance index	1	2	3	4	5	6	7	8	9
Distance (mm)	500	1000	1500	2000	2500	3000	3500	4000	4500

This section describes several groups of experiments that were conducted. In the first group, nine objects with different slopes were placed for estimation (Table 1) to show the large deviation of estimation result (Figure 8). In the second group, four objects with different slopes were placed to show the performance of the proposed algorithm where 60 historical samples were adopted for each object (Figure 9, 10, 11). It is generally the case that the robot has to distinguish the impassable terrain from the passable ones while the θ_T is set to 10^o. So four objects whose slopes are less than 10^o were chosen to represent the passable terrain, during which the slope increase

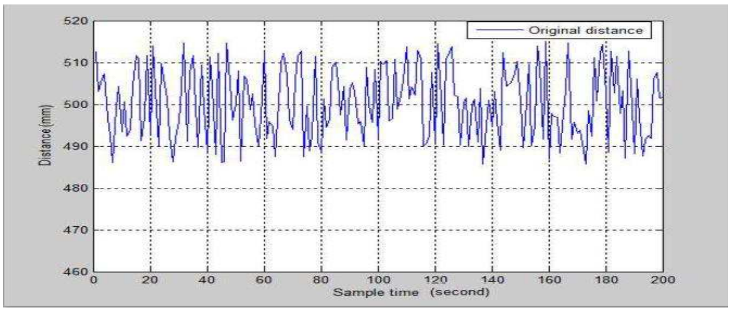

Figure 7: Ultrasonic sensor measuring value

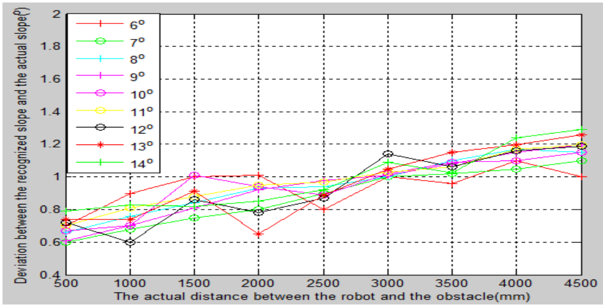

Figure 8: Deviation between the estimated slopes and the actual slopes

intervals are set to 1^o separately. Meanwhile, four objects whose slopes are larger than 10^o were also chosen to represent the impassable terrain, during which 1^o is set to be the slope increase interval.

The accuracy of the measuring may be getting worse with the growing distance. So, we set a group of increasing distances for the objects as shown in Table 1. The ultrasonic range finder can only operate within 5m, so the largest distance is set to 4.5m while the distance increase interval is set to 500mm, as shown in Table 2.

The nine objects with different slopes (Table 1), were set in front of the robot at different distances (Table 2). All the deviations between the estimation results and the actual slopes are shown in Figure 8, in which the horizontal ordinate denotes the actual horizontal distance (mm) between the objects and the sensors while the vertical ordinate denotes the deviation (^{o}). The nine lines in Figure 8 show the different deviations with different object slopes.

Overall, Figure 8 shows that larger distances result in larger errors due to the larger deviation in the sensor measuring. Moreover, a poor performance occurs when the slope of object is less than 10^o. This is mainly because of the misreading of the ultrasonic sensor caused by the specular reflection of the ultrasonic beam toward any direction other than toward the sensor. On the contrary, a better performance was observed when the slope is larger than 10^o, in which case the ultrasonic sensor is less likely to provide a misreading. However, an even better performance was observed when the distance is less than 2000mm, even if the slope is less than 10^o. This is mainly because the diffused reflected ultrasonic beam has been received by the sensor although most of the ultrasonic beam has been reflected to some other direction by the specular reflection. Fortunately, obstacles and impassable terrain generally refer to a surface whose slope is larger than 10^o.

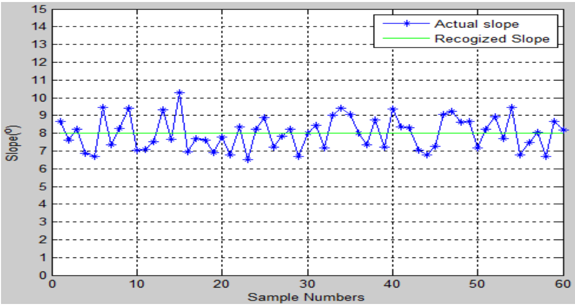

Figure 9: Estimation result for 8^o Slope

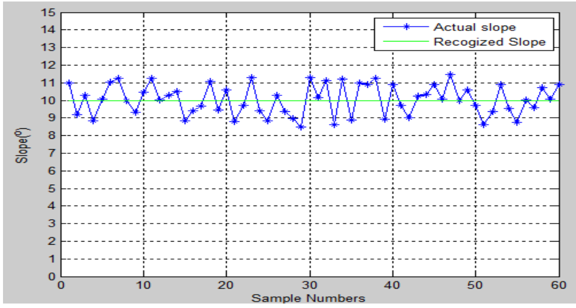

Figure 10: Estimation result for 10^o Slope

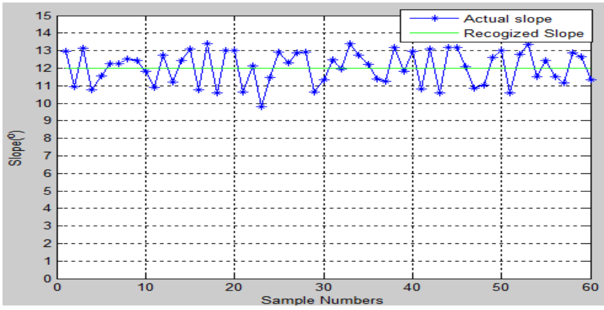

Figure 11: Estimation result for 12^o Slope

4.2 Terrain type recognition experiments

Figure 9, 10, 11 shows three objects set in front of the robot with different slopes close to the, a situation which is more likely to result in a wrong judgement. In each experiment, 60 historical slope estimation results were acquired for each object from which 50 estimation results were used to apply to the hypothesis testing. So, for each recognition, the number of samples $n = 50$, $P_u = 0.03$, $\alpha = 0.05$ then $K = 4$ could be obtained.

Table 3, 4, 5 shows the results of three groups of experiments for three objects where each group consists of three experiments. In Table 3, an object with 8^o slope is used, and only one result among the sampling sets of each experiment was larger than θ_T. As a result, this object was confirmed to be passable terrain in all three experiments. In Table 4, an object with 10^o slope is used instead, which resulted in more than 10 wrong slope estimation in each experiment, where the slope estimation result is less than θ_T. However, with the help of the hypothesis testing theory, our algorithm successfully made right recognition for the type of the terrain in all three experiments. In Table 5, an object with 12^o slope is used instead, which resulted in only one wrong slope estimation in both the first and the third experiments, where the slope estimation result is less than θ_T. Thus, the proposed approach confirms that this is an impassable terrain.

Table 3: The recognition results to objects with actual slope 8^o

Experiment Index	M	Result
1	1	Passable
1	1	Passable
1	1	Passable

Table 4: The recognition results to objects with actual slope 10^o

Experiment Index	M	Result
1	32	Impassable
1	36	Impassable
1	34	Impassable

Table 5: The recognition results to objects with actual slope 12^o

Experiment Index	M	Result
1	49	Impassable
1	50	Impassable
1	49	Impassable

5 Conclusion

This paper proposes an impassible terrain recognition algorithm for a mobile robot. Based on this algorithm, historical slope estimation results are used to lessen the influence of inaccurate estimation according to the hypothesis testing theory. This allows different types of low cost range finders with different diffusion angles and inaccurate measuring to be used in the task of recognizing impassible terrain. Because the simple slope estimation model is employed and only the estimations referring to impassable terrain are counted, this algorithm is rapid and easily implemented. Experiments have demonstrated that the proposed algorithm increases the reliability in most cases with an inexpensive mean for robots to recognize impassable terrain.

Acknowledgments

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Minimizing Uplink Cellular Outage Probability in Interference Limited Rayleigh and Nakagami Wireless Fading Channels

M. Hayajneh

Mohammad Hayajneh
Computer and Network Engineering Department,
College of Information Technology,
United Arab Emirates University, UAE
mhayajneh@uaeu.ac.ae

Abstract: We propose a game theoretic non-cooperative algorithm to optimize the induced outage probability in an uplink cellular interference limited wireless Rayleigh and Nakagami fading channels. We achieve this target by maximizing the certainty equivalent margin (CEM). We derive a closed-form formula of the outage probability in Nakagami flat-fading channels, then we show that minimizing the induced outage fading probability for both Rayleigh and Nakagami channels is equivalent to maximizing CEM. We present a non-cooperative power control algorithm using the game theory framework. Through this non-cooperative game, we argue that the best decision in such an environment is for all users to transmit at the minimum power in their corresponding strategy profiles. This finding considerably simplifies the implementation of the proposed game.
Keywords: cellular network, code-division-multiple-access (CDMA), outage probability, power control, non-cooperative game (NPG).

1 Introduction

Game theory was first brought to the literature by John Von Neumann and Oskar Morgenstern in 1944 [7], and by the end of 1970's game theory became a framework of great value in the researcher's resources whenever there is a situation in which an agent's action depends on the other agents' actions. The basic aim of game theory is the method where deliberate dealings between intelligent agents, produces outcomes according to the agents' desires [2], [10]. In a non-cooperative game, an agent counters the actions of other agents by selecting a strategy from his strategy space in aiming to optimize a utility function that quantifies its quality of service level (QoS).

In an uplink cellular data communications systems, cellular users (agents) prefer to have a high signal-to-interference ratio (SIR) at the base station (BS) while sending at the lowest possible power, this helps to have longer battery life and helps cope with interference problem in CDMA systems [8]. Also, it is important to have a high SIR, as this means having a low error rate, a more reliable system, and high channel capacity, which results in higher attainable bit rates [14], [9].

In game theoretic power control algorithms for cellular systems, each cellular user maximizes his utility function by transmitting at a feasible power level to reciprocate the other cellular users' aggregate transmitted powers. This action generates a series of power vectors that converges to an operating point that is called Nash equilibrium (NE) point. However, due to nature of the non-cooperative algorithms that lack cooperation between the users, it is not guaranteed that this operating point will be efficient, in the sense that it may not be the most preferred operating point by all cellular users [11].

Game theoretic framework was first exploited in [13] to provide solutions and insights for the power control problem for CDMA communication systems, then was more exploited in [11] and [12]. The research work in [5] presented a bound that relates the induced Rayleigh channel fading outage probability to the SIR margin. Where SIR margin is just the SIR with the signal power and the interference noise power are replaced by their statistical means. Then they used Perron-Frobenius eigenvalue theory to allocate the cellular users' transmit powers in a manner that minimizes the system outage probability. For more feasible case, that is, when the transmitted powers are constrained along with other constraints, they modeled the optimization problem as a geometric programming problem to find a global solution. However, the global solution was based on a centralized algorithm that run on the BS to collect data about all path gains of the links between transmitters and their corresponding receivers in the cellular communications system.

In this paper the problem addressed in [5] to minimize the outage probability and the certainty-equivalent margin for Rayleigh wireless fading channels, is solved in a non-centralized manner under both Rayleigh and Nakagami fading channels. We also provide a simpler proof of the strong relationship between the two problems, namely: Minimizing the fading induced outage probability, and maximizing the CEM. We then present a closed-form formula of the outage probability in a Nakagami flat-fading channel. Using the outage probability formula, we prove that both problems mentioned above remain equivalent in Nakagami flat fading channels.

What is left from the paper is presented as follows: The system model we studied in this paper is described in section 2. Deriving a closed-form formula of the induced outage probability in an interference limited Nakagami flat fading channels is performed in Section 3. The strong correlation between the minimization of the outage probability and the maximization of the CEM is presented in 4. In section 5, our proposed Non-cooperative power control game (NPG) is discussed. Simulation results are presented and explained in section 6, and our conclusions are casted in section 7.

2 System model

The system under investigation in this paper is similar to that studied in [3]. In [3], the solutions for optimizing the system CEM and the system uplink outage probability under Rayleigh flat-fading channels were introduced. In this paper however, we extend our study to figure out a non-centralized power control game theoretic-algorithm for also Nakagami flat-fading channels. Thus, the system under study is as follows: Assume we have one cell with N cellular users communicating with BS in the uplink direction. Which can be seen as N transmitter-receiver pairs, where the ith transmitter transmits messages at a power level p_i from his action profile P_i to the corresponding ith receiver (the BS). The power profile P_i set is assumed to be convex set. The received power level at receiver i from transmitter k is given by:

$$H_{i,k}\chi_{i,k}p_k \tag{1}$$

in which $H_{i,k} > 0$ is the link gain between transmitter k to receiver i. $H_{i,k}$ captures the effect of spreading gain and/or cross correlation between codes in CDMA (code division multiple access) systems. $\chi_{i,k},\ \ i,k = 1,2,...,N$ are exponentially independent distributed (id) random variables with mean equal to 1 in a wireless Rayleigh flat-fading channel. On the other hand in a Nakagami flat-fading channel, $\chi_{i,k},\ \ i,k = 1,2,...,N$ are Gamma id random variables with mean also equal to 1. Hence, the power received from user k at receiver i is modeled as Exponential (Gamma) random variable with expected value expressed as:

$$\mathrm{E}\left\{H_{i,k}\chi_{i,k}p_k\right\} = H_{i,k}p_k \tag{2}$$

In an interference limited fading channels, the background additive white Gaussian noise (AWGN) effect is considered minor compared to the power interference from the other active users. Therefore, the signal-to-interference ratio of the ith user at the corresponding receiver is given by:

$$SIR_i = \frac{H_{i,i}\chi_{i,i}p_i}{\sum_{k\neq i}^{N} H_{i,k}\chi_{i,k}p_k}. \tag{3}$$

It is clear from (3) that SIR_i is a random variable, which is a ratio of an exponentially (Gamma) distributed random variable to a summation of independent exponentially (Gamma) distributed random variables with different means under Rayleigh (Nakagami) fading link. The outage probability O_i, defined as the probability that the SIR of an active user i will be less than a threshold SIR_{th}, then for user i:

$$\begin{aligned} O_i &= \Pr\{SIR_i \le SIR_{th}\} \\ &= \Pr\{H_{i,i}\chi_{i,i}p_i \le SIR_{th} \sum_{k\neq i}^{N} H_{i,k}\chi_{i,k}p_k\} \end{aligned} \tag{4}$$

This probability was derived in [5] for a Rayleigh flat fading channel:

$$O_i = 1 - \prod_{k\neq i}^{N} \frac{1}{1 + SIR_{th}\frac{H_{i,k}p_k}{H_{i,i}p_i}} \tag{5}$$

The system outage probability, O is described as:

$$O = \max_{1\le i\le N} O_i \tag{6}$$

Where O may be considered as on of the performance metrics of the cellular system and the adopted power control algorithm. The CEM of user i is given as the ratio of his certainty-equivalent SIR to the corresponding threshold SIR. Mathematically,

$$CEM_i = \frac{SIR_i^{ce}}{SIR_{th}} \tag{7}$$

where, the certainty-equivalent SIR (SIR_i^{ce}) of user i is described as the ratio of the mean of his received power at the corresponding receiver to the mean of the interference from the active other users in the system, that is,

$$SIR_i^{ce} = \frac{H_{i,i}p_i}{\sum_{k\neq i}^{N} H_{i,k}p_k} \tag{8}$$

While, the system certainty-equivalent SIR, SIR^{ce} is given as:

$$SIR^{ce} = \min_{1\le i\le N} SIR_i^{ce} \tag{9}$$

Thus, the system CEM is given by:

$$CEM = \min_{1\le i\le N} CEM_i \tag{10}$$

The CEM is yet another cellular system performance metric for the deployed power control algorithm.

3 Interference limited outage probability under Nakagami flat fading Channel

In this section we present our extension to the previous work in [3]. Here, we derive a closed-form formula of the outage probability in an interference limited cellular communications system under Nakagami flat fading channels. Having said that, let $\alpha_{i,k}$ be the fading coefficient of the link connecting transmitter k with receiver i, then $\alpha_{i,k}$ has a Nakagami distribution:

$$f^{\alpha_{i,k}}(\omega) = \frac{2\,m^m}{\Gamma(m)\,\Omega^m}\;\omega^{2m-1}\;\exp\Big(-\frac{m}{\Omega}\omega^2\Big). \tag{11}$$

where Ω is defined as [9]

$$\Omega = E\{\alpha_{i,k}^2\}$$

It controls the spread of Nakagami distribution. The fading figure denoted by m is given as [9]

$$m = \frac{\Omega^2}{E\{(\alpha_{i,k}^2-\Omega)^2\}} \geq \frac{1}{2},$$

it stands as a measure of the harshness of the fading channel, for example when $m=\infty$, it corresponds to a nonfading channel, and if $m = 1/2$ it corresponds to the Half-normal which is the most severe fading channel. The coming lemma presents a closed-form of the outage probability in a flat-fading Nakagami channels.

Lemma 1. *Under Nakagami flat fading channel with $\Omega = 1$ and $m = 2$, the outage probability O_i is formulated as:*

$$O_i \;=\; 1-\left(N-\sum_{k\neq i}^{N}\left[\frac{1}{1+\frac{SIR_{th}\,H_{i,k}\,p_k}{H_{i,i}\,p_i}}\right]\right)\prod_{k\neq i}^{N}\left[\frac{1}{1+\frac{SIR_{th}\,H_{i,k}\,p_k}{H_{i,i}\,p_i}}\right]^2 \tag{12}$$

Proof: For simplicity, define $Y_{i,k} \triangleq H_{i,k}\chi_{i,k}p_k$, where $\chi_{i,k} = \alpha_{i,k}^2$, and hence $Y_{i,k}$ is a Gamma distributed random variable, that is:

$$f^{Y_{i,k}}(\omega) = \frac{\xi_{i,k}^m}{\Gamma(m)}\;\omega^{m-1}\;\exp(-\xi_{i,k}\,\omega) \tag{13}$$

Where $\xi_{i,k} = \frac{m}{\Omega\,H_{i,k}\,p_k}$. In the following calculations we set $m = 2$ and $\Omega = 1$. Henceforth, the probability O_i of user i can be expressed as:

$$\begin{aligned} O_i &= \Pr\{Y_{i,i} \leq SIR_{th}\;\sum_{k\neq i}^{N} Y_{i,k}\} \\ &= \int_0^{X_{i,k}} f^{Y_{i,i}}(\omega)d\omega \end{aligned} \tag{14}$$

Where $X_{i,k} \triangleq SIR_{th}\;\sum_{k\neq i}^{N} Y_{i,k}$. It is clear that $X_{i,k}$ is a summation of independent Gamma distributed random variables with different means. For the sake of simplicity, we first find a conditional outage probability in (14) $O_i^c(x_{i,k}) = \Pr(O_i|X_{i,k} = x_{i,k})$, with $x_{i,k}$ is a realization of the random variable $X_{i,k}$. Therefore, we have the following:

$$\begin{aligned} O_i^c(x_{i,k}) &= \xi_{i,i}^2\int_0^{x_{i,k}} \omega\;\exp(-\xi_{i,i}\;\omega)d\omega \\ &= 1-(1+\xi_{i,i}\;x_{i,k})\;\exp(-\xi_{i,i}\,x_{i,k}) \end{aligned} \tag{15}$$

And hence, outage probability O_i can be found as follows:

$$\begin{aligned} O_i &= \int_0^\infty O_i^c(\omega)\; f^{X_{i,k}}(\omega) d\omega \\ &= \mathrm{E}\left\{ O_i^c(X_{i,k}) \right\} \\ &= \mathrm{E}\left\{ 1-(1+\xi_{i,i}\; X_{i,k})\; \exp(-\xi_{i,i}\, X_{i,k}) \right\} \end{aligned} \tag{16}$$

Using the following intermediate equations:

$$\int_0^\infty \omega^n \, \exp(-a\,\omega) d\omega = \frac{\Gamma(n+1)}{a^{n+1}}, \tag{17}$$

$$\mathrm{E}\left\{\exp(-\xi_{i,i}\, SIR_{th}\, Y_{i,k})\right\} = \left[\frac{1}{1+\frac{SIR_{th}\, H_{i,k}\, p_k}{H_{i,i}\, p_i}}\right]^2, \tag{18}$$

and

$$\mathrm{E}\{Y_{i,k}\; \exp(-\xi_{i,i}\, SIR_{th}\, Y_{i,k})\} = H_{i,k}\, p_k \left[\frac{1}{1+\frac{SIR_{th}\, H_{i,k}\, p_k}{H_{i,i}\, p_i}}\right]^3 \tag{19}$$

we end up with the following formula of the outage probability O_i,

$$\begin{aligned} O_i &= 1-\prod_{k\neq i}^{N}\left[\frac{1}{1+\frac{SIR_{th}\, H_{i,k}\, p_k}{H_{i,i}\, p_i}}\right]^2 - \sum_{k\neq i}^{N} \frac{SIR_{th}\, H_{i,k}\, p_k}{H_{i,i}\, p_i}\left[\frac{1}{1+\frac{SIR_{th}\, H_{i,k}\, p_k}{H_{i,i}\, p_i}}\right]^3 \\ &\times \prod_{l\neq i, l\neq k}^{N}\left[\frac{1}{1+\frac{SIR_{th}\, H_{i,l}\, p_l}{H_{i,i}\, p_i}}\right]^2 \end{aligned} \tag{20}$$

To make (20) look like (12), we just need to substitute the following equations in (20):

$$\prod_{l\neq i, l\neq k}^{N}\left[\frac{1}{1+\frac{SIR_{th}\, H_{i,l}\, p_l}{H_{i,i}\, p_i}}\right]^2 = \left(1+\frac{SIR_{th}\, H_{i,k}\, p_k}{H_{i,i}\, p_i}\right)^2 \prod_{l\neq i}^{N}\left[\frac{1}{1+\frac{SIR_{th}\, H_{i,l}\, p_l}{H_{i,i}\, p_i}}\right]^2 \tag{21}$$

and

$$\begin{aligned} \sum_{k\neq i}^{N} \frac{SIR_{th}\, H_{i,k}\, p_k}{H_{i,i}\, p_i}\left[\frac{1}{1+\frac{SIR_{th}\, H_{i,k}\, p_k}{H_{i,i}\, p_i}}\right] &= \sum_{k\neq i}^{N}\left(1-\left[\frac{1}{1+\frac{SIR_{th}\, H_{i,k}\, p_k}{H_{i,i}\, p_i}}\right]\right) \\ &= \left(N-1-\sum_{k\neq i}^{N}\left[\frac{1}{1+\frac{SIR_{th}\, H_{i,k}\, p_k}{H_{i,i}\, p_i}}\right]\right) \end{aligned} \tag{22}$$

which concludes the proof. □

4 Relation between outage probability and CEM

4.1 Rayleigh flat fading channel

We present the following proposition which was first introduced as a remark in [5], and then we deliver our own simpler argument.

Theorem 2. *Minimization of the fading induced outage probability O_i and maximization of CEM_i of user i in a Rayleigh fading channel are equivalent in terms of power allocation.*

Proof: Here, we need to keep in mind that the problem under investigation is to minimize the system outage probability using non-centralized algorithm, that is, every cellular user allocates his transmit power level such that his outage probability is minimized. Mathematically speaking,

$$\min_{p_i \in P_i} O_i = \min_{p_i \in P_i} 1 - \prod_{k \neq i}^{N} \frac{1}{1 + SIR_{th} \frac{H_{i,k} p_k}{H_{i,i} p_i}} \tag{23}$$

and this of course is equivalent to the following:

$$\max_{p_i \in P_i} \prod_{k \neq i}^{N} \frac{1}{1 + SIR_{th} \frac{H_{i,k} p_k}{H_{i,i} p_i}} \tag{24}$$

or

$$\min_{p_i \in P_i} \prod_{k \neq i}^{N} \left(1 + SIR_{th} \frac{H_{i,k} p_k}{H_{i,i} p_i}\right) \tag{25}$$

Using the fact that the Logarithmic function is a monotonic function, therefore minimizing (25) is identical to minimizing the following:

$$\min_{p_i \in P_i} \sum_{k \neq i}^{N} \log\left(1 + SIR_{th} \frac{H_{i,k} p_k}{H_{i,i} p_i}\right) \tag{26}$$

Using the logarithmic inequality $\log(x) \leq x - 1$, an upper bound of (26) can be given as:

$$\min_{p_i \in P_i} \quad \textstyle\sum_{k \neq i}^{N} \log\left(1 + SIR_{th} \frac{H_{i,k} p_k}{H_{i,i} p_i}\right) \leq \min_{p_i \in P_i} \sum_{k \neq i}^{N} SIR_{th} \frac{H_{i,k} p_k}{H_{i,i} p_i} \tag{27}$$

It is intuitive to notice that the right-hand side of the inequality in (27) is equivalent to maximizing the CEM, that is

$$\max_{p_i \in P_i} \frac{H_{i,i} p_i}{SIR_{th} \sum_{k \neq i}^{N} H_{i,k} p_k} = \max_{p_i \in P_i} CEM_i \tag{28}$$

□

4.2 Nakagami flat fading channel

Similar to Rayleigh flat fading channels we have the following proposition for Nakagami flat fading channels.

Theorem 3. *Minimization of the fading induced outage probability O_i and maximization of CEM_i of user i under a Nakagami fading channel are equivalent in terms of power allocation.*

Proof: For simplicity, let us define $T_{i,k} \triangleq SIR_{th} \frac{H_{i,k}\, p_k}{H_{i,i}\, p_i}$. Minimizing the outage probability O_i given in (12) is equivalent to the following problem:

$$\max_{p_i \in P_i} \left\{ \left(N - \sum_{k \neq i}^{N} \left[\frac{1}{1+T_{i,k}} \right] \right) \prod_{k \neq i}^{N} \left[\frac{1}{1+T_{i,k}} \right]^2 \right\} \tag{29}$$

or

$$\begin{aligned}
& \max_{p_i \in P_i} \left\{ \ln \left(N - \sum_{k \neq i}^{N} \left[\frac{1}{1+T_{i,k}} \right] \right) + 2 \sum_{k \neq i}^{N} \ln \left(\frac{1}{1+T_{i,k}} \right) \right\} \\
= & \max_{p_i \in P_i} \left\{ \ln \left(1 + \sum_{k \neq i}^{N} \left(1 - \frac{1}{1+T_{i,k}} \right) \right) + 2 \sum_{k \neq i}^{N} \ln \left(1 - \frac{T_{i,k}}{1+T_{i,k}} \right) \right\} \\
\leq & \max_{p_i \in P_i} \left\{ \sum_{k \neq i}^{N} (1 - \frac{1}{1+T_{i,k}}) - 2 \sum_{k \neq i}^{N} \frac{T_{i,k}}{1+T_{i,k}} \right\} \\
= & \max_{p_i \in P_i} \left\{ \sum_{k \neq i}^{N} - \frac{T_{i,k}}{1+T_{i,k}} \right\}
\end{aligned} \tag{30}$$

Where we used the inequality $\ln(x) \leq x - 1$ again and the assumption that $T_{i,k} << 1$ (SIR is high) to get the inequality in (30). Now one can see that the problem in (30) is equivalent to:

$$\max_{p_i \in P_i} \left\{ \sum_{k \neq i}^{N} \frac{1+T_{i,k}}{T_{i,k}} \right\} = \max_{p_i \in P_i} \left\{ N - 1 + \sum_{k \neq i}^{N} \frac{H_{i,i}\, p_i}{SIR_{th}\, T_{i,k}\, p_k} \right\} \tag{31}$$

and since $N-1$ is a constant common for all users, therefore (31) is equivalent to:

$$\min_{p_i \in P_i} \left\{ \frac{\sum_{k \neq i}^{N} SIR_{th}\, H_{i,k}\, p_k}{H_{i,i}\, p_i} \right\} \tag{32}$$

Finally, this problem is clearly equivalent to the problem of maximizing CEM_i. □

In the next section we present a simple non-cooperative game $G2$, and we show that $G2$ results in an optimal power allocation to maximize the system CEM, minimize the system outage probability O, and minimize the total transmitted power.

5 Power control algorithm to optimize the outage probability

In this section we introduce a non-cooperative power control game as defined in (34), in which user i attempts to find the optimal transmit power level p_i from his strategy space P_i

that enables him to obtain a maximum possible certainty-equivalent-margin CEM^*, instead of maximizing CEM_i directly as given below:

$$\begin{aligned} G1 \quad : \quad & \max_{p_i \in P_i} \; CEM_i, \\ = \quad & \max_{p_i \in P_i} \; \frac{H_{i,i} p_i}{SIR_{th} \; \sum_{k \neq i}^{N} H_{i,k} p_k}, \forall \, i = 1, 2, ..., N \end{aligned} \tag{33}$$

The reason for avoiding maximizing CEM_i directly is that the game $G1$ in (33) has an objective function CEM_i which is linear in p_i given the power vector p_{-i} of all users except for the ith user. This will lead user i to send at the maximum power in his strategy space, as will all users. This selfish act will result in all users having very small CEMs. Due to this reason we propose the following non-cooperative power control game $G2$ defined as follows:

$$\begin{aligned} & G2 : \quad \max_{p_i \in P_i} \; CEM_i^*(n), \; n = 1, 2, \cdots \\ & \text{subject to} \\ & p_i(n) = \min \left(p_{i-max}, \frac{CEM_i^*(n) \; SIR_{th} \; \sum_{k \neq i}^{N} H_{i,k} p_k}{H_{i,i}} \right) \end{aligned} \tag{34}$$

Seemingly, game $G2$ is a multistage game where in the nth stage, user i transmits at a power level $p_i(n)$ that enables him to attain a constant $CEM_i^*(n)$ (e.g. $CEM_i^*(n) = 1$), then if transmit power level $p_i(n)$ is feasible, i.e., $p_i(n) < p_{i-max}$, user i seeks a higher value of CEM_i^* at the $(n+1)$th stage of the game. Mathematically speaking, user i sets $CEM_i^*(n+1) > CEM_i^*(n)$ and finds $p_i(n+1)$ such that $CEM_i^*(n+1) = \frac{H_{i,i} p_i(n+1)}{SIR_{th} \; \sum_{k \neq i}^{N} H_{i,k} p_k}$ and so forth until he/she is satisfied with the value of $CEM_i^*(n)$. However, it turns out that game $G2$ is a one shot game, that is, it has a Nash equilibrium point with all users able to attain their maximum CEM_i^* in the first stage ($n = 1$) as we show in the following lemma. The lemma also guarantees the existence, uniqueness, and optimality of the Nash equilibrium point:

Lemma 4. *The non-cooperative game $G2$ with strategy space $P_i = [p_{i-min}, \, p_{i-max}]$ for user i and with $p_{i-min} > 0$, has a unique Nash equilibrium operating point. Also, this Nash equilibrium point is optimal in the sense that it corresponds to the minimum total transmitted power of all users. Users in game $G2$ will attain their maximum possible CEM_i^* in the first trial.*

Proof: At each time instance, user i updates his transmit power p_i in order to satisfy the following equation:

$$CEM_i^* = \frac{H_{i,i} p_i}{SIR_{th} \; \sum_{k \neq i}^{N} H_{i,k} p_k}, \tag{35}$$

for a target CEM_i^*. Exploiting the linearity of equation (35), we rewrite it in a matrix form as follows:

$$\mathrm{A} \; \mathrm{p} = \mathrm{p} \; , \tag{36}$$

where the entries of the matrix A are given by:

$$\mathrm{A}(i,j) = \begin{cases} \frac{SIR_{th} \, CEM_i^* \, H_{i,j}}{H_{i,i}}, & \text{if } i \neq j \\ 0, & \text{if } i = j \end{cases}$$

And $\mathrm{p} = (p_1, p_2, ..., p_N)$ is the vector of transmit powers of all users. Since $H_{i,j} > 0$, matrix A is a nonnegative irreducible matrix. By the Perron-Frobenius theorem, the largest eigenvalue in magnitude of matrix A is real and positive [6], [1], and [4]. Therefore, if it happens that 1 is this eigenvalue of A, then the solution p will be the eigenvector that corresponds to eigenvalue 1. Otherwise, the only solution of equation (36) is the trivial solution p = 0. Since p = 0 is not a feasible solution, each user will transmit at the lowest power level in his strategy space. Therefore, the Nash equilibrium point of game $G2$ is unique and corresponds to an optimal point that minimizes the total transmitted power of all users.

Equation (36) holds true for any $CEM_i^* \geq 1$ including the maximum value that users can attain at the equilibrium point. This implies that the cellular users will attain their maximum possible CEM_i^* in their first trial, i.e., $G2$ is a one-shot game. □

It is easy to notice that if user i increases his power unilaterally to improve hisher CEM_i and O_i, at least one other user in the network will be harmed.

Lemma 4 implies that in an interference-limited wireless Rayleigh and Nakagamai flat fading channels the best policy is for all users to transmit at the minimum power in their corresponding strategy spaces. The question that may arise is: How do we guarantee the quality of service (QoS), e.g. SIR at the BS? The following lemma answers this question:

Lemma 5. *If users in an interference-limited wireless fading channels are not able to attain a satisfactory QoS (SIR) by transmitting at their minimum power vector* $p_{min} = (p_{1-min}, p_{2-min}, ..., p_{N-min})$ *in their corresponding strategy spaces, they will not be able to attain a satisfactory QoS by transmitting at any other power vector* $p^l = (p_1^l, p_2^l, ..., p_N^l)$ *larger than* p_{min}, $p^l > p_{min}$ *component wise.*

Proof: Let $\mathcal{N} = (1, 2, ..., N)$ be the indexing set of all active users in the cell. Suppose CEM_i^{min} is the CEM value user i attained by assuming that all users are transmitting at the minimum powers in their corresponding strategy spaces, that is, $\forall\, i \in \mathcal{N}$:

$$CEM_i^{min} = \frac{H_{i,i}\, p_{i-min}}{SIR_{th} \sum_{k \neq i}^{N} H_{i,k}\, p_{k-min}}, \tag{37}$$

and suppose that CEM_i^l is the value of CEM the ith user attains assuming all users transmitting at p^l, henceforth, $\forall\, i \in \mathcal{N}$ we have:

$$CEM_i^l = \frac{H_{i,i}\, p_i^l}{SIR_{th} \sum_{k \neq i}^{N} H_{i,k}\, p_k^l} \tag{38}$$

To prove lemma 5, it is enough to prove that there is a subset of users $\mathcal{K}_N \subset \mathcal{N}$, such that:

$$CEM_n^l \leq CEM_n^{min}, \forall\, n \in \mathcal{K}_N \tag{39}$$

Suppose this is not true, therefore

$$CEM_i^l > CEM_i^{min}, \forall\, i \in \mathcal{N} \tag{40}$$

Define $d_i^{l,min}$ as:

$$\begin{aligned} d_i^{l,min} &= CEM_i^l - CEM_i^{min} \\ &= \frac{1}{SIR_{th}} \left[\frac{H_{i,i}\, p_i^l}{\sum_{k \neq i}^{N} H_{i,k}\, p_k^l} - \frac{H_{i,i}\, p_{i-min}}{\sum_{k \neq i}^{N} H_{i,k}\, p_{k-min}} \right], \forall\, i \in \mathcal{N} \end{aligned} \tag{41}$$

Without loss of generality, $\forall\, i \in \mathcal{N}$ let $p_i^l = \delta_i\, p_{i-min}$, where $\delta_i > 1$. Then, (41) can be written as:

$$d_i^{l,min} = \frac{H_{i,i}\, p_{i-min}}{SIR_{th}} \left[\frac{\delta_i}{\sum_{k \neq i}^{N} \delta_k\, H_{i,k}\, p_{k-min}} - \frac{1}{\sum_{k \neq i}^{N} H_{i,k}\, p_{k-min}} \right], \forall i \in \mathcal{N} \tag{42}$$

Table 1: Equilibrium values of CEM_i and O_i for the first 10 users in a Rayleigh flat fading channel using Perron-Frobenius theorem and our NPG game $G2$ at $SIR_{th} = 3$

Results using Perron-Frobenius theorem [5]				**Results of game $G2$**		
i	p_i	CEM_i	O_i	p_i	CEM_i	O_i
1	0.1292	13.7107	0.0703	0.0100	14.9809	0.0645
2	0.1162	13.7107	0.0703	0.0100	16.6629	0.0582
3	0.1476	13.7107	0.0703	0.0100	13.0747	0.0736
4	0.1482	13.7107	0.0703	0.0100	12.9549	0.0742
5	0.1290	13.7107	0.0703	0.0100	14.9275	0.0647
6	0.1192	13.7107	0.0703	0.0100	16.3274	0.0594
7	0.1297	13.7107	0.0703	0.0100	15.0442	0.0643
8	0.1312	13.7107	0.0703	0.0100	14.6970	0.0657
9	0.1327	13.7107	0.0703	0.0100	14.4091	0.0670
10	0.1361	13.7107	0.0703	0.0100	14.2906	0.0675
average		13.7107	0.0703	**average**	13.7823	0.0704

The inequality in (40) implies that $d_i^{l,min} > 0$ for all $i \in \mathcal{N}$, therefore

$$\delta_i \sum_{k \neq i}^{N} H_{i,k}\, p_{k-min} > \sum_{k \neq i}^{N} \delta_k\, H_{i,k}\, p_{k-min}, \forall\, i \in \mathcal{N} \tag{43}$$

For simplicity define $x_{i,k} = H_{i,k}\, p_{k-min}$, then (43) can be expressed as:

$$\delta_i \sum_{k \neq i}^{N} x_{i,k} > \sum_{k \neq i}^{N} \delta_k\, x_{i,k}, \forall\, i \in \mathcal{N} \tag{44}$$

If we set $i = 1$ in the above equation we get the following result:

$$\delta_1 > \delta_m, m = 2, 3, ..., N, \tag{45}$$

while if we set $i = 2$, we get the following:

$$\delta_2 > \delta_m, m = 1, 3, ..., N, \tag{46}$$

From equation (45), we have $\delta_1 > \delta_2$, while from (46) we find $\delta_2 > \delta_1$, so we have a contradiction. This proves the statement in equation (39), and this concludes the proof of lemma 5. □

6 Simulation results

In our simulations, we considered one cell with $N = 50$ receiver and transmitter pairs in the uplink mode. The path gains $H_{i,k}$ were generated according to a uniform distribution on the interval $[0, 0.001]$ for all $i \neq k \in \mathcal{N}$ and $H_{i,i} = 1\ \forall\, i \in \mathcal{N}$. Game $G2$ was run for different values of the threshold signal-to-interference ratios (SIR_{th}) in the interval $[3, 10]$.

In Fig.1 we depict the system certainty-equivalent margin values (CEM) resulting from game G2 versus the threshold signal-to-interference ratios, SIR_{th} under both Rayleigh and Nakagami flat fading channels. While in Fig.2, we present the resulting system outage probability, O

Table 2: Equilibrium values of CEM_i and O_i for the first 10 users in a Rayleigh flat fading channel using Perron-Frobenius theorem and our NPG game $G2$ at $SIR_{th} = 10$

Results using Perron-Frobenius theorem [5]				**Results of game $G2$**		
i	p_i	CEM_i	O_i	p_i	CEM_i	O_i
1	0.1439	4.0985	0.2159	0.0100	4.0243	0.2194
2	0.1541	4.0985	0.2159	0.0100	3.7254	0.2347
3	0.1266	4.0985	0.2159	0.0100	4.5414	0.1971
4	0.1497	4.0985	0.2159	0.0100	3.8603	0.2275
5	0.1375	4.0985	0.2159	0.0100	4.1930	0.2116
6	0.1378	4.0985	0.2159	0.0100	4.1877	0.2118
7	0.1096	4.0985	0.2159	0.0100	5.3148	0.1711
8	0.1514	4.0985	0.2159	0.0100	3.8264	0.2293
9	0.1398	4.0985	0.2159	0.0100	4.1414	0.2139
10	0.1384	4.0985	0.2159	0.0100	4.1889	0.2118
average		4.0985	0.2159	**average**	4.1255	0.2156

Table 3: Equilibrium values of CEM_i and O_i for the first 10 users in a Nakagami flat fading channel using Perron-Frobenius theorem and our NPG game $G2$ at $SIR_{th} = 3$

Results using Perron-Frobenius theorem				**Results of game $G2$**		
i	p_i	CEM_i	O_i	p_i	CEM_i	O_i
1	0.1368	13.7415	0.0580	0.0100	14.2272	0.0561
2	0.1501	13.7415	0.0580	0.0100	12.9034	0.0618
3	0.1305	13.7415	0.0580	0.0100	14.6840	0.0543
4	0.1360	13.7415	0.0580	0.0100	14.2485	0.0560
5	0.1270	13.7415	0.0580	0.0100	15.0958	0.0528
6	0.1539	13.7415	0.0580	0.0100	12.5887	0.0633
7	0.1499	13.7415	0.0580	0.0100	12.8494	0.0620
8	0.1402	13.7415	0.0580	0.0100	13.7151	0.0581
9	0.1577	13.7415	0.0580	0.0100	12.2655	0.0649
10	0.1552	13.7415	0.0580	0.0100	12.5932	0.0633
average		13.7415	0.0580	**average**	13.8343	0.0581

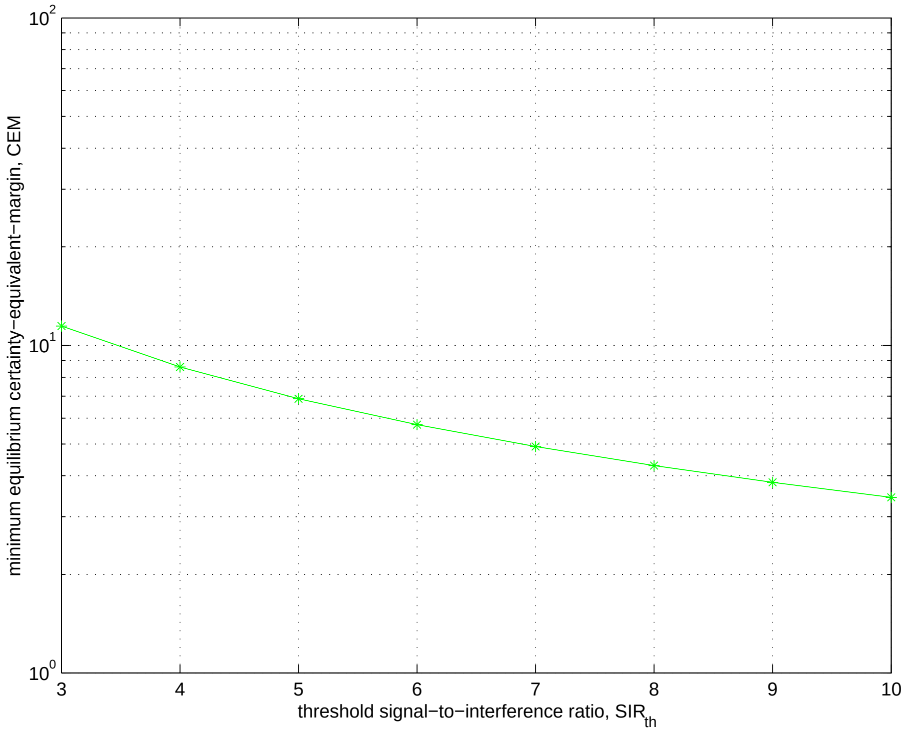

Figure 1: Minimum equilibrium CEM in Rayleigh and Nakagami fading channels versus the threshold SIR ratio.

of a Rayleigh fading channel($*$) and a Nakagami fading channel ($\circ$) versus the threshold SIR (SIR_{th}) compared to the minimum bound $1/(1 + CEM)$ (solid line) and the upper bound $1 - e^{-1/CEM}$ (dashed line) derived in [5]. In this figure, as one can see, in the Rayleigh case, the upper bound overlaps with the equilibrium outage probability which is the output of game $G2$. The results shown in Fig.1 and Fig.2 happened to be very close to the results obtained using Perron-Frobenius theorem [5] (in Rayleigh fading channel) but at a lower power allocation. This is clear in tables 2 - 4. In these tables we are casting CEM_i and O_i for the first 10 users as evaluated by the Perron-Frobenius theorem in [5] and as equilibrium outcomes of the NPG game $G2$ of both channel models: Rayleigh flat fading channel and Nakagami flat fading channel. The averages of CEM_i and O_i presented in the tables are calculated for all the 50 users in the system. We noticed that the average value of CEM obtained through NPG game $G2$ was higher than that obtained by the Perron-Frobenius theorem based algorithm for all values of SIR_{th}. The average value of O achieved through NPG game $G2$ was sometimes lower and sometimes higher than that achieved by Perron-Frobenius theorem. By examining tables 2 - 4, one can see that by transmitting at Perron-Frobenius power eigenvector many users attain lower values of CEM than they obtained when all users transmitted at the minimum power vector. This exactly agrees with what was proved in lemma 5. Finally, notice that in Fig.2 results show that users can achieve better performance in a Nakagami fading channel with ($m = 2$) than in a Rayleigh channel. This is expected since a Nakagami fading channel with fading figure $m = 2$ represents a less severe fading channel than a Rayleigh fading channel which is a Nakagami fading channel with fading figure $m = 1$.

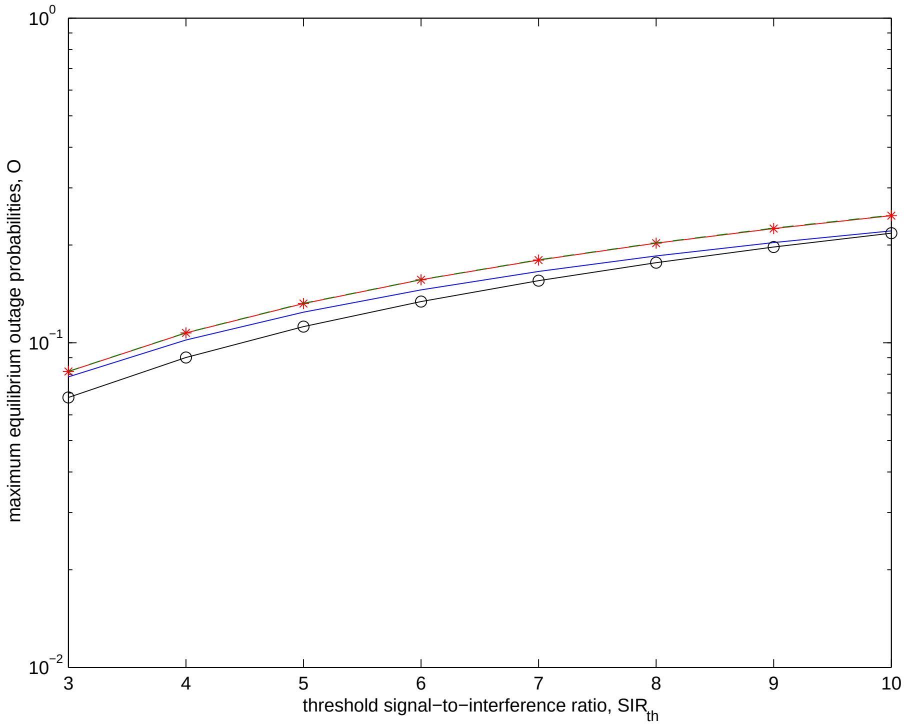

Figure 2: Maximum equilibrium Rayleigh fading induced outage probability ($*$), the lower bound of the outage probability $\frac{1}{1+CEM}$ (solid line), the upper bound $1 - e^{-1/CEM}$ (dashed line) and the maximum outage probability in a Nakagami channel ($\circ$) versus the threshold SIR ratio.

Table 4: Equilibrium values of CEM_i and O_i for the first 10 users in a Nakagami flat fading channel using Perron-Frobenius theorem and our NPG game $G2$ at $SIR_{th} = 10$

Results using Perron-Frobenius theorem				**Results of game $G2$**		
i	p_i	CEM_i	O_i	p_i	CEM_i	O_i
1	0.1539	4.0590	0.1906	0.0100	3.7011	0.2078
2	0.1432	4.0590	0.1906	0.0100	3.9928	0.1936
3	0.1384	4.0590	0.1906	0.0100	4.1278	0.1876
4	0.1553	4.0590	0.1906	0.0100	3.6718	0.2094
5	0.1378	4.0590	0.1906	0.0100	4.1369	0.1872
6	0.1305	4.0590	0.1906	0.0100	4.3997	0.1766
7	0.1593	4.0590	0.1906	0.0100	3.5804	0.2143
8	0.1553	4.0590	0.1906	0.0100	3.6847	0.2087
9	0.1456	4.0590	0.1906	0.0100	3.9305	0.1965
10	0.1483	4.0590	0.1906	0.0100	3.8569	0.2000
average		4.0590	0.1906	**average**	4.0948	0.1903

7 Conclusion

We proved the tight relationship between the two optimization problems: minimizing the system outage probability and maximizing the system CEM under Rayleigh and Nakagami flat fading wireless channels and. A closed-form of the outage probability under Nakagami flat fading channel was also provided. We then proposed an asynchronous distributed non-cooperative power control game-theoretic algorithm to optimize the system CEM and the system outage probability. Using the proposed non-cooperative game $G2$, we proved that the best power allocation in an interference limited Rayleigh and Nakagami fading wireless channels is the minimum power vector in the total strategy spaces of active users in the system. Power was more effectively and more simply allocated according to this proposed non-centralized algorithm than the centralized algorithm in [5].

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Interval Certitude Rule Base Inference Method using the Evidential Reasoning

L.Q. Jin, X. Fang

Liqian Jin
School of Economics and Management,
Chongqing University of Posts and Telecommunications,
P. R. China
jinlq@cqupt.edu.cn

Xin Fang*
1. Chongqing Engineering Research Center for Processing Storage and Transportation of Characterized Agro-Products, P. R. China
2. School of Business Planning,
Chongqing Technology and Business University, P. R. China
*Corresponding author: Xin_F@ctbu.edu.cn

Abstract: Development of rule-based systems is an important research area for artificial intelligence and decision making, as rule base is one of the most general purpose forms for expressing human knowledge. In this paper, a new rule-based representation and its inference method based on evidential reasoning are presented based on operational research and fuzzy set theory. In this rule base, the uncertainties of human knowledge and human judgment are designed with interval certitude degrees which are embedded in the antecedent terms and consequent terms. The knowledge representation and inference framework offer an improvement of the recently developed rule base inference method, and the evidential reasoning approach is still applied to the rule fusion. It is noteworthy that the uncertainties will be defined and modeled using interval certitude degrees. In the end, an illustrative example is provided to illustrate the proposed knowledge representation and inference method as well as demonstrate its effectiveness by comparing with some existing approaches.
Keywords: interval certitude rule, knowledge representation, uncertainty inference, evidential reasoning.

1 Introduction

There are several types of uncertainties of knowledge such as incompleteness, randomness, fuzziness, inexactness and ignorance. The inference method which is based on uncertain knowledge is the uncertainty inference method. Because of the uncertainty is ubiquitous, the uncertainty knowledge representation and uncertainty inference method have become the most visible and fastest growing branch of artificial intelligence [38].

In the existed methods of knowledge representation, rule base seems to be the most common form for expressing various types of knowledge [27]. The rule bases can be used to support decision making with both quantitative and qualitative knowledge under various types of uncertainties. Specifically, different types of data such as exact number, fuzzy number, interval value, even subjective judgment can be represented by rule.

In the last four decades, the development of uncertainty methods have received extensive attention. Many methods have been proposed for showing uncertain knowledge and information. Such as the certainty factor based inference method [36], inference method using the Dempster-Shafer theory [12], *Belief Rule Base Inference Methodology using the Evidential Reasoning* (RIMER) [31, 38–40], subjective Bays method [36], fuzzy inference method [29], et al.

In these methods, inference method using the Dempster-Shafer theory has a shortcoming in the aspect of dealing with conflict evidence, the subjective Bayes method is mainly used in the randomness but does not apply to other uncertainties, fuzzy inference method is used in the vagueness.

With the Dempster-Shafer theory, fuzzy set theory and If-then rule, Yang et al [38] have researched and given RIMER. The uncertain knowledge is described by *Belief Rule Base* (BRB), and it is able to handle many types of information. *Evidential Reasoning* (ER) approach is an uncertainty inference method which make up for the deficiencies of the inference method using the Dempster-Shafer theory. However, there are still some defects [17].

Liu et al. [5, 21] proposed the *Extended Belief Rule Base* (EBRB) based on BRB and the *Extended Belief Rule Base Inference Methodology using the Evidential Reasoning* (RIMER+). And the uncertainty of antecedent is described with belief structure and different evaluation grade set, but there is only one consequent attribute and knowledge should be converted to belief structure.

The fuzzy set has been widely researched and applied in various fields [20, 30, 34]. Interval number is an important fuzzy number, and it has been widely used in a lot of fields such as decision making science [2,32,37,41], operational research [6,9,19], [8,33]. The main reasons are as follows:

- In the theoretical research, interval numbers are closely linked with other forms of uncertainty.
- In the practical application, in order to evaluate the things, people are mainly inclined to give the upper and the lower bounds of information, and the interval number's expression is nearly accord with this uncertainty characteristics of human thought.

According to the above analysis, the certitude rule base is not accord with actual situation. Because of the limitations of human cognition and the complexity of the objective things, decision maker can not always be confident enough to provide subjective judgment with exact certitude degrees. But at times, a range of the certitude degree can be assessed, such range is referred to as interval certitude degree. In order to apply the interval uncertainty, the knowledge representation which is based on the interval certitude rule and its inference method should be proposed. [16]

This paper is organized as follows. In Section 2, the *Interval Certitude Rule Base Inference Method using the Evidential Reasoning* (ICRIMER) is given. First, the structure and representation of *Interval Certitude Rule Base* (ICRB) is presented. Then a new generic knowledge base inference method ICRIMER is proposed. In Section 3, the performances of ICRIMER is demonstrated by comparing with some existing approaches using a case study of classifications with eight data sets of UCI Machine Learning Repository. The paper is concluded in Section 4.

2 Interval certitude rule base inference method

In this section, the basic knowledge of interval value fuzzy number is introduced, include concept, ranking method and similarity measure. Then the interval certitude rule is proposed as knowledge representation method. In the end of this section, the interval certitude rule base inference method using the evidential reasoning with nonlinear programming is presented.

2.1 Interval value fuzzy number

Note $a = \left[a^L, a^U\right]$ be a bounded closed interval, and satisfies $a^L \le a^U$, a^L is the lower bound of a, a^U is the upper bound of a. If $a^L, a^U \in R$, then $a = \left[a^L, a^U\right]$ is an interval number; if

$a^L, a^U \in [0,1]$, then $a = \left[a^L, a^U\right]$ is an interval value fuzzy number (for short, interval number). Specially, if $a^L = a^U$, then $a = \left[a^L, a^U\right]$ is an exact number, note $a = a^L$.

A ranking method based on the technique for order preference by similarity to ideal solution (TOPSIS) and distance is given in order to rank the interval number.

According to TOPSIS [22], for interval number, the positive ideal solution is $[1,1]$, the negative ideal solution is $[0,0]$. The relative similarity degree η of interval number $a = \left[a^L, a^U\right]$ is as follows:

$$\eta(a) = \frac{d^-(a)}{d^+(a) + d^-(a)}$$

where $d^-(a) = \left|\frac{a^L+a^U}{2} - 0\right| = \frac{a^L+a^U}{2}$ is the distance [23] between $a = \left[a^L, a^U\right]$ and negative ideal solution $[0,0]$, $d^+(a) = \left|\frac{a^L+a^U}{2} - 1\right| = 1 - \frac{a^L+a^U}{2}$ is the distance [23] between $a = \left[a^L, a^U\right]$ and positive ideal solution $[1,1]$.

The relative similarity degree η satisfies that the larger the relative similarity degree is the larger the interval number will be. So the ranking of interval number can be given based on the relative similarity degree:

- If $\eta(a) > \eta(b)$ then $a \succ b$, '$\succ$' denotes the fuzzified version of '$>$' and has the linguistic interpretation 'greater than'.
- If $\eta(a) = \eta(b)$ then $a = b$, means that the ranking orders of $a = \left[a^L, a^U\right]$ and $b = \left[b^L, b^U\right]$ are identical, $a = \left[a^L, a^U\right]$ is equal to $b = \left[b^L, b^U\right]$, but $a^L = b^L$ and $a^U = b^U$ may be not always realized.

The similarity measure of interval numbers is also an important content of interval type data processing. According to the Lukasiewicz implication algebra on $[0,1]$, suppose $a = \left[a^L, a^U\right]$ and $b = \left[b^L, b^U\right]$ are interval numbers, the similarity measure $S_{[]}$ is as follows:

$$S_{[]}(a,b) = \left[S_{[]}^L(a,b), S_{[]}^U(a,b)\right]$$

$$S_{[]}{}^L(a,b) = \min\left\{\min\left\{1 - a^L + b^L, 1 - b^L + a^L\right\}, \min\left\{1 - a^U + b^U, 1 - b^U + a^U\right\}\right\}$$

$$S_{[]}^U(a,b) = \max\left\{\min\left\{1 - a^L + b^L, 1 - b^L + a^L\right\}, \min\left\{1 - a^U + b^U, 1 - b^U + a^U\right\}\right\}$$

2.2 Interval certitude rule

An interval certitude rule base (ICRB) with K rules can be represented as follows:

$$R = \left\langle (X, A), (Y, C), ICD_{[]}, \Theta, W, F \right\rangle$$

where $X = \{X_i \,|i = 1, 2, \cdots, I\}$ is the set of antecedent attributes, the relationship among the antecedent attributes is taken as '$\wedge$', '$\wedge$' is the logical connective; $A_i = \left\{A_{i,I_i} \left| I_i = 1, 2, \cdots, L_i^A \right.\right\}$ is the set of attribute values for antecedent attribute $X_i\,(i = 1, 2, \cdots, I)$, note $A = \{A_i \,|i = 1, 2, \cdots, I\}$ be the set of antecedent attribute value sets; $Y = \{Y_j \,|j = 1, 2, \cdots, J\}$ is the set of consequent attributes, the relationship among the consequent attributes is taken as '$\wedge$'; $C_j = \left\{C_{j,J_j} \left| J_j = 1, 2, \cdots, L_j^C \right.\right\}$ is the set of attribute values for consequent attribute $Y_j\,(j = 1, 2, \cdots, J)$, note $C = \{C_j \,|j = 1, 2, \cdots, J\}$ be the set of consequent attribute value sets; $\Theta = \left\{\theta^k \,|0 \leq \theta^k \leq 1, k = 1, 2, \cdots, K\right\}$ is the set of the importance degree of each rule, θ^k is the rule weight of the kth rule; $W = \left\{ w_i \middle| 0 \leq w_i \leq 1, i = 1, \cdots, I, and \sum_{i=1}^{I} w_i = 1 \right\}$ is the set of the antecedent attribute weights, w_i is the weight of X_i ; $ICD_{[]} = \{Icd(\Delta) | Icd(\Delta) \subseteq [0,1]\}$ is interval certitude degree set, $Icd(\Delta)$ is the interval certitude degree of event Δ, $Icd(\Delta)$ is called interval certitude degree. $Icd(\Delta)$ satisfies the more higher the degree of certainty is, the more large $Icd(\Delta)$ will be. $Icd(\Delta) = [0,0]$ means completely uncertainty, $Icd(\Delta) = [1,1]$ means completely certainty, $Icd(\Delta) = [0,1]$ means that we know nothing about the uncertainty of event Δ. F is a logical function.

More specifically, the kth rule in the ICRB R can be written as R^k $(k = 1, 2, \cdots, K)$:

If $\left(X_1 = A_1^k, Icd^k\left(X_1 = A_1^k\right)\right) \wedge \cdots \wedge \left(X_I = A_I^k, Icd^k\left(X_I = A_I^k\right)\right)$
then $\left(Y_1 = C_1^k, Icd^k\left(Y_1 = C_1^k\right)\right) \wedge \cdots \wedge \left(Y_J = C_J^k, Icd^k\left(Y_J = C_J^k\right)\right)$
with rule interval certitude degree $Icd^k\left(R^k\right)$, rule weight θ^k and antecedent attribute weights $(w_1, w_2, \cdots, w_I)$

where '=' means 'is'; θ^k is the weight of the kth rule R^k; $(w_1, w_2, \cdots, w_I)$ are the weights of the antecedent attributes.

For $i = 1, 2, \cdots, I$, A_i^k is the referential value of the ith antecedent attribute X_i that is used in the kth rule R^k , $A_i^k \in A_i$ or $A_i^k = \phi$, (ϕ is default, means that the ith attribute A_i of the kth rule. R^k has no effect on the consequent); $Icd^k\left(X_i = A_i^k\right) \subseteq [0,1]$ is the interval certitude degree of that A_i^k is the referential value of X_i in R^k , means the degree of A_i^k influence on the consequent; if $A_i^k = \phi$ then $Icd^k\left(X_i = A_i^k\right) = 0$ and this antecedent attribute can be left out.

For $j = 1, 2, \cdots, J$, C_j^k is the referential value of the jth consequent attribute Y_j that is used in R^k , $C_j^k \in C_j$ or $C_j^k = \phi$ (means that the kth rule R^k and its antecedent have no effect on the jth consequent C_j), $Icd^k\left(Y_j = C_j^k\right) \subseteq [0,1]$ is the interval certitude degree of that C_j^k is the referential value of Y_j in R^k, means the degree of that Y_j is C_j^k , if $C_j^k = \phi$ then $Icd^k\left(Y_j = C_j^k\right) = 0$ and this consequent attribute can be left out; $Icd^k\left(R^k\right) \subseteq [0,1]$ is the interval certitude degree of R^k, means the degree of that R^k is true.

For shortly, the kth rule R^k can be written as:

If $\left(A_1^k, Icd^k\left(A_1^k\right)\right) \wedge \cdots \wedge \left(A_I^k, Icd^k\left(A_I^k\right)\right)$
then $\left(C_1^k, Icd^k\left(C_1^k\right)\right) \wedge \cdots \wedge \left(C_J^k, Icd^k\left(C_J^k\right)\right)$
with rule certitude degree $Icd^k\left(R^k\right)$, rule weight θ^k and antecedent attribute weights $(w_1, w_2, \cdots, w_I)$

Note:

$$\alpha_i^k = Icd^k\left(A_i^k\right) = \left[\left(\alpha_i^k\right)^L, \left(\alpha_i^k\right)^U\right], \beta_j^k = Icd^k\left(C_j^k\right) = \left[\left(\beta_j^k\right)^L, \left(\beta_j^k\right)^U\right]$$

$$\gamma^k = Icd^k\left(R^k\right) = \left[\left(\gamma^k\right)^L, \left(\gamma^k\right)^U\right]$$

where $0 \leq \left(\alpha_i^k\right)^L \leq \left(\alpha_i^k\right)^U \leq 1, 0 \leq \left(\beta_j^k\right)^L \leq \left(\beta_j^k\right)^U \leq 1, 0 \leq \left(\gamma^k\right)^L \leq \left(\gamma^k\right)^U \leq 1$; and the kth rule R^k can be given as:

If $\left(A_1^k, \alpha_1^k\right) \wedge \cdots \wedge \left(A_I^k, \alpha_I^k\right)$, then $\left(C_1^k, \beta_1^k\right) \wedge \cdots \wedge \left(C_J^k, \beta_J^k\right)$.
with rule certitude degree $\left[\left(\gamma^k\right)^L, \left(\gamma^k\right)^U\right]$, rule weight θ^k and antecedent attribute weights $(w_1, w_2, \cdots, w_I)$

Note:

$$A^k = \left\{ A_i^k \left| A_i^k \in A_i or A_i^k = \phi, i = 1, 2, \cdots, I \right. \right\}$$

$$C^k = \left\{ C_j^k \left| C_j^k \in C_j or C_j^k = \phi, j = 1, 2, \cdots, J \right. \right\}$$

$$\wedge A^k = A_1^k \wedge A_2^k \wedge \cdots \wedge A_I^k$$

$$\wedge C^k = C_1^k \wedge C_2^k \wedge \cdots \wedge C_J^k$$

where A^k is the set of antecedent attribute values of the kth rule R^k; $\wedge A^k$ is the antecedent of the kth rule R^k; C^k is the set of consequent attribute values of the kth rule R^k; $\wedge C^k$ is the consequent of the kth rule R^k.

The kth rule R^k can be given as:

$$\text{If } \left(\wedge A^k, \alpha^k\right) \text{ then } \left(\wedge C^k, \beta^k\right)$$

with rule certitude degree γ^k, rule weight θ^k and antecedent attribute weights $(w_1, w_2, \cdots, w_I)$

where $\alpha^k = \left[\left(\alpha^k\right)^L, \left(\alpha^k\right)^U\right] \subseteq [0,1]$ is the interval certitude degree of $\wedge A^k$, $\beta^k = \left[\left(\beta^k\right)^L, \left(\beta^k\right)^U\right] \subseteq [0,1]$ is the interval certitude degree of $\wedge C^k$, $\gamma^k = \left[\left(\gamma^k\right)^L, \left(\gamma^k\right)^U\right] \subseteq [0,1]$ is the interval certitude degree of the kth rule R^k, θ^k is the weight of the kth rule R^k, $(w_1, w_2, \cdots, w_I)$ are the weights of the antecedent attributes.

2.3 Inference method

The interval certitude rule base inference method using the evidential reasoning is given as follows.

The input actual vector can be noted as

$$Input() = \{(a_1, \alpha_1), (a_2, \alpha_2), \cdots, (a_I, \alpha_I)\}$$

where $a_i \in A_i$ or $a_i = \phi\,(i = 1, 2, \cdots, I)$ is one-to-one correspondence with the ith antecedent attribute X_i; $\alpha_i = \left[(\alpha_i)^L, (\alpha_i)^U\right] \left(0 \le (\alpha_i)^L \le (\alpha_i)^U \le 1, i = 1, 2, \cdots, I\right)$ is the interval certitude degree of a_i. If $a_i = \phi$ then $\alpha_i = 0$.

Suppose that the input fact $Input()$ and the kth rule R^k match successfully, for all $i = 1, 2, \cdots, I$, a_i is equal to A_i^k without $A_i^k = \phi$. But the interval certitude degrees of input fact value and antecedent attribute value may be different; so according to the similarity measure, there is a similarity degree should be given as activation certitude factors.

The activation certitude degree of $A_i^k\,(i = 1, 2, \cdots, I)$ under the input fact is given with similarity measure $S_{[]}$ as follows:

$$\tilde{\alpha}_i^k = \begin{cases} S\left(A_i^k, a_i\right) & A_i^k \in A_i \\ 1 & A_i^k = \phi \end{cases}$$

where $S\left(A_i^k, a_i\right) = S_{[]}\left(\alpha_i^k, \alpha_i\right)$, α_i^k is the interval certitude degree of A_i^k, α_i is the interval certitude degree of a_i, $S\left(A_i^k, a_i\right)$ is the similarity degree of A_i^k and a_i. $A_i^k{=}\phi$ is a specific case, if $A_i^k{=}\phi$ then the value of will not influence the matched conclusions, whether a_i is default or some other values, the ith antecedent attribute in the kth rule always can be satisfied.

Note

$$\tilde{\text{A}}^k = \left\{ \tilde{\alpha}_i^k \left| i = 1, 2, \cdots, I \right. \right\}$$

$\tilde{\text{A}}^k$ is the collection of activation certitude degree.

The activation weight set of the kth rule R^k is given as follows:

$$W^k = \left\{ w_i^k \,|i = 1, 2, \cdots, I \right\}$$

where

$$w_i^k = \begin{cases} w_i & A_i^k \in A_i \\ 0 & A_i^k = \phi \end{cases}$$

after normalization, the activation weight set is given as

$$\tilde{W}^k = \left\{ \tilde{w}_i^k \,|i = 1, 2, \cdots, I \right\}$$

where

$$\tilde{w}_i^k = \frac{w_i^k}{\sum\limits_{t=1}^{I} w_t^k}.$$

Because that the '$\wedge$' connective is used in rules, so the aggregation function of antecedent is referred to as the T-norm operator. The interval certitude degree of antecedent $\wedge A^k$ can be obtained as follows:

$$\tilde{\alpha}^k = \left[\left(\tilde{\alpha}^k\right)^L, \left(\tilde{\alpha}^k\right)^U \right] = \left[\prod_{i=1}^{I} \sqrt[I]{\left[\left(\tilde{\alpha}_i^k\right)^L \right]^{\bar{w}_i^k}}, \prod_{i=1}^{I} \sqrt[I]{\left[\left(\tilde{\alpha}_i^k\right)^U \right]^{\bar{w}_i^k}} \right]$$

where

$$\bar{w}_i^k = \frac{\tilde{w}_i^k}{\max\limits_{l=1,\cdots,I} \left\{ \tilde{w}_l^k \right\}}$$

$\bar{w}_i^k$ means that the smaller the weight is, the less the impact on certitude degree $(\left(\tilde{\alpha}_i^k\right)^{\bar{w}_i^k}$ is approaches the limit of 1), if $\tilde{w}_i^k = 0$ then $\sqrt[I]{\left[\left(\tilde{\alpha}_i^k\right)^L \right]^{\bar{w}_i^k}} = \sqrt[I]{\left[\left(\tilde{\alpha}_i^k\right)^U \right]^{\bar{w}_i^k}} = 1$ [23].

According to ER approach, $\left\{ \wedge C^k \right\}$ is the set of the consequent of the kth rule R^k as the frame of discernment, let $\Omega^k = \left\{ \ \emptyset, \ \ \left\{ \wedge C^k \right\} \ \right\}$, R^k and $\wedge A^k$ are evidences, the weights of them should be confirmed, the new weight is called credibility degree. By the definition of ICRB, $\gamma^k = \left[\left(\gamma^k\right)^L, \left(\gamma^k\right)^U \right]$ is the degree of that the rule R^k is true, it can be seem as the degree of R^k influence on $\wedge C^k$ when R^k is true; $\tilde{\alpha}^k = \left[\left(\tilde{\alpha}^k\right)^L, \left(\tilde{\alpha}^k\right)^U \right]$ is the degree of $\wedge A^k$ influence on $\wedge C^k$ when $\wedge A^k$ is true. Based on the above analysis, the credibility degree w_R^k of R^k and the credibility degree w_A^k of $\wedge A^k$ can be obtained as follows:

$$w_R^k = \left[\left(w_R^k\right)^L, \left(w_R^k\right)^U \right] = \left[\frac{\left(\gamma^k\right)^L}{\left(\tilde{\alpha}^k\right)^U + \left(\gamma^k\right)^L}, \frac{\left(\gamma^k\right)^U}{\left(\tilde{\alpha}^k\right)^L + \left(\gamma^k\right)^U} \right]$$

$$w_A^k = \left[\left(w_A^k\right)^L, \left(w_A^k\right)^U \right] = \left[\frac{\left(\tilde{\alpha}^k\right)^L}{\left(\tilde{\alpha}^k\right)^L + \left(\gamma^k\right)^U}, \frac{\left(\tilde{\alpha}^k\right)^U}{\left(\tilde{\alpha}^k\right)^U + \left(\gamma^k\right)^L} \right]$$

The basic probability masses are:

$$m_R\left(\wedge C^k\right) = w_R^k \gamma^k = \left[m_R^L\left(\wedge C^k\right), m_R^U\left(\wedge C^k\right) \right] = \left[\left(w_R^k\right)^L \left(\gamma^k\right)^L, \left(w_R^k\right)^U \left(\gamma^k\right)^U \right]$$

$$m_R\left(\Omega^k\right)=1-m_R\left(\wedge C^k\right)=\left[m_R^L\left(\Omega^k\right),m_R^U\left(\Omega^k\right)\right]=\left[1-\left(w_R^k\right)^U\left(\gamma^k\right)^U,1-\left(w_R^k\right)^L\left(\gamma^k\right)^L\right]$$

$$\bar{m}_R\left(\Omega^k\right)=1-w_R^k=\left[\bar{m}_R^L\left(\Omega^k\right),\bar{m}_R^U\left(\Omega^k\right)\right]=\left[1-\left(w_R^k\right)^U,1-\left(w_R^k\right)^L\right]$$

where $m_R\left(\wedge C^k\right)$ is the basic probability mass of R^k; $m_R\left(\Omega^k\right)$ is the remaining probability mass that is unassigned to C^k which is caused by R^k; $\bar{m}_R\left(\Omega^k\right)$ is amount of remaining support left uncommitted by the weight of R^k.

$$m_A\left(\wedge C^k\right)=w_A^k\tilde{\alpha}^k=\left[m_A^L\left(\wedge C^k\right),m_A^U\left(\wedge C^k\right)\right]=\left[\left(w_A^k\right)^L\left(\tilde{\alpha}^k\right)^L,\left(w_A^k\right)^U\left(\tilde{\alpha}^k\right)^U\right]$$

$$m_A\left(\Omega^k\right)=1-m_A\left(\wedge C^k\right)=\left[m_A^L\left(\Omega^k\right),m_A^U\left(\Omega^k\right)\right]=\left[1-\left(w_A^k\right)^U\left(\tilde{\alpha}^k\right)^U,1-\left(w_A^k\right)^L\left(\tilde{\alpha}^k\right)^L\right]$$

$$\bar{m}_A\left(\Omega^k\right)=1-w_A^k=\left[\bar{m}_A^L\left(\Omega^k\right),\bar{m}_A^U\left(\Omega^k\right)\right]=\left[1-\left(w_A^k\right)^U,1-\left(w_A^k\right)^L\right]$$

where $m_A\left(\wedge C^k\right)$ is the basic probability mass of $\wedge A^k$, $m_A\left(\Omega^k\right)$ is the remaining probability mass that is unassigned to $\wedge C^k$ which is caused by $\wedge A^k$; $\bar{m}_A\left(\Omega^k\right)$ is amount of remaining support left uncommitted by the weight of $\wedge A^k$.

With the Dempster combination method [12], the upper bound $\left(\tilde{\beta}^k\right)^U$ and the lower bound $\left(\tilde{\beta}^k\right)^L$ of the activation degree $\tilde{\beta}^k$ of consequent $\wedge C^k$ are given as follows:

$$Max/Min\tilde{\beta}^k$$

$$S.t.\tilde{\beta}^k=\frac{m_R^*\left(\wedge C^k\right)m_A^*\left(\wedge C^k\right)+m_R^*\left(\wedge C^k\right)m_A^*\left(\Omega^k\right)+m_R^*\left(\Omega^k\right)m_A^*\left(\wedge C^k\right)+m_R^*\left(\Omega^k\right)m_A^*\left(\wedge C^k\right)}{1-\bar{m}_R^*\left(\Omega^k\right)\bar{m}_A^*\left(\Omega^k\right)}$$

$$m_R^*\left(\wedge C^k\right)+m_R^*\left(\Omega^k\right)=1$$

$$m_A^*\left(\wedge C^k\right)+m_A^*\left(\Omega^k\right)=1$$

$$\bar{m}_R^*\left(\Omega^k\right)+\bar{m}_A^*\left(\Omega^k\right)=1$$

the solutions of the optimization problem are the upper bound $\left(\tilde{\beta}^k\right)^U$ and lower bound $\left(\tilde{\beta}^k\right)^L$ of the activation degree $\tilde{\beta}^k$.

$$\tilde{\beta}^k=\left[\left(\tilde{\beta}^k\right)^L,\left(\tilde{\beta}^k\right)^U\right]$$

$$\left(\tilde{\beta}^k\right)^L = Min \quad \tilde{\beta}^k$$

$$\left(\tilde{\beta}^k\right)^U = Max \quad \tilde{\beta}^k$$

Then the interval certitude degree of consequent attribute value $C_j^k\ (j=1,2,\cdots,J)$ is obtained based on the similarity measure $S_{[]}$:

$$\tilde{\beta}_j^k=\left[\left(\tilde{\beta}_j^k\right)^L,\left(\tilde{\beta}_j^k\right)^U\right]$$

$$\left(\tilde{\beta}_j^k\right)^L = \begin{cases} \left[\min\left\{1-\left(\beta_j^k\right)^L+\left(\tilde{\beta}^k\right)^L, 1-\left(\beta_j^k\right)^U+\left(\tilde{\beta}^k\right)^U\right\}\right]\left(\beta_j^k\right)^L \tilde{\alpha}^k=1 \\ \min\left\{\left(\tilde{\beta}^k\right)^L\left(\beta_j^k\right)^L, 1\right\}\tilde{\alpha}^k<1 \end{cases}$$

$$\left(\tilde{\beta}_j^k\right)^U = \begin{cases} \left[\max\left\{1-\left(\beta_j^k\right)^L+\left(\tilde{\beta}^k\right)^L, 1-\left(\beta_j^k\right)^U+\left(\tilde{\beta}^k\right)^U\right\}\right]\left(\beta_j^k\right)^U \tilde{\alpha}^k=1 \\ \min\left\{\left(\tilde{\beta}^k\right)^U\left(\beta_j^k\right)^U, 1\right\}\tilde{\alpha}^k<1 \end{cases}$$

If there are T rules which are matching successfully with the input fact and having the same consequent attribute value $C\prime$, then the combination method should be given. First of all, the tth rules can be given as R_t:

$$\text{If } \left(\wedge A^t, \tilde{\alpha}^t\right) \text{ then } \left(C\prime, \tilde{\beta}_n^t\right) \wedge \cdots \wedge \left(C_{n-1}^t, \tilde{\beta}_{n-1}^t\right) \wedge \left(C_{n+1}^t, \tilde{\beta}_{n+1}^t\right) \wedge \cdots \wedge \left(C_J^t, \tilde{\beta}_J^t\right)$$

with rule certitude degree γ^t, rule weight θ^t and antecedent attribute weights $w_1, w_2, \cdots, w_I$

where $= 1, 2, \cdots, T$, $n \in \{1, 2, \cdots, J\}$ and n is determinate; $\wedge A^t$ is the antecedent of rule R_t, $\tilde{\alpha}^t = \left[\left(\tilde{\alpha}^t\right)^L, \left(\tilde{\alpha}^t\right)^U\right] \subseteq [0,1]$ is the interval certitude degree of $\wedge A^t$; $C\prime$ and C_j^t $(j = 1, \cdots, n-1, n+1, \cdots, J)$ are the consequent attribute values of rule R_t, $\tilde{\beta}_n^t = \left[\left(\tilde{\beta}_n^t\right)^L, \left(\tilde{\beta}_n^t\right)^U\right] \subseteq [0,1]$ is the interval certitude degree of $C\prime$ under the input fact, $\tilde{\beta}_j^t = \left[\left(\tilde{\beta}_j^t\right)^L, \left(\tilde{\beta}_j^t\right)^U\right] \subseteq [0,1]$ $(j = 1, \cdots, n-1, n+1, \cdots, J)$ is the interval certitude degree of C_j^t under the input fact; $\gamma^t = \left[\left(\gamma^t\right)^L, \left(\gamma^t\right)^U\right] \subseteq [0,1]$ is the rule certitude degree of rule R_t, $\theta^t \in [0,1]$ is the rule weight of rule R_t, the activation weights of rules are under the influence of $\Theta = \{\theta_t \,|t = 1, 2, \cdots, T\}$, $w_1, w_2, \cdots, w_I$ are antecedent attribute weights.

The rule weights are the relative weights (preference weights), according to the preference weight method [25], the credibility degrees of rules are given as $\varpi = \{\varpi_t \,|t = 1, 2, \cdots, T\}$, and ϖ_t is the credibility degree of the tth rule R_t.

According to the evidential reasoning approach, $\{C\prime\}$ is frame of discernment, let $\Omega\prime = \{\ \emptyset,\ \ \{C\prime\}\ \}$, the basic probability masses are given as follows:

$$m_t\left(C\prime\right) = \varpi_t \tilde{\beta}_n^t = \left[m_t^L\left(C\prime\right), m_t^U\left(C\prime\right)\right] = \left[\varpi_t\left(\tilde{\beta}_n^t\right)^L \varpi_t\left(\tilde{\beta}_n^t\right)^U\right]$$

$$m_t\left(\Omega\prime\right) = 1 - m_t\left(C\prime\right) = 1 - \varpi_t\tilde{\beta}_n^t = \left[m_t^L\left(\Omega\prime\right), m_t^U\left(\Omega\prime\right)\right] = \left[1-\varpi_t\left(\tilde{\beta}_n^t\right)^U, 1-\varpi_t\left(\tilde{\beta}_n^t\right)^L\right]$$

$$\bar{m}_t\left(\Omega\prime\right) = 1 - \varpi_t$$

where $m_t\left(C\prime\right)$ is the basic probability mass of R_t, $m_t\left(\Omega\prime\right)$ is the remaining probability mass that is unassigned to $C\prime$ which is caused by the incompleteness of rule R_t; $\bar{m}_t\left(\Omega\prime\right)$ is amount of remaining support left uncommitted by the weight of R_t.

Suppose $m_{\Lambda(t)}\left(C\prime\right)$ is the combined basic probability mass of $C\prime$ by aggregating the first $t\,(t = 1, 2, \cdots, T)$ rules $(R_1, \cdots, R_t)$, and $m_{\Lambda(t)}\left(\Omega\prime\right)$ is unassigned to $C\prime$ which is caused by the incomplete-ness of the first t rules $(R_1, \cdots, R_t)$; $\bar{m}_{\Lambda(t)}\left(\Omega\prime\right)$ is amount of remaining support left uncommitted by the weight of the first t rules $(R_1, \cdots, R_t)$.

Obviously, for the first $t = 1$,

$$m_{\Lambda(1)}\left(C\prime\right) = m_1\left(C\prime\right) = \varpi_1\tilde{\beta}_j^1 = \left[m_{\Lambda(1)}^L\left(C\prime\right), m_{\Lambda(1)}^U\left(C\prime\right)\right] = \left[\varpi_1\left(\tilde{\beta}_n^1\right)^L, \varpi_1\left(\tilde{\beta}_n^1\right)^U\right]$$

$$m_{\Lambda(1)}(\Omega\prime) = m_1(\Omega\prime) = \left[m^L_{\Lambda(1)}(\Omega\prime), m^U_{\Lambda(1)}(\Omega\prime)\right] = \left[1 - \varpi_1\left(\tilde{\beta}^1_n\right)^U, 1 - \varpi_1\left(\tilde{\beta}^1_n\right)^L\right]$$

$$\bar{m}_{\Lambda(1)}(\Omega\prime) = 1 - \varpi_1$$

The combined masses of the first t rules are given as follows:

- $m_{\Lambda(t+1)}(C\prime)$

$$Max/Min \quad m_{\Lambda(t+1)}(C\prime) = m^*_{\Lambda(t)}(C\prime)\, m^*_{t+1}(C\prime) + m^*_{\Lambda(t)}(C\prime)\, m^*_{t+1}(\Omega\prime) + m^*_{\Lambda(t)}(\Omega\prime)\, m^*_{t+1}(C\prime)$$

$$S.t. \quad m^*_{\Lambda(t)}(C\prime)\, m^*_{t+1}(C\prime) + m^*_{\Lambda(t)}(\Omega\prime)\, m^*_{t+1}(\Omega\prime) + m^*_{\Lambda(t)}(C\prime)\, m^*_{t+1}(\Omega\prime) + m^*_{\Lambda(t)}(\Omega\prime)\, m^*_{t+1}(C\prime) = 1$$

$$m^*_{t+1}(C\prime) + m^*_{t+1}(\Omega\prime) = 1$$

The result of solving the optimization model is

$$m_{\Lambda(t+1)}(C\prime) = \left[m^L_{\Lambda(t+1)}(C\prime), m^U_{\Lambda(t+1)}(C\prime)\right]$$

$$m^L_{\Lambda(t+1)}(C\prime) = \quad Min \quad m_{\Lambda(t+1)} \quad (C\prime)$$

$$m^U_{\Lambda(t+1)}(C\prime) = \quad Max \quad m_{\Lambda(t+1)} \quad (C\prime)$$

- $m_{\Lambda(t+1)}(\Omega\prime)$

$$Max/Min \quad m_{\Lambda(t+1)}(\Omega\prime) = m^*_{\Lambda(t)}(\Omega\prime)\, m^*_{t+1}(\Omega\prime)$$

$$S.t. \quad m^*_{\Lambda(t)}(C\prime)\, m^*_{t+1}(C\prime) + m^*_{\Lambda(t)}(\Omega\prime)\, m^*_{t+1}(\Omega\prime) + m^*_{\Lambda(t)}(C\prime)\, m^*_{t+1}(\Omega\prime) + m^*_{\Lambda(t)}(\Omega\prime)\, m^*_{t+1}(C\prime) = 1$$

$$m^*_{t+1}(C\prime) + m^*_{t+1}(\Omega\prime) = 1$$

The result of solving the optimization model is

$$m_{I(t+1)}(\Omega\prime) = \left[m^L_{I(t+1)}(\Omega\prime), m^U_{I(t+1)}(\Omega\prime)\right]$$

$$m^L_{I(t+1)}(\Omega\prime) = \quad Min \quad m_{I(t+1)} \quad (\Omega\prime)$$

$$m^U_{I(t+1)}(\Omega\prime) = \quad Max \quad m_{I(t+1)} \quad (\Omega\prime)$$

- $\bar{m}_{\Lambda(t+1)}(\Omega\prime)$

$$\bar{m}_{\Lambda(t+1)}(\Omega\prime) = \bar{m}_{\Lambda(t)}(\Omega\prime)\, \bar{m}_{t+1}(\Omega\prime)$$

The composition certitude degree of the consequent attribute value $C\prime$ is given as follows:

$$\beta\prime = \left[(\beta\prime)^L, (\beta\prime)^U\right], (\beta\prime)^L = \frac{m^L_{\Lambda(T)}(C\prime)}{1 - \bar{m}_{\Lambda(T)}(\Omega\prime)}, (\beta\prime)^U = \frac{m^U_{\Lambda(T)}(C\prime)}{1 - \bar{m}_{\Lambda(T)}(\Omega\prime)}.$$

Obviously, interval certitude degree satisfies that the interval certitude degree is more greater the consequent attribute value is more certain. If there are more than one matches and values of each consequent attribute, then the consequent attribute value with the greater interval certitude degree is the final consequent attribute value under the actual input vector.

3 Illustrative examples

In this section, a case study of classification with UCI data sets is provided. This example is used to illustrate the effectiveness of ICRIMER by comparing with some existing approaches.

In order to compare ICRIMER inference method with other methods which are based on different data types as well as missing values, eight data sets from the UCI Machine Learning Repository are used. **Table 1** shows for each data set its name, the numbers of instances, attributes, linear attributes, nominal attributes, linguistic attributes, classes, and the percentage of the missing values.

Table 1: Properties of eight data sets from UCI

Dataset	Instances	Attributes	Linear Attributes	Nominal Attributes	Linguistic Attributes	Classes	Missing Values (%)
cancer	699	10	0	0	10	2	0.25
glass	214	9	9	0	0	6	0
horse	368	27	7	20	0	2	24
ionosphere	351	34	34	0	0	2	0
iris	150	4	4	0	0	3	0
liver	345	6	6	0	0	2	0
pima	768	8	8	0	0	2	0
wine	178	13	13	0	0	2	0

These data sets are used to compare the performances of Interval Certitude Rule Base Inference Method using Evidential Reasoning approach (ICRIMER), Rule Based Inference Method using Dempster-Shafer theory (RIMDS) [15], Feature Interval Learning algorithm (FIL) [11], k-Nearest Neighbor algorithm (k-NN) [4] Logistic Regression (LoR) [3,26], Naive Bayesian classifier (NB) [7], Pruning Decision Tree (PDT) [13].

ICRIMER and RIMDS are interval feature projection based logical inference algorithms. FIL is an interval feature projection based algorithm. LoR and NB are probability based algorithm. PDT is a structure based algorithm and decision tree can be used to describe If-then rules. k-NN is a famous machine learning method and give excellent results on many real-world examples [24].

To illustrate the significance of the accuracy of the rule base, a comparison rule base is given, and the interval certitude degrees and weights of rules are given based on some artificial restrictions. For example, if two rules which have the same antecedent and the different consequent, then these two rules will be given the smaller interval certitude degrees and weights; the weights of attribute are given using the feature selection method based on Relief [18]. The learning method based on ICRIMER and the comparison rule base is recorded as ICRIMER-c.

In the eight data sets, there are different data types: linear values, nominal values, linguistic values (evaluation grade) and missing values. So the instances should be transformed into interval certitude rules firstly.

Table 2 and Figure 1 report the correctly classified accuracy rate of the FIL, k-NN, LoR, NB, PDT, RIMDS and ICRIMER which are obtained by averaging the correctly classified accuracy rates over five repetitions of 5-folder cross validations. In this paper, k=5 for k-NN which exactly consistent with the case study in Ref. 29 as 5-NN gives the best correctly classified accuracy rate.

From Table 2 and Figure 1, we can find some phenomena as follows.

(i) ICRIMER may not always be the best classification method except data sets cancer and iris, but ICRIMER outperforms the interval classification methods RIMDS and FIL on five data sets, cancer, glass, horse, iris and liver. It means that ICRIMER has a higher classification capability on interval data sets.

Table 2: Correctly classified accuracy rates of the FIL, k-NN, LoR, NB, PDT, RIMDS, ICRIMER and ICRIMER-c

Learning Method	cancer	glass	horse	ionosphere	iris	liver	pima	wine
FIL	0.9688	0.5502	0.7718	0.9253	0.9426	0.6185	0.7054	0.9663
k-NN	0.9691	0.6455	0.8157	0.8501	0.9640	0.6110	0.7353	0.9540
LoR	0.9342	0.6355	0.8300	0.8775	0.8533	0.6870	0.6355	0.9607
NB	0.9740	0.5392	0.8027	0.8842	0.9293	0.6151	0.7262	0.9348
PDT	0.9299	0.6822	0.8033	0.8974	0.9600	0.6870	0.6822	0.9157
RIMDS	0.9629	0.5844	0.7700	0.8643	0.9739	0.6232	0.5195	0.9444
ICRIMER	0.9759	0.6047	0.7733	0.8942	0.9800	0.6318	0.6987	0.9055
ICRIMER-c	0.9900	0.6512	0.8132	0.8971	0.9899	0.6957	0.7532	0.9722

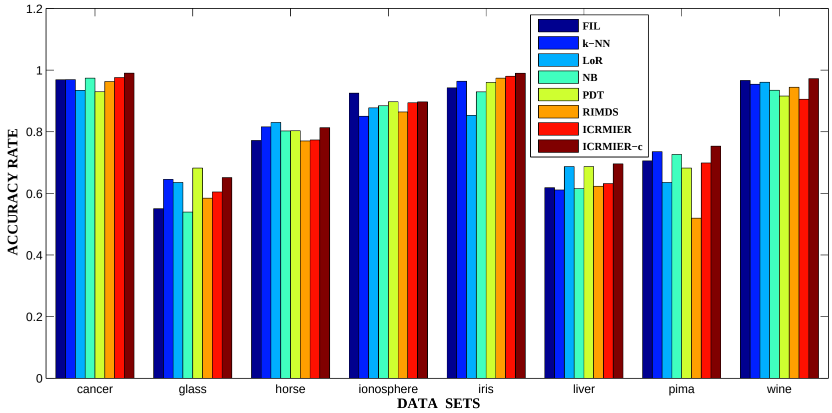

Figure 1: Correctly classified accuracy rates of the FIL, k-NN, LoR, NB, RIMDS, ICRIMER and ICRIMER-c

(ii) With regard to If-then rules, ICRIMER outperforms or a bit underperforms PDT on five data sets, cancer, ionosphere, iris, pima and wine. It means that ICRIMER has advantages in this respect.

(iii) ICRIMER-c is the best classification method on five data sets cancer, iris, liver, pima and wine, on the other three data sets the accuracy rate of ICRIMER-c is higher than the accuracy rate of ICRIMER and ICRIMER-c is the second best method in the eight methods. It means that, with a relatively accurately rule base, ICRIMER has general applicability and high classification capability.

(iv) Compare the classified accuracy rates of ICRIMER and ICRIMER-c, the classified accuracy rate of ICRIMER-c is higher than the classified accuracy rates of ICRIMER. It means that a relatively accurately rule base is an important influencing factors of ICRIMER and the rule base can be more accurately by adjusting the interval certitude degrees and weights of rules, the knowledge representation method ICRB is effective.

In general, ICRIMER is the better algorithm on this eight UCI data sets, with the relatively accurate rule bases, the results of classification would be better. And the interval certitude structure can be used to describe the uncertainties of knowledge; the ICRB can better reflect the uncertainty, correctness and importance of instance or knowledge. Moreover, if the weights and interval certitude degrees are given by domain expert or gained through training, then the results will be more rational and better.

4 Conclusions

In this paper, a new knowledge representation, interval certitude rule base (ICRB), was proposed to capture uncertainty and nonlinear causal relationships based on the If-then rule and fuzzy set theory. The inference process of interval certitude rule base was characterized by all interval certitude rules expression and was reasoning using the evidential reasoning. And an illustrative example with UCI data sets was used to illustrate the application of the proposed method.

There are several features of the interval certitude rule base inference method (ICRIMER). First, due to the use of interval certitude rule, the ICRIMER method gives a description framework of relationships between inputs and outputs which may be complete or incomplete, linear or nonlinear, discrete or continuous, or their mixture, which are based on both numerical data and human judgments. Second, the uncertainty of human judgment is characterized with interval certitude structure, and ICRIMER is a multi-output uncertainty inference method with one or more than one consequent attributes. These features are more close to the experience and perception of human.

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SHRP - Secure Hybrid Routing Protocol over Hierarchical Wireless Sensor Networks

B. Muthusenthil, H. Kim

Balasubramanian Muthusenthil
1. Information Security Research Institute,
Wookyoung Information Technology,
Daegu, South Korea.
2. Computer Science and Engineering,
Valliammai Engineering College, India.
bmssen@gmail.com

Hyunsung Kim*
1. Dept. of Mathematical Sciences,
University of Malawi, Malawi
2. Dept. of Cyber Security,
Kyungil University, Korea
*Corresponding author: kim@kiu.ac.kr

Abstract: A data collection via secure routing in wireless sensor networks (WSNs) has given attention to one of security issues. WSNs pose unique security challenges due to their inherent limitations in communication and computing, which makes vulnerable to various attacks. Thus, how to gather data securely and efficiently based on routing protocol is an important issue of WSNs. In this paper, we propose a secure hybrid routing protocol, denoted by SHRP, which combines the geographic based scheme and hierarchical scheme. First of all, SHRP differentiates sensor nodes into two categories, nodes with GPS (NG) and nodes with antennas (NA), to put different roles. After proposing a new clustering scheme, which uses a new weight factor to select cluster head efficiently by using energy level, center weight and mobility after forming cluster, we propose routing scheme based on greedy forwarding. The packets in SHRP are protected based on symmetric and asymmetric cryptosystem, which provides confidentiality, integrity and authenticity. The performance analyses are done by using NS2 and show that SHRP could get better results of packet loss rate, delivery ratio, end to end delay and network lifetime compared to the well known previous schemes.
Keywords: Wireless Sensor Network (WSN), routing protocol, information security, anonymity, greedy forwarding.

1 Introduction

Wireless sensor networks (WSNs) are complex distributed system which comprises of large number of tiny wireless sensor nodes. These sensor nodes are widely deployed over a geographical area for monitoring and observe data in various ambient conditions. This real time data could be used to design various applications with intelligence. WSN is a technology which becomes more mature and is gaining momentum as one of the enabling technologies for the future Internet. The major applications of WSN focus predictive maintenance, intelligent buildings, enhanced safety & security, smart home, health care and disaster management etc. The characteristics of WSN such as rapid deployment, self-organization and fault tolerance make a very promising sensing technique for military applications [2, 10]. WSN plays a dominant role and lots of researches and practical applications have been contributing to improve in terms of device size, date rate, energy etc. But the main bottleneck is based on energy factor. Since WSN operates on resource constrained environment, either changing or recharging batteries is an unmanageable task. Even the failure of single node due to low energy can prostrate the entire network. This problem forced researchers for developing an energy efficient protocol at network level [33]. At the network level various energy efficient routing protocols were developed [8, 9, 28]. Mainly the routing protocols in WSN are classified in three main categories: data centric protocols, geographic based protocols, heterogeneous protocols and hierarchical protocols. Recently, heterogeneous wireless sensor network (HWSN) routing protocols have drawn more and more attention. Various HWSN routing protocols have been proposed to improve the performance of HWSNs like EDFCM, MCR, EEPCA, LEACH and SEP. In SEP, the cluster head of the advanced node frequently becomes the cluster head than the normal node [9].

This paper mainly proposes a secure hybrid routing protocol (SHRP) which combines the concepts of geographic based and hierarchical. SHRP is consisted of two phases (i) clustering and cluster head selection phase (ii) secure routing phase.

SHRP uses a weight factor to select cluster head by considering energy level, center weight and mobility after clustering. Secure routing phase is designed based on greedy forwarding and the packets are protected based on symmetric and asymmetric cryptosystem. Thereby the routing scheme could provide confidentiality, integrity and authenticity. WSN is composed of a set of clusters. In each cluster, a node called cluster head (CH) and remaining sensor nodes are called as cluster member nodes (CM). The role of each CH is to carry out the following three roles. The first role is to gather sensed data from the cluster nodes periodically and aggregates the data to remove redundancy among correlated values [30]. The second role is to generate a time division multiple access (TDMA) schedule in which sensor nodes receive a time slot for data transmission. The third role is to transmit the aggregated data to the destination by using secure routing. Hence the lifetime of CH would be a very short span of time performs all three roles and it becomes essential to shift the cluster head periodically in a well-structured manner.

In SHRP,

(1) *a novel cluster head selection scheme is proposed between the sensor nodes based on the three factors center weight, residual energy and mobility factor*, and

(2) *secure routing scheme is designed. The performance analysis by varying the percentage of nodes with GPS (NG) and nodes with antenna (NA) is done using NS2 and shows results of the parameters like packet delivery ratio, control overhead, percentage of attacks and energy consumption varies in SHRP.*

This paper is organized as follows: Section 2 discusses about related works. Section 3 proposes our network model and proposed system in detail and devises a new secure hybrid routing protocol. Performance analysis and results are provided in Section 4. Section 5 concludes with future direction of this research.

2 Related work

This section discusses on the various clustering schemes, cluster head selection schemes and secure routing schemes over WSNs [5, 9].

Baker et al. proposed linked cluster algorithm (LCA) mainly focuses on forming an efficient network topology to handle mobility of nodes [5]. Xu et al. proposed random competition based clustering (RCC) applicable to WSN which applies "first declaration win" rule [29]. Nagpal et al. proposed clubs algorithm in which clusters are formed by local broadcast and converge in time proportional to the local density of nodes [19]. Bandyopadhyay et al. proposed energy efficient hierarchical clustering (EEHC) with the objective of minimizing the network lifetime [6]. Heinzelman et al. proposed low energy adaptive clustering hierarchy (LEACH) which is one of the popular clustering algorithm in which clusters are formed based on received signal strength and uses the cluster head as routers [11,12]. LEACH obtains energy efficiency by partitioning the nodes into clusters which comprises of setup phase and steady state phase. During setup phase the cluster head selection process is based on predetermined probability, and steady state phase is for data transmission. Wang et al. proposed clustering scheme based on queries and attributes of data [27]. Mostafaei et.al [18] presents an algorithm based on Imperialist Competitive algorithm for improving the network lifetime in WSN by diving the nodes into various cover-sets.

Alasem et al. [3] proposed a location based energy-aware reliable routing protocol (LEAR) for WSN based on enhanced greedy forwarding (EGF) protocol which selects the nearest node to be active node based on its distance but it practically fails. LEACH also does the cluster head selection process but it is based on predetermined probability does not considered the energy efficiency for cluster head selection. LEACH-centralized (LEACH-C) uses centralized algorithm for the cluster head selection where the base station collects the position and energy level of the sensor nodes and the node having greater energy than average energy of all sensor nodes would be elected as cluster head. Since this approach only considers the energy level of sensor nodes while selecting the cluster head, there may be a greater probability of elected cluster head is far away from base station which consumes more energy for the communication between base station and cluster head. Mehmood et.al [16] proposes LEACH-VH for improving the performance of LEACH in which introducing the concept of Vice Cluster Head (VH) to support CH but it leads to additional energy for electing VH. Younis et al. presented hybrid energy-efficient distributed clustering (HEED) protocol, which periodically selects cluster head according to their residual energy [31]. But the disadvantage is the authors do not make any assumptions about infrastructure or node capabilities, other than the availability of multiple power levels in sensor nodes. However, HEED supports two-level hierarchy. Ming et al. proposed a new energy-efficient dynamic clustering scheme where each node estimates the number of active nodes in real-time and computes its optimal probability of becoming a cluster head by monitoring the received signal power from its neighbor nodes [10]. Jung et al. proposed a cluster based energy-efficient forwarding scheme which uses the binary exponential back off algorithm for cluster head selection [14].

Han [9] proposes heterogeneous cluster-based protocols which has ability to manage the clusters and member nodes for better balance energy consumption of the nodes in the whole network whereas it does not satisfy for unequal distribution of clusters. Song [24] proposes a heterogeneous sensor network to improve the efficiency of network coverage but optimization needs to be addressed. Ndiaye et al. [20] proposed that Software Defined Networking (SDN) provides a promising solution in flexible management WSNs by allowing the separation of the control logic from the sensor nodes/actuators [17]. The advantage with this SDN-based management in WSNs is that it enables centralized control of the entire WSN making it simpler to deploy network-wide management protocols and applications on demand.

The cluster head selection algorithms described above is considering the two important parameters such as distance among the nodes and residual energy of the nodes. The proposed solution uses different approach from the previous where cluster head selection process is done based on the weight factor of center weight, residual energy and mobility of each node.

Bohge et al. proposed secure hierarchical routing protocol by using TESLA certificates for authentication [7]. But it cannot prevent intruders from coming into the network and sending packets and cannot protect against eavesdropping. Tubaishat et al. proposed a secure routing protocol uses the symmetric key cryptography and proposed a group key management scheme and drawback associated with this protocol is that, while changing the CH all group key i.e. inter-cluster and intra-cluster key should have to compute once again, which is a cumbersome task [26]. Parno et al. proposed LHA-SP on securing heterogeneous hierarchical WSNs uses the symmetric key scheme Authentication and confidentiality is maintained by shared pairwise key but it deals with orphan node problem [23]. Oliveria et al. proposed FLEACH, a protocol for securing node to node communication uses random key pre-distribution scheme with symmetric key cryptography but it is vulnerable to node capturing attack [22]. Ibriq et al. proposed a secure hierarchical energy efficient routing protocol (SHEER) which provides secure communication at the network layer which uses HIKES a secure key transmission protocol and symmetric key cryptography [13].

Leao et al. proposed an Alternative-Route Definition (ARounD) communication scheme for WSNs. The underlying idea of ARounD is to setup alternative communication paths between specific source and destination nodes, avoiding congested cluster-tree paths [15].

Srinath et al. proposed cluster based secure routing protocol which uses both public key (in digital signature) and private key cryptography [25]. This protocol deals with interior adversary or compromised node but it requires high computational requirement (use of public key cryptography), which is not efficient for the WSNs. Oliveira et al. proposed Sec-LEACH an efficient solution for securing communications uses random-key pre distribution and μTESLA for secure hierarchical WSN with dynamic cluster formation [21]. Quan et al. proposed secure routing protocol cluster-gene-based (SRPBCG) for WSNs [34]. Biological 'gene' as encryption key but it only deals with the adversary's attack and compromised nodes but computation and communication burden are more in this protocol. Adnan et al. [1] proposed a Secure Region-Based Geographic Routing Protocol (SRBGR) to increase the probability of selecting the appropriate relay node. By extending the allocated sextant and applying different message contention priorities more legitimate nodes can be admitted in the routing process but it fails when increasing number of nodes with different scenarios of network terrain.

3 SHRP: Secure hybrid routing protocol

This section proposes a novel secure hybrid routing protocol (SHRP) in WSN. We differentiate sensor nodes into two categories: nodes with GPS (NG) and nodes with antennas (NA). In order to propose SHRP, we need to undergo two phases: (1) clustering and cluster head selection and (2) secure routing. In Phase 1, clustering is done based on any one of the best approaches from the previous clustering schemes. However the clustering approach should satisfy that the percentage of NG must be at least three nodes in each cluster in order to support position requirement from each node. After that the cluster head selection process is done based on the weight factor of center weight, residual energy and mobility of each node. In phase 2, secure routing is designed where the packets are protected by using symmetric and asymmetric cryptosystem to support confidentiality, integrity and authenticity.

The network architecture is composed of CH and CM as entities:

- *Cluster head* (CH_i): It is node which acts as a coordinator of each cluster. We assume that NA only could be a candidate of cluster head. Any NA nodes in a cluster could be selected as the cluster head which has maximum weight factor and but with less mobility factor.

- *Cluster member* (CM_i): It is a node in a WSN is capable of performing some processing, gathering sensory information and communicating with cluster head in the network. Any NA or NG nodes could be member nodes in each cluster which is attached with CH exclusively.

Based on these assumptions, a transmission model between a source node (CM_S) and a destination node (CM_D) can be designed as follows:

Table 1: Notations

Notation	Meaning
NG	Nodes with GPS
NA	Nodes with antennas
CH_i	Cluster head i
CM_S	Cluster member source
CM_D	Cluster member destination
μ_i	Weight factor of node i
C_i	Center weight of node i
ER_i	Residual energy of node i
M_i	Mobility of node i
N_{mid}	Center of each cluster
$E_i(0)$	Initial energy level of node i
$E_i(T)$	Initial energy level of node i at time T
R_{REQ}, R_{REP}	Route request and route reply message
$AE(K, M)$	Asymmetric key encryption function with 2 inputs of key K and message M
$AD(K, M)$	Asymmetric key decryption function with 2 inputs of key K and message M
$SE(K, M)$	Symmetric key encryption function with 2 inputs of key K and message M
$SD(K, M)$	Symmetric key decryption function with 2 inputs of key K and message M
$H()$	Secure hash function
PR_D, PU_D	Private-public key pair for destination
PR_S, PU_S	Private-public key pair for source
ID_S, ID_D	Real identities for source and destination
$AID_S, , AID_D$	Amplified identities for source and destination
SK_S	Session key generated by source
T_i	Time stamp for node i
EN_S, EN_D	Encrypted messages by source and destination
MAC_S, MAC_D	Message authentication codes for source and destination
AU_S, AU_D	Authenticated values by source and destination
$\|\|$	Concatenation operator
SF	Security field
Q	Query message
M_{ID}	Message ID

Table 2: Recommended clustering algorithms

Algorithms Required Parameters	Cluster overlapping	Location awareness
LCA	No	Required
Adaptive clustering	No	Required
RCC	No	Required
GS3	Low	Required
EEHC	No	Required
DWEHC	No	Required
Attribute based clustering	No	Required

- If CM_S is located within the distance r_s from CM_D, CM_S transmits the packet to CM_D via the cluster head CH_S.
- When CM_D is outside of the transmission range from CM_S, the packet is forwarded to the intermediate cluster heads in the direction of CM_D.

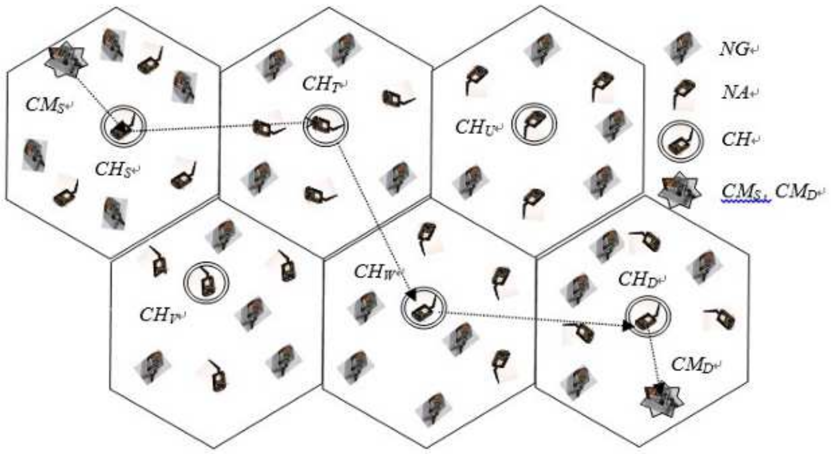

Figure 1: Network configuration

3.1 Clustering and cluster head selection phase

Clustering

WSN involves large number of sensors for which clustering is an effective and efficient way for managing high volume of nodes. There are many clustering schemes, which were proposed by various researchers based on different categories. Many of the clustering algorithms are given in related works [8,10]. This objective of clustering is out of scope to our research but the research objective we tabulated few clustering schemes which suits for our network model . Therefore clustering is done based on any of the clustering approaches in in Table 2. However, the clustering should satisfy that the percentage of NG nodes must be at least three nodes in each cluster in order to support requisition requirement from each node.

Cluster head selection

As we mentioned at the network initialization and transmission model, each node could get their location information with the help of NG nodes. The cluster head selection process is done based on the parameters of weight factor (μ_i) along with center weight (C_i), residual energy (ER_i) and mobility (M_i) of each node i. The Weight factor of the node is defined as the weight assigned to a node based on its residual energy and mobility, in order to give less or more importance to the other nodes in the cluster. Weight factor of the node i (μ_i) is computed by (1).

$$\mu_i = (x_1 * C_i) + (x_2 * ER_i) - (x_3 * M_i), \tag{1}$$

where x_1, x_2 and x_3 are threshold values such that $x_1 + x_2 = 1$. x_3 is a deduction factor due to its mobility.

Table 3: Cluster head selection message format

Node ID	Weight factor (μ_i)	Node mobility (M_i)

Let N_{mid} be the center of each cluster which can be determined by help of NG nodes. The center weight (C_i) of the node i is computed by using (2).

$$C_i = N_{mid} * \alpha, \tag{2}$$

where α is the distance from the border node of its cluster to N_{mid}, which ranges from 0 to 1 depending upon the location.

Let $E_i(0)$ be the initial energy level (ER_i) of the node i. At a time period T, the energy consumed by the node i ($E_i(T)$) is computed by using (3).

$$E_i(T) = n_{tx} * \beta + n_{rx} * \gamma, \tag{3}$$

where n_{tx} and n_{rx} are the numbers of data packets transmitted and received by the node i at time T, respectively. β and γ are in the range $(0, 1)$ to measure energy consumption level.

The residual energy of the node $i(ER_i)$ at time T is computed using (4).

$$ER_i = E_i(0) - E_i(T). \tag{4}$$

The node mobility (M_i) of node i is computed using (5).

$$M_i = \frac{\sqrt{(u_2 - u_1)^2 + (v_2 - v_1)^2}}{T_2 - T_1}, \tag{5}$$

where (u_1, v_1) and (u_2, v_2) are the coordinates of the node i at time T_1 and T_2, respectively.

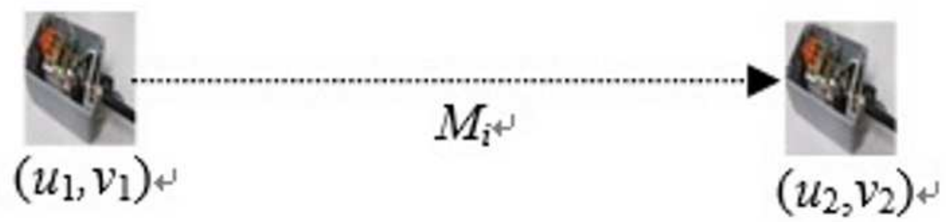

Figure 2: Node mobility

The steps involved in cluster head selection are as follows.

1. When the nodes are deployed in a WSN, all the nodes compute μ_i and broadcast cluster head selection message to its neighbors, which follows the format of Table 3. It includes the parameters such as node ID, weight factor and node mobility.

2. When node receives the message, it forms a member list (ML), and checks whether it has the maximum weight factor $\mu_{\max}$ by using the obtained ML.

3. Node with $\mu_{\max}$ is elected as cluster head (CH_i) as shown in Figure 1

4. If there are more than one node with $\mu_{\max}$ value, less mobility factor node is selected as the cluster head and it transmits cluster head election message (CH_{Elec}), which contains ID_{CHi} to every nodes in the cluster.

If a node in ML needs to leave from the cluster, it sends leave request (L_{Req}) message to CH_i. CH_i broadcasts the updated ML to every member nodes which removes the node from ML. Similarly, when a node in ML needs to join into the cluster, it sends join request (J_{Req}) message to CH_i. CH_i broadcasts the updated ML to every member nodes which adds the node into ML.

3.2 Secure routing phase

The task of secure routing is to form route from source CM_S to destination CM_D by sending packets while complying with the condition of that CM_S is informed about the position of CM_D. The secure routing is described as the following steps:

1. When CM_S wants to transmit a route construction request with a query to CM_D, it invokes form_message(), unicasts R_{REQ} to its CH_S and stores M_{ID} in its route cache termed as session table (ST), which helps to distinguish the respective R_{REQ} while receiving R_{REP}.

Table 4: Route request message format

Message ID (M_{ID})	Source ID (AID_S)	Destination ID (ID_D)	Location of CH_i (NL)	Destination location (L_D)	Security field (SF)	Query (Q)

2. When CH_S receives R_{REQ}, it checks L_D and invokes request_route_CH(R_{REQ}).

function REQUEST_ROUTE_CH(R_{REQ})
  if L_D is within ML or ID_D is member of CH_S **then**
    Send R_{REQ} directly to CM_D
  else
    Send R_{REQ} directly to CM_i towards direction of L_D
    do
      CH_i broadcast to nearest NL towards L_D
    while (not reach to CH_D)
  end if
end function

function FORM_MESSAGE()
  CM_S generates a session key K_S and forms a message $M_S = ID_S \| ID_D \| K_S \| PU_S \| T_S$ with T_S
  Encrypts M_S with PU_D by applying asymmetric encryption $EN_S = AE(PU_D, M_S)$
  Computes $MAC_S = H(EN_S \| K_S)$
  Computes authenticated value $AU_S = AE(PR_S, T_S)$
  Sets $NL = NULL$
  returns (EN_S, MAC_S, AU_S)
end function

3. If R_{REQ} reaches to MN_D, CH_D invokes verify_message() and respond_route(R_{REP}) to return back R_{REP} to CH_S

function VERIFY_MESSAGE()
  CM_D decrypts EN_S by using PR_D and retrieves $M'_S = ID'_S \| ID'_D \| K'_S \| PU'_S \| T'_S$ by using $AD(PR_D, EN_S)$
  Computes $MAC'_S = H(EN_S \| K'_S)$
  Checks the validity MAC_S by comparing with MAC'_S
  Checks authenticity of source by $AD(PU_S, AU_S)$

CM_D forms acknowledgement message $M_A = ID_S \| ID_D \| K_S \| PU_D \| T_D$
if verification is successful **then**
Compute $EN_D = SE(K_S, M_A)$
Computes $MAC_D = H(EN_D \| T_D)$
end if
$AU_D = AE(PR_D, T_D)$ **return** EN_D
end function

function RESPOND_ROUTE_$CH(R_{REP})$
if L_S is within ML or ID_S is member of CH_D **then**
Send R_{REP} directly to CM_S
else
Send R_{REP} directly to CM_i towards the direction of L_S
do
CH_i broadcast to nearest NL towards L_S
while (not reach to CH_S)
end if
end function

4. If CM_S receives R_{REP}, the secure routing process is successful.

4 Analysis

This section provides performance analysis and security analysis after providing simulation results on SHRP. We used NS2 to provide simulation results of SHRP, which uses parameters of Table 5. Simulations were carried out based on LEACH, EEHC and SHRP [**?**, **?**]

Table 5: Simulation parameter

Parameters	**Values**
Initial energy of nodes E_{unit}	$0.5J$
Amplification coefficient of the free space model E_{fs}	$10pJ \cdot m^2/b$
Amplification coefficient of the multipath transmission model E_{amp}	$0.0013pJ \cdot m^2/b$
Table data fusion rate E_{DA}	$5nJ/b$
Circuit loss E_{elec}	$50nJ/b$
Clustering probability of nodes p	0.05
Data packet length	$4000b$
Control packet length	$80b$

4.1 Performance analyses

Figure 3 and Figure 4 show the packet loss rate results depending on the different number of nodes to form clusters based on various clustering techniques.

SHRP minimizes the packet loss rate approximately 3.27% in the number of NG nodes and 3.34% in the number of NA nodes than EEHC. Furthermore, it reduces the rate approximately 40.02% in NG nodes and 47.06% in NA nodes than LEACH.

SHRP has less end to end delay compared to EEHC and LEACH as shown in Figure 5 and Figure 6.

As shown in Figure 5 and Figure 6, SHRP has better performance than LEACH and EEHC

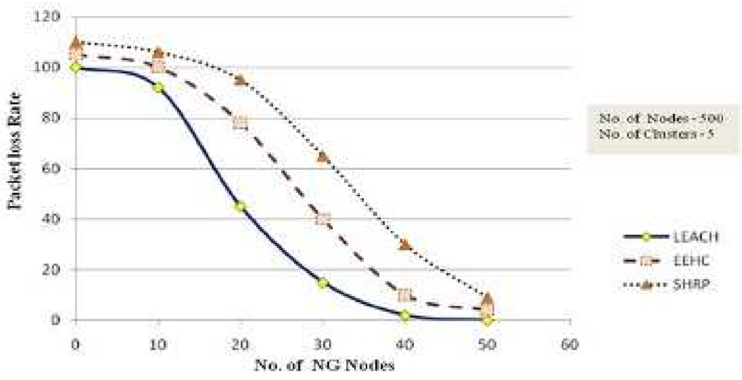

Figure 3: Packet loss rate depending on changes of the number of NG nodes

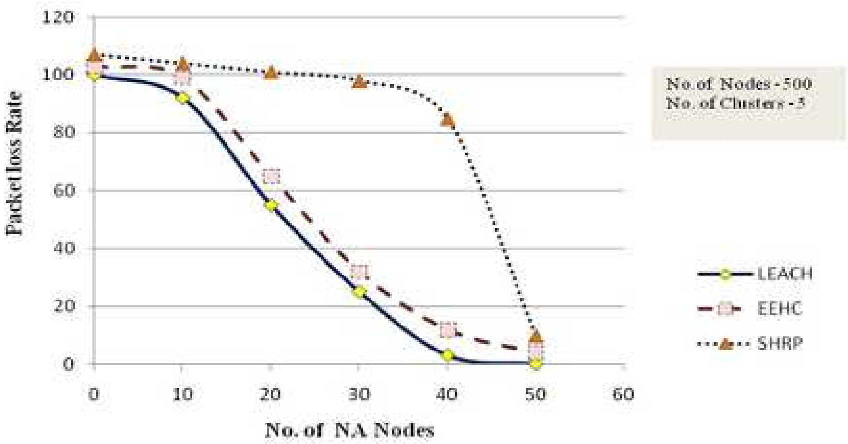

Figure 4: Packet loss rate depending on changes of the number of NA nodes

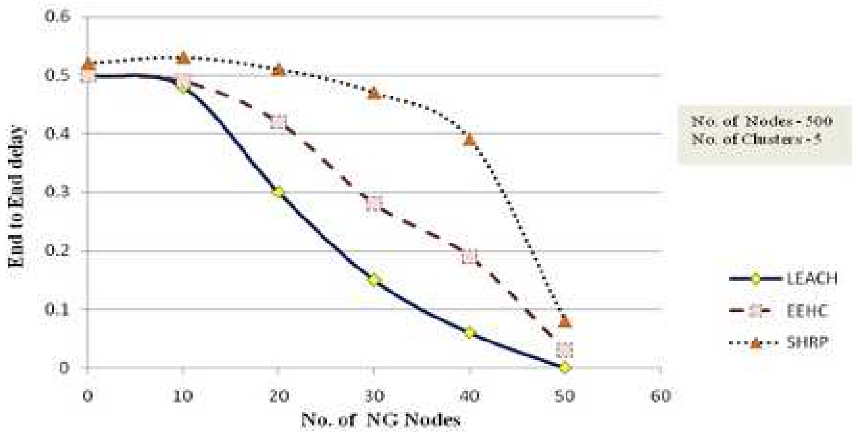

Figure 5: End to end delay depending on changes of the number of NG nodes

for the number of NG and NA nodes changes. Hence the delivery latency of SHRP in the number of NG nodes changes is higher than the other case.

Figure 7 and show the variations on the three schemes and they characterize that incurs approximately 97.9% packet delivery ratio. LEACH and EEHC achieve the packet delivery ratio

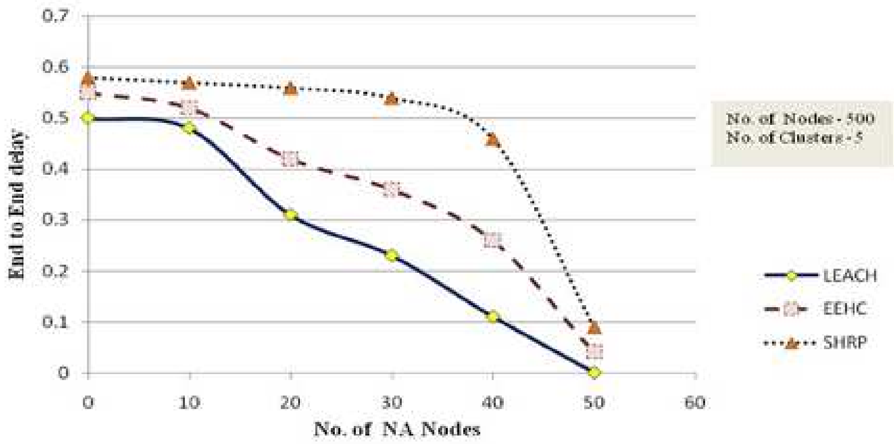

Figure 6: End to end delay depending on changes of the number of NA nodes

in average of 95.2% and 91%, respectively. From Figure 8 the SHRP in number of NA nodes incurs 98.2% (approx) delivery of data packets and results in better rate compared to delivery rate in NG nodes.

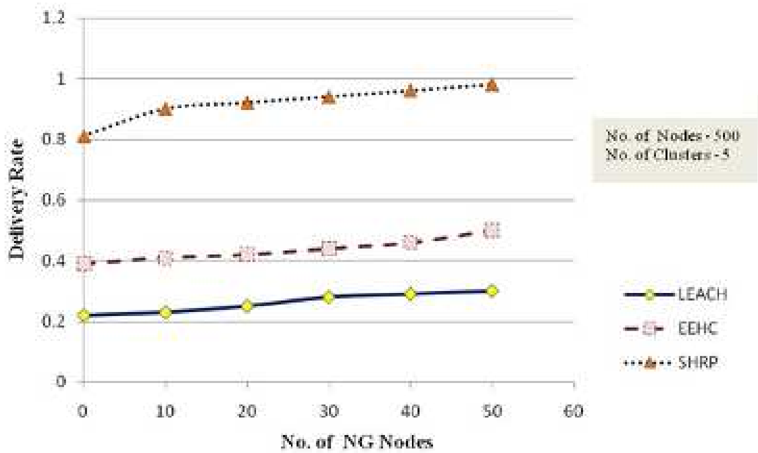

Figure 7: Delivery ratio depending on changes of the number of NG nodes

From Figure 9 and Figure 10 it is understood that SHRP has 32% of delay in delivering data packets. LEACH and EEHC delivery delay rate at a rate of 48% (approx) and 43.05%. Hence SHRP result has better performance than LEACH and EEHC for number of NG nodes and SHRP has 28% (approx) of delay in delivering data packets for NA nodes.Hence delivery latency of SHRP in number of NG node is high than delivery latency of SHRP in number of NA nodes.

Figure 11 and Figure 12 shows the network lifetime in number of NG nodes. SHRP has the network lifetime of 30.05% (approx). LEACH and EEHC has the network lifetime of 32.6% (approx) and 35.09% (approx).

Figure 11 and Figure 12 show the comparison of network lifetime, which shows that SHRP has longest lifetime compared to LEACH and EEHC.

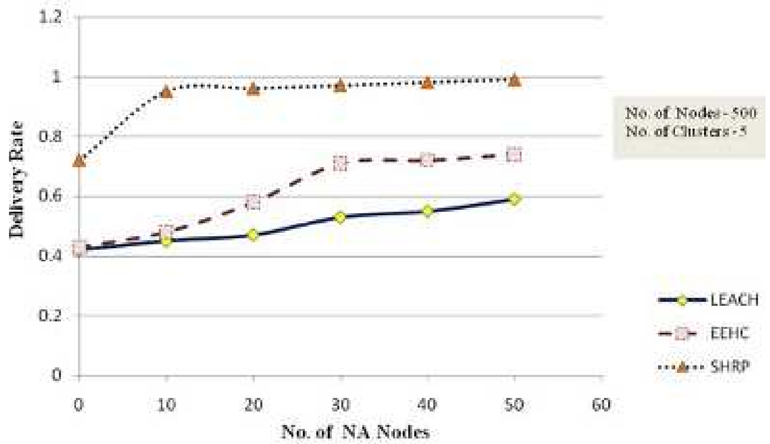

Figure 8: Delivery ratio depending on changes of the number of NA nodes

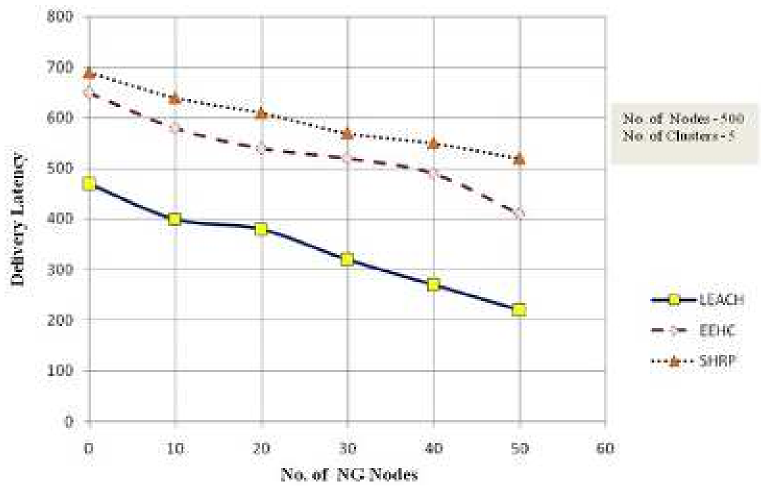

Figure 9: Delivery latency depending on changes of the number of NG nodes

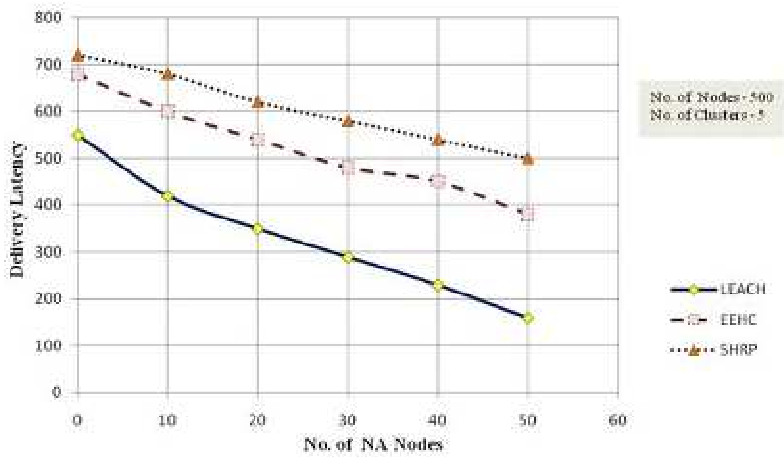

Figure 10: Delivery latency depending on changes of the number of NA nodes

4.2 Security analysis

The focus of this analysis is to ensure how secure the message transmissions in SHRP between CM_S and CM_D, which is only focused on the secure routing phase.

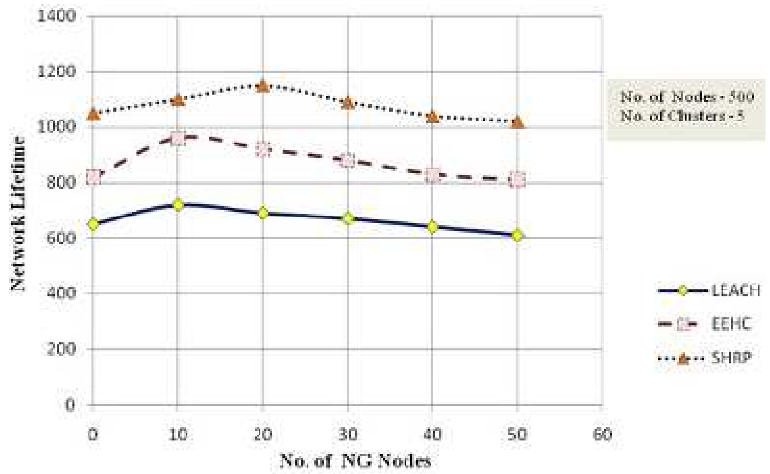

Figure 11: Network lifetime depending on changes of the number of NG nodes

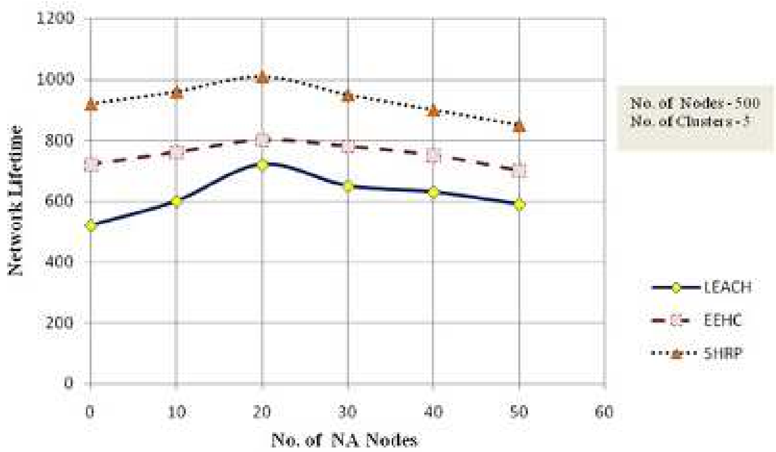

Figure 12: Network lifetime depending on changes of the number of NA nodes

Once the messages to establish route are secured, it is inferred that communications over the WSN are secure.

1. *Unlinkability/Anonymity*: SHRP achieves anonymity by using encrypted message of identities, which could provide security of ID_S. This is achieved by sending the encrypted message EN_S during route construction request message formatting. There is no way an attacker can discover the source node's real identity because no user identification information is transmitted in plain. Therefore, SHRP provides entity anonymity. Further unlinkability is provided because the timestamp T_S is protected from the preying eyes of an adversary and therefore cannot be related to a particular node by anyone other than CM_D. So, entity privacy is guarded against eavesdropper. This means the session key derived after authentication ensures privacy of end entity information like sensed data or any encrypted messages.

2. *Impersonation Attack*: An attacker may attempt to use a bogus CH_i or CM_i to impersonate the real one that the attacker has access to. As much as the attacker has no knowledge of any entity in the network due to anonymity and unlinkability properties, the attacker cannot manage to impersonate any entity in WSN with a malicious CH_i or CM_i. Even

from the transmitted message, (EN_S, MAC_S, AU_S) and (EN_D, MAC_D, AU_D) relayed between CM_S and CM_D, the attacker cannot modify them to pass authentication because he/she will need to have the secret values related to the message in order to impersonate either CM_i or CH_i to pass the counterpart's verification. This attack is difficult to materialize because the real identity of the entity is still concealed to all players in SHRP.

3. *Replay Attack*: An attacker may wish to initialize a replay attack from eavesdropped data packets of an authenticated communication between CM_S and CM_D and retransmit them at a later time as if it comes from the real entity. This attack is thwarted in SHRP because the authenticated message $EN_S = AE(PU_D, M_S)$ for route construction message contains timestamp T_S meant to be used once, so there is no way an attacker can devise a replay of any message encrypted with the related secret keys. In the same way the session key SK is unique per session and is updated after any successful secure routing procedure. So, its arguable SHRP resists against the replay attack.

4. *Man-in-the Middle Attack*: In man-in-the-middle attack, an adversary eavesdrops and intercepts the communication between or among communicating legal entities in WSN and relays authentic messages to the victims to make them that believe they are communicating confidentially. Thus, the adversary controls the whole communication sessions without knowledge of the intended entities in WSN. However this attempt though cannot succeed in SHRP because no attacker can manage to initiate the fabrication of the legal message that seems acceptable to CM_D. Since to achieve this attack, the adversary must find a means of sending verifiable components EN_S, MAC_S and AU_S in order to pretend as CM_S to CM_D. Obviously, there is no other way of forging EN_S without knowledge of the parameters of M_S. Furthermore, the extraction of MS from EN_S means the ability to solve the discrete logarithm problem that can be solved by CM_D only. Therefore the attacker will not succeed and besides the message M_S is not sent in plain, thus the attacker will not know the information targeted to CM_D. Conclusively, SHRP is resilient against impersonation attack.

5. *Mutual Authentication*: In SHRP, both end point the origin and the destination of a transmitted message authenticate and verify the counterpart, thereby providing mutual authentication. Before CM_S and CM_D can communicate securely they first share the counter part's public key. So based on the public key, the parties transmit messages authentic and verifiable only between themselves. For instance, when CM_S sends login message EN_S, MAC_S and AU_S to CM_D, it is formed in a way that only CM_D with the knowledge of the private key can extract the message. Having extracted EN_S, CM_D verifies the counterpart entity and establish a session key SK securely only after the proper authentication success. On the other hand CM_D authenticates an CM_S by checking the received MAC_S and AU_S. CM_D trust that it is communicating with an unintended party is based on the assumption that computing EN_S, MAC_S and AU_S without knowledge of $CM_D's$ private key involves solving the discrete logarithm, which is infeasible by an attacker. At the end, CM_S and CM_D mutually authenticate each other.

5 Conclusion

This paper has been proposed a secure hybrid routing protocol (SHRP), which combines the geographic based scheme and hierarchical scheme. SHRP classified sensor nodes into two categories, NG nodes and NA nodes, to put different roles in WSNs. SHRP is consisted with two phases: the clustering and cluster head selection phase and the secure routing phase. In the clustering and cluster head selection phase, SHRP selects a clustering scheme from the previous schemes to satisfy that the percentage of NG must be at least of three nodes in each cluster in order to support location requirement of each node. After that the cluster head selection process is done based on a new weight factor of center weight, residual energy and mobility of each node. In the secure routing phase, a secure routing is designed where the packets are protected by using symmetric and asymmetric cryptosystem to support confidentiality, integrity and authenticity. As shown in the performance analyses, SHRP could get better results of packet loss rate, delivery ratio, end to end delay and network lifetime compared to the well known previous schemes.

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Implementation of Leader-Follower Formation Control of a Team of Nonholonomic Mobile Robots

A. Widyotriatmo, E. Joelianto, A. Prasdianto, H. Bahtiar, Y.Y. Nazaruddin

Augie Widyotriatmo*, Endra Joelianto, Yul Yunazwin Nazaruddin
Instrumentation and Control Research Group
Institut Teknologi Bandung, Indonesia
Ganesha 10, Bandung 40132, Indonesia
*Corresponding author: augie@tf.itb.ac.id
ejoelianto@yahoo.com, yul@tf.itb.ac.id

Agung Prasdianto, Hafidz Bahtiar
Engineering Physics Program
Institut Teknologi Bandung, Indonesia
Ganesha 10, Bandung 40132, Indonesia
prasfoster@gmail.com, hafidzbahtiar@students.itb.ac.id

Abstract: A control method for a team of multiple mobile robots performing leader-follower formation by implementing computing, communication, and control technology is considered. The strategy expands the role of global coordinator system and controllers of multiple robots system. The global coordinator system creates no-collision trajectories of the virtual leader which is the virtual leader for all vehicles, sub-virtual leaders which are the virtual leader for pertinent followers, and virtual followers. The global coordinator system also implements role assignment algorithm to allocate the role of mobile robots in the formation. The controllers of the individual mobile robots have a task to track the assigned trajectories and also to avoid collision among the mobile robots using the artificial potential field algorithm. The proposed method is tested by experiments of three mobile robots performing leader-follower formation with the shape of a triangle. The experimental results show the robustness of formation of mobile robots even if the leader is manually moved to the arbitrary location, and so that the role of a leader is taken by the nearest mobile robot to the virtual leader.
Keywords: Leader-follower, formation, nonholonomic, trajectory control, collision avoidance, multiple mobile robots.

1 Introduction

Leader-follower formation of a team of mobile agents has received special attention from for researchers because of its usefulness to many applications, e.g. military applications, transportation, warehouse automation, etc. In performing a formation of team of mobile robots, multidisciplinary technologies of computing, communication, and control need to be conducted. In particular applications, such as transportation, leader-follower formation of multi agents has bounded regulation. For example, in road transportation and warehouse automation, some vehicles should follow particular track, designed by the global coordinator, and have to avoid collisions among others. In this case, some vehicles, which are assigned to follow the same track, can co-operate performing leader-follower formation. One advantage is that it can avoid congestion due to width limitation of the lane. This paper discusses a strategy for a team of mobile robots to perform leader-follower formation. The mobile robot used in this paper is differential-type mobile robot which is categorized as nonholonomic system. Formation control of nonholonomic system is also of special interest because of its difficulty in controlling a system with nonholonomic constraints. Several methods in control of nonholonomic system have been shown in [12]- [24].

The problem of multi-vehicle formation control has been studied in [16]- [14], and many others, where the focus is on consensus based formation control. Ren and Cao in [16] classify the formation control problems become formation shaping problems, in which the objective control is to establish formation shape, and formation tracking problem, which is to find a control algorithm so that the agents track the predefined trajectories. In [11] and [14], graph theoretic methods and consensus, cooperation in networked multiagent systems are the focus. In the case of road transportation or warehouse automation, the tracks or lanes have been determined and the tasks have been provided by a fleet system or a global coordinator. This paper focuses on the architecture and control strategy for mobile robots in performing leader-follower formation in which the tracks and tasks are predetermined by the global coordinator.

Oh, Park, and Ahn in [13] studies the categorization of formation control which is focused on sensory systems and topology between agents. It leads to three categories, which are position-based, displacement-based, and distance-based formation controls. In the position-based control, agents control to achieve the predetermined formation based on the measurement of their own position in global coordinate system. In the displacement-based control, the measurement used is displacement of neighboring agents. In the distance-based control, the agents control their distance in performing formation. The position-based control needs more advanced sensing capability and lesser interactions inter-agents comparing to the two other methods. The advancement of position sensors have been shown including global positioning system (GPS) [1], inertial navigation system- (INS) [4], vision- [19], [20], laser-based localization [21], [22], and many more. This paper focuses on the position-based formation control.

Several position-based of multi vehicle controls for have been presented in several literature. Dong and Farrel in [6] and Widyotriatmo, Pamosoaji, and Hong in [23] study the position-based method for nonholonomic agents. Ren and Atkins in [15] proposes the position-based method for formation control double integrator agents. The trajectory tracking problem for agent with unicycle-type kinematic model is proposed in [3]. The position based-method requires the ability of mobile agents to measure their position and orientation in the global coordinate.

A system architecture performing feedback coordination between mobile robots and global coordinate system is usually used in the position-based method formation control [7], [26]. The method consists of two steps, which are: first, the global coordinator generate formation virtual trajectories; second, the mobile robots execute control to track the desired virtual trajectory. In this paper, a leader-follower formation control for a group of mobile robots is proposed. The main contributions of this paper is the extension of functions of the global coordinator and of the controller of mobile robots in performing leader-follower formation. The global coordinator performs the virtual trajectories generation of mobile robots. The generated virtual followers are classified by stages. The scheme creates main virtual leader which is the virtual leader for all agents and sub virtual leaders which are the leaders for the consecutive stage followers. In addition, task of global coordinator also assign roles for mobile agents to fill positions of leader or followers. Using the scheme, the minimum communication link between the robots is between the main leader or the sub-leaders and their pertinent followers. The mobile robots' controller has task to track the virtual trajectory given by the global coordinator, and also executes collision avoidance algorithm using potential field methods [8]- [25], in such a way that the mobile robots track the virtual trajectories while avoids collision among other mobile robots and obstacles.

The rest of the paper is organized as the following. Section 2 depicts the proposed leader-follower formation strategy which consists of system architecture of leader-follower formation, the formation of virtual leader and followers, the role assignment algorithm, and the trajectory tracking control of the mobile robots which also includes collision avoidance strategy. Section

3 shows the simulation and experimental results. Section 4 draws conclusion and the future research directions.

2 Leader-follower formation control strategy

2.1 System architecture of leader-follower formation

The leader-follower formation control of mobile robots study purposes to design control that drives multiple mobile robots to achieve certain moving or static formation. The strategy of leader-follower formation control of mobile robots can be described as follows. First, virtual trajectories of virtual leader and followers, as well as the formation parameters are generated from a global coordinator system. Several methods in the global coordinator system are artificial potential field, sample-based motion planning, cell decomposition, or others. In this paper, the virtual trajectories of the virtual leaders and followers form a triangle. The formation parameters are assumed to be predetermined from a motion planning algorithm. Second, the role of leader and follower of mobile robots position of leader and followers is voted based on the shortest distance to the leader-follower trajectories. Finally, the leader and followers employ the designed trajectory tracking control and obstacle avoidance algorithms to keep them following individual trajectories while also to prevent them to collide with each other. The architecture of the leader follower strategy is shown in Fig. 1.

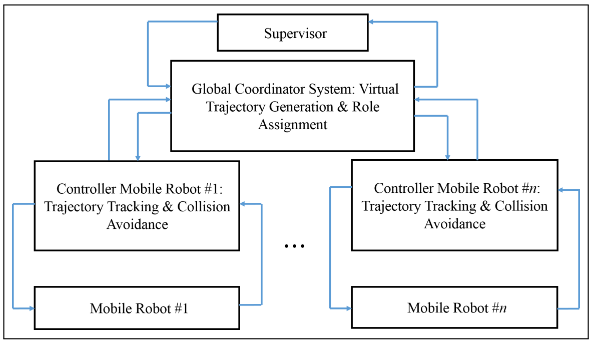

Figure 1: The architecture of the formation control of a team of n mobile robots

2.2 Formation of virtual leader and followers

In this subsection, we consider mobile robots with one leader and two followers performing triangular formation. Then, we show that the number of followers can be expanded by assigning the virtual followers to become sub-leaders.

Let (x, y) be a global coordinate system. Fig. 2(a) shows the formation of one virtual leader and two virtual followers which are located at the first stage follower. The coordinate of the virtual leader is denoted by $(x_{v,1}, y_{v,1})$ and that of the virtual followers are denoted by $(x_{v,i}, y_{v,i})$, $i = 2, 3$. The virtual leader and two first stage followers form a triangle formation. The velocity and the direction angle of the virtual leader are $v_{v,1}$ and $\theta_{v,1}$, and those of the virtual followers are $v_{v,i}$ and $\theta_{v,i}$, $i = 2, 3$.

The distance between leader and follower are denoted by $b_{v,i:1}$, $i = 2, 3$. The angle between the line projecting from the coordinate of one follower of the first stage follower to the leader and the x-axis is represented by $\gamma_{v,i:1}$, $i = 2, 3$. The angle between the line projecting from the coordinate of one follower to that of the other follower in the same stage and the line projecting from the coordinate of that follower to the leader is denoted by $\varphi_{v,i:1}$, $i = 2, 3$.

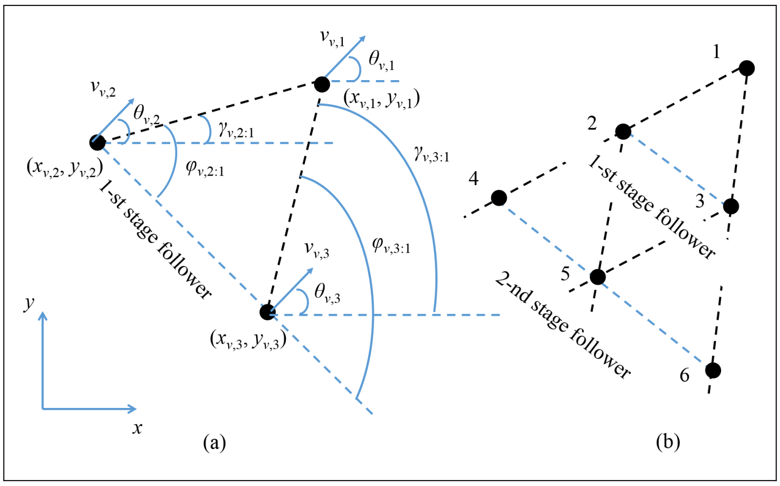

Figure 2: (a) The configuration of virtual leader and two virtual followers shaping a triangular formation until the first stage follower; (b) the formation configuration is expanded to the second stage follower.

The individual agents of first stage virtual follower become the virtual leader of agents in the second stage followers. Hence the determination of virtual trajectories configuration can be expanded for the succeeding stages (Fig. 2(b)). For the second stage followers, the virtual trajectory 5 can be developed from virtual trajectory 2 as the second follower or trajectory 3 as its first follower.

The virtual leader trajectory is developed by the following equations:

$$\dot{x}_{v,1} = v_{v,1} cos\theta_{v,1} = v_{x,v,1}, \tag{1}$$

$$\dot{y}_{v,1} = v_{v,1} sin\theta_{v,1} = v_{y,v,1}. \tag{2}$$

The relation of $\gamma_{v,i:1}$, $\varphi_{v,i:1}$, and $\theta_{v,1}$, for $i = 2, 3$, are

$$\gamma_{v,i:1} = \varphi_{v,i:1} + \theta_{v,1}(t) - \pi/2. \tag{3}$$

The position of the first stage followers at time t are calculated as follows:

$$x_{v,i}(t) = x_{v,i}(t) - b_{v,i:1} \cos(\gamma_{v,i:1}(t)), \tag{4}$$

$$y_{v,i}(t) = y_{v,i}(t) - b_{v,i:1} \sin(\gamma_{v,i:1}(t)), \tag{5}$$

$i = 2, 3$.

2.3 Role assignment algorithm

Once the trajectories of virtual leader and followers have been developed, a group of vehicles are assigned to those trajectories. Let us consider one virtual leader and two first-stage-virtual-followers as in the previous section. Three mobile robots are to be assigned to individual virtual trajectories. The configuration is illustrated in Fig. 3. Let the position of the j-th robot be defined as $(x_{r,j}, y_{r,j}), j = 1, 2, 3$ and that of the k-th virtual trajectory be $(x_{v,k}, y_{v,k}), k = 1, 2, 3$.

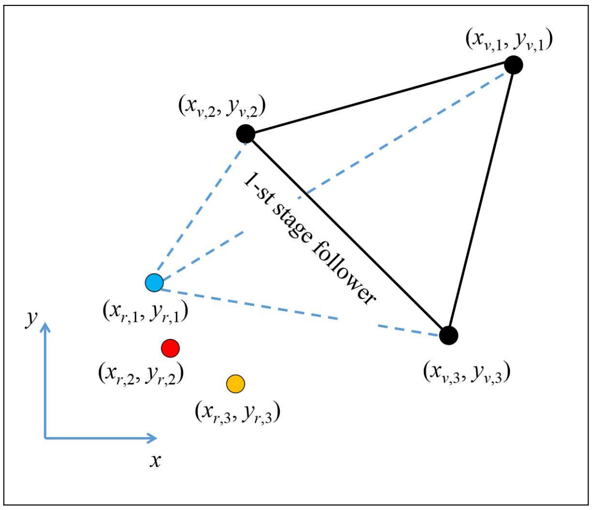

Figure 3: The configuration of robot and virtual trajectory. The assignment of a robot to a particular trajectory is based on the distance from the robot to each trajectory.

The distance between a robot and a virtual trajectory are denoted by $r_{r:v;j:k}$, which is calculated as follows:

$$r_{r:v;j:k} = \sqrt{(x_{r,j} - x_{v:k})^2 + (y_{r,j} - x_{y:k})2}. \tag{6}$$

Each robot knows the information of each virtual trajectory position and that of each robot position. The role assignment algorithm is described as follows.

Algorithm: Role Assignment of Robots-Virtual Trajectories

1. Calculate the distance for every pair robots-virtual trajectories;

2. Compare the distance for each pair robot to the virtual leader. The robot with minimum distance to the virtual leader is assigned to become the leader;

3. Compare the distance of other robots, which have not been assigned as the virtual leader, to the virtual followers. The robot that has the shortest distance to the first follower is assigned as that virtual follower trajectory. If the distance between the robots are the same, the vehicle with lower assigned number is delegated to that virtual follower trajectory.

The algorithm is checked every loop time so that the roles of individual robots can be changed according to the distance of one mobile robot to a configuration of virtual trajectories.

2.4 Trajectory tracking control and collision avoidance of the differential-wheel-type mobile robots

After the virtual trajectories are developed and the robots have been assigned to individual virtual trajectories, the control of a mobile robot to track a particular trajectory is designed. For the first step of control design, the model of differential-wheeled mobile robot is derived. Fig. 4 shows the configuration of a mobile robot.

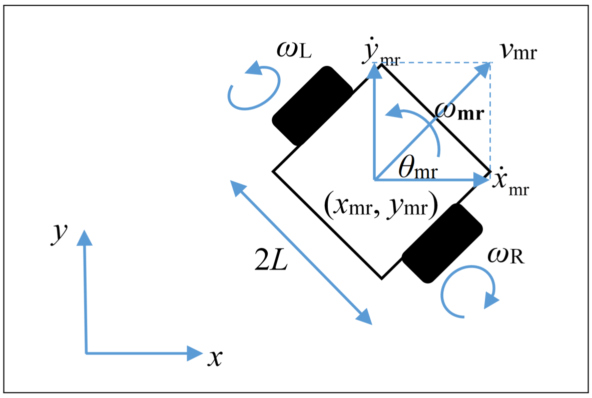

Figure 4: The schematic of differential-wheeled mobile robot.

The coordinate of the mobile robot is (x_{mr}, y_{mr}) and the angle of the robot with respect to x-axis is θ_{mr}. Let the distance between the left and right wheels be $2L$ and the radius of left and right wheels be R. Linear and rotational velocities, v_{mr} and ω_{mr}, of the mobile robot are obtained by arranging the right wheel velocity ω_R and left wheel velocities ω_L, as follow:

$$\begin{bmatrix} v_{mr} \\ \omega_{mr} \end{bmatrix} = R \begin{bmatrix} 1 & 1 \\ \frac{1}{L} & -\frac{1}{L} \end{bmatrix} \begin{bmatrix} \omega_R \\ \omega_L \end{bmatrix}. \tag{7}$$

If the linear and the rotational velocities, v_{mr} and ω_{mr}, are designed, the solution of the right and left wheel velocities, ω_R and ω_L, are directly obtained as:

$$\begin{bmatrix} \omega_R \\ \omega_L \end{bmatrix} = \frac{1}{2R} \begin{bmatrix} 1 & L \\ 1 & -L \end{bmatrix} \begin{bmatrix} v_{mr} \\ \omega_{mr} \end{bmatrix}. \tag{8}$$

The mobile robot kinematic equation is derived as:

$$\begin{bmatrix} \dot{x}_{mr} \\ \dot{y}_{mr} \\ \dot{\theta}_{mr} \end{bmatrix} = \begin{bmatrix} \cos\theta_{mr} & 0 \\ \sin\theta_{mr} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_{mr} \\ \omega_{mr} \end{bmatrix}. \tag{9}$$

A reference point (x_r, y_r) is chosen as in Fig. 5, satisfies the following:

$$x_r = x_{mr} + l\cos\theta_{mr}, \tag{10}$$

$$y_r = y_{mr} + l\sin\theta_{mr}. \tag{11}$$

The motion of reference point is obtained as follows:

$$\dot{x}_r = \dot{x}_{mr} - \dot{\theta}_{mr} l \sin\theta_{mr}, \tag{12}$$

$$\dot{y}_r = \dot{x}_{mr} + \dot{\theta}_{mr} l \sin\theta_{mr}. \tag{13}$$

The linear and angular velocities (v_r and ω_r) of the reference point are the same as those of

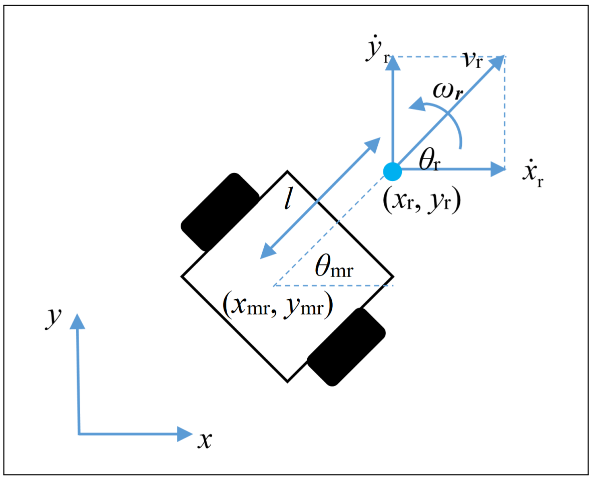

Figure 5: The chosen reference point (x_r, y_r).

mobile robot coordinate (v_{mr} and ω_{mr}). The angle θ_{mr} and θ_r are also equal. Substituting (9) into (12) and (13), we obtain

$$\dot{x}_r = v_r \cos\theta_r - \omega_r l \sin\theta_r, \tag{14}$$

$$\dot{y}_r = v_r \sin\theta_r + \omega_r l \cos\theta_r, \tag{15}$$

The relationship between linear and angular velocities and the motion of reference point is obtained as follows:

$$\begin{bmatrix} v_r \\ \omega_r \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ -\frac{\sin\theta_r}{l} & \frac{\cos\theta_r}{l} \end{bmatrix} \begin{bmatrix} \dot{x}_r \\ \dot{y}_r. \end{bmatrix} \tag{16}$$

Note that l can be chosen as a non-zero positive value, thus (16) always has a solution. From (16), if the velocity of the reference point $(\dot{x}_r, \dot{y}_r)$ is designed, the linear and rotation velocities (v_r and ω_r) of the mobile robot can be directly calculated, and so do the rotational velocities of right and left wheels (ω_R and ω_L) by applying (8). The problem becomes how to obtain a control algorithm so that the reference point of a particular robot follows the virtual trajectory which has been assigned to that robot.

The errors between the reference point of j-th robot and its assigned k-th virtual trajectory ($e_{x,j:k}$, $e_{y,j:k}$) are as follow:

$$e_{x,j:k} = x_{v,k} - x_{r,j}, \tag{17}$$

$$e_{y,j:k} = y_{v,k} - y_{r,j}. \tag{18}$$

The differentiation of the errors in (17) and (18) with respect to time can be derived as follows:

$$\dot{e}_{x,j:k} = \dot{x}_{v,k} - \dot{x}_{r,j}, \tag{19}$$

$$\dot{e}_{y,j:k} = \dot{y}_{v,k} - \dot{y}_{r,j}. \tag{20}$$

The velocity of reference point $(\dot{x}_{r,j}, \dot{y}_{r,j})$ is designed as

$$\dot{x}_{r,j} = \dot{x}_{v,k} + K_{Px,j}\left((x_{v,k} - x_{r,j}) + \frac{1}{T_{Ix,j}}\int_0^t (x_{v,k} - x_{r,j})\,\mathrm{d}t + T_{Dx,j}\frac{\mathrm{d}(x_{v,k} - x_{r,j})}{\mathrm{d}t}\right), \quad (21)$$

$$\dot{y}_{r,j} = \dot{y}_{v,k} + K_{Py,j}\left((y_{v,k} - y_{r,j}) + \frac{1}{T_{Iy,j}}\int_0^t (y_{v,k} - y_{r,j})\,\mathrm{d}t + T_{Dy,j}\frac{\mathrm{d}(y_{v,k} - y_{r,j})}{\mathrm{d}t}\right), \quad (22)$$

where $K_{Px,j}$, $T_{Ix,j}$, $T_{Dx,j}$, $K_{Py,j}$, $T_{Iy,j}$, and $T_{Dy,j}$ are positive constants. The control laws (21) and (22) utilize the measurement of robot coordinate $(x_{r,j}, y_{r,j})$ and its correspond virtual trajectory $(x_{v,k}, y_{v,k})$.

Substituting (21) and (22) into (19) and (20), it is obtained

$$K_{Px,j}\left(e_{x,j:k} + \frac{1}{T_{Ix,j}}\int_0^t e_{x,j:k}\,\mathrm{d}t + (1 + T_{Dx,j})\dot{e}_{x,j:k}\right) = 0, \quad (23)$$

$$K_{Py,j}\left(e_{y,j:k} + \frac{1}{T_{Iy,j}}\int_0^t e_{y,j:k}\,\mathrm{d}t + (1 + T_{Dy,j})\dot{e}_{y,j:k}\right) = 0. \quad (24)$$

From (23) and (24), it can be seen the uniform asymptotic stability of errors $(e_{x,j:k}, e_{y,j:k}) = (0,\ 0)$ since the values of $K_{Px,j}$, $T_{Ix,j}$, $T_{Dx,j}$, $K_{Py,j}$, $T_{Iy,j}$, and $T_{Dy,j}$ are positive and thus the equations (23) and (24) satisfy the Routh-Hurwitz stability criterion. Therefore, the errors $(e_{x,j:k}(t), e_{y,j:k}(t))$ converge to zero as $t \to \infty$ for any initial conditions $(e_{x,j:k}(0), e_{y,j:k}(0))$. The spectrum response of the errors $(e_{x,j:k}(t), e_{y,j:k}(t))$ can also be designed by choosing the parameters $T_{Ix,j}$, $T_{Dx,j}$, $T_{Iy,j}$, and $T_{Dy,j}$.

When the trajectory control is executed, it is possible that the mobile robots collide with each other. To avoid the circumstances, the control algorithms (23) and (24) are modified by applying additional input to repel a mobile robot towards collision. This technique is known as artificial potential field method [17]- [25].

3 Simulation and experimental results

3.1 Simulation of Three Mobile Robots Performing Leader-Follower Formation

The simulation is intended to assure that the chosen of reference point as well as of the control parameters are suitable for the mobile robots. The constant l which determines the reference point of the mobile robot can be analyzed as follows: the smaller value of l, the motion of robot becomes more oscillation; whereas the larger value of l, the lag between the robot and the virtual trajectory is larger. The motion also depends on the distance between right and left wheels.

From the simulations, the value of l between 2 cm and 8 cm shows good performance. The controller parameters $K_{Px,j}$, $T_{Ix,j}$, $T_{Dx,j}$, $K_{Py,j}$, $T_{Iy,j}$, and $T_{Dy,j}$, $j = 1, 2, 3$ are designed by using the pole placement method with the desired poles of equations (23) and (24) are: -0.2 and -0.01. Thus, the control parameters are obtained as follow: $K_{Px,j} = K_{Py,j} = 0.21$, $T_{Ix,j} =$

$T_{Iy,j} = 105.0$, and $T_{Dx,j} = T_{Dy,j} = 0.01$ for $j = 1, 2, 3$. Using these parameters, the simulation is shown in Fig. 6. For the assigned three virtual trajectories v1, v2, and v3, the robots r1, r2, and r3 which are started from different locations successfully perform leader-follower formation. The control inputs given to right and left wheels of individual robots stay below 14% of their maximum power which is suitable for the design (Fig. 7).

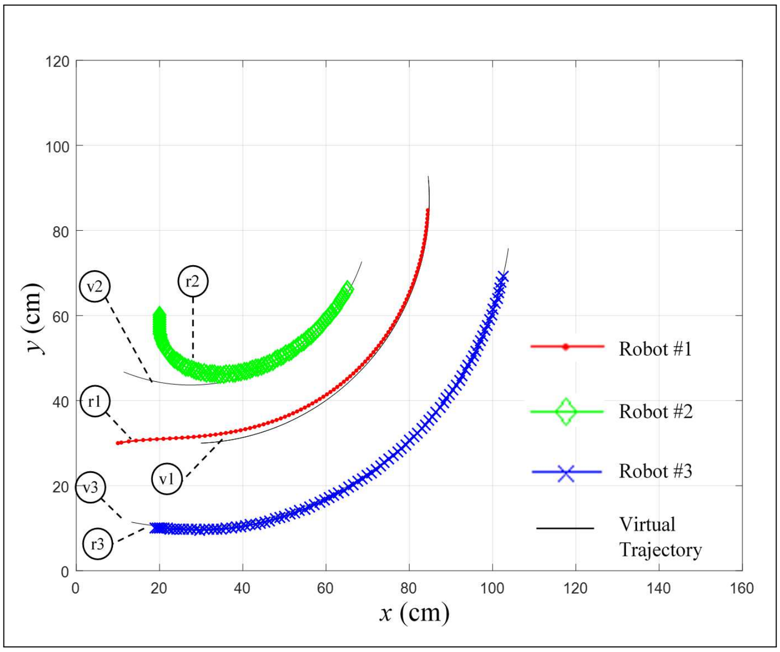

Figure 6: Robots r1, r2, r3 performs leader-follower formation using the proposed method.

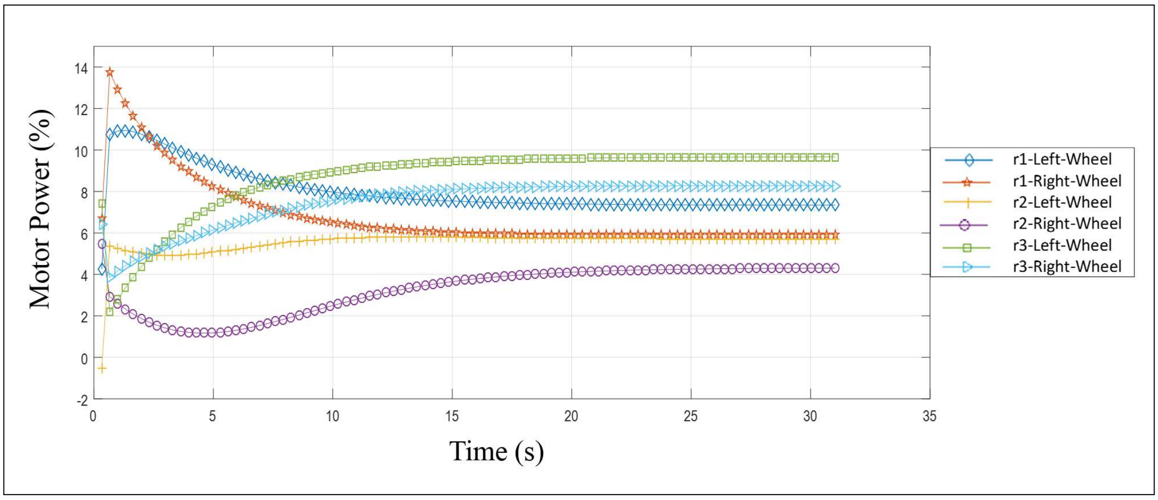

Figure 7: Motor power given to individual motors (left and right wheels) of robots r1, r2, r3 in performing leader-follower formation of Fig. 6.

3.2 Experiments of leader-follower formation using three mobile robots

Fig. 8(a) shows the experimental setup which includes the arena, three mobile robots, camera-based localization system, and personal computer (PC) as the global coordinator system. The arena is colored white, and three robots are colored with three different colors: red, green, and blue. The localization sensor is a camera mounted at the height of 114 cm. The camera is utilized to differentiate the colors of individual mobile robots and of the arena. Two colors patched in a mobile robot are utilized to measure its orientation. Fig. 8(b) shows the picture from the camera point of view. The position and orientation of all robots are calculated in a microcontroller from the measured position of colored rectangular shape patched on the mobile robots. Then, the control input for each mobile robots are is calculated and sent to mobile robots using wireless Bluetooth communication. The control parameters used in the experiment are the same as those used in the simulation.

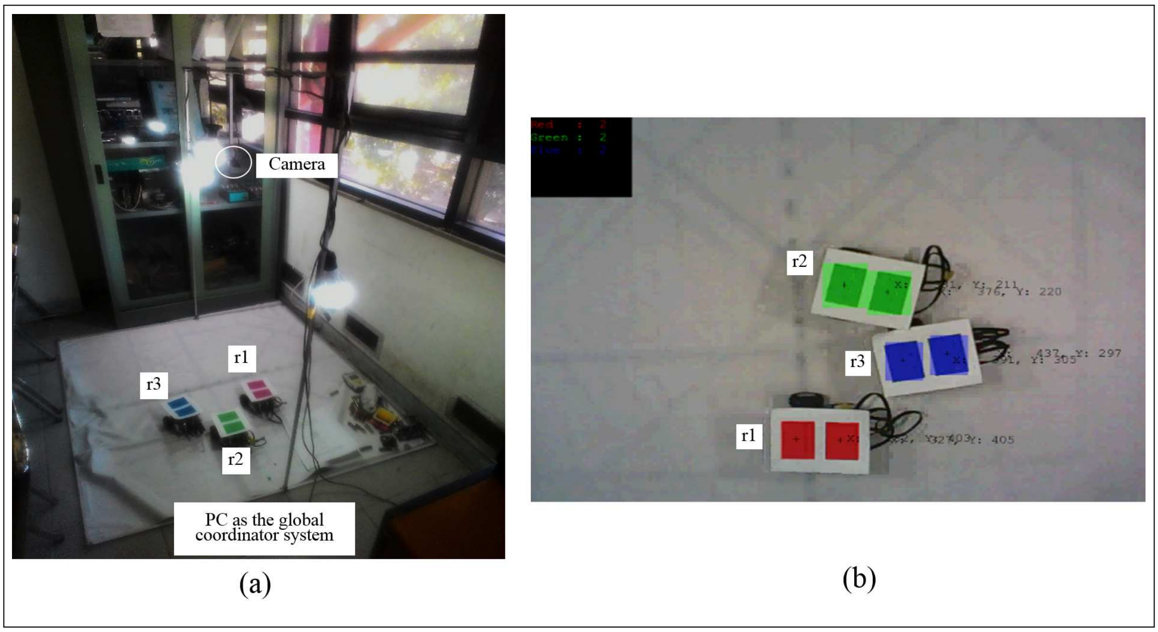

Figure 8: (a) The experimental setup consists of arena (white pad), three robots, camera, and PC as the global coordinator system; (b) Top-view picture is captured from the camera. The position of front and back rectangular is obtained so that the position and orientation of the three mobile robots can be calculated.

Fig. 9 shows the first experiment of three mobile robots performing leader-follower formation without being disturbed. The mobile robots are initially located near the virtual trajectories. From Fig. 9, the mobile robots perform leader-follower formation following the given individual virtual trajectories. Using the proposed control method, the mobile robots r1, r2, and r3 follow the pertinent virtual trajectories v1, v2, and v3, respectively. In this case, the mobile robot r1 becomes the leader and mobile robots r2 and r3 become the followers, all together perform triangular formation. Fig. 10 shows the control signals, which are power signals, given to the motors of mobile robots for this experiment.

In the second experiments (Fig. 11), while three mobile robots perform leader-follower formation, the leader, mobile robot r1, is intentionally disturbed by moving its location the back. In this case, the virtual trajectories are still moving forward. The role assignment algorithm is performed so that the r2 becomes the leader and the r1 replaces the position of r2 in the formation. While tracking the new trajectories, the mobile robot r1 also performs obstacle avoidance algorithm so there is no collision between r1 and r2. Fig. 12 shows the control signals which are the power given to the individual motors of mobile robots for this experiment.

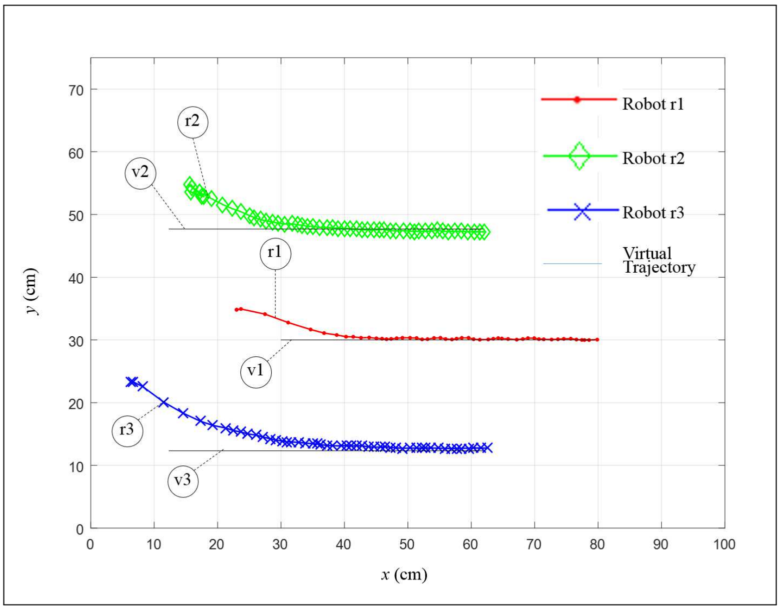

Figure 9: The motion of three mobile robots in the first experiment: Three mobile robots are located in various location and then performs leader-follower formation.

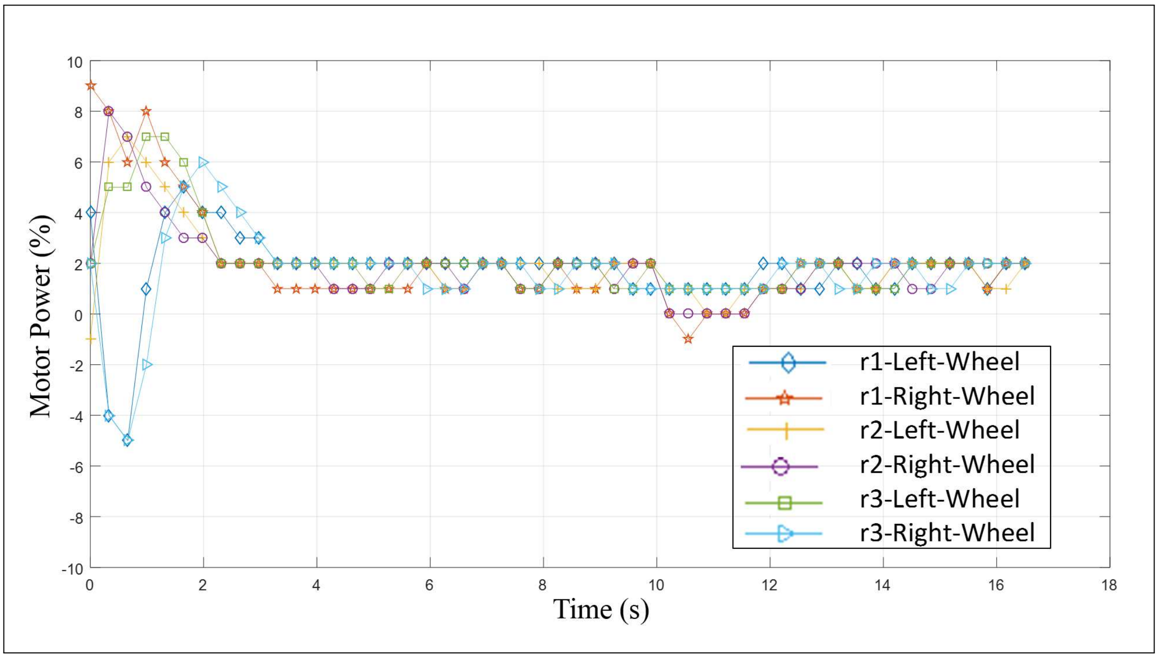

Figure 10: The motion of three mobile robots in the first experiment: Three mobile robots are located in various location and then performs leader-follower formation of Fig. 9.

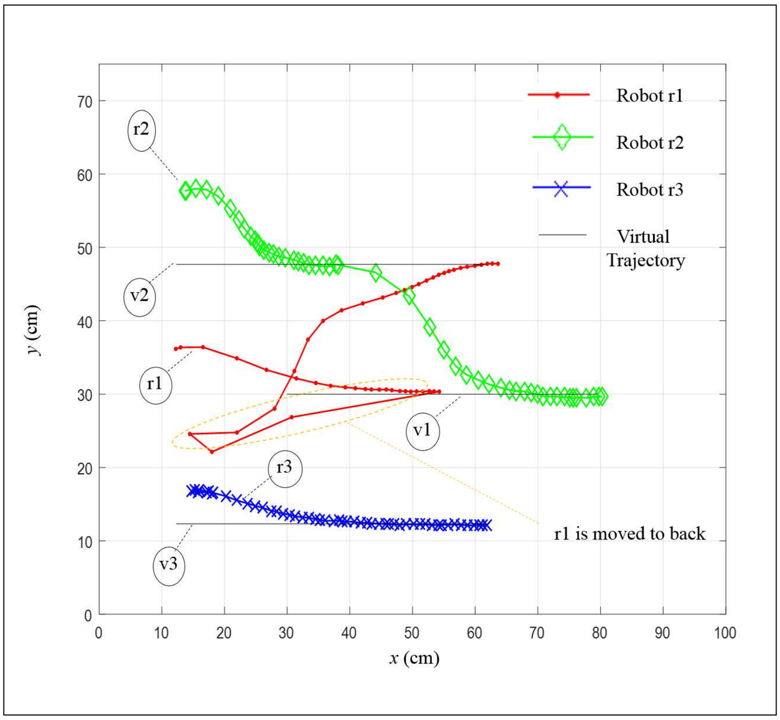

Figure 11: The motion of mobile robots in the second experiment: the leader r1 is intentionally disturbed by moving its location to the back. The role assignment algorithm is performed in which r2 replaces the leader formation and r1 replaces the r2 position in the formation.

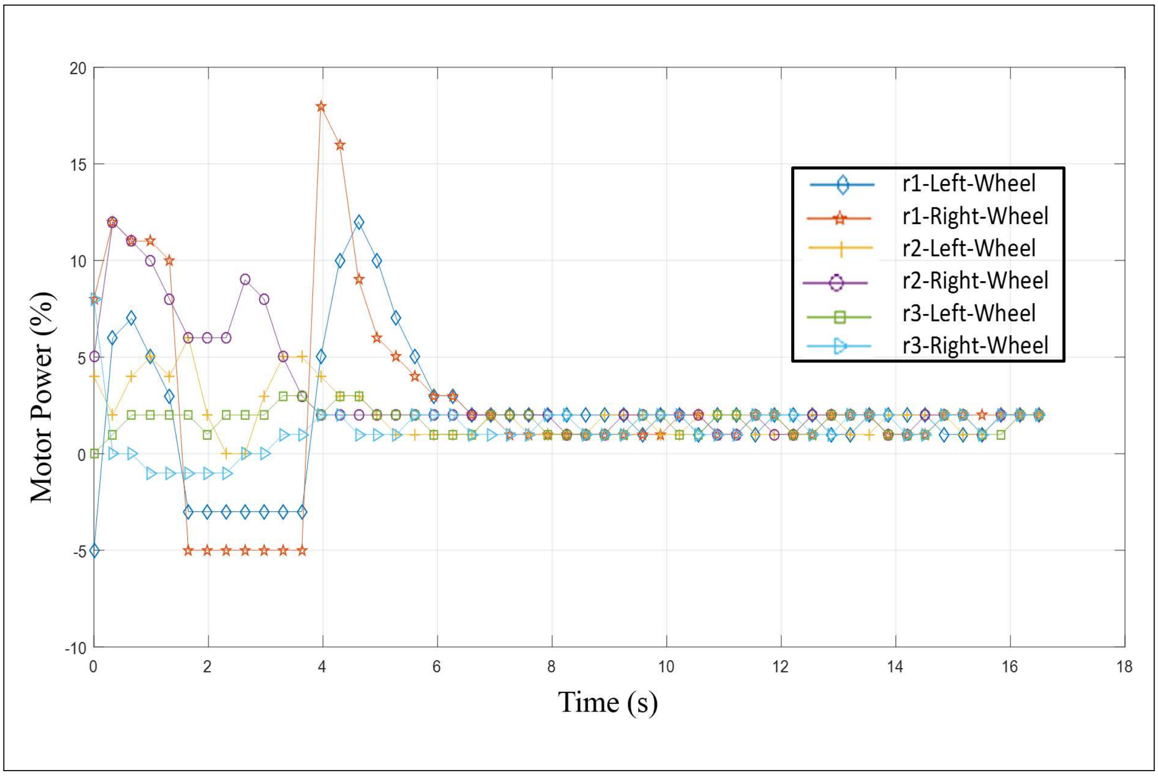

Figure 12: The power signals given to the individual motors (left and right wheels) of the mobile robots in performing leader-follower formation of Fig. 11.

4 Conclusions and future work

In this paper, a strategy of leader-follower formation of mobile robots is presented. A role assignment algorithm is proposed to allocate mobile robots following individual virtual trajectories in the leader-follower formation. A trajectory tracking control law is developed. Control parameters are designed by the pole-placement method for mobile robots to track their individual virtual trajectories. The combination of trajectory tracking control and artificial potential field assures that the mobile robots track the pertinent virtual trajectories and avoided collisions among others. The proposed method is tested by simulation and experiments of mobile robots performing leader-follower formation. The method is also tested by experiment in which the leader is intentionally disturbed by moving the leader to the back. By the implementation of the role assignment algorithm, the mobile robots successfully switch their position to maintain the leader-follower formation.

The future works include the integration of the motion planning and control which can handle double collision avoidance layers. One collision avoidance layer lies on the motion planning which is designed at the trajectories generation, and the other is on the low level controller as it is implemented in this paper. By establishing the double collision avoidance layers, the safety is more guaranteed and thus the implementation of multiple wheeled vehicles performing leader-follower formation is closer to a real application.

Acknowledgment

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Using Blockchain to Protect Personal Privacy in the Scenario of Online Taxi-hailing

N. Zhang, S. Zhong, L. Tian

Ning Zhang, Shan Zhong, Li Tian*
School of Information,
Central University of Finance and Economics,
Beijing, China
zhangning@cufe.edu.cn, 2015211624@email.cufe.edu.cn
*Corresponding author: tianli@email.cufe.edu.cn

Abstract: Personal privacy protection issues has gradually caused widespread concern in society which will lead to economic and reputation losses, hinder network and E-commerce innovation or some other consequences if not handled properly. In this paper, we make use of the de-centralization, permanent and audibility of the blockchain to propose a blockchain-based personal privacy protection mechanism, which uses Online taxi-hailing as the application scenario. We not only provide the details of the blockchain custom transaction domain used by the scene, but also expound the information exchanging and blockchain auditing between passengers, Online taxi-hailing platform and drivers in Online taxi-hailing scene, providing a case model for the blockchain solution to personal privacy protection and a technical mechanism solution for further study of personal privacy protection issues.
Keywords: Online taxi-hailing, blockchain, personal privacy protection,

1 Introduction

With the popularization of computer and network, the issue of personal privacy protection has gradually become a concern and concern. If we ignore the personal privacy protection issue or handle it improperly, it may lead to reputation and economic losses or even hinder the network and E-commerce innovation. The problem of personal privacy protection can be solved by both legal and technical means, and it can be also effectively solved by blockchain technology currently. The blockchain is a distributed book that records the history of each transaction sent and verified, as well as the additional information contained in the transaction [3]. All the blocks in the blockchain are arranged in chronological order [11], created by the miners [5], and each node has a copy of the whole blockchain [12]. Because of the features of de-centralization [14], permanent recording and convenient auditing [10], blockchain technology can be used to meet the data security requirements such as integrity and audibility of privacy data, so it can be used as an effective solution of personal privacy protection issues.

There are few literatures on blockchain technology and the literature on the blockchain technology's application in personal privacy protection is more scarce. In the application aspect of blockchain's protecting personal privacy, Melanie Swan [13], referring to the seriousness of health privacy issues, argued that blockchain could provide a mechanism for protecting the privacy of personal health data against infringement, but she didn't give the scenario implementation details of blockchain's protecting personal privacy. In the aspect of using blockchain technology to solve practical problems and providing specific implementation details, Guy Zyskind [15] proposed a decentralized personal information management system in which bit-coins can be used to pass storage, query, and data analysis instructions through some agreement, ensuring that users own and control their own information, but the paper doesn't propose a specific case of application, neither does it provide any personal privacy theory on the issue. Ahmed Kosba [7] argue that the current blockchain trading environment lacks the privacy protection of transactions, and that money flows between virtual addresses are completely exposed to the blockchain environment, so they propose a decentralized intelligent contract system called Hawk to protect the privacy of transactions by avoiding the clear text storage form of financial transactions on the blockchain. But the method can only protect the privacy of transaction information, which lacks a broader field of real life application. Amir Lazarovich [8] gave a detailed discussion on how to use blockchain technology protect personal privacy, and proposed a distributed-storage based third-party database named escrow, and a blockchain-audit based invisible ink system, taking medical information privacy protection as an example to illustrate the blockchain technology's application in personal privacy issues. But it lacks a discussion on individual privacy issues and the presentation of blockchain application details. In summary, domestic and foreign scholars' research on blockchain application for personal privacy protection is very limited. Therefore, by putting the solution method into the specific application scenarios, we will explain the details of blockchain's privacy protection application one by one, which can provide a mechanism for scholars to further study on the issue.

Some people concern about the information security risks of blockchain technology application like the haker attacks, as the attack sources of information security are characterized as spectral and concealed[9]. The practice shows that compared with other techniques, the possibility of blockchain being attacked by a hacker successfully is very low. Furthermore, it is the time we have come to start thinking about a new paradigm of law, which could balance the power of blockchain technology and emerging autonomous systems in ways that promote economic growth, free speech, democratic institutions, and the protection of individual liberties [14]. As businesses and government strive to accommodate this new way of doing business, countries have been started for blockchain application legal provisions. Such as Arizona Governor Doug Ducey signed HB 2417 into law in March 2017, Delaware's historic blockchain law became effective in August 2017 and Chinese first standard under the guidance of the government released in May 2017.

In addition, it is pointed out that the technical solution of personal privacy protection needs to consider the problems and needs of anonymity, data access control, auditing, online social network privacy protection, mobile location privacy protection and database privacy protection. Online taxi-hailing service just fit those above problems and has more universality and representation than others, so we use it as the application scenario of blockchain's protecting personal privacy. The Didi, one of the hottest online taxi-hailing platform, happened to information leakage because several staff use their permissions to check user travel records and make profits illegally. Leaked information, include the driver's identity, vehicle information and passenger's identity and common address and so on, are likely to threaten users' property and life security.

2 The online taxi-hailing scene and its exposure to personal privacy

2.1 Online taxi-hailing and its process

Online taxi-hailing is a "car rental & designated driving" model for passengers, providing a new way for urban travel.

Consider a scenario where passenger U1 wants to go to work by using Online taxi-hailing software (such as the current popular *Dididache* in China). First of all, the passenger input departure and destination on the Online taxi-hailing software. Then the Online taxi-hailing software automatically obtain departure of passengers, and recommend drivers to the passenger and send passenger's information and travel routes to those drivers. Finally, drivers receive passenger's routes and decide whether to grab the order. The first one who completes it has the right to complete the transaction.

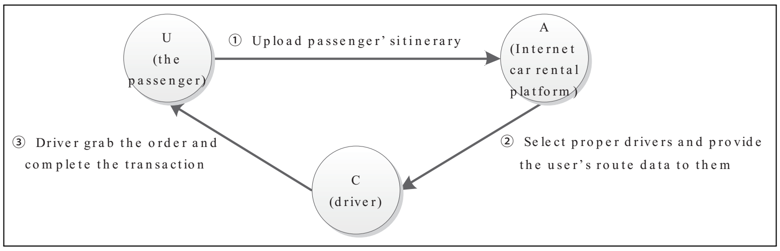

Figure 1: The original Online taxi-hailing scene

2.2 Exposed problems of processes

The passenger uses the software every day and his route is hardly changed. In the process, the passenger encounters some personal privacy issues:

- Problem 1: The passenger can't guarantee that the Online taxi-hailing platform will be confidential to his personal information, and his itinerary and other information may be stolen by the taxi platform to promote advertising, as well as acquisition of other commercial value (such as selling it to third-party data company).
- Problem 2: Platform and drivers can freely view passenger's driving route information, leading to passenger's anxiety that he can't control his personal privacy information.
- Problem 3: When the passenger decides to stop using the Online taxi-hailing software, his information stored on it can't be emptied.
- Problem 4: Imagine that the passenger has asked the Online taxi-hailing software to delete his personal information, and soon after the Online taxi-hailing platform was attacked by hackers. Unfortunately, the passenger found out that his name was on the list while he didn't have any evidence to file a lawsuit against the Online taxi-hailing software.

2.3 Solution

In order to solve the above four personal privacy issues, we use the third-party database and the data interactive audit platform to protect the personal privacy. The third-party certification, reputation, and return policy are interacted to produce a different overall effect on the level of trust [2].

Third-party database means that the user can choose his own trusted database to achieve personal privacy data hosting. Third-party database is an open source database that users can use it through its corresponding link. Different users may choose different third-party database, and through such a distributed data storage we can increase the security of data [7] and reduce the amount of data stored in an Online taxi-hailing software service. Moreover, the third-party database stores user data in the form of encryption, as a result of which the third-party database can't see the specific content of user's privacy and can only serve a loyal guardian on user's data.

Data interactive audit platform is a system built on the blockchain that audits all data operation behaviors. The platform uses blockchain to record all operations on the user data, including data-reading, data-writing, data-updating, and license management for the Online taxi-hailing platform, drivers, and other groups. Forced by pressures of personal privacy protection needs, Online taxi-hailing software platform and other profit institutions can rent the data interactive audit platform to announce to the public their improvement on personal privacy protection. The platform can ensure that all relevant data operations are recorded in the blockchain which will further strengthen the operation compliance of Online taxi-hailing platform and other parties, allowing users to truly control and master their own data. In addition, due to the Online taxi-hailing software platform renting data interactive audit platform for some privacy purposes, so one data interactive platform may correspond to a number of Online taxi-hailing software platforms.

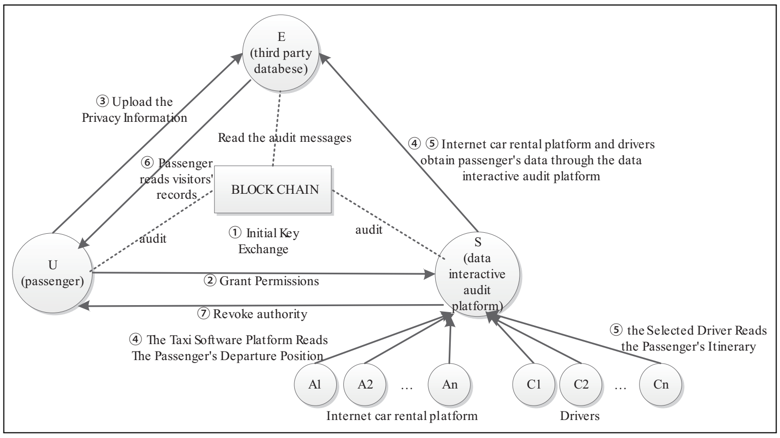

Figure 2: Solve Online taxi-hailing privacy problems

We can use third party database and data interactive audit platform to solve the problem of privacy protection in the Online taxi-hailing scene and its process is as follows.

Firstly, the passenger, the third party database, and data interactive audit platform have their initial key exchange between each other, and the passenger grants permissions to the data interactive audit platform. In order to rent a car, the passenger will upload his itinerary and other privacy information to his third party database. Through third party database and blockchain audit method, he can avoid the Online taxi-hailing software platform getting his entire itinerary (only get the departure, but not the destination). As a result of it, the problem 1 has been solved.

Then, the Online taxi-hailing software platform reads the passenger's departure location and recommends the corresponding matching driver to him. The selected driver reads the entire itinerary of the passenger and decides whether to receive the order. The third party database can't see the passenger's data cause the uploaded data is encrypted, so we can protect passenger's data security by the third party database's decentralized storage of user data. Online taxi-hailing software platform and the driver can access to passenger data through data interactive audit platform, and all operations are recorded in the blockchain. As a result of it, the passenger gets the ability to control his own personal privacy information. The problem 2 has been solved.

Passengers can improve their control of the data by reading the visitor records on the blockchain. At the same time, if the platform leak passenger's private information, the passenger can also have evidence against platform's illegal operation. Therefore, the problem 4 will be solved.

Finally, when the user doesn't want to continue to use the Online taxi-hailing software platform, he can withdraw the operating authority of the data interactive audit platform on the Online taxi-hailing platform to protect his privacy from infringement. So the problem 3 will be solved.

3 Model design and definition

3.1 Actors profiles

- Passenger mobile terminal (U1). The passenger mobile terminal can be a user handset that downloads the Online taxi-hailing platform APP, representing the user identity. U1's action is to upload passenger's itinerary, read other groups' information access records, and grant / revoke the data interactive audit platform S1's access to its data and so on.

- Data interactive audit platform (S1). S1 has been described above in detail, so we will not repeat them here again. S1's action is to help Online taxi-hailing software platform and drivers to read user data, and audit each operation on the blockchain.

- The server of the third party database (E1). E1 has been described above in detail, so we will not repeat them here again. E1's action is to find the blockchain audit records and to determine whether to accept the user's write-data request, and whether to accept software and drivers' read-data request.

- Online taxi-hailing platform (A1). A1 is the Online taxi-hailing company's platform. The action that A1 needs to complete is to obtain the passenger's departure location in order to provide optimal compatible drivers (for example, drivers less than three km away from U1).

- Online taxi-hailing software driver (C1). Online taxi-hailing software drivers can be those drivers' phones that download the Online taxi-hailing platform. The position of the driver is not required to be protected as personal information, so it is visible to the passenger (U1). When A1 finds out a plurality of optimum drivers (C1) that can be matched, then it will send U1's departure point to C1. C1 automatically applies to view the itinerary of U1, and then decides whether to compete for the transaction with U1.

3.2 Blockchain databases

For the design of blockchain database, it is necessary to refer to the specification of blockchain's transaction. Herbert and Litchfield [6] mentioned two approaches to solve the problem of authorization, which are the Master Bitcoin Model and the Bespoke Model. The problem they want to solve is how to use the blockchain to complete the authorization of software using, and how to protect software integrity, prevent software piracy, and complete software updating. In the Master Bitcoin Model, the software vendors transfer 1 unit of Master bitcoin [6] to the user's wallet address via blockchain to granting user the right of using the software. User's software can automatically read transactions. By verification, if the software find that the Master bitcoin in the user address does come from the specific vendor address, it will automatically starts the installation, otherwise it will not be allowed to install. The Bespoke model uses blockchain with a special specification [6], which contains a number of additional domain components in the specification. These additional domains are tailored for flexible requirements of software licensing. For example, we can add token, license, hash software, signature and other domains in the specification, to further implement the software ownership transfer, integrity checks and other advanced features. In addition, the blockchain specifications for different encryption currency is different, and sometimes we can build such a specification based on our own needs to meet the specific needs of the application.

The method also has some inspiration for our Online taxi-hailing case. Through different individuals' sending transactions on the blockchain, we can easily audit the content of their transactions. Of course, we can also construct a more unique blockchain specification in accordance with our specific purpose. Our specific specification is shown below.

TRANSACTION SPECIFICATION			
Tx-id	Hash(meta-data)	Token	signature

Figure 3: A special definition of specification fields

Hash(meta-data) is the hash value of the message meta-data that will be conveyed by the transaction, the purpose of which is to store the longer message meta-data in a shorter way. Token is used to record who has seen or operated the passenger U1's information. Signature is used to record the sender's signature, mainly to verify the identity of the sender, so as to determine the authenticity of the transaction. Tx-id is a specific transaction number, which plays a role in the blockchain that can uniquely identify the transaction. In fact, tx-id is automatically generated after the completion of the transaction. We put it in the transaction specification to effectively distinguish those different transactions.

In the custom transaction, the sender encrypts the message to a hash value using the public key of the receiver, and the receiver uses its own private key to decrypt it. The sender uses his own private key to generate the signature, and the receiver uses the sender's public key for signature verification.

3.3 Third party database

In addition, the third party database needs to have the ability to establish and maintain *the chain of title* for the user to record all blockchain transactions' number tx-id it has validated and its corresponding transaction *Hash(meta-data1) /Token /Signature /encrypt(meta-data2)* of the tx-id. The third party database needs to maintain a table for each user and data interactive audit platform's combination. The table is constructed as follows. The definitions of Tx-id, Token and Signature are the same as the transaction specification mentioned above, while the content of Hash(meta-data1) is other actors' manipulation on user's private data, and Encrypt(mata-data2) is the encryption of user's private data.

THE CHAIN OF TITLE				
Tx-id	Hash(meta-data1)	Token	signature	Encrypt(meta-data2)

Figure 4: The chain of title

In addition, we should also note that *Hash(meta-data1)* is the hash value of meta-data1, which is invisible to E1. E1 can read token's content and E1 can take appropriate measures based on the token's specific content. Signature is the part that E1 need to verify by using sender's public key which can guarantee the authenticity of the transaction, as long as the verification is successful. *Encrypt(meta-data2)* is the content that E1 can write in the table in accordance with other actor's submitted information.

3.4 Data interactive audit platform database

As mentioned above, the data interactive audit platform is a system which builds on the blockchain and audits all data operation behaviors. The data interactive audit platform's database stores various actors (such as U/E/A/S)'s necessary information when they make some data exchange, including blockchain address (such as UAddress), ID number (such as UID), etc. In this section, the symmetric key (such as keyUS) and the private key of asymmetric key (such as UPrivateKey) are also put into the parameter information in order to express the logical structure of the system more clearly. But in the real world, for the sake of information security, the key can't be stored in the data interactive audit platform database, but should be stored and maintained by a special mechanism (such as the PKI system). This database's UML, attributes and methods are shown below.

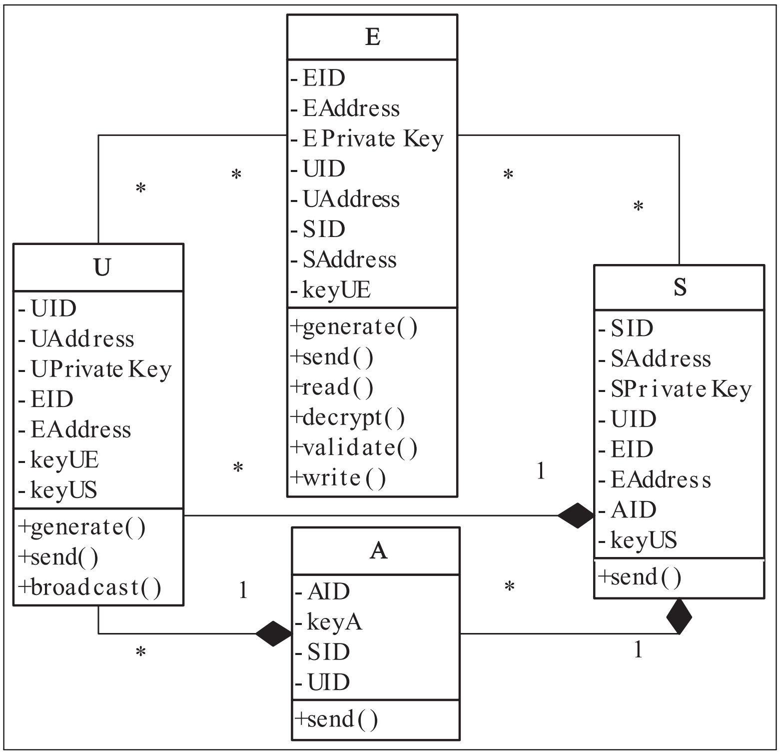

Figure 5: UML of data interactive audit platform database

Actors' attribute definitions are shown as follow.

- XID: X's non-blockchain address. It is the only identification of X. For example, X1's email address.
- XAddress: X's blockchain address, but also X's public key. It is not unique because X1 can have multiple blockchain addresses.
- XPrivateKey: X's private key. For X1, a blockchain address (public key) corresponds to a private key.
- KeyXY: Symmetric key between X and Y. As for U1, he can select multiple E at the same time, but he has a specific symmetric key with each E.

  Actors' method definitions are shown as follow.

- Generate(X):

  There are different kinds of keys' generating methods.

  1. Symmetric key generation: The system will automatically generate the symmetric key by the user's mouse or touch screen sliding route. We can use route data as input, and use DES TripleDES algorithm to generate the key which can served as the shared key.
  2. Asymmetric key generation: The system will automatically generate the asymmetric key by the user's mouse or touch screen sliding route. We can use route data as input, and use DES TripleDES algorithm to generate the public/private keys.

- Send(X;Y):

  Send content Y to X. The receiving address includes the blockchain address and the non-blockchain address.

  1. Sending to blockchain address means that we can send transaction to actor's blockchain wallet address. Because the custom domain in the blockchain contains customized content such as meta-data, we can audit its loading information by this transaction. The general form of transmission is *U. send(XAddress; hash(meta-data, token, signature))*.
  2. Sending to non-blockchain address means that we can send information via email or some other means. Like E1 and S1, each actor has its own address and its receiving new message will trigger the corresponding action. The general form of transmission is *U.send(X;Y)*. The receiver has the ability to identify the contents of Y and thus triggers the corresponding action. There are several types as follows.

     (1) Send general information, such as *U.send (EID; UAddress, keyUE)*. It triggers the receiver to record the contents such as "*UAddress, keyUE*" into the database.

     (2) Send authorization instructions, such as *U.send (EID; permission)*. It triggers the receiver to check whether the sender's authorization action has been audited in the blockchain.

     (3) Send request instruction, such as *U.send (AID; request)*. It triggers the receiver to query the sender what information he needs.

     (4) Send authorization instruction, such as *U. send(SID; authorization)*. It triggers the recipient to continue to perform the desired action (as has been authorized).

- Broadcast(X):

  Broadcast content X on the blockchain. The so-called broadcast means that the user send the transaction on the blockchain which will be verified by each node, so as to be able to learn the specific content of X.

- Read(X):

  Read the transaction X on the blockchain. E1's reading transaction means that finding corresponding transaction from blockchain via tx-id. For example, we can find out a corresponding transaction according to tx-id "002", and then extract it for preparing for the next operation step.

- Decrypt(X):

  Decryption means that, after E1 extract corresponding transaction, he will use his own private key to get the specific content of the transaction, which includes tx-id, hash (meta-data), token, as well as signature.

- Validate(X):

  Verification means that E1 uses sender's public key to verify token and signature that he decrypts. After verification, E1 will save his extracted information to his own maintenance table the chain of title. E.validate (token) as an example, the pseudo code of its general process is as follows:

  E.read(token); / E reads the current token

  E.check(U.the_chain_of_title); / In the table the chain of title, E finds the table belongs to U.

  test=ture / Set test variables to true

  For(tx_id=1;tx_id<=tx_id.max; tx_id++) / Loop, in turn to traverse tx-id in U's table the chain of title

  {if(U.token =" U revoke S's authority on operating U's data")

  {test=false;break;}} / If the tx-id's corresponding token's content is revocation, the test variable change to false; if there is no revocation, the test variable is still true

  If(test=true) / After loop ending, check the value of the test variable

  {Insert token into U1.the_chain_of_title;

  Execute(token)} / If test is true, insert the token at the end of the table the chain of title (Of course, in details, it should be inserted together with tx-id, hash(meta-data1), token,signature, encrypt(meta-data2).

  Then execute the contents of the token.

  Else refuse. / If test is false, the execution is rejected.

- write(X):

  Writing content X in the database. When E1 receives tx-id and its corresponding content X from other actors to E1's non-blockchain address, he will write this information to the tx-id's corresponding place. For example, when E1 receives the information sent by U1 whose tx-id is "002" and corresponding content information is encryptkeyUS(meta-data2), he will write this message to the "002" entry.

3.5 Online taxi-hailing software platform database

Online taxi-hailing software platform database is maintained by the Online taxi-hailing software platform itself. In the real world, Online taxi-hailing software platform database are generally more complex, and it is designed according to the specific function and structure of the Online taxi-hailing software. However, this paper simplifies the database, leaving only the key parts of the blockchain interaction to display the database. This database's UML is shown as follows while its role's attributes and methods are defined in the front tables so we will not repeat them here.

4 Model framework and implementation

Overall, the model includes processes such as the initial key exchange, granting permissions, uploading privacy information, reading the passenger departure location, reading the passenger travel, reading the visitor log and revoking permissions.

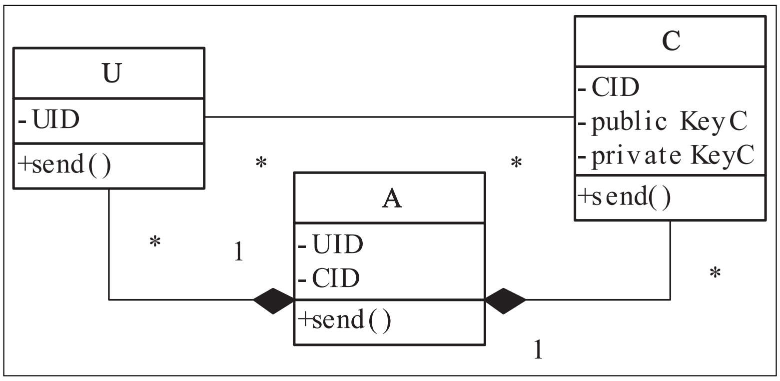

Figure 6: UML of Online taxi-hailing software platform database

4.1 Initial key exchange

U, S, E will exchange their keys firstly. Its process is as shown below.

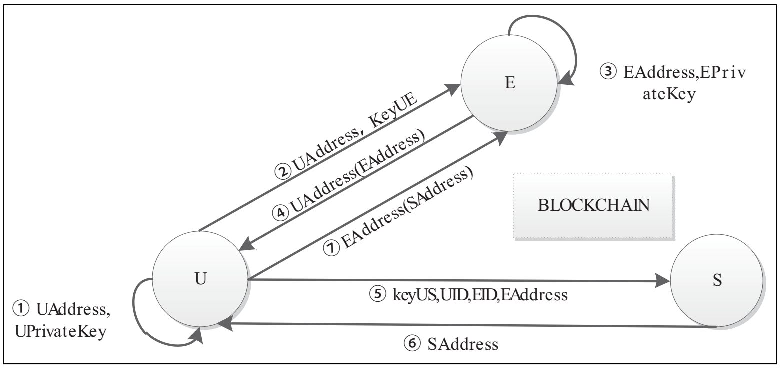

Figure 7: Initial key exchange

① U.generate(UAddress,UPrivateKey)
② U.send(EID; UAddress,keyUE)
③ E.generate(EAddress,EPrivateKey)
④ E.send(UID; UAddress(EAddress))
⑤ U.send(SID; keyUS,UID,EID,EAddress)
⑥ S.send(UID; SAddress)
⑦ U.send(EID; EAddress(SAddress))

4.2 Grant permissions

Passenger U1 requests to use the data interactive audit platform S1 on the Online taxi-hailing software platform and grants the privilege to S1. After authorization, S1 will have the right to read or manipulate U1's data.

① U.send(EAddress; hash(),token,signature)

Note that the content of hash () is *empty*, and the content of token is "*U grant data operation rights to S*".

② B.return(tx-id)
③ U.send(EID; permission,tx-id)
④ E.read(EAddress.transaction)
E.decrypt(EAddress.transaction)

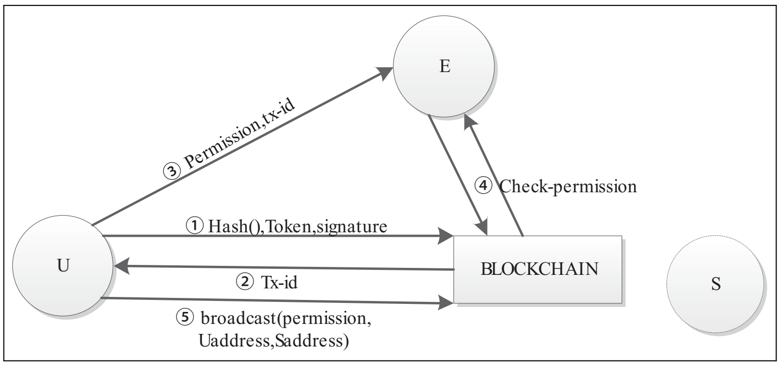

Figure 8: Grant permissions

E.validate(signature)
E.validate(token)

Note that E view the table *the chain of title* which belongs to some user U and find the according transaction through tx-id, finding that the transaction token's all following tokens do not write "*U revoke S's authority to operate its data*" at all. So we can conclude that it is still valid for S to operate U's data.

⑤ U.broadcast(permission,UAddress,SAddress)

4.3 Upload the privacy information

To carry out an Online taxi-hailing order, U1 should first provide personal privacy information such as his own departure and destination, and upload the above itinerary route information to E1 and audit them in the blockchain. As the block size is limited, the audited information uploaded to the blockchain is a shorter hash value. After the passenger upload the departure and destination to the third party database, it will automatically trigger a series of actions (such as the Online taxi-hailing platform recommends several drivers to the passenger). The automatic triggering mechanism is achieved through passenger's sending request to the Online taxi-hailing platform.

Thus, we solved the problem1 that the travel route of the passenger is leaked to A1, so that A1 can't obtain the entire trip route privacy of the passenger or sell passenger's itinerary to other groups.

① U.send(EAddress; hash(meta-data),token,signature)

meta-data's content is "*U1's itinerary and other private information*", while token's content is empty.

② B.return(tx-id)

③ U.send(AID; request)

④ U.send(EID; encryptkeyUS(meta-data),tx-id)

⑤ E.read(EAddress.transaction)
E.decrypt(EAddress.transaction)
E.validate(signature)
E.validate(token)

Note that, although the token's content is empty, E still has to perform the validation process in a flow.

⑥ E1.write(encryptkeyUS(meta-data),tx-id)

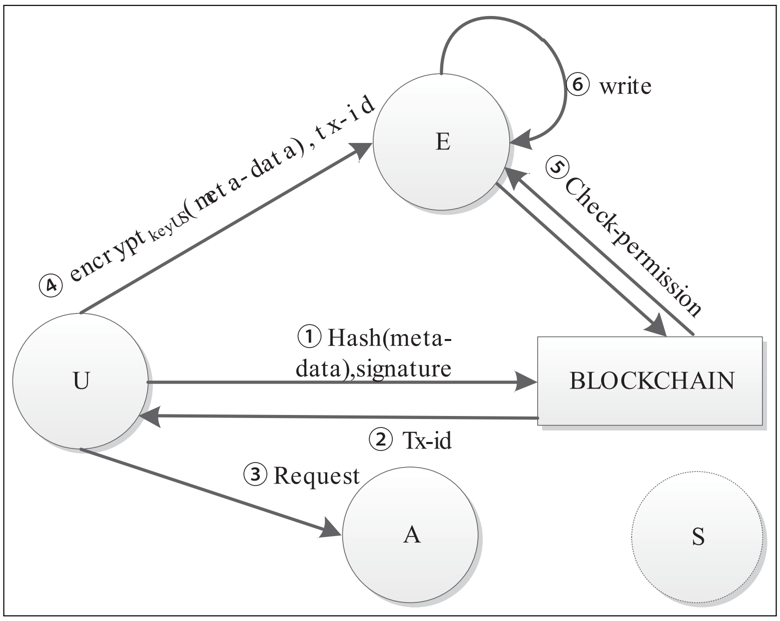

Figure 9: Upload privacy information

4.4 The Online taxi-hailing Software Platform Reads the Passenger's Departure Position

The taxi software platform A1 reads the departure position of the passenger U1 and provides recommended drivers to the passenger on the basis of it. S1 is the privacy protection system selected by the taxi software platform A1. Therefore, if A1 wants to acquire the departure of U1, it still needs to apply to the third party database E1 through S1.

① A.send(SID; keyA, meta-data1)

the content of Meta-data1 is "*A want to get the initial position of U*".

② S.send(UID; meta-data1)

③ U.send(SID; authorization)

④ S.send(EAddress; hash(meta-data1), token,signature)

the content of token is "*U1 authorized A1 to read its initial position*".

⑤ B.return(tx-id)

⑥ S.send(EID; meta-data1,tx-id)

⑦ E.read(EAddress.transaction)
E.decrypt(EAddress.transaction)
E.validate(signature)
E.validate(token)

⑧ E.send(SID,encryptkeyUS(meta-data2))

the content of Meta-data2 is "*the initial position of U1*".

⑨ S.send(AID,encryptkeyA(meta-data2))

4.5 The selected driver reads the passenger's itinerary and compete for the order

The taxi software A1 has read the passenger departure position, matched the optimum position driver C1 through the system, and sent the departure of U1 to C1. C1 will automatically apply to view the itinerary (if user think it's not convenient, he can set the system to automatically authorize, because the entire reading process will be recorded in the blockchain), and

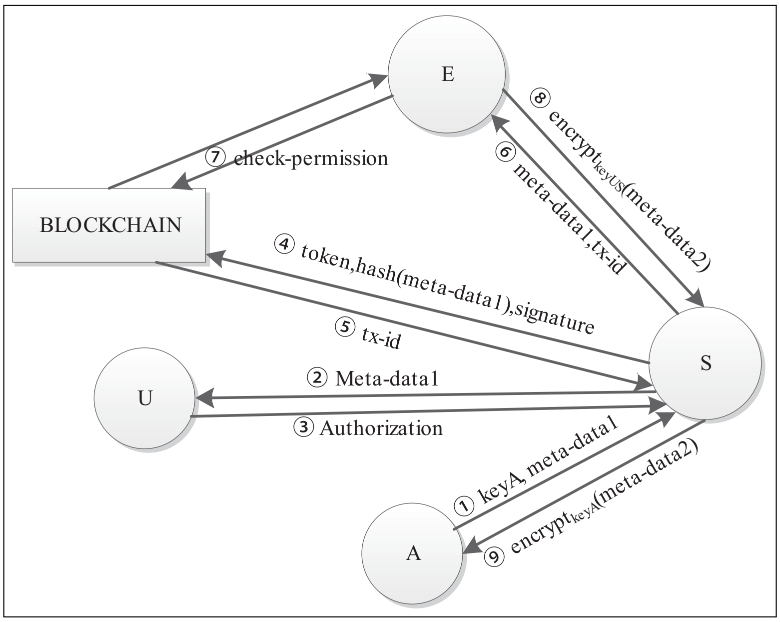

Figure 10: The Online taxi-hailing platform reads passenger departure location

decide whether to compete for it. The entire process avoids A1's obtaining U1's privacy of the itinerary information. After successful competition, some lucky drivers will have the opportunity to provide taxi service to the user.

Thus, we solve Problem 2 and then all operations of A1 and C1 are recorded on the blockchain, which can provide U1 the ability to control his own personal privacy information.

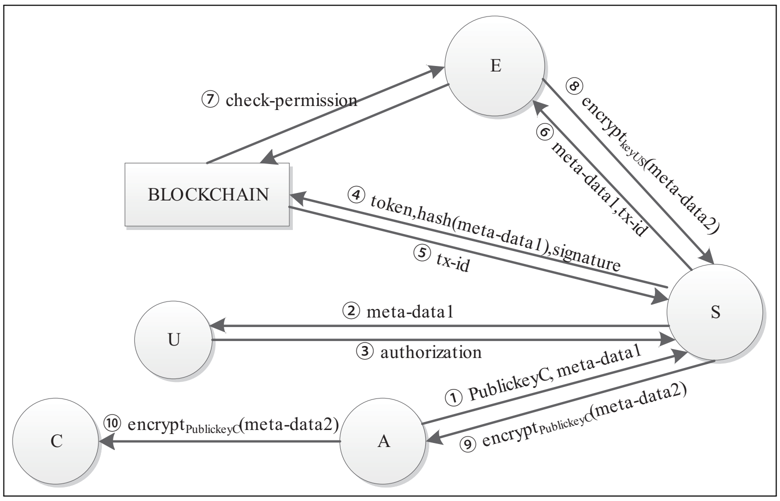

Figure 11: The selected driver reads the passenger's itinerary

① A.send(SID; publicKeyC, meta-data1)
The content of Meta-data1 is "*C1 wants to get U1's itinerary*".
② S.send(UID; meta-data1)
③ U.send(SID; authorization)
④ S.send(EAddress; hash(meta-data1), token,signature)
The content of token is: "*U1 authorizes C1 to get the itinerary of U1*".
⑤ B.return(tx-id)

⑥ S.send(EID; meta-data1,tx-id)
⑦ E.read(EAddress.transaction)
E.decrypt(EAddress.transaction)
E.validate(signature)
E.validate(token)
⑧ E.send(SID; encryptkeyUS(meta-data2))
The content of Meta-data2 is "*U's itinerary*".
⑨ S.send(AID; encryptpublicKeyC(meta-data2))
⑩ A.send(CID; encryptpublicKeyC(meta-data2))

4.6 The Passenger reads visitors' records

Passenger U1 can figure out which actor has attempted to read his data. Here we will use the information stored in the token before, because the token contains U1's authorization records about which visitor visited which information of U1.

Thus, we solved problem 2 and problem 4. U1 can not only see all the visitor records to strengthen his control over the data, but also have evidence to inform the privacy breach platform's illegal operation (failed to clear U1's personal information in time).

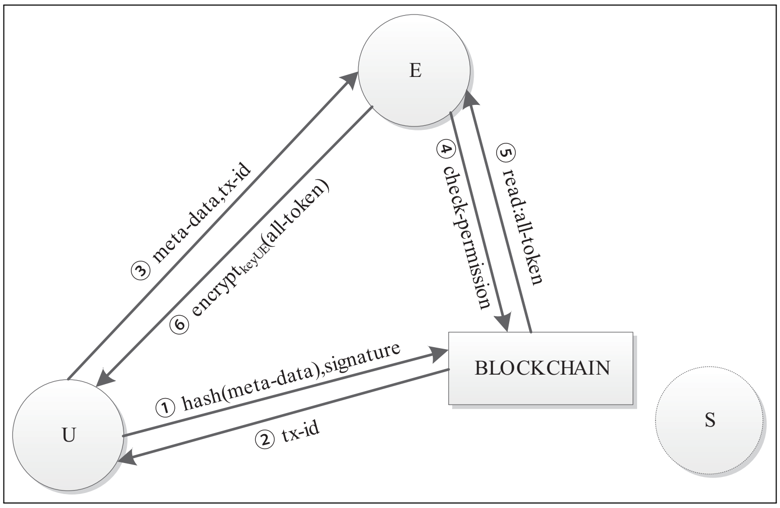

Figure 12: The passenger reads the visitor record

① U.send(EAddress; hash(meta-data),token,signature)
The content of Metadata is "*U1 wants to read which group has tried to access his privacy information*", or "*U1 want to read all his related tokens that have been audited in the blockchain*". The content of token is *null*.
② B.return(tx-id)
③ U.send(EID; meta-data,tx-id)
④ E.read(EAddress.transaction)
E.decrypt(EAddress.transaction)
E.validate(signature)
E.validate(token)
⑤ E.read(all-EAddress.all-token)
E.decrypt(all-EAddress.all-token)
E1 reads all tokens related to U1 from his addresses and then extracts them (E1 can use his own private key to decrypt them) .

⑥ E.send(UID; encryptkeyUE(all-token))

4.7 Revoke permissions

Passenger U1 may, for some reason, wish to terminate the use of the current Online taxi-hailing software platform A1 and wish to terminate A1's manipulation on his own data by revoking the permissions of its corresponding data interactive audit platform S1. On the other hand, U1 can give up the current third-party database E1 and select another one, but he doesn't need to change the current E1 because E1 can't see his privacy information at all.

Thus, we solved problem 3, so that once U1 decide to stop using the Online taxi-hailing software, he can immediately revoke S1's access to his data to protect his privacy from infringement.

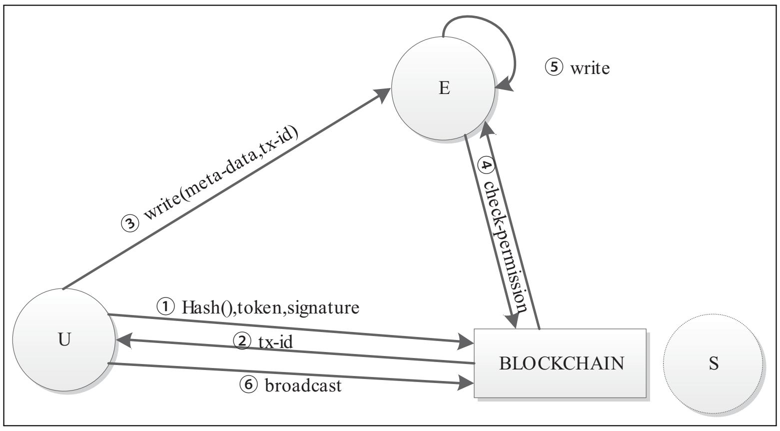

Figure 13: Revoke permissions

① U.send(EAddress; hash(),token,signature)

The content of hash() is *null*. The content of token is "*U want to revoke S's data operation authority on U*".

② B.return(tx-id)

③ U.send(EID; write(meta-data,tx-id))

The content of meta-data is: "*U request to revoke S's data operation authority on U* ". Write means that E is expected to be able to write meta-data in its corresponding table *the chain of title*.

④ E.read(EAddress.transaction)
E.decrypt(EAddress.transaction)
E.validate(signature)
E.validate(token)

⑤ E.write(meta-data,tx-id)

E writes meta-data and tx-id. From now on, as long as E reads "*U request to revoke the operating authority of S on U's data*" in meta-data, he will refuse to continue to provide S services related to U's data. E can also read tokens related to U in *the chain of title*. Once E finds that the last token record of U on S is "*U want to revoke S's data operating authority on U*", E will refuse to provide U's data related services for S.

⑥ U.broadcast(token)

5 Conclusions and future works

Personal privacy problem of Online taxi-hailing has not been effectively solved. In addition to lack of improvement motivation due to users' privacy protection consciousness, the Online taxi-hailing platform also lacks the improvement ability due to the current deficiency of privacy protection technology. Many developing countries, like China, have yet to enact special laws on personal information protection. However, blockchain technology provides an effective mechanism solution to personal privacy protection currently as a strong complement to the legal system. Through the application of our blockchain model, firstly, the taxi software platform can't obtain the entire itinerary privacy of the user, so that the privacy information won't be sold to other for-profit organization anymore. Secondly, the user can see all the visitor records, thereby enhancing his control over his privacy data. Moreover, once the user decides to stop using the Online taxi-hailing software, he can revoke its data interactive audit platform's access to his data. Finally, if the Online taxi-hailing software platform is attacked by hacker which leads to user's information leakage, the user can sue the platform for that it doesn't clear his information promptly, with the evidence of visitor records. In fact, in our opinion that blockchain technology can solve the problem of identity hacking, because if your identity is controlled by a private key, and your own holds that the private key, then there is no way to hack your identity, or at least compared with the traditional database system, the possibility of attack is very low. In addition, maybe separate blockchain may not be the solution to data hacking and identity theft from a technical point of view, but combining with other blockchains rather than fighting alone can solve it.

We boldly apply the blockchain technology to the issue of personal privacy protection, and take the lead in the current popular Online taxi-hailing scenario, where we comprehensively describe the details of blockchain's application in individual privacy protection through processes such as rights-granting, data-writing, data-reading and permissions-revoking, providing a technical mechanism solutions for scholars to further study personal privacy protection issues.

However, this paper still has some limitations. Firstly, from the theoretical point of view, our analysis to personal privacy protection is relatively a little less due to space limitations. Secondly, from the application point of view, our domestic Online taxi-hailing passengers' awareness is relatively weak about personal privacy protection issue. Finally, from the implementation point of view, we provides the data exchange between entities, but doesn't provide the specific implementation and simulation of the system, meaning that further study will be carried out to complete the specific implementation and simulation experiments of the system refer to papers of Barlas et al. [1] and Cotet et al. [4].

Acknowledgment

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