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E-learning multimedia applications: Towards an engineering of content creation

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Abstract: In the same manner that e-learning applications are becoming increasingly important at the university, there are still some critical questions that should be solved with the objective of making use of the potential offered by current Web Technologies. The creation of contents that are able of capturing the attention of interest of the students and their disposal in an appropriate way constitute the main purpose of this work. The teaching content engineering expounded shows the different stages that should form part of the process. A development team, composed of different professional profiles, will work together with the lecturers of the subject to which the contents are been created, i.e. multimedia videos and interactive applications. This process should be developed according to a methodology that assure the use of appropriate resources, all that tasks -suitable of being- should be modularized and factorized. This paper presents the acquired experience in the development and use of multimedia contents for e-learning applications, created for some of the subjects of the degree in computer science engineering. The deliveries of these contents make use of Internet and video streaming techniques. The result of the work shows the students satisfaction, including their comments.
Keywords: Teaching content engineering, Didactic objectives, Active learning, Passive learning.

1 Introduction

During recent years University Education has experienced an important progress with respect to the resources used for lecturing. Techniques have changed from traditional blackboard methods to the use of projector transparencies (slices) and, later on, the use of video projector and PowerPoint to present the content of the lessons. Nowadays, the use of these technologies has become more common. As far as content availability for the student is concerned, it has passed from traditional notes taken in classrooms, books and photocopies to digital format of books or notes taken in classrooms, which are available in the subject's web page. In fact, the universities use to place courses on the web focusing on information delivery rather than learning. The proposal of European Higher Education Area provides the framework to take an important step forward in techniques used in lectures and in the methodology used to create them. For this reason, new methodological approaches are introduced in order to value an active learning [1] as opposed to a traditional passive learning. To value the effort that students should make in order to assimilate knowledge and not only consider the number of hours of attendance to classes. The use of e-learning techniques makes this easier; its wide range of application allows increasing education quality and delivery of information.

2 E-learning in EHEA

The European Higher Education Area proposes the setting up of a convergence process of educational material in Europe. New methodological approaches are introduced in order to value an active learning as opposed to a traditional passive learning. To value the effort that students should make in order to assimilate knowledge and not only consider the number of hours of attendance to classes. All this is made easier by using an e-learning [2] approach, whose extensive work field, in all range of subjects, allows the quality of education and its availability to increase [3]. The creation of multimedia contents for e-learning could be developed together with other European Universities, and its use could be shared within the same knowledge areas. This allows a new common line of work to be opened. It will be possible to promote European cooperation to guarantee the quality of higher education using comparable methodologies and criteria.

3 Teaching content engineering

We understand for that concept the whole methodological corpus that allows inserting development e-learning technologies in the production of didactic solutions with appropriate invests in production time, resources and person/hour. In this manner, the creation of contents will be developed in a systematic way, planning the process and using adequate techniques. The integration of these techniques and the extent of the teaching material development project require a multidisciplinary team. This multidisciplinary team composed of a group of different professional profiles will carry out different tasks using a wide variety of technologies. These tasks will come together in order to create a production line to maximize results. The improvement of productivity and quality in teaching content creation will constitute the main objective of this engineering [4]. The proposed engineering of teaching content is carried out by means of a methodology, which divides the multimedia production process into phases and assigns tasks to each member of this professional development team. All these different phases include research on suitability of the content for e-learning, a previous analysis to select multimedia techniques to apply, the development of the contents based on the project design and, finally, the maintenance. With respect to the multidisciplinary team, it will be composed of a project manager, programmers, designers, and multimedia experts, as well as the lecturers of each subject.

4 Methodology

The obtaining of an optimum workflow [5] and the use of resources by the different production tasks is the main purpose of the proposed methodology. For that, we define different production phases.

4.1 Suitability of the content for e-learning

To create multimedia material for subjects using e-learning techniques means a considerable resource investment. Therefore, some factors, which help to make a decision about its profitability, should be taken into consideration. In this first phase a study on the suitability is made in accordance with the factors below:

The content validity. The period of time in which teaching contents do not need to be updated.

The number of students who attend classroom training. This factor takes into consideration the number of resources used in their learning.

The modularity and reusability of independently operable units, which are part of the total structure for creating more contents.

4.2 Contents analysis

The creation of multimedia contents is carried out through the division of teaching contents in didactic objectives. In this phase the modularization of content takes place. The extraction of the lecturers' knowledge will be necessary for the selection and proposal of different multimedia didactic elements, which will constitute part of these multimedia didactic units. It is recommendable to follow a methodology belonging to knowledge engineering, where the knowledge is produced according to the lecturer's subject specific knowledge, and contains the knowledge and analytical skills of one or more human experts. To achieve this aim, the tasks below are introduced:

Meetings with the lecturers. In these meetings lecturers expound the teaching objectives of the subject, explain the lesson content and the current way to portray the contents to the students.

The selection of lessons for multimedia format. The project manager, together with the lecturers, carries out the selection of lessons for which multimedia teaching content will be created

Proposal and techniques selection [6]. According to the techniques selected, and the modules repository, the project manager makes a proposal to the lecturers.

4.3 Development

Starting from the analysis of the previous phase, a formal design is carried out, this formal design will identify the activities and work planning that will be done under the supervision of the project manager [7]. Therefore, this phase is structured as shown below:

Formal design includes all the multimedia didactic elements to be used. In accordance with this design, both human and material resources are managed. It is a process of problem solving and planning for reaching the objectives of the project.

Development of interactive applications will follow a development methodology belonging to software engineering.

Creation of videos, for which the work will be divided into: script writing, recordings, postproduction and codification [8].

On-line disposition of multimedia contents, becoming, this way, accessible for the students.

In the process the creativity of the development team is considered fundamental.

4.4 Maintenance

Once the project is finished, it is difficult to assure that it will work properly unless it is tested. In order to realize a high quality solution, testing throughout each phase of the process is proposed. The project team should be involved in the maintenance phase. They are expected to work on their known issues and prepare for a new release of the created material. In order to detect defects and deficiencies in the multimedia material, some tasks are introduced:

Interviews with lecturers and students, to know first hand how they feel about this new content to use, in various aspects: accessibility, manage, design.

Questionnaires, for recover statistics results about all the aspects to be evaluated.

Comparison of academic results, where an evaluation report will be made, and academic results will be compared with those of other groups of students that have made use of traditional learning methodologies.

All these tasks will help to obtain a constructive feedback and to enhance and optimize this multimedia material and its different aspects evaluated. A thorough study of time and staff required for project development will take us to a suitable planning and this to an appropriate economic investment. Therefore, cost and resources affect directly in the amortization of the investment made for the creation of contents.

5 Resources

Among the means that will be used to carry out this technology we find both human and material resources. The competences of the multidisciplinary team are defined by different profiles:

Lecturers, whose main tasks include the structure of the subject program, script writing, and the proposal and collective agreement with the project manager on the multimedia didactic units.

Project manager, who advises lecturers, coordinates efforts of the development team and assigns tasks according to the planning made.

Designers, which will carry out tasks of graphic design, user interfaces development, and 2D - 3D elements creation.

Analysts/programmers, to analyze and develop software application and programs.

Multimedia technicians, in charge of recording, editing, and postproduction.

Regarding to material resources, these are comprised of the multimedia recording studio and the laboratory room for development of software applications and editing of contents. The workstations of the editing room in the laboratory are fully equipped with the necessary computer material for creating and editing audiovisual content. Figure 1.

Figure 1: On the left we can observe the record Studio used for the recording of lessons. On the right workstation of the editing room.

6 Other methodologies

There are different strategies for the creation of teaching content for e-learning. These approaches often use a similar set of stages or phases for content development. Among them we find the "waterfall philosophy" characterized by the use of a number of phases strictly ordered in such a way that each phase begins once the previous one is finished; and the "evolutionary philosophy" or "based in prototypes", characterized by considering since the beginning that, although the project start out with a set of requirements, will arise changes in these requirements as the project is developed. However, the methodological proposal made in this work for an e-learning content engineering focuses on lecturing and this means a set of differences, related below:

Scope. Traditional methodologies are directed, generally, towards content development for corporate e-learning. The proposed methodology is focused on content development for lecturing.

Contents modularity. In each knowledge area to create independently operable units intended for reuse in the same or a different one is proposed. This means the use of a knowledge area thorough analysis in order to make these operable units relocation possible when creating new teaching programs.

Extend of involvement. Lecturers should be part of the work team that will create multimedia contents for e-learning, should be involved not only in didactic advises tasks, according to the teaching objectives of the subject, but also should take part in the conception of the whole set of tools proposed by the project manager.

Resources. The wide variety and quantity of multimedia resources used are essential in the proposed methodology for e-learning content creation. Multimedia technology and the development of interactive applications provide suitable capabilities to develop quality contents at the university level.

7 Lecturing experiences

For the evaluation of e-learning techniques in lecture content, some subjects have been selected. Specifically, the subjects correspond to bachelor and graduate degrees on "Computer Science Engineering", *Multimedia and Automaton Theory* and *Formal Languages II*. Specially, the subject of Multimedia has the particular feature of covering two fundamental aspects in the teaching of computer science knowledge. On the one hand, we find purely theoretical and mathematical content which supports audio compression, image and video technologies. On the other, we find content that makes reference to the use of multimedia tools and web programming languages. In particular, the subject of Multimedia has a teaching timetable of 30 theoretical hours (twice a week), using traditional classrooms, and other 30 hours of practical lessons in the laboratory. The prepared material embraces half the timetable in the classroom. The content generated for Automaton Theory and Formal Languages II corresponds to the practical exercises of the subject. As lecturers can now count on this new multimedia teaching material, the methodology, which has been followed till now in Multimedia, has changed substantially. Firstly, the students still have the same number of learning hours; however, they receive some lessons by means of video in a dedicated server. This means that they receive, weekly, one hour in the classroom and another one through video streaming. This new material allows traditional lessons to be divided into two groups. In this way the lesson in the classroom is repeated and the student attends the most convenient classes. Therefore, not only do they not miss the opportunity to ask the lecturer doubts, but also the number of students is reduced, allowing a more personalized treatment. With respect to Automaton Theory and Formal Languages II, the prepared material only provides support to the personal training of the student. The results of this experience have been very positive. Students have valuated unanimously this new teaching model as completely recommendable. Even, the students have taken part in the improvement of the material contributing with their own ideas, needs, and wishes, like including random questions in order to implement interactivity [9]. From the valuation questionnaire issues below are recovered: *Multimedia videos are very appreciated. No comments were made about accessibility or reproduction difficulties or even misunderstanding. Although students think it is necessary: the inclusion of subject's content in a pdf format file and an index to facilitate access directly to each unit of the lesson. And just only one student pointed out that the teacher should propose more practical material in the classroom.* The valuation questionnaire results are represented in the Table 1.

As we can observe, percentage for the last one question is quite good. Figure 2.

With respect to the academic efficiency revealed in the assessments, we should say that the percentage of success in the exams remains constant if we compare with the results of past years where lessons were taught in a traditional way. However, a particular fact, which is known by all lecturers when the exams'

		Totally disagree	Disagree	Average	Above average	Excellent	
1	Multimedia videos expound the subject suitably and clearly	0	1	7	29	35	72
2	This way of teaching facilitates the subject's understanding	0	1	7	30	34	72
3	Lessons in the classroom can be improved, since doubts are resolved and illustrated by real and practical examples, as well as debates are proposed	2	7	17	17	26	69
4	I think this multimedia content is suitable for teaching the subject, I would like to study another one using this type of material	0	1	2	25	44	72
5	I have had some kind of difficulty accessing videos	48	11	8	3	1	71
6	With the use of this material I can make my lessons schedule compatible with other subjects and other activities	1	2	3	11	55	72
7	My general assessment is good	0	2	3	26	41	72
						Total number of answer:	500

Table 1: Results from bachelor and graduate degrees on "Computer Science Engineering"

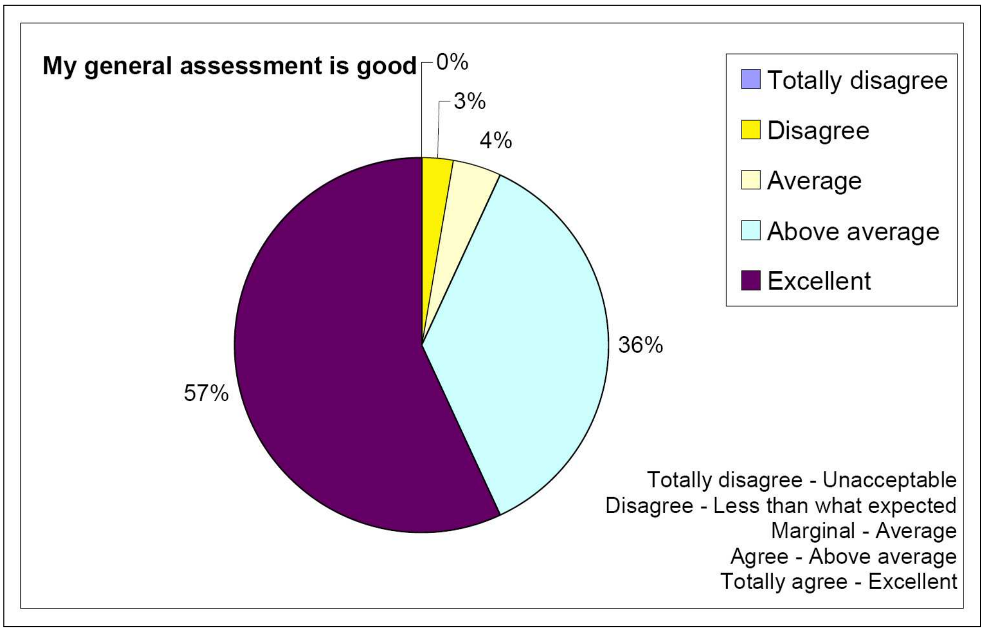

Figure 2: Graphical representation for general assessment. Results from bachelor and graduate degrees on "Computer Science Engineering"

dates come close, should be commented. In the previous weeks to exam dates the students come more frequently, and in many cases only on those dates, to the tutorials. It is remarkable that during this teaching experience there have been practically no consultations in tutorials in all the academic year, not even on dates coming up to the exams.

8 Future research

The acquired experience in the development of multimedia contents for e-learning applications shows that this emergent task should be tackled through the use of a systematic, disciplined, quantifiable approach to the development, manage and maintenance of this teaching content material. In the near future, we will test the process of development of a new project from the University of Las Palmas de Gran Canaria. This project involves the creation of multimedia material for subjects of three different areas: the technical area, the health care science area, and the human, society and legal area. The election of the subjects has been made according to the factors expounded in the phase of suitability of the subject. It has been preferential for the technical department to choose subjects of the first courses of various degrees with similar contents, what implies a considerable number of lessons in common. So that, there will be subjects with the 85 or 90 per cent of their content delivered with multimedia material, which is more profitable than having only one or two subjects with the 100 per cent of the content delivered with this new material. The subject is named mathematics in some degrees and calculus in other ones. Something similar has happened in the other two knowledge areas: in the health care science area anatomy has been chosen, this is a subject of the first course of "Medical Degree" with a huge number of students. For the human, society and legal area has been chosen constitutional law, which corresponds to two different degrees: "Law" and "Economics and Business Sciences", degrees with a large number of students in the first courses too. In this way, we will delve into each phase of this new engineering focusing on improving the efficiency and cost-effectiveness of the development of multimedia contents for e-learning in these subjects selected.

9 Conclusions

New information technologies and e-learning will be indispensable tools in lecturing in the near future. The increasing bandwidth available for Internet connection and multimedia capacities found in current computers allow them to be used as a completely valid way for teaching. However, the lack of multimedia content production is a very important cause that limits an e-learning widespread. The creation of large-scale teaching content for lecturing needs a production methodology to assure the optimization of resources and, therefore, a reduction in costs. This work intends to contribute with the methodological lines applied in the production of multimedia teaching content for lecturing. New teaching methodologies require new teaching aims; the role of lecturers in the new educational process should be restated in the whole educational process. Lecturers should reduce the time dedicated to teaching lessons using traditional blackboard methods. This activity could be mainly, replaced by e-learning techniques. Lecturers could dedicate time to activities that offer a better quality in teaching, transmitting motivation about the subject being studied and directing the students in their studies [10]. The future of teaching in the European society should see an improvement in the quality of education, its availability, and a lower cost for students as well as for educative organizations.

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Design of a MIMO PID Robust Controller using moments based approach

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Abstract: In this paper we present a new technique for robust MIMO controllers synthesis and reduction based on a reference model and moments approach intended to control a MIMO thermal system.
The reference model allows to specify the performances requirements for the closed loop and improve the controller robustness while the moments tool (frequency and time ones) is used to reduce the controller structure using a Non Linear Optimization.
The implementation on the real system associates this methodology of MIMO PID controllers synthesis with Broïda's identification technique in order to carry out a auto-tuning procedure [2][11].
Keywords: PID control, Reference model, Moments, Optimization, Robustness, Broïda's identification technique.

1 Introduction

The method of moments was introduced in a previous contribution [1] to show how we can treat Single-Input Single-Output (SISO) control systems. We saw that the moments represent a good tool to obtain a reduced robust controller in order to approximate the closed loop behaviour to a reference model one. The reference model gathers all performances requirements like time response and overshoot.

An extension of this method to the multivariable (Multi-Inputs Multi-Outputs) systems is presented in this paper; in this case the fundamental idea is to choose a diagonal reference model to make inputs outputs pairing [10] where the diagonal reference transfer functions are chosen using the same method for the SISO case.

In this paper we present our control methodology for MIMO systems with an application to a thermal system. The control of the MIMO thermal system is realized with the help of a PID controller using *moments based approach and reference model*.

The aim of this technique is to synthesize a reduced robust controller (PID for example) for the implementation.

The identification was realized thanks to Broïda's method which is an elementary technique very used in the industry in order to develop a auto-tuning procedure requiring a minimum intervention of the user.

The controller achieving the performances for the worst case model is called *ideal controller* [10] which will be reduced using the moments based approach to have a PID structure for implementation [4].

The reduced controller must preserve the same performances as the ideal one; this rises from frequency and time moments which represent a good tool for synthesis and analysis [7]. Concretely, the reduction procedure is based on a Non Linear Optimization and its initialization is given by the *Least Squares Algorithm* [8].

The paper is organized as follows: in section 2 we give a complete description of the application; in section 3 we develop our synthesis methodology; in section 4 and 5 we describe the moments theory and the reduction method and we finish this communication by presenting the different results obtained and a conclusion.

2 Description

The general diagram of the temperature control device is illustrated by Fig. 1.

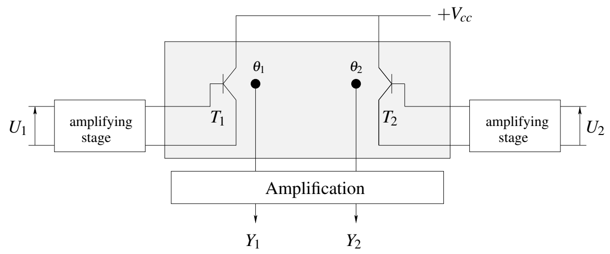

Figure 1: The general diagram of the system

It is composed of a radiator on which we placed two power transistors T_1 and T_2 controlled by the tensions U_1 and U_2 which vary between 0 and 10 Volts.

Near these power transistors, which represent the heat source, two temperature sensors (Pt 100) are laid out. After adaptation and amplification, we obtain the tensions Y_1 and Y_2 (which vary between 0 and 10 Volts) proportional to the temperatures θ_1 and θ_2.

The ratio tension-temperature is of $0.02 Volts/C$.

2.1 Modelling

The aim is to define the model connecting the tensions delivered by the temperature sensors Y_1 and Y_2 to the control tensions U_1 and U_2 applied to the transistors.

The conduction of the heat in the radiator, towards the temperature sensors produced by the power transistors is governed by the following diffusion equation:

$$\mu \frac{\partial^2 \theta}{\partial x^2} = \frac{\partial \theta}{\partial t} \tag{1}$$

where μ is the coefficient of thermal diffusion process.
consequently the resulting physical model is of distributed parameters and we preferred to present a black box model adapted to the synthesis of a control law, this model is given from identification. Let:

$$\begin{bmatrix} Y_1(s) \\ Y_2(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \begin{bmatrix} U_1(s) \\ U_2(s) \end{bmatrix} \tag{2}$$

where $G(s)$ is the transfer matrix of the system.
Notice that the system is symmetrical because of the provision of the heat sources and the position of the sensors.

Indeed, we must obtain:

$$\begin{cases} G_{11}(s) = G_{22}(s) \\ G_{12}(s) = G_{21}(s) \end{cases} \tag{3}$$

in addition, since the sensors θ_1 and θ_2 are very close to the sources T_1 and T_2, the transfers G_{11} and G_{22} can be reasonably modelled by a first order system ($\frac{k_{11}}{1+\tau_{11}s}$). On the other hand θ_2 is less sensitive to the effect of T_1 than that of T_2 (so $k_{21} < k_{11}$), with a settling time definitely higher. We can thus approach this transfer by an aperiodic n^{th} order system with ($n >> 1$) or more simply by a first order system with a time delay ($\frac{k_{12}e^{-\alpha_{12}s}}{1+\tau_{12}s}$).

2.2 Identification

Several sophisticated identification techniques (minimization of a quadratic cost by Least Squares or Non Linear Optimization) (Ljung [5] and Walter [12]) can be used to estimate the parameters of $G(s)$.

Taking into account the fact that the aim is to synthesize PID controllers (in a auto-tuning objective), we preferred to choose a basic identification method requiring only step tests. Our choice thus is Broïda's method which delivers an approached model of the form $(\frac{ke^{-\alpha s}}{1+\tau s})$, so well adapted to the selected modelling [2][11].

Let us recall that the coefficient $\{k, \alpha \text{ et } \tau\}$ are obtained with the help of the following formulas:

$$\begin{cases} k_{ij} &= y_\infty \\ \alpha_{ij} &= 2.8t_1 - 1.8t_2 \\ \tau_{ij} &= 5.5\,(t_2 - t_1) \end{cases} \tag{4}$$

where y_∞ is the final value of the system step response, t_1 (respectively t_2) is the time where the output attains 28% (respectively 40%) of its final value.

We made 5 tests which provided:

	$test1$	$test2$	$test3$	$test4$	$test5$
k_{11}	0.1221	0.1221	0.1172	0.1172	0.1318
τ_{11}	577	414	449	451	457
k_{12}	0.0634	0.0636	0.0586	0.0586	0.0684
τ_{12}	910.5	862.95	684.2	683.1	863
α_{12}	7	26.2	59.6	58.9	6
k_{21}	0.083	0.0781	0.0684	0.0684	0.083
τ_{21}	715	654.5	808.5	808.5	715
α_{21}	113	99.8	73.4	73.4	113
k_{22}	0.0977	0.0977	0.0977	0.0928	0.1074
τ_{22}	450	445	447	447	600

the settling times of $G_{11}(s)$ and $G_{22}(s)$ are close and equal $33 minutes$.

2.3 The nominal model

The nominal model was obtained by carrying out the average of the 5 tests, thus:

$$G_{nom}(s) = \begin{bmatrix} \frac{0.122}{470s+1} & \frac{0.0625e^{-31.5s}}{801s+1} \\ \frac{0.0762e^{-94.5s}}{740s+1} & \frac{0.0987}{478s+1} \end{bmatrix} \tag{5}$$

From the values of the preceding table, we note that the theoretical symmetry is not checked in practice, well that $G_{11}(s)$ and $G_{22}(s)$ are close ($G_{12}(s)$ and $G_{21}(s)$ respectively), these differences are the consequences of the noises level disturbing the measurements and the non perfect reproducibility of the assembly.

2.4 Taking into account of uncertainties

Identification uncertainties will deteriorate the performances of the control device if they are not taken into account during the synthesis. The table recapitulating the 5 tests shows that two uncertainties types are present:

- uncertainties on the d.c gains (of type low frequencies).

- uncertainties on time-constants and time delays, which causes modelling errors (of type high frequencies).

Since the transfer matrix $G(s)$ is theoretically symmetrical, we decided to make the synthesis by basing us on a symmetrical *worst case model* $G_p(s)$.

Using $G_p(s)$, we took into account all the uncertainties by raising:

- low frequencies uncertainties by taking k_{max}.

- high frequencies uncertainties by introducing a time delay $e^{-\delta s}$ (see [1]).

Remark 1. The worst case model has been chosen to take into account all the identification uncertainties:

- low frequencies uncertainties, by choosing the max of the d.c gains.

- high frequencies, by introducing time delays in all input-output transfers.

thus, we obtain the following worst case model:

$$G_p(s) = \begin{bmatrix} \frac{0.132e^{-5s}}{500s+1} & \frac{0.085e^{-125s}}{800s+1} \\ \frac{0.085e^{-125s}}{800s+1} & \frac{0.132e^{-5s}}{500s+1} \end{bmatrix} \quad (6)$$

3 Synthesis

The control configuration is illustrated by Fig. 2

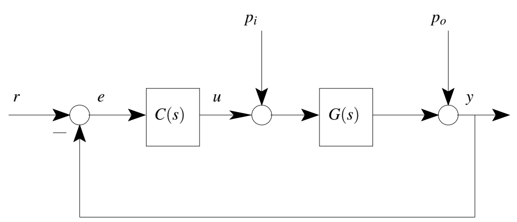

Figure 2: Unitary feedback configuration

$C(s)$ is the controller to implement, $G(s)$ is the plant, r represent the reference inputs, y the outputs to be controlled, u the control inputs, p_i and p_o are the input and output disturbances and e is the tracking error.

The synthesis of $C(s)$ is based on the Internal Model Control [6][10], so:

$$C(s) = Q(s)\left(I - G(s)Q(s)\right)^{-1} \quad (7)$$

where $Q(s)$ is any stable transfer matrix [3].

3.1 The reference model

$Q(s)$ is calculated using $G_p(s)$ in order to approach the closed loop $T_{yr}(s)$ to a reference model $T_{ref}(s)$, so:

$$T_{yr}(s) = G_p(s)\,Q(s) = T_{ref}(s) \tag{8}$$

The reference model gathers all the objectives of the synthesis in terms of stability and performances (i.e inputs-outputs decoupling, settling time... etc).

In our case, $T_{ref}(s)$ is given by:

$$T_{ref}(s) = \begin{bmatrix} \frac{T_2(s)e^{-\delta s}}{d(s)} & 0 \\ 0 & \frac{T_2(s)e^{-\delta s}}{d(s)} \end{bmatrix} \tag{9}$$

where $T_2(s)$ represent the dominant poles to fixe the closed loop dynamic, $d(s)$ represent the auxiliary poles, which reduce the control input energy, confer robustness to the controller by making a sufficient roll-off of $T_{yr}(s)$ and ensure its causality, finally $e^{-\delta s}$ represents the singularity of $G_p(s)$ which is integrated in $T_{ref}(s)$ to have $Q(s)$ stable and realizable.

So $Q(s)$ is given by:

$$Q(s) = G_p(s)^{-1}\,T_{ref}(s) \tag{10}$$

since the singularities of $G_p(s)$ (i.e time delays and RHP zeros) are integrated in the reference model $T_{ref}(s)$, so the stability of $Q(s)$ is guaranteed [3].

$T_2(s)$ and $d(s)$ are given by:

$$\begin{aligned} T_2(s) &= \frac{\omega_n^2}{s^2+2\xi\omega_n s+\omega_n^2} \\ d(s) &= (1+\eta s)^n \end{aligned} \tag{11}$$

where ω_n and ξ, fixe the settling time and the overshoot of the outputs.

We can recapitulate our reference model by saying that it imposes a inputs-outputs decoupling and the same dynamics for the two outputs of $G(s)$.

3.2 Robustness and the reference model

It is well-known that the relative modelling errors $\Delta_r(s)$ modify the dynamics of the system with a possibility of instability because:

$$\begin{aligned} S_{yp_o}(s) &= \left(I - G(s)\,Q(s)\,(I+\Delta(s)\,Q(s))^{-1}\right) \\ &= S_{nom}(s)\,(I+\Delta_r(s)\,T_{ref}(s))^{-1} \end{aligned} \tag{12}$$

So robustness of stability and performances is guaranteed if:

$$\|\,\Delta_r(s)\,T_{ref}(s)\,\|_\infty \leq \delta_{SR}^{-1} \tag{13}$$

where δ_{SR}, represents stability margin; notice that from (13), we can act on the auxiliary poles of $T_{ref}(s)$ to ensure the robustness [3].

3.3 The ideal controller

From (10), we deduce the ideal controller $C(s)$:

$$C(s) = Q(s)\left(I - G_p(s)\,Q(s)\right)^{-1} \tag{14}$$

It is clear that the implementation of $C(s)$ is very hard to do because of time delays; for that we will reduce its structure to get an implementable one which must preserve the same performances of those ensured by the ideal controller. The *moments* tool, particularity of our approach is used for reduction.

4 The Moments

Let us consider a linear SISO system, characterized by its transfer function $G(s)$ analytic in the RHP plan (.i.e $Re(s) > 0$) and let $g(t)$ be its impulse response:

$$G(s) = \int_0^{\infty} g(t)\, e^{-st}\, dt \tag{15}$$

The transfer function is given by the following state space (not necessary minimal) realization:

$$G(s) \stackrel{s}{=} \left[\begin{array}{c|c} A & B \\ \hline C & D \end{array}\right] = C\,(sI - A)^{-1} B + D \tag{16}$$

where $A \in \mathscr{R}^{n\times n}, B \in \mathscr{R}^{n\times 1}, C \in \mathscr{R}^{1\times n}$ and $D \in \mathscr{R}^{1\times 1}$.

4.1 Computing the moments using state space realization

Using the following equality:

$$(sI - A)\left(-A^{-1} - sA^{-2} - s^2A^{-3} - \cdots -\right) = I \Rightarrow (sI - A)^{-1} = -\sum_{n=0}^{\infty}\left(s^n A^{-(n+1)}\right) \tag{17}$$

Frequency moments

Realizing a variable change $\mu = j\omega - j\omega_0$, equation (15) becomes:

$$G(\mu) = \sum_{n=0}^{\infty} (-1)^n (\mu)^n \underline{A}_{n,\omega_0}(g) \tag{18}$$

and (16):

$$G(\mu) = C\left(\mu I - (-j\omega_0 I + A)\right)^{-1} B + D \tag{19}$$

so, we get:

$$\underline{A}_{0,\omega_0}(g) = -C\,(-j\omega_0 I + A)^{-1} B + D \tag{20}$$

$$\underline{A}_{n,\omega_0}(g) = (-1)^{n+1} C\,(-j\omega_0 I + A)^{-(n+1)} B, \quad (n = 1 \cdots \infty) \tag{21}$$

Remark 2. The time moments are giving by remplacing $\omega_0 = 0$. Both time and frequency moments can be calculated easily using the previous algorithm. Thanks to the computation of the moments using state space realization, we can compute moments for MIMO systems (Multi Inputs Multi Outputs).

5 The controller reduction

For more details of our model reduction procedure, please refer to [1]. It is interesting to have a reduced structure of the implemented controller (PID for example) [6].

Let:

$$\theta = \begin{bmatrix} \underline{\theta}_{11}(s) & \cdots & \underline{\theta}_{1M}(s) \\ \vdots & \ddots & \vdots \\ \underline{\theta}_{M1}(s) & \cdots & \underline{\theta}_{MM}(s) \end{bmatrix} \tag{22}$$

be the matrix representing the controller's parameters to be calculated.
$\underline{\theta}_{ij}$ represents the parameters vector of numerator and denominator of $C_{r,ij}(s)$; i.e the reduced controller between the j^{th} input and the i^{th} output.
Let us define our cost function J as the 2 norm of the errors between the different moments of the ideal controller and those of the reduced one.

$$J = \sum_{n=0}^{N} ||\varepsilon_n||_2^2 = \sum_{n=0}^{N} ||\underline{\mathcal{A}}_{n,\omega_0}(C) - \underline{\mathcal{A}}_{n,\omega_0}(C_r)||_2^2 \tag{23}$$

where $\underline{\mathcal{A}}_{n,\omega_0}(C_r)$ represents n^{th} order moments matrix, which is function of the parameters θ:

$$\underline{\mathcal{A}}_{n,\omega_0}(C_r) = f_n(\theta) \tag{24}$$

let:

$$J = \sum_{n=0}^{N} ||\underline{\mathcal{A}}_{n,\omega_0}(C) - f_n(\underline{\theta})||_2^2 \tag{25}$$

The objective is to determine the estimated parameters $\hat{\theta}$ minimizing J around ω_0.
This frequency ω_0 is chosen in order to preserve stability of the system (i.e critical pulsation), (see the Generalized Nyquist Criterion [10]).

5.1 Linear optimization

The first step consists on imposing the common denominator $D_r(s)$ of the reduced controller (for example we can take the auxiliary poles of the reference model $D_r(s) = d(s)$). So only the zeros have to be determined; the function $f_n(\theta)$ is linear; thus the minimization of J is obtained by Least Squares, let:

$$C_r(s) = C_{LS}(s) \tag{26}$$

be the reduced controller which will be used to initialize the Non Linear Programming algorithm.

Remark 3. by imposing the poles of the reduced controller, for example a pole with an integral action we define so a PID structure. For example we can take $D_r(s) = s(1+\eta s)$.

5.2 Non linear optimization

The fact of imposing the poles of the reduced controller, this will limit its performances and consequently those of the closed loop. So, it is preferable to optimize all the structure (i.e. poles and zeros); the function $f_n(\theta)$ is non linear; the estimation of θ is obtained by Non Linear Programming [7]. We use MARQUARDT's algorithm which is a good combination between rapidity and convergence [8].

The parameters are updated with the help of the following algorithm:

$$\hat{\theta}_{i+1} = \hat{\theta}_i - \{[J'' + \lambda_i I]^{-1}.J'\}_{\hat{\theta}=\hat{\theta}_i} \tag{27}$$

where:

$$\left(\frac{\partial J}{\partial \theta}\right) = J^{'} \quad : \quad \text{Gradient vector} \tag{28}$$

$$\left(\frac{\partial^2 J}{\partial \theta^2}\right) = J^{''} \quad : \quad \text{Hessian matrix} \tag{29}$$

$$\lambda_i \quad : \quad \text{coefficient to adjust} \tag{30}$$

The initialization is given by the Least Squares solution:

$$\hat{\theta}_0 = \hat{\theta}_{LS} \tag{31}$$

6 Results and comments

The controllers synthesis and reduction technique was applied to the thermal system with 2 inputs and 2 outputs. Let us recall that this thermal system is characterized by an important open loop settling time (approximately 33 minutes); moreover the elementary modelling used in a disturbed context involves important uncertainties. The objective of the temperature control, in a auto-tuning context, will be double:

- reduce considerably the closed loop settling time by using a controller of a simplified structure: PID controller.
- guarantee robustness in spite of the simplicity of the controller, the level of uncertainty and the reduction of the settling time.

Let us specify that the implementation of the PID controllers was ensured thanks to *XPC Target software* of MATLAB. We used for that a sample time $T_e = 1s$.

Our objective is to accelerate the system reasonably, in a ratio of 6, thus passing from $33mn$ in open loop to $5mn$ in closed loop all while maintaining the relative overshoot around 5%; for that, we fixed:

$$\begin{aligned} \omega_n &= 0.02 rd/s \\ \xi &= 0.7 \end{aligned}$$

the auxiliary poles ensuring the robustness condition (13) are:

$$d(s) = (1+3s)^3$$

The PID controller obtained using the synthesis and the reduction procedures described obviously is:

$$C_r(s) = \begin{bmatrix} c_{11}(s) & c_{12}(s) \\ c_{21}(s) & c_{22}(s) \end{bmatrix} \tag{32}$$

with:

$$\begin{aligned} c_{11}(s) = c_{22}(s) &= \frac{-3.162s^2+52.81s+0.14}{s(1+34.87s)} \\ c_{12}(s) = c_{21}(s) &= \frac{-2019e^{-7}s^2+4403e^{-6}s-7193e^{-5}}{s(1+15.88s)} \end{aligned} \tag{33}$$

The implementation provides the results illustrated by Fig. (3) and Fig. (4).

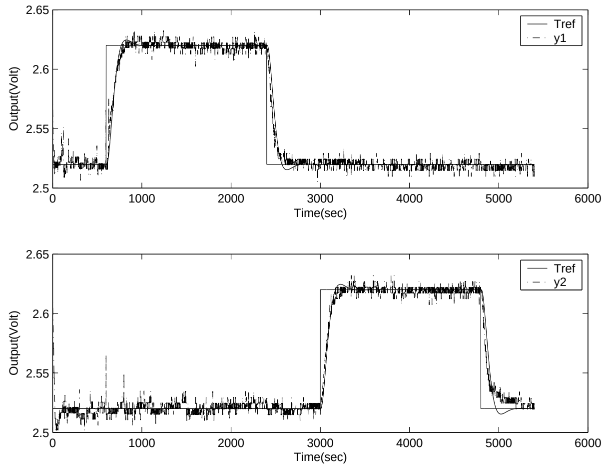

Figure 3: Step responses

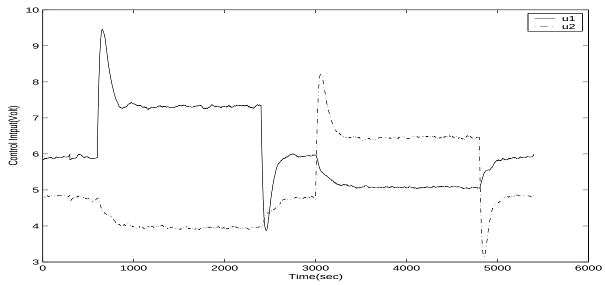

Figure 4: The control inputs

Remark 4. We can check that the system's responses correspond perfectly to those of the reference model. We can also check the perfect decoupling of the system outputs, Y_2 being insensitive to the reference input applied to Y_1 and reciprocally.
It is checked finally that the control input obtained is completely reasonable, that it is with respect to its initial magnitude or of its insensitivity to the output noise (of considerable level).

7 Conclusion

We presented in this communication a synthesis and reduction technique of robust controllers to the multivariable control of a thermal system. This methodology is based on a reference model integrating explicitly the desired performances. The experimental results show that the closed loop system verifies well the performances described by the reference model.

The moments approach, characteristic of this methodology, allows the reduction of the ideal controller to lead to a PID structure, while guaranteeing the dynamic performances and especially the robustness as testify the experimental results.

Let us recall finally that this synthesis methodology and reduction was associated with Broïda's identification technique to carry out the auto tuning of multivariable PID controllers.

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Feedback Gain Design Method for the Full-Order Flux Observer in Sensorless Control of Induction Motor

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Abstract: This paper deals with a feedback gain design method for the full-order flux observer with adaptive speed loop, which enables the minimizing the unstable operation region of this observer to a line in the torque-speed plane. The stability in regenerating mode is studied using necessary condition of stability based on determinant of matrix and a linearized model. Simulations results where the proposed observer is compared with an exiting solution (where the unstable region is not totally removed) are presented to validate the proposed observer design.
Keywords: Induction motor, full-order flux observer, sensorless control, stability analysis, adaptive speed estimator, regenerating mode

1 Introduction

The speed-sensorless control of induction motor drives have developed significantly during the last number of years. Speed adaptive full observers introduced by [8], [15] are promising flux estimators for inductions motors drives. The speed adaptive observer consists of a state variable observer augmented with a speed adaptation loop. The observer gain and the speed adaptive law determine the properties of the observer. The speed adaptation law is based on the component of the current estimation error with the estimated rotor flux. The adaptation law was originally derived using the Lyapunov stability theory [8]. However, the stability of the adaptation law is not guaranteed and stability problem exist in the regenerating mode. The derivation in [8] neglects a term including the actual rotor flux (which is not measurable). The positive-realness condition is not satisfied as shown [5]. Some limits of operation were quickly highlighted [9], [13]. In particular, a well known instability region was described in regenerating mode. Thus, the drive stability can't be guaranteed when this type of observer is associated with a field oriented control. There was many work in order to reduce this region of instability which is due to inadequate observer design [1, 2, 5, 14]. In this paper, we describe the design of an adaptation law that minimizes the instability region of an adaptive speed estimator. The paper is organized as follows. The induction motor model and the speed adaptive flux observer are first defined in section 2 and 3 respectively. We introduce the observer gain design in section 4 leading to a reduced instability region limited to a line. Finally, simulations results are presented and discussed in section 5, where the proposed observer is compared with an exiting solution [5, 13].

2 Induction motor model

The induction motor is described by the following state equations in the synchronous rotating reference frame with complex notations:

$$\frac{d}{dt}\underline{x} = \underline{A}(\omega, \omega_s)\underline{x} + B\underline{u}_s \tag{1}$$

$$\underline{i}_s = C\underline{x} \tag{2}$$

where $\underline{x} = [\ \underline{\psi}_r \quad \underline{i}_s\ ]^T$

$$\underline{A} = \begin{bmatrix} -(\frac{1}{T_r} + j\omega_{sl}) & \frac{L_m}{T_r} \\ \frac{L_m}{b}(\frac{1}{T_r} - j\omega) & -(a + j\omega_s) \end{bmatrix},\ B = \begin{bmatrix} 0 \\ \frac{1}{\sigma L_s} \end{bmatrix},\ C = [\ 0_{(2\times 2)} \quad I\ ],\ I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{3}$$

and the mechanical equation is:

$$\frac{d}{dt}\omega = p^2\frac{L_m}{JL_r}\Im(\underline{i}_s\underline{\psi}_r^*) - p\frac{T_L}{J} \tag{4}$$

where $*$ means a conjugate, j a complex number and $\Im$ an imaginary part. $\underline{\psi}_r$: rotor flux; $\underline{i}_s$: stator current; $\underline{u}_s$: stator voltage; ω_s : stator angular frequency; ω : motor angular speed; $\omega_{s_l} = \omega_s - \omega$: slip angular frequency; R_s, R_r : stator and rotor resistance; L_s, L_r : stator and rotor self-inductance; L_m : mutual inductance; T_L : load torque; J : rotor inertia ; p : number of pole pairs; $T_r = L_r/R_r$: rotor time constant; $a = (L_r^2R_s + L_m^2R_r)/(\sigma L_sL_r^2)$; $b = \sigma L_sL_r$; $\sigma = 1-(L_m^2)/(L_sL_r)$: leakage coefficient.

3 Adaptive Observer

The conventional full-order observer, which estimates the stator current and the rotor flux together [10, 11], is written as the following state equation.

$$\frac{d}{dt}\widehat{\underline{x}} = \widehat{\underline{A}}(\widehat{\omega},\widehat{\omega}_s)\widehat{\underline{x}} + B\underline{u}_s + \underline{G}(\underline{i}_s - \widehat{\underline{i}}_s) \tag{5}$$

$$\widehat{\underline{i}}_s = C\widehat{\underline{x}} \tag{6}$$

where $\widehat{}$ means the estimated values and $\underline{G} = [\ \underline{G}_1 \quad \underline{G}_2\ ]^T$ is the observer gain matrix.
We assume that all machine parameters are perfectly known except the motor speed. Using the assumption of constant angular rotor speed $\dot{\omega} = 0$ (i.e. the speed variations are slow with respect to electrical mode) [8], [5], the speed adaptive law is [8]:

$$\frac{d}{dt}\widehat{\omega} = \frac{\lambda L_m}{b}(e_{id}\widehat{\psi}_{rq} - e_{iq}\widehat{\psi}_{rd}) \tag{7}$$

where λ is a positive constant and will be tuned in (7) to improve observer dynamics. In practice, proportional-integral action is used in order to improve the dynamic behavior of the estimator.

$$\frac{d}{dt}\widehat{\omega} = K_p\frac{d}{dt}(e_{id}\widehat{\psi}_{rq} - e_{iq}\widehat{\psi}_{rd}) + K_i(e_{id}\widehat{\psi}_{rq} - e_{iq}\widehat{\psi}_{rd}) \tag{8}$$

where $e_{id} = i_{sd} - \widehat{i}_{sd}$, $e_{iq} = i_{sq} - \widehat{i}_{sq}$, (i_{sd}, i_{sq}) are (d,q) components of stator current, (ψ_{rd}, ψ_{rq}) are (d,q) components of rotor flux. The speed adaptive observer scheme with the speed adaptation mechanism is presented in Fig. 1.

4 Observer gain design

4.1 linearized model

The nonlinear and complicated dynamics of the speed adaptive observer can be studied via small-signal linearization. It is useful to proceed with a local analysis based in the principle of stability in the first approximation [12, 7].
We will choose the particular form $\underline{G}_1 = g_1I_{2\times2}$ where $I_{2\times2}$ is the identity matrix and $\underline{G}_2 = 0_{2\times2}$. The complete adaptive observer may be written as equation (10). Note that according the assumption $\dot{\omega} = 0$, the motor model (1) may be written as (9)

$$\begin{cases} \frac{d}{dt}\underline{\psi}_r = -(\frac{1}{T_r} + j\omega_{s_l})\underline{\psi}_r + \frac{L_m}{T_r}\underline{i}_s \\ \frac{d}{dt}\underline{i}_s = \frac{L_m}{b}(\frac{1}{T_r} - j\omega)\underline{\psi}_r - (a + j\omega_s)\underline{i}_s + \frac{1}{\sigma L_s}\underline{u}_s \\ \frac{d}{dt}\omega = 0 \end{cases} \tag{9}$$

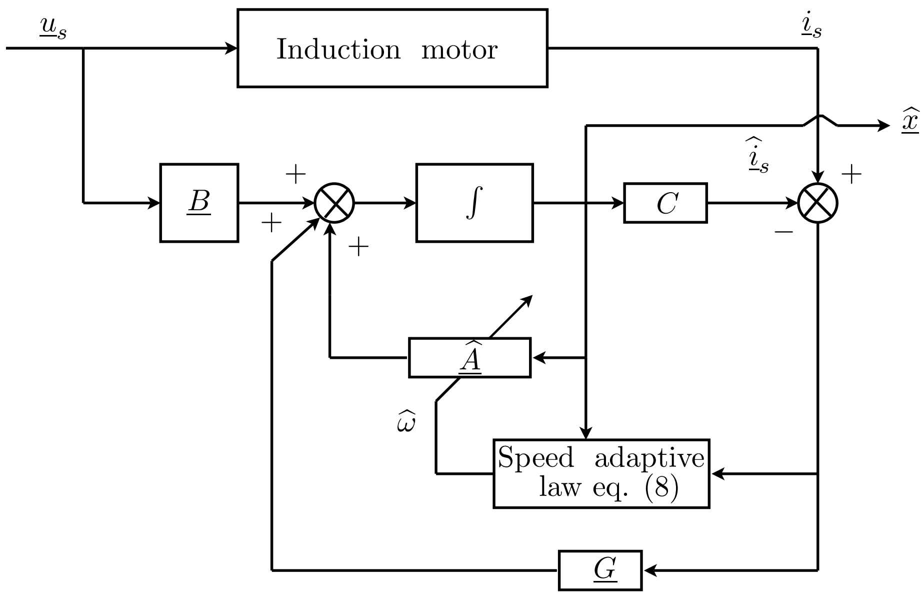

Figure 1: Speed adaptive observer

$$\begin{cases} \frac{d}{dt}\widehat{\underline{\psi}}_r = -(\frac{1}{T_r} + j\widehat{\omega}_{s_l})\widehat{\underline{\psi}}_r + \frac{L_m}{T_r}\widehat{\underline{i}}_s + g_1\delta e_i \\ \frac{d}{dt}\widehat{\underline{i}}_s = \frac{L_m}{b}(\frac{1}{T_r} - j\widehat{\omega})\widehat{\underline{\psi}}_r - (a + j\widehat{\omega}_s)\widehat{\underline{i}}_s + \frac{1}{\sigma L_s}\underline{u}_s \\ \frac{d}{dt}\widehat{\omega} = K_p\frac{d}{dt}(e_{id}\widehat{\psi}_{rq} - e_{iq}\widehat{\psi}_{rd}) + K_i\ (e_{id}\widehat{\psi}_{rq} - e_{iq}\widehat{\psi}_{rd}) \end{cases} \tag{10}$$

We investigate the stability of the observer by linearizing the two systems (10) and (9) around an equilibrium operating point.Defining the new state vectors $\underline{x} = \underline{x}_o + \delta\underline{x}$ with $\underline{x}_o = [\ \underline{\psi}_{ro}\quad \underline{i}_{so}\quad \omega_o\ ]^T$, $\delta\underline{x} = [\ \delta\underline{\psi}_r\quad \delta\underline{i}_s\quad \delta\omega\ ]^T$ and $\widehat{\underline{x}} = \widehat{\underline{x}}_o + \delta\widehat{\underline{x}}$ with $\widehat{\underline{x}}_o = [\ \widehat{\underline{\psi}}_{ro}\quad \widehat{\underline{i}}_{so}\quad \widehat{\omega}_o\ ]^T$, $\delta\widehat{\underline{x}} = [\ \delta\widehat{\underline{\psi}}_r\quad \delta\widehat{\underline{i}}_s\quad \delta\widehat{\omega}\ ]^T$. The reference frame is synchronized with the estimated rotor flux ($\widehat{\psi}_{rqo} = 0$), then its two components are $\widehat{\psi}_{rd} = \widehat{\psi}_o + \delta\widehat{\psi}_{rd}$ and $\widehat{\psi}_{rq} = \delta\widehat{\psi}_{rq}$. In these two systems, the stator frequencies are regarded as identical : $\omega_s = \widehat{\omega}_s$ [5]. Preserving only dynamic parts, the two systems (9), (10) become after linearization,:

$$\begin{cases} \frac{d}{dt}\delta\underline{\psi}_r = -(\frac{1}{T_r} + j\omega_{s_{lo}})\delta\underline{\psi}_r + \frac{L_m}{T_r}\delta\underline{i}_s - j\Psi_o\delta\omega_{sl} \\ \frac{d}{dt}\delta\underline{i}_s = \frac{L_m}{b}(\frac{1}{T_r} - j\omega_o)\delta\underline{\psi}_r - (a + j\omega_{so})\delta\underline{i}_s + \frac{1}{\sigma L_s}\delta\underline{u}_s - j\frac{L_m}{b}\psi_o\delta\omega - j\underline{i}_{so}\delta\omega_s \\ \frac{d}{dt}\delta\omega = 0, \end{cases} \tag{11}$$

$$\begin{cases} \frac{d}{dt}\delta\widehat{\underline{\psi}}_r = -(\frac{1}{T_r} + j\widehat{\omega}_{s_{lo}})\delta\widehat{\underline{\psi}}_r + \frac{L_m}{T_r}\delta\widehat{\underline{i}}_s - j\widehat{\Psi}_o\delta\widehat{\omega}_{sl} + g_1\delta\underline{e}_i \\ \frac{d}{dt}\delta\widehat{\underline{i}}_s = \frac{L_m}{b}(\frac{1}{T_r} - j\widehat{\omega}_o)\delta\widehat{\underline{\psi}}_r - (a + j\widehat{\omega}_{so})\delta\widehat{\underline{i}}_s + \frac{1}{\sigma L_s}\delta\underline{u}_s - j\frac{L_m}{b}\widehat{\psi}_o\delta\widehat{\omega} - j\widehat{\underline{i}}_{so}\delta\widehat{\omega}_s \\ \frac{d}{dt}\delta\widehat{\omega} = -K_p(-\frac{L_m}{b}\omega_o\widehat{\psi}_o\delta\widehat{\underline{\psi}}_{rd} + \frac{L_m}{bT_r}\widehat{\psi}_o\delta\widehat{\underline{\psi}}_{rq} - \omega_{so}\widehat{\psi}_o\delta\widehat{\underline{i}}_{sd} - a\widehat{\psi}_o\delta\widehat{\underline{i}}_{sq} - \frac{L_m}{b}\widehat{\psi}_o\delta\widehat{\omega}_s) \\ \qquad -K_i(-e_{ido}\delta\widehat{\underline{\psi}}_{rq} + e_{iqo}\delta\widehat{\underline{\psi}}_{rd} + \widehat{\underline{\psi}}_o\delta e_{iq}). \end{cases} \tag{12}$$

Defining $\delta \underline{e} = [\ \delta \underline{e}_\psi \quad \delta \underline{e}_i \quad \delta e_\omega\ ]^T$, the system describing the estimation error is as follows:

$$\begin{cases} \frac{d}{dt}\delta \underline{e}_\psi = -(\frac{1}{T_r} + j\omega_{s_{lo}})\delta \underline{e}_\psi + (\frac{L_m}{T_r} - g_1)\delta \underline{e}_i - j\underline{e}_{\psi_o}\delta \omega_{sl} + je_{\omega_o}\delta \underline{\widehat{\psi}}_r + j\widehat{\psi}_o \delta e_\omega \\ \frac{d}{dt}\delta \underline{e}_i = \frac{L_m}{b}(\frac{1}{T_r} - j\omega_o)\delta \underline{e}_\psi - (a + j\omega_{so})\delta \underline{e}_i - j\frac{L_m}{b}e_{\psi_o}\delta\omega - j\frac{L_m}{b}e_{\omega_o}\delta \underline{\widehat{\psi}}_r \\ \qquad - j\underline{e}_{io}\delta\omega_s - j\frac{L_m}{b}\underline{\widehat{\psi}}_o \delta e_\omega \\ \frac{d}{dt}\delta e_\omega = K_p(-\frac{L_m}{b}\omega_o\widehat{\psi}_o\delta \underline{e}_{\psi d} + \frac{L_m}{bT_r}\widehat{\psi}_o\delta \underline{e}_{\psi q} - \omega_{so}\widehat{\psi}_o\delta \underline{e}_{id} - a\widehat{\psi}_o\delta \underline{e}_{iq} - \frac{L_m}{b}\widehat{\psi}_o\delta e_\omega) \\ \qquad + K_i(-e_{ido}\delta \underline{\widehat{\psi}}_{rq} + e_{iqo}\delta \underline{\widehat{\psi}}_{rd} + \underline{\widehat{\psi}}_o \delta e_{iq}). \end{cases} \tag{13}$$

Separating each state in d and q components, we obtain the corresponding state matrix $\widehat{A}_1$:

$$\widehat{A}_1 = \begin{bmatrix} -\frac{1}{T_r} & \omega_{s_{lo}} & \frac{L_m}{T_r} - g_1 & 0 & 0 \\ -\omega_{s_{lo}} & -\frac{1}{T_r} & 0 & \frac{L_m}{T_r} - g_1 & \widehat{\psi}_o \\ \frac{L_m}{bT_r} & \frac{L_m}{b}\omega_o & -a & \omega_{so} & 0 \\ -\frac{L_m}{b}\omega_o & \frac{L_m}{bT_r} & -\omega_{so} & -a & -\frac{L_m}{b}\widehat{\psi}_o \\ -\frac{L_m}{b}K_p\omega_o\widehat{\psi}_o & \frac{L_m}{bT_r}K_p\widehat{\psi}_o & -K_p\omega_{so}\widehat{\psi}_o & (K_i - aK_p)\widehat{\psi}_o & -\frac{L_m}{b}K_p\widehat{\psi}_o \end{bmatrix} \tag{14}$$

Note the dependency of the dynamic matrix $\widehat{A}_1$ by the operating condition. In order to obtain analytic conditions about the local stability using the necessary condition for stability based on the determinant of (14) [4], it is possible to obtain a relevant result as reported in the next section.

4.2 Stability criterion

We use the following property:

$$det(\widehat{A}_1) = \prod_{i=1}^{5} \lambda_i \tag{15}$$

where λ_i are the eigenvalues of matrix $\widehat{A}_1$.
The determinant of matrix $\widehat{A}_1$ is:

$$det(\widehat{A}_1) = -L_m\widehat{\psi}_o^2 K_i\omega_{so}((\omega_{so} - \omega_o)abT_r + L_m^2\omega_o - L_m\omega_o g_1 T_r + \omega_{so}b)/(b^2Tr) \tag{16}$$

The condition $det(\widehat{A}) = 0$ leads to:

$$\omega_{so} = 0, \tag{17a}$$

$$\omega_{so} = \omega_o \frac{g_1 L_m + R_s L_r}{(R_r L_s + R_s L_r)}. \tag{17b}$$

These conditions of stability may be expressed in the torque/speed plane. Let us consider the mechanical equation:

$$\frac{d}{dt}\omega = p^2\frac{L_m}{JL_r}\Im(\underline{i}_s\underline{\psi}_r^*) - p\frac{T_L}{J}. \tag{18}$$

Under RFOC conditions and steady state ($\widehat{\psi}_{rqo} = \psi_{rqo} = 0$), we obtain:

$$0 = p\frac{L_m}{L_r}\widehat{\psi}_o i_{sqo} - T_{Lo} \tag{19}$$

then

$$i_{sqo} = \frac{L_r}{pL_m\widehat{\psi}_o} T_{Lo}. \tag{20}$$

From system (1), in the same conditions, we find :

$$\omega_{slo} = \frac{L_m}{T_r\widehat{\psi}_o} i_{sqo}. \tag{21}$$

Finally using $\omega_{so} = \omega_{s_{lo}} + \omega_o$, equations (17a) and (17b) become

$$T_{Lo} = -\frac{p\widehat{\psi}_o^2}{R_r}\omega_o \tag{22a}$$

$$T_{Lo} = -\frac{p\widehat{\psi}_o^2}{R_r}\frac{(1-\frac{g_1L_m}{R_rL_s})\omega_o}{(1+\frac{T_s}{T_r})} \tag{22b}$$

with $T_s = L_s/R_s$. Above relations describe respectively two lines, defining two well known instability regions in regenerating mode.
An sufficient condition for instability is then:

$$det(\widehat{A}_1) > 0. \tag{23}$$

The condition (23) defines a set whose the instability region is a subset. In order to complete the study of local stability, we plot for each eigenvalue, the locus in the torque/plane where conditions $(\Re(\lambda_i) > 0,\ i = 1\ldots5)$ are verified.
In one hand, if we chose a zero observer gain, as in [9],

$$g_1 = 0 \tag{24}$$

we obtain the instability region limited by lines D_1 and D_2, (Fig. 1) where $\Re\lambda_i > 0, i = 1...5$, are the positive real part of the eigenvalues λ_i of the state matrix $\widehat{A}_1$. The eigenvalues correspond respectively to the states variables $\delta\underline{e}_{\psi_{rd}}, \delta\underline{e}_{\psi_{rq}}, \delta\underline{e}_{id}, \delta\underline{e}_{iq}$ and δe_{ω}.

$$T_{Lo} = -\frac{p\widehat{\psi}_o^2}{R_r}\frac{\omega_o}{(1+\frac{T_r}{T_s})} \tag{25}$$

In other hand, in order to reduce (not totally remove) the unstable region, a real valued observer gain was considered in [13] which corresponds to the region limited by lines D_1 and D_3, (Fig. 3). The value of the parameter g_1 selected is:

$$g_1 = -0.25R_s \tag{26}$$

It is be noted that the curves corresponding to zero observer gain are similar, except that the unstable region is larger.

$$T_{Lo} = -\frac{p\widehat{\psi}_o^2}{R_r}\frac{(1+\frac{0.25R_sL_m}{R_rL_s})\omega_o}{(1+\frac{T_r}{T_s})} \tag{27}$$

The principle of the instability reduction proposed here consists in the calculation of the feedback gain so that the unstable region will be limited to the inobservabilité line (D_1). We can note that, whatever the structure of the matrix G, (D_1) is always defined by $\omega_{so} = 0$. From equation (16), we can write the

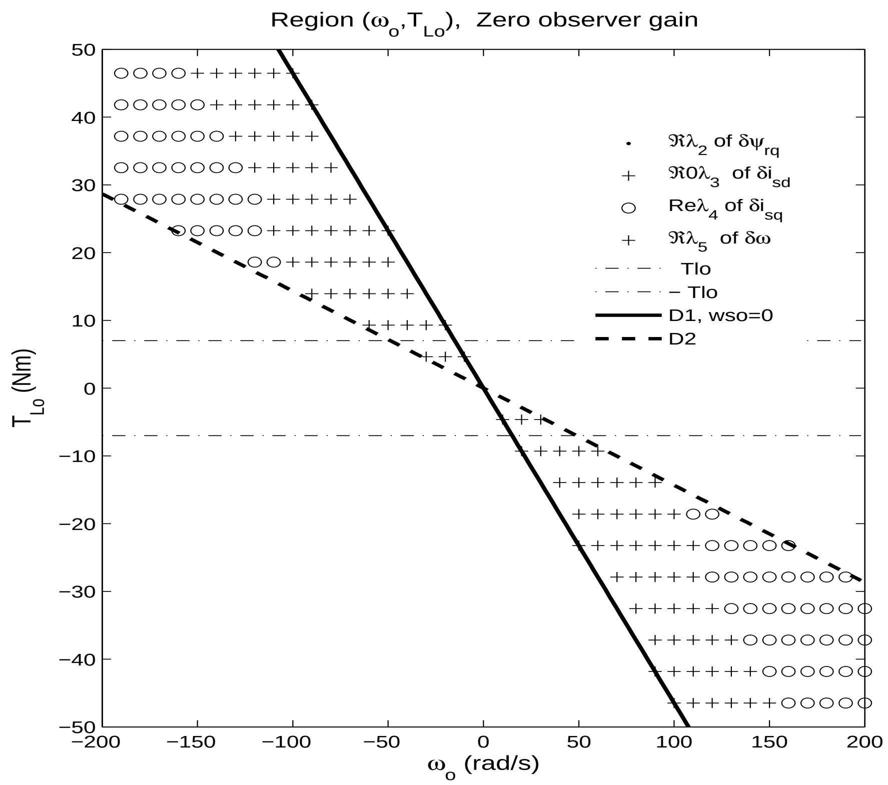

Figure 2: Torque/speed plane, $g_1 = 0$, $\Re(\lambda_i) > 0, i = 1...5$

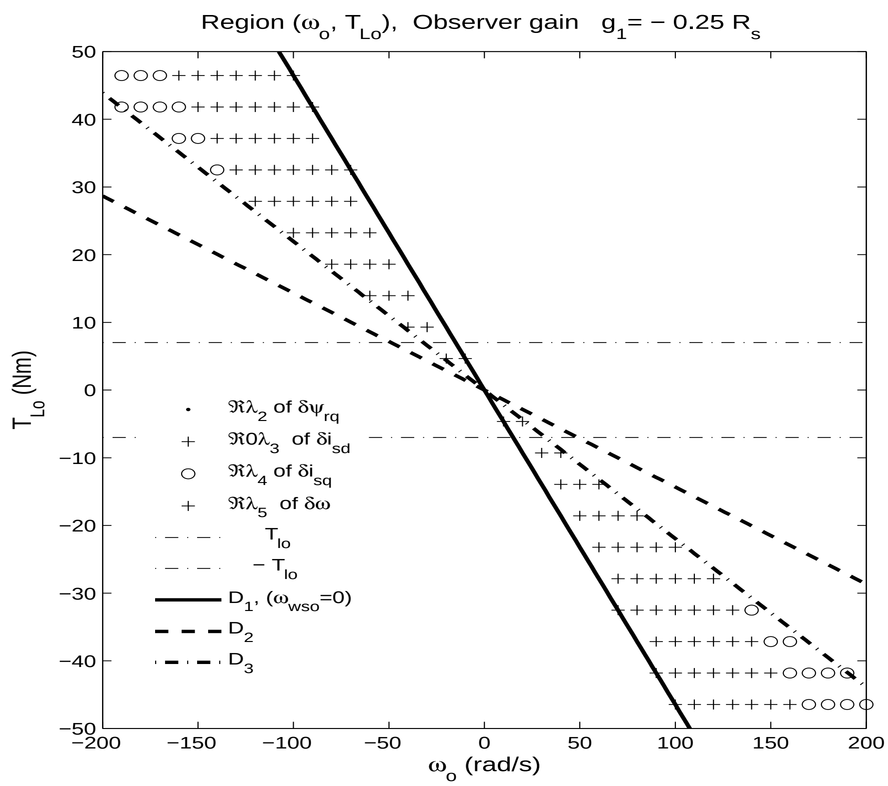

Figure 3: Torque/speed plane, $g_1 = -0.25R_s$, $\Re(\lambda_i) > 0, i = 1...5$

condition $\omega_{so} = 0$ in equation (28)

$$(\omega_{so} - \omega_o)abT_r + L_m^2\omega_o - L_m\omega_o g_1 T_r + \omega_{so}b = 0 \quad (28)$$

which can be achieved by choosing the following observer gains

$$g_1 = -\frac{L_r R_s}{L_m} \quad (29)$$

The straight line (D_1) correspond to zero synchronous speed $\omega_s = 0$. It is known in the literature as the inobservability line (normally referred as dc-excitation) [6, 3] and seems to be a generic problem for sensorless control of induction motors.

5 Simulations results

In order to validate the proposed design, the regenerating mode low speed operation of the speed adaptive observer was investigate by means of simulations. A rotor flux oriented control (RFOC) is simulated using Matlab/Simulink software. The block diagram of the control system is shown in Fig.4. The flux reference is fixed to the nominal value ψ_o^{ref} where ref denotes the reference value. The proposed

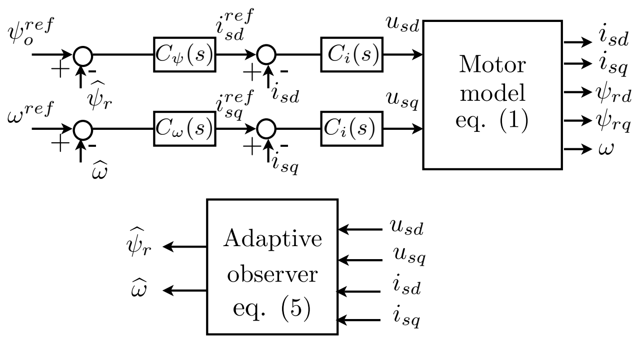

Figure 4: Block diagram of sensorless RFOC induction motor simulator.

observer is compared with an exiting solution [13]. In order to validate the proposed design, we studied a conventional test used by industrial drive designers: very low and progressive load torque increase under constant speed; Fig. 5 depicts results in regenerating mode obtained using the observer gain $g_1 = -0.25R_s$, [13], [5]. The speed reference was set to $(-25rad/s)$ (dashed line) and a rated-load torque ramp was applied at t=0. After applying the load progressively, the drive should operate in the regenerating mode. However, the actual angular speed et actual flux of the motor collapse and the system becomes unstable. Fig. 6 present results obtained using the proposed observer design. The system behaves stably. On Fig. 7, the observer gain $g_1 = -0.25R_s$ was used. Real speed diverges. First subplot shows reference (dashed line) and actual angular speed. Second subplot shows rated-load torque ramp. Third subplot present actual flux components $(\psi_{r\alpha}, \psi_{r\beta})$ in stator reference frame. Fouth subplot, shows control voltages. In the fifth and six subplot respectively, we present current and current norm. We note that when the load torque increases, the control voltage, the current and the current norm increase too.
On Fig.8, the proposed observer design was used. The system becames stable. Real rotor angular speed converges well towards the reference value in response to the same rated-load torque. Note the behavior of the actual flux at $(t \approx 3.75\ s)$ when the real angular rotor speed crosses the line $(D_1 = D_3)$. The system becomes unobservable at this time.

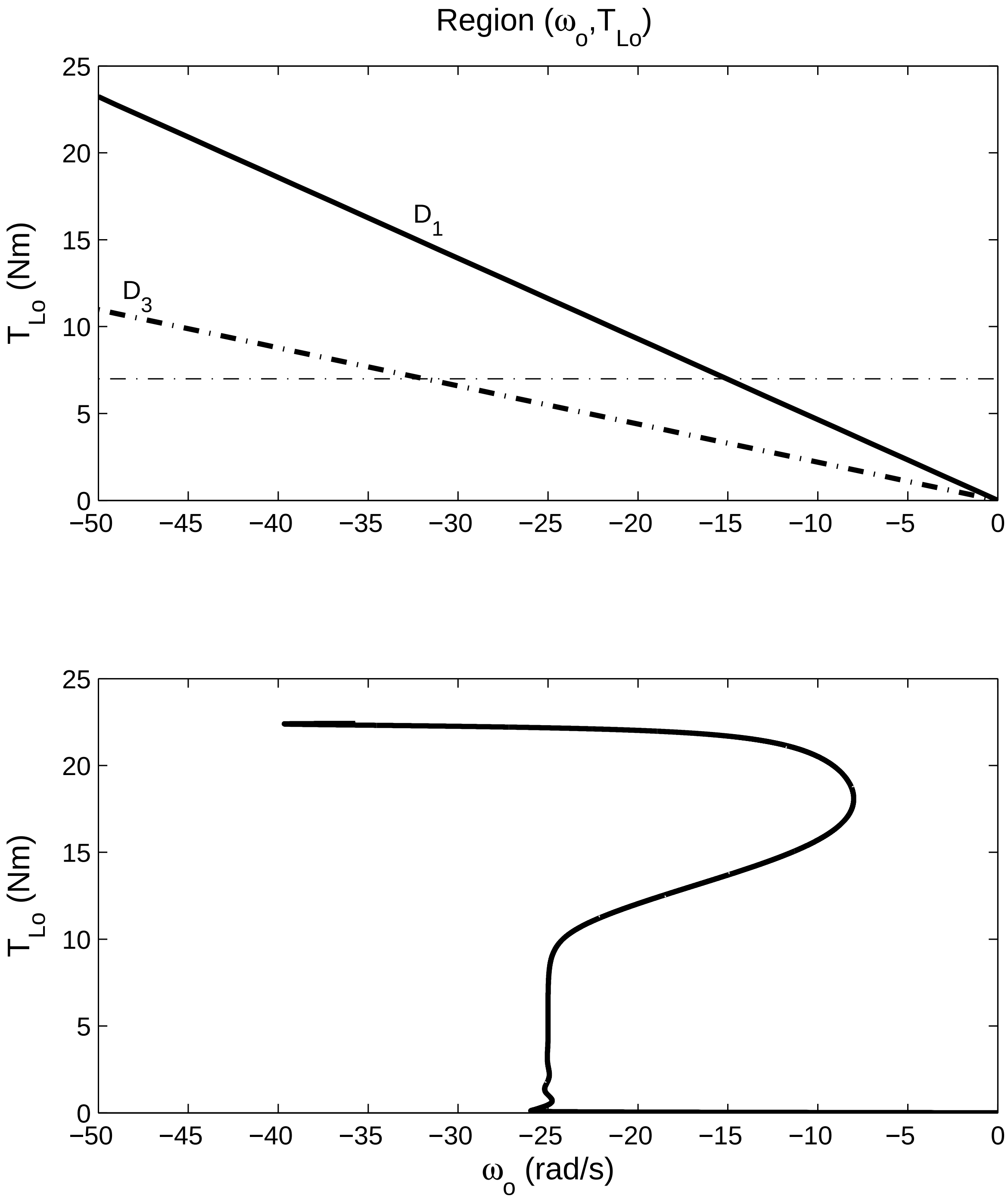

Figure 5: A rated-load torque ramp is applied with the observer gain $g_1 = -0.25R_s$. First subplot shows region (ω_o, T_{Lo}) with the two lines D_1 and D_3. Second subplot shows the actual angular speed.

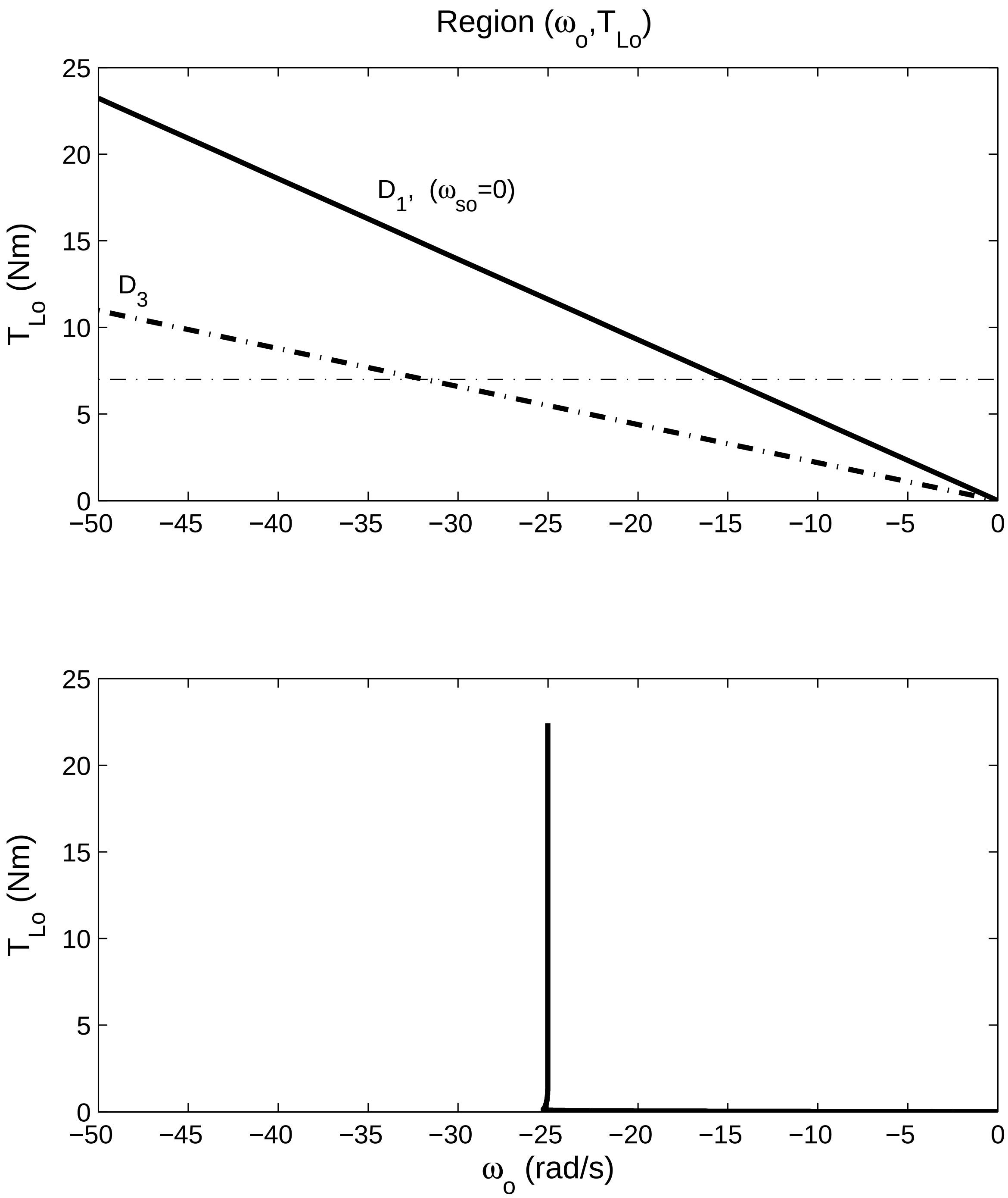

Figure 6: A proposed observer design was used. First subplot shows region (ω_o, T_{Lo}) with the line $D_1 = D_3$. Second subplot shows the actual angular speed.

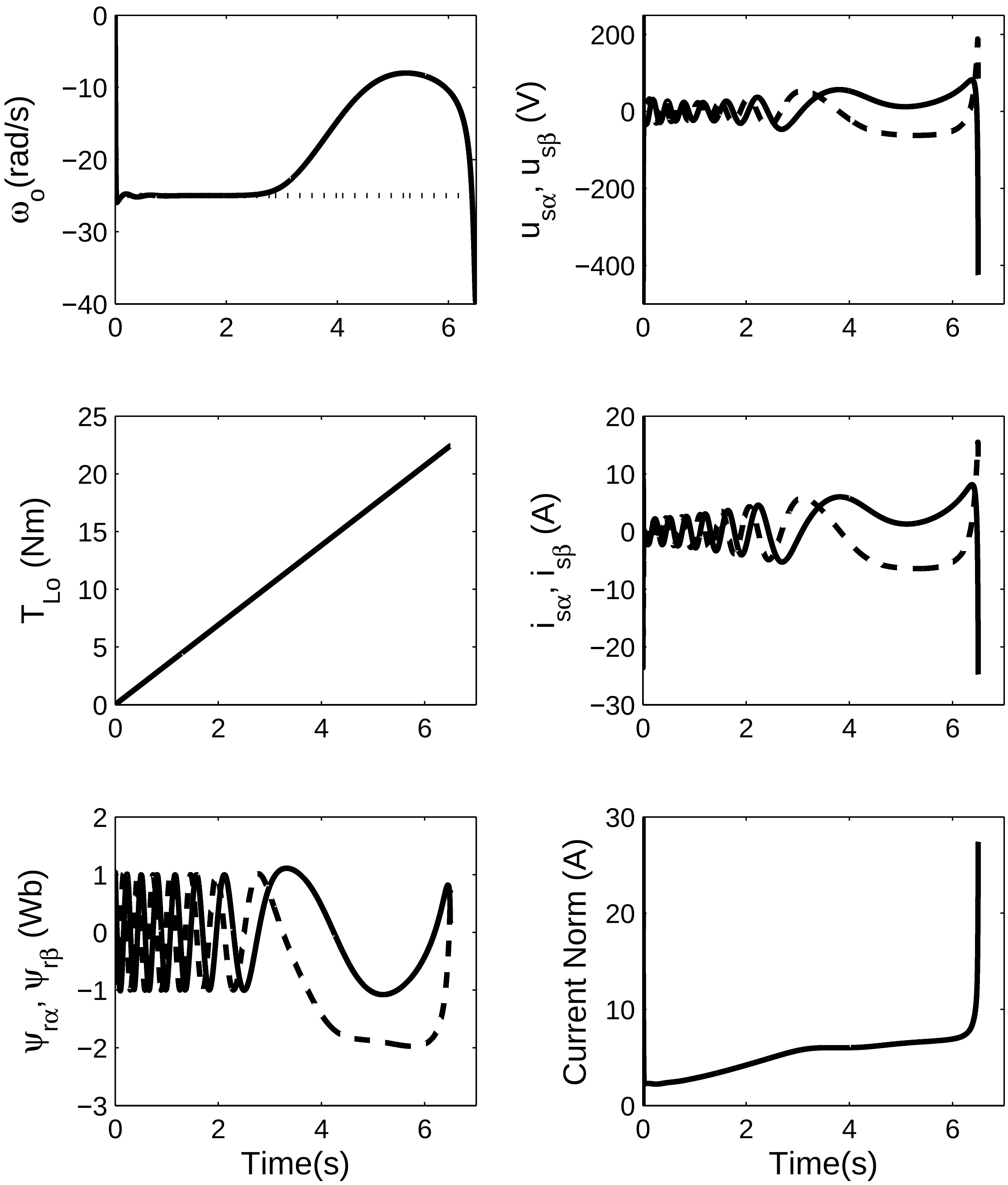

Figure 7: Instability phenomenon with observer gain $g_1 = -0.25R_s$.

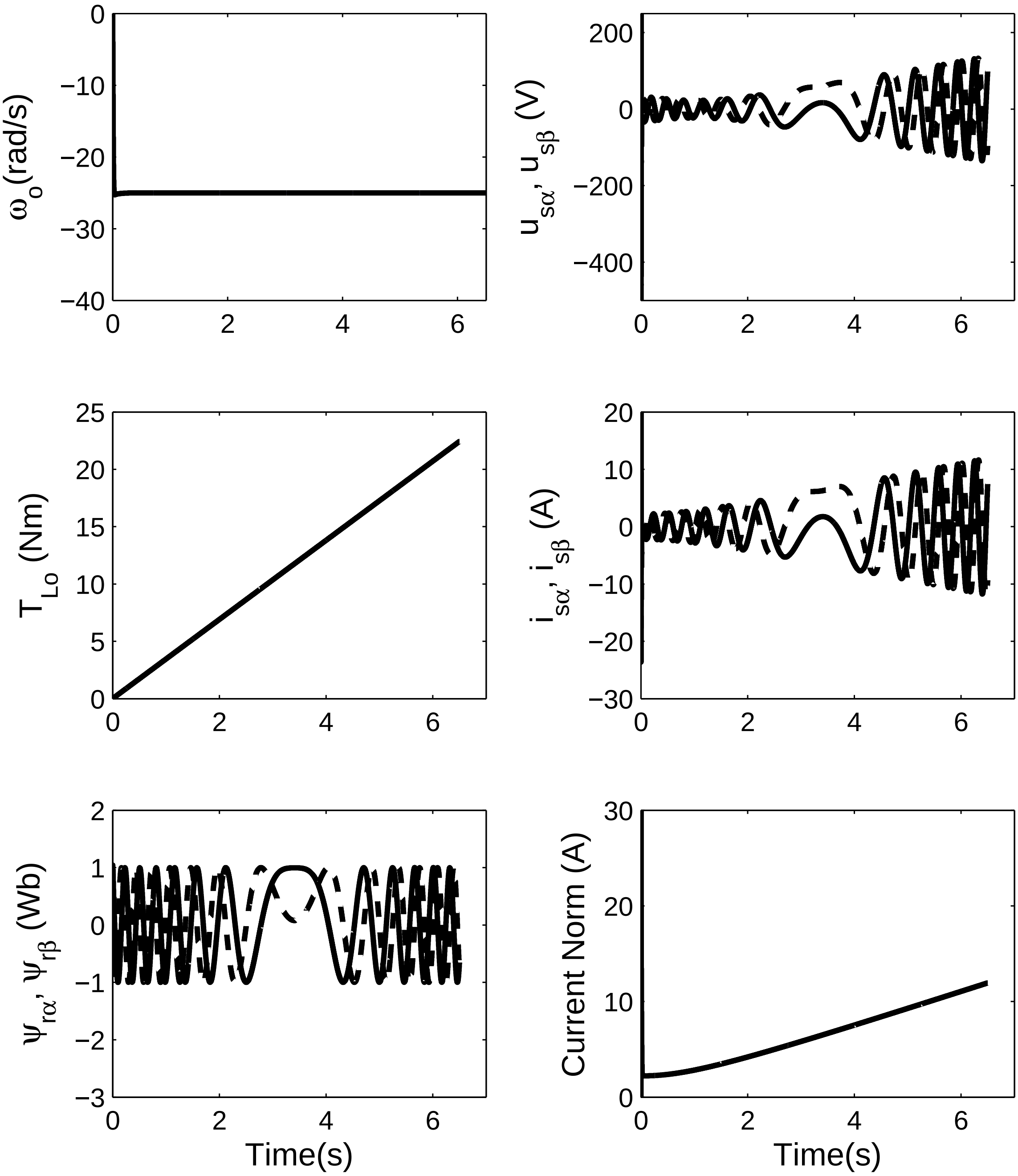

Figure 8: The instability was removed by the proposed observer design $g_1 = -L_r R_s / L_m$.

6 Appendix

6.1 Induction motor parameters

Voltage rating : 380 V, Current rating: 2.2 A, Number of phases: 3, Rated power: 1.1 kW, Frequency: 50 Hz, Rated speed: 1430 rpm/min, $p = 2$, $L_s = 0.472\ H$, $L_r = 0.4721\ H$, $L_m = 0.4475\ H$, $R_s = 9.65\ \Omega$, $R_r = 4.3\ \Omega$.

7 Conclusions

The feedback gain design method proposed in this paper reduces the instability region of adaptive observer to a inobservability line (D_1) $(\omega_{so} = 0)$. The observer using the proposed gain does not have the unstable region, which was shown by means of speed/torque plane and a linearized model. The stability of the regenerating-mode operation was also confirmed by simulations.

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A Neural Approach of Multimodel Representation of Complex Processes

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Abstract: The multimodel approach was recently developed to deal with the issues of complex processes modeling and control. Despite its success in different fields, it still faced with some design problems, and in particular the determination of the models and of the adequate method of validities computation.
In this paper, we propose a neural approach to derive different models describing the process in different operating conditions. The implementation of this approach requires two main steps. The first step consists in exciting the system with a rich (e.g. pseudo random) signal and collecting measurements. These measurements are classified by using an adequate Kohonen self-organizing neural network. The second step is a parametric identification of the base-models by using the classification results for order and parameters estimation. The suggested approach is implemented and tested with two processes and compared to the classical modeling approach. The obtained results turn out to be satisfactory and show a good precision. These also allow to draw some interpretations about the adequate validities' calculation method based on classification results.
Keywords: complex processes, modeling, multimodel approach, Kohonen map

1 Introduction

Nowadays, technological developments increase the complexity of systems. This complexity can be caused by non linearity, non stability, wide operating domain, variations of system parameters or external perturbations. As a result, it is often difficult or even impossible to propose a simple model which could reckon with the whole process complexity by using physical laws. Consequently, it is very useful to focus on advanced and practical approaches in order to handle this complexity.

The multimodel approach has recently been developed and applied in several science and engineering domains. It was proposed as an efficient and powerful method to cope with modeling and control difficulties when complex non linear and/or uncertain processes are concerned. The multimodel approach supposes the definition of a set of models. Then, it becomes possible to replace the unique model by a set of simpler models thus making a so-called models' base. Each model of this base describes the behavior of the considered process at a specific operating point. The multimodel approach objective is to decrease the process complexity by its study under certain specific conditions.

Several researchers have been interested in multimodel analysis and control approaches [7, 8, 19] and many applications have been proposed in different contexts.

In spite of its success in many fields (academic, biomedical, ...), the multimodel approach remains confronted with several difficulties such as the calculation of models' validities, the adequate technique of fusion or switching between models as well as the determination of the models' base.

Indeed, in 1985, Takagi and Sugeno [21] suggested a fuzzy process representation by the contribution of local models. This approach has been applied in many fields of activities but often faced problems related to the lack of information about the system structure or the incertitude of its parameters. Besides, it can sometimes lead to a large number of models which generates a high computational burden when designing the control algorithm. This has led several researchers to develop other approaches in order to cope with these difficulties.

For uncertain complex systems with bounded parameters, some approaches were developed for the determination of the models' base [9, 11]. An extension for uncertain discrete systems has been proposed by Mezghani [13]. The case of multivariable systems was addressed by Raissi [16]. The approaches, previously named, require the knowledge of parameters' variations limits, which is generally not possible, in particular in case of uncertain systems for which parameters variations domains are unknown or ill-known.

Other related studies [12, 19] suggest the system be described by a set of local models often defined by using a reference model and some linearization methods.

In another context, both fuzzy logic and neural networks were carried out for the multimodel control [1, 18]. An idea was to use neural approaches for complex systems modeling. These methods have the advantage of requiring very little information about the considered process and are useful for uncertain systems. Within this context, very few studies [2, 3, 15, 17, 20, 22] were proposed but they don't address strongly non-linear systems.

In this paper, a neural approach for the determination of the models' base for uncertain complex systems is proposed, in particular those which exhibit strong non-linearities. The proposed approach requires a priori little knowledge about the considered system; only input/output information can be sufficient.

In the following section, the different steps of the proposed modeling approach are detailed. Two simulation examples and some interpretations are then presented. The evaluation of the suggested modeling strategy is the topic of the last section. We finish the present paper by a conclusion.

2 Complex systems' modeling: Neural approach

In this section, a models' base-determination approach for uncertain complex systems is described. This approach requires neither a global model definition nor the knowledge of parameters variations domains; only input/output information are needed.

The suggested approach allows the generation of the base-models' structure and parameters. The application of this approach requires first to classify the numerical data by exploiting a Kohonen map and to determine the number of models. Secondly, a structural and parametric identification of different base-models is carried out by using classification results. Then, the validity index of each model is computed. Finally, the multimodel output is obtained by the fusion of the models' outputs weighted by their validity indexes.

2.1 Classification of the numerical data by using a Kohonen map

As a first step, the output or input/output measurements collected from the considered process have to be classified in order to identify operating clusters from which the models' base will be deduced. This classification is carried out by using a self-organizing Kohonen map.

Self-organizing Kohonen map methodology

The Self-Organizing Map (SOM) represents a specific kind of neural networks. In its original form, the SOM was invented by the founder of the Neural Networks Research Center, Professor Teuvo Kohonen in 1981-82. The special property of the SOM is that it effectively creates spatially organized internal representations of various features of input signals and their abstractions [10]. The schematic representation of this network is given in figure 1.

Neurons in the target layer are ordered and correspond to cells of a bi-dimensional map. Every neuron of the input layer is connected to every neuron of the output layer. The classification strategy consists in applying the Kohonen rule. This rule is characterized by an unsupervised competitive learning where a competition takes place before the modification of the network-weights. Only the neurons which win the competition have the right to change their weights.

The Kohonen rule works as follows:

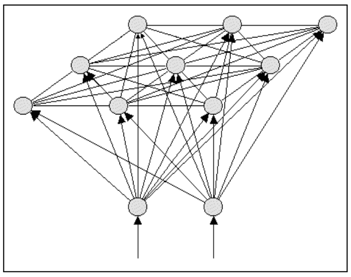

Figure 1: Kohonen map

- weights are initialized to random values;
- an input vector is presented to the network;
- the distance between the input vector and weights connecting inputs to each output neuron is computed;
- the neuron corresponding to the smallest distance, i.e. the nearest to the input vector, wins the competition, weights connecting inputs to this neuron are modified accordingly [5].

This procedure is repeated several times until weights stabilize. At the end of the learning stage, the representative vectors of different clusters and their centers are obtained.

Determination of the operating-system clusters

The determination of the operating-system clusters requires firstly that the considered system be excited. Secondly, the number of clusters has to be determined. The third step consists in classifying data by using a Kohonen neural network.

The first step consists in applying an input signal and then collecting (output or input/output) measurements that will be used for classification. The excitation signal must be rich enough and persistently exciting with well-chosen parameters in order to allow a full excitation of the operating dynamics, and to take in consideration the non-linear aspect of the considered process.

For the second step, the method proposed by Talmoudi has been adopted for the determination of the adequate number of clusters which corresponds to the number of models [22]. Within this scope, a Kohonen network, with an important number n of neurons in the output layer, has been considered. At the end of the learning procedure, if the repartition of classes is not good, the clusters i having a number of elements N_{Ci} verifying the relation (1), will have to be removed [22].

$$N_{Ci} \leq \frac{1}{2}\frac{N_H}{n} \ , \tag{1}$$

where N_H represents the number of the considered measures.

Else, the number of neurons in the output layer is increased and training is restarted. The same procedure is repeated over and over until the satisfactory number of clusters is obtained. Afterwards, the data classification is tackled by using a Kohonen network for which the number of neurons in the input layer equals the number of system-variables to be considered and the number of neurons in the output layer equals the number of clusters determined with the help of the method previously described. The classification results will then be exploited for the identification of the different base-models.

2.2 Parametric identification of the base-models

In this section, the orders of the models are estimated in a first step. The chosen method is the so-called instrumental determinants' ratio-test. This method is mainly based on the conditions concerning a matrix called "information matrix" which contains the input/output measurements [4]. This matrix is described as follows:

$$Q_m = \frac{1}{N_H} \sum_{k=1}^{N_H} \begin{bmatrix} u(k) \\ u(k+1) \\ u(k-1) \\ \vdots \\ u(k-m+1) \\ u(k+m) \end{bmatrix} \begin{bmatrix} y(k+1) & u(k+1) & \cdots & y(k+m) & u(k+m) \end{bmatrix}, \tag{2}$$

where N_H is the number of observations. The instrumental determinants' ratio (*RDI*) is given by:

$$RDI(m) = \left| \frac{det(Q_m)}{det(Q_{m+1})} \right|. \tag{3}$$

For every value of m, the determination procedure of the order consists in building the matrices Q_m and Q_{m+1} and in evaluating the ratio $RDI(m)$, the retained order m is the value for which the ratio $RDI(m)$ quickly increases for the first time.

As a second step, the parametric identification issue consists in calculating the values of the parameters of the corresponding model-equation, given several experimental measures which describe the dynamic behavior of the system. As previously mentioned, the data classification gives a certain repartition of clusters. For each cluster, input/output measurements are collected. These measurements allow the identification of the corresponding model. For this, the recursive least-squares method (*RLS*) [4] was applied to achieve the parameters estimation.

2.3 Computation of Validities

The validity coefficient is a number belonging to the interval [0 1]. It represents the relevance degree of each base-model calculated at each instant. In literature, several methods have been proposed to deal with the validity issue. In our study, the residues' approach was adopted for the calculation of validities. This method is based on the distance measurement between the process and the considered model. For example, the residue can be given by the following expression:

$$r_i = |y - y_i| \qquad i = 1, \ldots, N \tag{4}$$

where: N: number of base-models;
y: process output;
y_i: output of the model M_i.

If this residue value is equal to zero, the corresponding model M_i perfectly represents the process at that time. On the contrary, a non null value translates the fact that the model M_i represents the system partially. The normalized residues are given by:

$$r_i' = \frac{r_i}{\sum_{j=1}^{N} r_j} . \tag{5}$$

Within the context of the residues' approach, several methods have been proposed for the calculation of validities [6, 13, 14]. Only two methods will be considered: the simple and the reinforced validities. The validities are given by:

$$v_i = 1 - r_i'. \tag{6}$$

The simple and reinforced validities are defined by using the following formulas.

Simple validities: the normalized simple validities are defined so that their sum must be equal to 1 at each time:

$$v_i^{simp} = \frac{v_i}{N-1} \quad . \tag{7}$$

Reinforced validities: for this type of validities, the reinforcement expression is introduced as:

$$v_i'^{renf} = v_i \prod_{j=1,\, j\neq i}^{N} (1 - v_j)\,. \tag{8}$$

The normalized reinforced validities could be written as follows:

$$v_i^{renf} = \frac{v_i'^{renf}}{\sum_{j=1}^{N} v_j'^{renf}} \quad . \tag{9}$$

2.4 Computation of the multimodel output

The multimodel output is calculated by a fusion of the models' outputs weighted by their respective validity indexes, as illustrated by the following expression:

$$y_{mm}(k) = \sum_{i=1}^{N} y_i(k)\; v_i(k)\,. \tag{10}$$

$v_i(k)$ could be a simple or a reinforced validity for which $\sum_{i=1}^{N} v_i(k) = 1$.

3 Simulation examples

In order to underline the interest and the performance of the proposed approach, some simulation examples are carried out.

3.1 Example 1: second order discrete system

The considered system is a complex discrete system whose evolution is described by the following equation:

$$y(k) = -a_1(k)\; y(k-1) - a_2(k)\; y(k-2) + b_1(k)\; u(k-1) + b_2(k)\; u(k-2)\,. \tag{11}$$

The variation laws of different parameters of the process are given by:

$$a_1(k) = 0.04\sin(0.035k) - 0.8\;,\; a_2(k) = 0.005\sin(0.03k) + 0.1\,, \tag{12}$$

$$b_1(k) = 0.02\sin(0.03k) + 0.5\;,\; b_2(k) = 0.01\sin(0.035k) + 0.2\,. \tag{13}$$

First, the system is excited by a uniform random signal $u(k\,)$. Then, the measurements $y(k\,)$ and $y(k-1)$ are collected at different instants.

The adequate number of clusters determined by using the method described in paragraph 3.1.2, is equal to three. The numerical data are fed into a Kohonen network which presents an input layer with two neurons and three neurons in the output layer. The classification results are given in figure 2.

From each of the three data sets relative to the various clusters, the orders and the parameters of the transfer functions relative to the three base-models are estimated. Figure 3 shows the evolutions of the $RDI_i(m)$ for the three models.

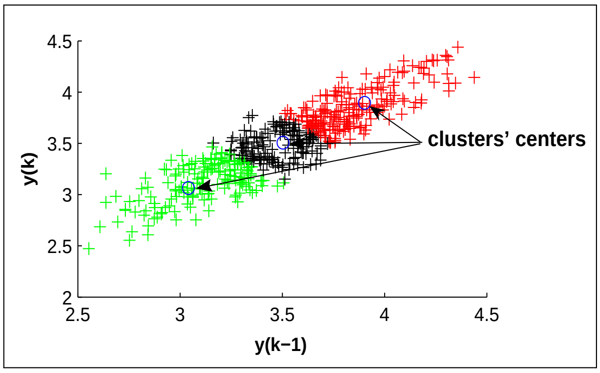

Figure 2: Classification results

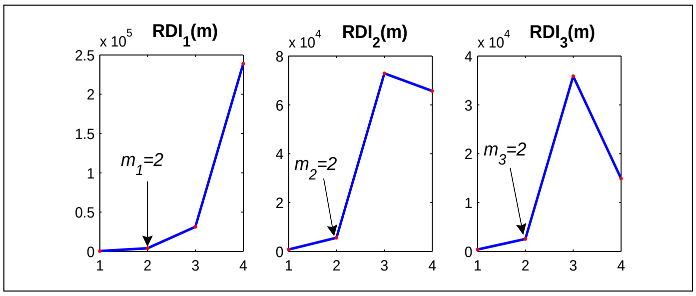

Figure 3: Evolutions of the RDI for the three base-models

It appears clearly that the estimated orders of the three models are equal to two. This result is predictable since the considered system is a second order one. The application of the recursive least-squares method allows us to write the following transfer functions:

$$F_1(z^{-1}) = \frac{0.33549\,z^{-1} - 0.047793\,z^{-2}}{1 - 0.83697\,z^{-1} - 0.039754\,z^{-2}}\ , \tag{14}$$

$$F_2(z^{-1}) = \frac{0.41086\,z^{-1} - 0.021659\,z^{-2}}{1 - 0.8633\,z^{-1} - 0.055068\,z^{-2}}\ , \tag{15}$$

$$F_3(z^{-1}) = \frac{0.36985\,z^{-1} - 0.0079934\,z^{-2}}{1 - 0.9234\,z^{-1} - 0.060727\,z^{-2}}\ . \tag{16}$$

In order to evaluate the obtained global model, a validation step is worked out where other inputs which are different from those used for classification are fed into the system. Then, the real and the multimodel outputs are compared. Let us consider the following input sequence:

$$u(k) = 1 + \sin(0.08k)\,. \tag{17}$$

The validation results are given in figures 4 and 5.

y: real output of the system.

ymm_r, ymm_s: multimodel outputs obtained by using respectively the methods of reinforced and simple validities.

$$y_{mm_r}(k) = \sum_{i=1}^{N} y_i(k)\ v_i^{renf}(k)\,,\ y_{mm_s}(k) = \sum_{i=1}^{N} y_i(k)\ v_i^{simp}(k)\,. \tag{18}$$

e_r, e_s: relative errors between the real and the multimodel outputs.

$$e_r(k) = \left|\frac{y(k) - y_{mm_r}(k)}{y(k)}\right|,\ e_s(k) = \left|\frac{y(k) - y_{mm_s}(k)}{y(k)}\right|. \tag{19}$$

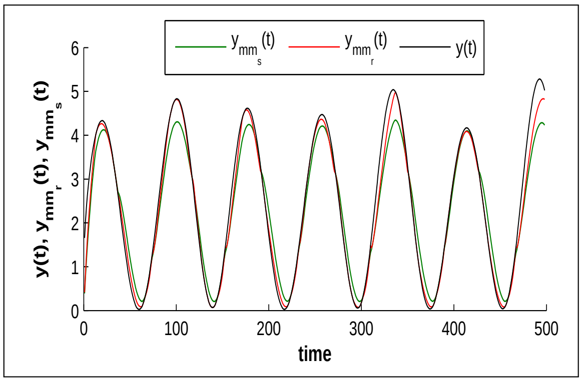

Figure 4: Real and multimodel outputs

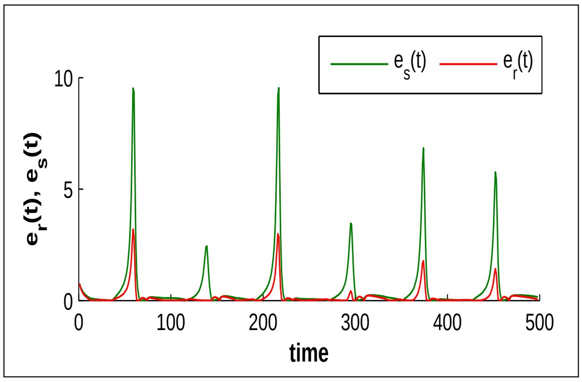

Figure 5: Evolutions of the relative errors

It can be seen that the multimodel output, obtained by the fusion of the base-models' outputs weighted by the reinforced validities, follows the real output with a negligible error ($e_r(t)$). This error is more important when applying the simple validities method ($e_s(t)$). This allows to conclude that, for this kind of system, the reinforced validities method is more appropriate than the simple validities one.

3.2 Example 2: second order continuous system with input/output-dependent parameters

As a second simulation example, we consider the system whose evolution is described by the following equations:

$$a_0 y + a_1 \dot{y} + \ddot{y} = u + b\dot{u}\,, \tag{20}$$

$$a_0(y) = 0.3 + sigm(y-2)\,,\, a_1(y) = sat(y^2)\,,\, b(u) = sat(u)\,, \tag{21}$$

sigm is the sigmoid function; *sat* is the saturation function.

The considered system is complex and strongly non-linear with parameters being functions of both the input and the output, which makes the modeling task difficult.

The chosen excitation signal (figure 6) is a sine curve distorted by a random uniform signal since this input is richer than a simple random signal and allows considering the complex and non-linear aspects of the system. It is worthy to note that signal parameters (frequency, amplitude) need to be adjusted in order to obtain good results.

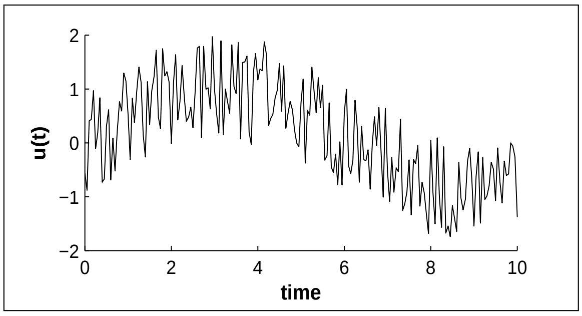

Figure 6: Evolution of the excitation signal

Moreover, in order to describe the system dynamics, the number of variables used for classification is increased. In fact, not only the output data $y(k)$ and $y(k-1)$ are considered but also the input data

$u(k-1)$. After generating the output, a sampling of the input and output signals followed, with an adequate sampling period, in order to collect the different measurements: $y(k)$, $y(k-1)$, and $u(k-1)$.

Once the number of clusters determined, the numerical data are presented to a Kohonen network owning three neurons in both input and output layers. At the end of the learning procedure, three data sets (figure 7) are obtained, each of which being used for the identification of the corresponding model.

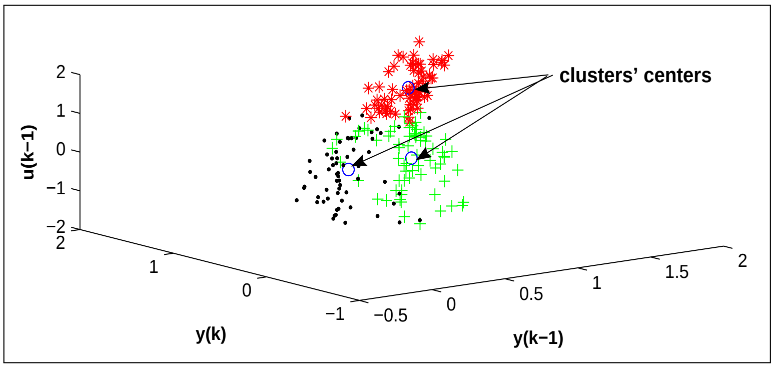

Figure 7: Three data sets relative to the different clusters

The application of the instrumental determinants' ratio-test method allows us to determine the three models' orders which are respectively: two, three and two. The corresponding transfer functions are given by the following expressions:

$$F_1(z^{-1}) = \frac{0.058303\,z^{-1} + 0.052302\,z^{-2}}{1 - 0.43246\,z^{-1} - 0.45748\,z^{-2}}\ , \tag{22}$$

$$F_2(z^{-1}) = \frac{-0.023815\,z^{-1} + 0.0013593\,z^{-2} + 0.031481\,z^{-3}}{1 - 0.68802\,z^{-1} - 0.24025\,z^{-2} - 0.072128\,z^{-3}}\ , \tag{23}$$

$$F_3(z^{-1}) = \frac{0.12995\,z^{-1} - 0.014359\,z^{-2}}{1 - 0.64023\,z^{-1} - 0.37958\,z^{-2}}\ . \tag{24}$$

The application of the following input sequence is the purpose of the validation step:

$$u(k) = 1 + \sin(k)\,. \tag{25}$$

The validation results are illustrated by the figures 8 and 9.

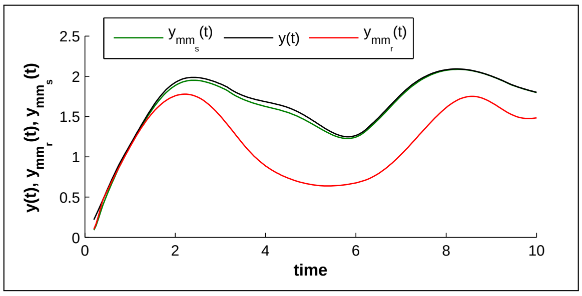

Figure 8: Real and multimodel outputs

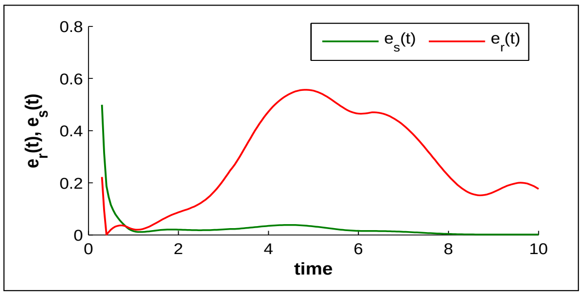

Figure 9: Evolutions of the relative errors

Contrary to the first example, the results obtained by the application of the simple validities' method are much better than those given by the reinforced validities' method. In fact, the figures 8 and 9 show that the multimodel output $y_{mm_s}(t)$, deducted by fusion of the base-models' outputs weighted by the simple validities, follows almost perfectly the real output with an error $e_s(t)$ nearly null compared to the

error $e_r(t)$ which is relatively important.
In order to give prominence to the capacity of the identified models to reproduce the operating system in different domains, let us consider another input sequence given by:

$$u(k) = 1.2 + 1.5\sin(2k). \tag{26}$$

The multimodel output is generated by application of the simple validities' method. The result is given in figure 10.

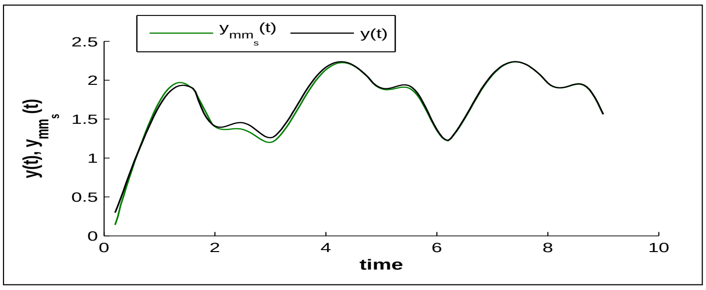

Figure 10: Real and multimodel outputs (second validation)

3.3 Interpretations

Referring to the obtained simulation results, it can be noticed that the application of the suggested approach allows a good modeling of the considered systems.
We can also make an important interpretation about the use of the validities' calculation methods. As remarked before, in some cases simple validities give better results and in other cases it is preferable to use reinforced validities. So, more simulations and observations were worked out to conclude that the choice of the validities' calculation method depends on the classification results i.e. the clusters structure and repartition. Thus, it can be noted that when there are several variations in the same cluster and when an overlapping between clusters occurs, which is the case in the second simulation example (figure 7), it is worth to use the simple validities' method since it takes account of different models' outputs refering to the expression (7). In this case, no model could represent ideally the process at any time. But when the clusters present very few variations and are well separated (figure 2), the reinforced validities' method is better-adapted. The application of this method, thanks to the reinforcement expression (8), promotes the contribution of the most dominant model which represents at best the process behavior.

4 Evaluation of the suggested modeling strategy

In order to highlight the interest and the performance of the proposed modeling strategy, the classical modeling approach involving the identification of a global model was carried out. Then, the results given by the suggested approach were compared to those given by classical modeling strategy.
Let us consider the second simulation example described by the equations (20) and (21) and the excitation signal given by figure 6. By using the instrumental determinants' ratio-test method for the estimation of the order and the recursive least-squares method for the parametric identification, the transfer function $F(z^{-1})$ of the global model is given by the following expression:

$$F(z^{-1}) = \frac{0.03601\,z^{-1} + 0.0035236\,z^{-2}}{1 - 0.55726\,z^{-1} - 0.42595\,z^{-2}} . \tag{27}$$

By using the same numerical data, the classification and the identification steps give the three models described by equations (22), (23) and (24). The input sequence given by the equation (25) was applied again. Figure 11 represents the evolutions of the real, the multimodel and the global model outputs. The multimodel output is obtained by fusion of the models' outputs weighted by their simple validities degrees calculated at each instant.

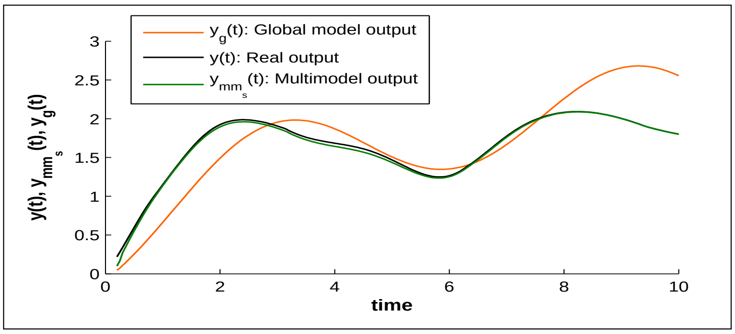

Figure 11: Evolutions of the real, multimodel and global model outputs

The adopted multimodel approach offers a very satisfactory precision compared to the case of the classical modeling approach based on the unique global model.

5 Conclusion

In this paper, a neural approach of multimodel representation is proposed. This approach is applicable when dealing with complex, strongly non-linear and uncertain processes. It allows the determination of the models' base by using a Kohonen network and two methods of structural and parametric identification. The different steps were detailed. The multimodel output is obtained by using the technique of fusion and the adequate validities' computation method. The suggested approach has been implemented and tested for different complex systems. Simulation results, two of which were described in this paper, prove the efficiency and the precision of the proposed modeling strategy and show that the method works well with various processes even when highly complex. Some interpretations have been made about the choice of the adequate validities' calculation method to be applied. Furthermore, in order to demonstrate the performance and the relevance of the suggested approach, a comparison with the classical modeling approach has been made.

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Antenna Arrays Principle and Solutions: Robust Control Approach

Florin Hutu, Sebastien Cauet, Patrick Coirault

Abstract: This paper treats solutions on the ability of a chain of non identical oscillators to drive antenna arrays. Frequency approaches were studied in order to solve the problem of synchronization of the oscillators. However, in this article, a new structure of chain of oscillators is introduced. Secondly, Lyapunov theory of stability is used to design a dynamical controller guarantying the oscillators synchronization. The problem of synchronization is transformed into a problem of asymptotic stabilization for a nonlinear system. It is formulated as a system of linear matrix inequalities where the parameter variations of the two oscillators and their differences are modeled by polytopic matrices. The theoretical result is successfully applied to an array of transistor-based oscillators used in "smart antenna" systems.
Keyword : Nonlinear systems, Control applications, Antenna arrays

1 Introduction

The demand of mobile communication services is in a continuous growth, moreover, it is estimated that the rate will be maintained in the next years. This continuous development has stimulated the research of new hardware and software solutions in order to increase the volume of exchanged data and a better management of the emitted or received electromagnetic field.

Smart antenna arrays comprise a number of antennas that work in conjunction with an intelligent system that processes the received and transmitted data. The processing can be realized in a hardware or in a software way and allows smart antenna arrays to focus beams into particular directions.

This problem can be partially solved by using several directional antennas. This solution divides the 360-degree coverage area into sectors. However, smart antenna arrays provide a much more effective solution by focusing the transmitted power toward user and only looking in the direction of the user for the up link signal. This ensures that the user receives the optimum quality of service and the maximum coverage from a base station.

The new technologies development increases the antenna array performances and minimizes the costs of production and the occupied space. It makes them implementable in domains like wireless or satellite communications, radar systems, missile defense systems, automobile industry, etc.

Smart antennas or antenna arrays are a part of communication systems that can improve their global performances. This technique can increase the spectral efficiency and reduce the multi path fading, bit error rate (BER), the co-channel interferences (CCI) and the system complexity [1]. This is possible by electronically adjusting the beam pattern of the antenna array in order to provide important gain for the desired signals and small gain for interference signals.

At emission, the purpose of smart antennas is to minimize the interference between the different transmitters who works on the same communication channel and, thus to more efficiently use the emitted power. For this reason, the beam shape must be controlled in order to minimize the amplitude of the side lobes and to maximize the energy in the main lobe. Moreover, the direction of the main lobe must be controlled. the focused application is inter-vehicle communication. The bandwidth will be, first of all, in the area of 24Ghz and finally around 79GHz. At these frequencies, technique like "software defined radio" can not be used. One of the main objectives that is pointed out is to develop a structure which will extend in both space and time the safety information available to drivers by using the infrastructure and vehicles as sources.

When the smart antennas are used in reception systems, the signals coming from interference directions must be rejected and those which comes from the desired directions must be privileged. For this reason, different phases and amplitudes must be assured by the carrier signals locally generated [2, 3, 4].

The work that has been done in the field of dynamics of coupled nonlinear systems using the frequency approach [5][6, 7][8] shows that they offer methods of phase control among array elements and beam scanning capabilities but also implies problems of stabilization.

The proposed structure of the array of antennas is based on unidirectional coupled oscillators.

In details, this paper treats the synchronization of a system made by two oscillators with an unidirectional coupling and this problem of synchronization is transformed in a problem of stabilization for a nonlinear system. The strategy chosen is to find an output feedback dynamic controller using Lyapunov functions that assures a robust synchronization despite parameters variations of the oscillators.

The problem of computing dynamic output feedbacks on LTI (linear time-invariant) systems in term of matrix inequalities is difficult to solve. There are two known techniques: the iterative algorithms and the cancellation of variable products by using the matrix separation lemma. The reader can found some papers on treatment of this problem by LMI (Linear Matrix Inequality)-s who can be numerically solved [9, 10, 11, 12, 13].

The variations of the parameters of the oscillators are taken into account by considering the state matrix as a polytopic one. The polytopic structure is easily tractable by Linear Matrix Inequalities. Once the stability of the vertices, defined for the polytope is proved, the stability and the synchronization of the two oscillators is assured for all systems inside the polytope.

The nonlinear character of the oscillators allows the synchronization (if their free running frequencies are in a certain domain [6]) but also makes them dependent of initial conditions. The main objective is to cancel the nonlinear effect and to maintain the synchronization when the physical parameters of the oscillators and external conditions are modified. The originality of the method comes from the inclusion of the non-linear term and the undesired variations in a perturbation. This problem is transformed in a $\mathcal{H}_\infty$ optimization.

In section 2 is presented an overview of the antenna array theory. In section 3 a model of Master and Slave oscillators and the controller synthesis are introduced. Section 4 presents the numerical results in the case of an array of coupled nonlinear oscillators.

2 Antenna array theory overview

2.1 Theoretical background

A smart antenna is composed by an array of individual radiative elements (elementary antennas), which are placed in a particular configuration (linear, circular or matrix). By gathering these elementary antennas in such arrays and by changing the characteristics of the signals associated to each element, the array can present different gains according to the direction.

Let us consider an uniform linear array of N identical patch antennas placed at the same distance d between them as in Fig. 1.

For the theoretical study of this configuration, it is assumed that in the elementary antennas, harmonic signals of the same frequency but different amplitudes and phases are injected.

The mathematical expression of the total electromagnetic field generated by the array in far-field regions (Fraunhofer regions) can be written as the product of the electromagnetic field of the reference antenna (which is considered the first antenna in the array) and a term which depends on the amplitudes and phases of the injected signals

$$\mathbb{E}_{total} = \mathbb{E}_{ref} * f(\Theta). \tag{1}$$

Thereafter, the gain of the antenna array will be considered, knowing that it is a normalization of the

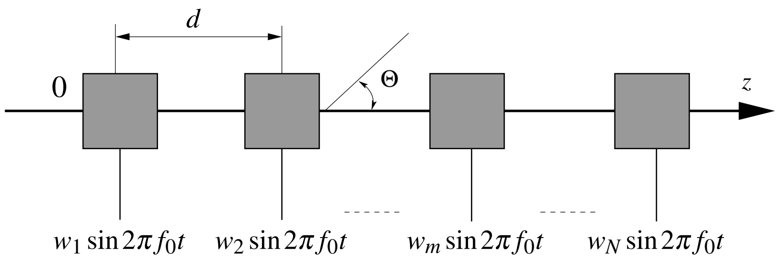

Figure 1: An uniform antenna array

amplitude of the electromagnetic field. The array factor can be written as

$$f(\Theta) = \sum_{m=1}^{N} \mathbf{w_m} e^{-j(m-1)k_0 d \cos\Theta}, \tag{2}$$

where $\mathbf{w_m} = A_m e^{j\varphi_m}$.

In the easiest emission case, the amplitudes have the same value, the mathematical expression of the radiation pattern is

$$f(\theta) = \frac{1}{N} \frac{\sin\frac{N\gamma}{2}}{\sin\frac{\gamma}{2}}, \tag{3}$$

where $\gamma = \varphi - k_0 d \cos(\theta)$, N the number of antennas, d the distance between them. It can be seen that a quantity of the radiated energy is lost in the side lobes which implies a certain weakening of the antenna array gain.

It is obvious that in the emission case, both variations of the amplitudes and the phases of the carrier signals are in a large interval. This paper proposes a new technique to generate such signals, which have the same frequency and different phases and amplitudes. It can be concluded that both variations of the amplitudes and phases are in a large interval.

3 Problem formulation

3.1 Problem statement

If the amplitude variation can be easily solved by using variable gain amplifiers, the problem of the phase variation is more constraining.

There are several techniques which permits solving this problem. The main technical problem with beamforming for transmit is realizing the phase and amplitude of the signals in each antenna channel. The first step will be generating the reference signal with the selected or required frequency. It has to be modulated with the information to be transmitted (e.g. radar, communication). Then it has to be amplified and distributed to all transmit channels. Then the individual signals have to be weighted for beamforming, that means amplified or attenuated, according to the desired weighting amplitude. The desired phase has to be realized by a suitable steerable phase shifter or delay line. Digital devices are now available, under the headline "software defined radio". This technique is not usable on frequencies over 400 Mhz. Here, techniques, which are pointed out, are designed for applications over 2GHz.

Techniques can be divided into both main approaches. The first approach uses the signal generated by one oscillator and the second which uses signals generated by array of coupled oscillators.

Signals with the same frequency but different phases and amplitudes can be built by delaying the signal generated with one master oscillator using high-frequency power dividers and variable delay lines or Butler couplers. This approach is very useful when discrete-time systems are built. Another approach is to use polyphasic oscillators and a multiplexing system [5]. But in these techniques, it can not be obtained continuous phase variations.

The second approach is based on the synchronization of arrays of oscillators having their free running frequencies with a weak dispersion. In [6, 8] it was demonstrated that arrays of coupled nonlinear oscillators can synchronize. Moreover, according to the coupling strength and to free-running frequencies, phase variations can be made. Recent works [14] shows how the phase variation can be guaranty by changing only the free-running frequencies of all coupled oscillators in the array.

In order to generate these carrier signals, the following general schematic Fig. 2 is proposed.

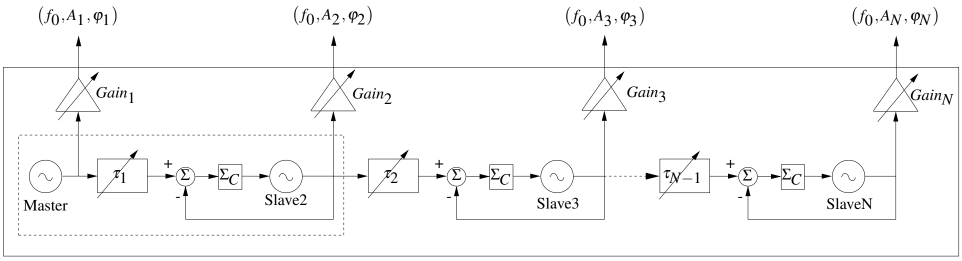

Figure 2: Unidirectional coupling of a chain of oscillators

This schematic is a variation of the York's approach shown in [15]. Because of the unidirectional coupling, each slave oscillator is driven only by its left neighbor. Hence, the study of this configuration is reduced to the study of a pair of two non-linear systems (Master-Salve synchronization). The purpose is to design the parameters of the controller system Σ_C in order to make the output $y_e(t)$ tends toward zero. When this objective is fulfilled, the delayed output of the master oscillator and the output of the slave oscillator become identical, so both oscillators are synchronized.

Generally, because of the technological realization, the oscillators don't have the same free running frequencies. This is the reason why the feedback loop was introduced to guarantee the robust synchronization between both oscillators. The delay element and the variable gain amplifier will guaranty different phases and amplitudes for the output signals.

The difference between the oscillators will be modeled as a variation of the slave oscillator parameters around those of the master oscillator parameters, which is considered as the reference. The variations due to the temperature or at the ageing of the components are modeled by a polytopic uncertainty of the master oscillator parameters around the nominal values.

The oscillators are built using a double differential pair structure. In order to determine the parameters of the dynamical controller, the nonlinear oscillators is modeled using the van der Pol model.

In this article, we consider that the system is a perturbed van der pol model as:

$$\begin{cases} \dot{x} = A(\theta_1)x + g(x,t,\theta_1) + Bu \\ y = Cx \end{cases}, \tag{4}$$

where

$$x = \begin{bmatrix} i_L \\ v_0 \end{bmatrix} \quad A(\theta_1) = \begin{bmatrix} 0 & \frac{1}{L_0} \\ -\frac{1}{C_0} & 0 \end{bmatrix} \quad u = \frac{i_{inj}}{C_0}$$
$$g(x,t,\theta_1) = \begin{bmatrix} 0 \\ \frac{\alpha}{C_0}x_2 - \frac{\beta}{C_0}{x_2}^3 \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad C = \begin{bmatrix} 0 & 1 \end{bmatrix}, \tag{5}$$

with the uncertain parameters $\theta_1 = [\alpha, L_0, C_0]$.

3.2 Master-slave synchronization

The structure is made up by two different systems which belong to the class previously described. The master system is considered independent ($u = 0$) and the dynamical controller Σ_C drives the slave system using the error signal as reference. The error signal is constituted by the difference between a delayed version of the master output and the slave output.

The state-space representation of the master system can be written as follows

$$\Sigma_M : \begin{cases} \dot{x_M} = A_M(\theta_1)x_M + g_M(x_M, t, \theta_1) \\ y_M = Cx_M \end{cases} . \tag{6}$$

For the slave system, the state-space representation can be written as

$$\Sigma_S : \begin{cases} \dot{x_S} = A_S(\theta_1)x_S + g_S(x_S, t, \theta_1) + B_2 u \\ y_S = Cx_S \end{cases} . \tag{7}$$

Between the parameters of the master and the slave oscillators, it is considered that there is the same difference δ

$$\begin{cases} L_S = L_M\,(1+\delta) \\ C_S = C_M\,(1+\delta) \\ \alpha_S = \alpha_M\,(1+\delta) \\ \beta_S = \beta_M\,(1+\delta) \end{cases} . \tag{8}$$

In that case, this notation can be introduced

$$A_M(\theta_1) = A_S(\theta_1) + B_1(\theta_2). \tag{9}$$

This difference is transformed into the difference between the state matrix of the master and the slave. With the assumptions in (8), $B_1(\theta_2)$ can be written as follows

$$B_1(\theta_2) = \begin{bmatrix} 0 & -\dfrac{\delta}{L_M\,(1+\delta)} \\ \dfrac{\delta}{C_M\,(1+\delta)} & 0 \end{bmatrix} . \tag{10}$$

If an error state is defined as

$$e(t) = x_M(t-\tau) - x_S(t), \tag{11}$$

a state-space representation can be written

$$\Sigma_e : \begin{cases} \dot{e} = A_M(\theta_1)e - B_1(\theta_2)x_s + e_g(x_M, x_S, t, \theta_1) - B_2 u \\ y_e = Ce \end{cases} , \tag{12}$$

where

$$e_g(x_M, x_S, t, \theta_1) = g_M(x_M, t, \theta_1) - g_S(x_S, t, \theta_1). \tag{13}$$

3.3 Nonlinear bound determination

In order to determine the bounds of the nonlinearities difference, the scalar function $f : \mathcal{D}_1 \mapsto \mathcal{D}_2$ $f(x) = -\alpha x + \beta x^3$ is used. The bounds can be considered as the slopes of the tangents passing through $x = x_m$ and $x = 0$ of $f(x)$.

$$\begin{gathered} -\alpha(x_2 - x_1) \leq (f(x_2) - f(x_1)) \leq (-\alpha + 3\beta {x_m}^2)(x_2 - x_1) \\ \forall x_1, x_2 \in \mathcal{D}_1 \end{gathered} \tag{14}$$

Consider both nonlinear oscillators and the domain $\mathcal{D}_1 = [-1.35V, 1.35V]$, then the bound of the nonlinearities difference (13) can be written as follows

$$\begin{bmatrix} 0 \\ -\frac{1}{C_0}\left(\alpha+3\beta-0.2^2\right) \end{bmatrix} \leq e_g(x_M, x_S, t, \theta) \leq \begin{bmatrix} 0 \\ \frac{\alpha}{C_0} \end{bmatrix}. \tag{15}$$

3.4 Controller synthesis

Assume that $A_M(\theta_1)$ resp. $B_1(\theta_2)$ are two matrices that belong to a polytope of matrices and it is represented by a convex combination of the extreme matrices A_i resp. B_{1i} with $i = 1 \ldots 2^M$.

$$\mathcal{A}_M = \left\{ A_M(\theta_1) |\; A_M(\theta_1) = \sum_{i=1}^{2^M} \xi_i A_i;\; \xi_i \in \Delta_1 \right\} \tag{16}$$

and consider that the matrix $e_g(x_M, x_S, t, \theta_1)$ can be bounded with $N_B(\theta_1)$ being its upper bound

$$e_g(x_M, x_S, t, \theta_1) \leq N_B(\theta_1)e. \tag{17}$$

The worst case for our system is the superior limit, then the matrix $A_N(\theta) = A_M(\theta_1) + N_B(\theta_1)$.

Assume that the dynamical output controller of the system (12) is described by the following state-space representation and its dimension is n_c.

$$\Sigma_C : \begin{cases} \dot{x_c} = A_c x_c + B_c y_e \\ u = C_c x_c + D_c y_e \end{cases} \tag{18}$$

The purpose of this controller is to make the slave system follow the delayed output of the master system. This condition is performed when the error signal defined in (11) tends toward zero. The term $B_1(\theta_2)x_s$, representing the difference between both systems, acts as a perturbation on the error state e.

The synthesis of this controller has been made with a technique similar to [9, 10] The following theorem solves the problem of variable matrices product in the synthesis problem by introducing extra unknown variable matrices.

Theorem 1. *If there exists a set of matrices $P_i > 0$, a state feedback controller K_0, an unknown variable square and nonsingular matrix $G \in \mathbb{R}^{n_u+n_c}$, an unknown variable matrix $H \in \mathbb{R}^{(n_u+n_c)\times(n_u+n_c)}$ and four unknown variables matrices $F_1, F_4 \in \mathbb{R}^{(n_x+n_c)\times(n_x+n_c)}$, $F_2 \in \mathbb{R}^{n_x\times(n_x+n_c)}$ and $F_3 \in \mathbb{R}^{(n_\infty+n_c)\times(n_x+n_c)}$ such that the inequality (19) is verified, then the dynamical controller $K = G^{-1}L$ makes the error system (12) asymptotically stable for all matrices $A_N(\theta_1)$ and $B_1(\theta_2)$ described as a polytope.*

$$\begin{aligned} \Phi_2 + {}^1\mathsf{Sym}\left\{ \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ \mathbb{O} \end{bmatrix} \begin{bmatrix} \mathbb{O} & \mathbb{O} & \mathbb{O} & \mathbb{O} & \widetilde{B}_2 \end{bmatrix} \right\} + \mathsf{Sym}\left\{ \begin{bmatrix} \mathbb{O} \\ \mathbb{O} \\ \mathbb{O} \\ \mathbb{O} \\ \mathbb{I} \end{bmatrix} L \begin{bmatrix} \widetilde{C} & \mathbb{O} & \mathbb{O} & \mathbb{O} & \mathbb{O} \end{bmatrix} \right\} \\ + \mathsf{Sym}\left\{ \begin{bmatrix} \mathbb{O} \\ \mathbb{O} \\ \mathbb{O} \\ \mathbb{O} \\ \mathbb{I} \end{bmatrix} G \begin{bmatrix} -K_0 & \mathbb{O} & \mathbb{O} & \mathbb{O} & -\mathbb{I} \end{bmatrix} \right\} < \mathbb{O}; \end{aligned} \tag{19}$$

The matrix Φ_2 is defined as follows

$$\Phi_2 = \begin{bmatrix} \mathbb{O} & \mathbb{O} & {C_{cl}}^T & P_i & \mathbb{O} \\ \mathbb{O} & -\gamma\mathbb{I} & \mathbb{O} & \mathbb{O} & \mathbb{O} \\ C_{cl} & \mathbb{O} & -\gamma\mathbb{I} & \mathbb{O} & \mathbb{O} \\ P_i & \mathbb{O} & \mathbb{O} & \mathbb{O} & \mathbb{O} \\ \mathbb{O} & \mathbb{O} & \mathbb{O} & \mathbb{O} & \mathbb{O} \end{bmatrix} + \mathsf{Sym}\left\{ \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ \mathbb{O} \end{bmatrix} \begin{bmatrix} \widetilde{A}_{0i} & \widetilde{B}_{1j} & \mathbb{O} & -\mathbb{I} & \mathbb{O} \end{bmatrix} \right\}, \quad (20)$$

$$\forall i \in \{1 \dots 2^M\} \text{ and } \forall j \in \{1 \dots 2^P\}$$

where $\widetilde{A}_{0i} = \widetilde{A}_{Ni} + \widetilde{B}K_0$ and

$$K = \left[\begin{array}{c|c} D_c & C_c \\ \hline B_c & A_c \end{array}\right]. \quad (21)$$

The expression (16) can be numerically solved using Matlab's© "LMI Toolbox".

4 Numerical results

In order to check the theoretical result, a transistor-based simulation has been done using Agilent's ADS© software and MOSFET transistors in $0.35\mu m$ silicon technology.

It was considered that all the parameters of $A_N(\theta)$ have $\pm 5\%$ variation around their nominal values. This variation can be seen as the variation depending on the temperature of the oscillators that are built on the same integrated circuit substrate. This is mathematically transformed into the variation of the state matrix $A_N(\theta_1)$ inside the polytope. Using the Matlab's "LMI Toolbox" applied to the 8 vertices of the polytope, the following output-feedback controller was found

$$K = \left[\begin{array}{c|c} D_c & C_c \\ \hline B_c & A_c \end{array}\right] = \left[\begin{array}{c|c} 2.66588 \cdot 10^{11} & 22.3994 \\ \hline 7.51499 \cdot 10^{9} & -1.1885 \end{array}\right]. \quad (22)$$

It assures the synchronization of oscillators having $\delta = \pm 5\%$ difference between parameters. This difference is represented by variation of the perturbation matrix $B_1(\theta_2)$ inside the polytope.

Variations between L_M, C_M and L_S, C_S parameters, corresponds to a possible difference between the free-running frequencies of both oscillators

$$f_{0S} \in \left[f_{0M}(1-|\delta|)^2 \ f_{0M}(1+|\delta|)^2 \right]. \quad (23)$$

The difference between α_M, β_M and α_S, β_S stands for a possible difference between the transistor operating points of both nonlinear oscillators.

This controller was applied to a pair of both non-linear oscillators. Their free running frequencies are $f_{0M} = 2GHz$ and $f_{0S} = 2.2GHz$. It has been chosen those frequencies in order to build a discrete component platform.

In fig. 4 are presented both output voltages for master and slave oscillators and is divided into three sequences. a first sequence in which, the controller Σ_c is not activated, both oscillators oscillates from their free-running frequencies. the second step at $t = 55ns$, the controller Σ_c is activated. The obtained delay is closed to the imposed value ($\tau = T/4 = 1.25 \cdot 10^{-10}s$). This delay will correspond to a orientation of the main lobe in $\Theta = 120°$. Finally, at $t = 60ns$, in order to verify the robustness of the dynamical controller, the free running frequency of the master oscillator was changed to $f_M = 2GHz$.

In fig. 3 the error between both output signals is presented. It can be seen that the error tends toward zero after a short period of time when the controller is started.

[1] $\mathsf{Sym}\{X\} = X^T + X; \forall X \in \mathbb{R}^n$

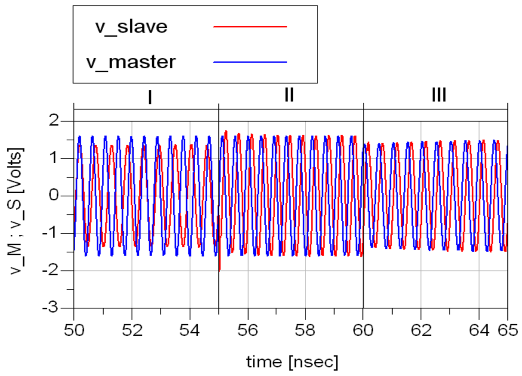

Figure 3: Output voltages of both oscillators

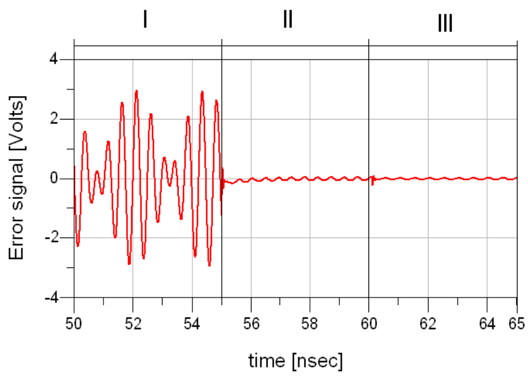

Figure 4: The error between both signals provided by the oscillators

4.1 Array of oscillators

Consider the situation where the $\Theta_p = 60°$ direction must be privileged and $\Theta_{i1} = 90°$ and $\Theta_{i2} = 120°$ must be rejected.

In table 4.1, the necessary and final values of the amplitudes and phases are shown for $N = 8$ antennas. Figure fig.5 depicts the corresponding radiation pattern. The orientation of the main lobe is closed to the desired value $\Theta_p = 58.14$ and both interference directions $\Theta_{i1} = 90°$ and $\Theta_{i2} = 120°$ are rejected.

5 Conclusion

This paper presents a novel method to drive antenna arrays. It is based on unidirectionally coupled oscillators. An output feedback controller has been designed to assure synchronization with advanced control theory using LMI (Linear Matrix Inequalities) tools. The result was successfully extended to a chain of eight unidirectionally coupled oscillators. Additional research will be made to constrain the dynamical controller to realize the desired delay in order to eliminate the delay element.

Amplitudes $[V]$		Phases $[°]$	
necessary	simulated	necessary	simulated
0.269	0.21	0	0
0.21	0.2	143	138
0.14	0.14	180	179
0.4	0.4	-162	160
0.08	0.08	0	-2
0.14	0.13	63.1	57
0	0	0	7
0.3	0.29	-24.4	-30

Table 1: computed and final values for the amplitudes and phases

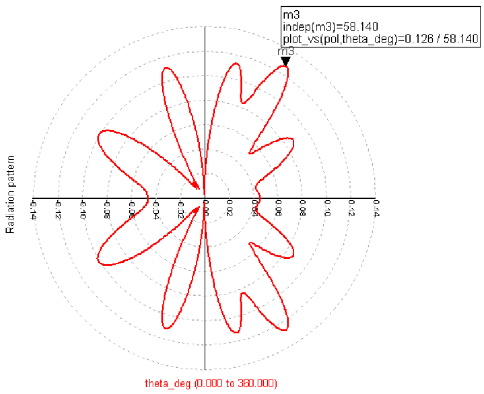

Figure 5: The radiation pattern in the particular case of $\Theta_p = 60°$

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Analytical Model For a Multiprocessor With Private Caches And Shared Memory

Angel Vassilev Nikolov

Abstract: We develop an analytical model of multiprocessor with private caches and shared memory and obtain the following results: the instantaneous state probabilities and the steady-state probabilities of the system. Both transient behaviour and equilibrium can be studied and analyzed. We showed that results can be applied to determine the output parameters for both blocking and non-blocking caches.
Keywords: Invalidate cache-coherence protocol, queuing system, discrete transform

1 Introduction

Shared memory multiprocessors are widely used as platforms for technical and commercial computing [2]. Performance evaluation is a key technology for design in computer architecture. The continuous growth in complexity of systems is making this task increasingly complex [7]. In general, the problem of developing effective performance evaluation techniques can be stated as finding the best trade-off between accuracy and speed.

The most common approach to estimate the performance of a superscalar multiprocessor is through building a software model and simulating the execution of a set of benchmarks. Since processors are synchronous machines, however, simulators usually work at cycle-level and this leads to enormous slowdown [9]. It might take hours even days to simulate.

For memory structures relatively accurate analytical models were developed [3, 7, 9, 10] through extensive use of various queuing systems. Open queue system with Poisson arrivals and exponential service times is considered quite good for description of memory hierarchies [7]. Our focus is on the impact of the cache-coherence protocols on the overall system performance. The most commonly used technique for this purpose is the Mean Value Analysis (MVA) [3, 5, 7, 8, 9]. It allows the total number of the customers to be fixed (closed queue system), and this seems to be more adequate representation of the processes of self-blocking requestors [5]. Calculations of output parameters such as residency times, waiting times and utilization are shown in [3, 8, 9]. MVA is based on the forced flow that means in equilibrium output rate equals input rate. However, instantaneously, we can have input rate different from output rate, so that the instantaneous probabilities could be different from equilibrium [7]. MVA offers no possibility to study transient effects. Moreover, the assumption of exponential service times is not realistic, in fact all bus access times and memory access times are constants. It will be seen later in this paper that state probabilities depend on the server's time density function.

We use the technique of Markov processes to describe the behaviour of the multiprocessor implementing cache-coherence protocols.

2 Definition and Analysis of the Model

A multiprocessor consists of several processors connected together to a shared main memory by a common complete transaction bus. Each processor has a private cache. When a processor issues a request to its cache, the cache controller examines the state of the cache and takes suitable action, which may include generating bus transaction to access main memory. Coherence is maintained by having all cache controllers "snoop" on the bus and monitor the transaction. Snoopy cache-coherence protocols fall in two major categories: Invalidate and Update [2, 3, 10]. Invalidating protocols are studied here but the concepts can be applied with some modifications to updating protocols too. Transactions may or may not include the memory block and the shared bus. Typical transaction that does not include memory block is Invalidate Cache Copy which occurs when a processor requests writing in the cache. All other processors simply change the status bit(s) of their on copies to Invalid. If the memory block is uncached or not clean it can be uploaded from the main memory, but in today's multiprocessors it is rather uploaded from another cache designated as Owner (O) (cache-to cache transfer). Memory-to-cache transfer occurs when the only clean copy is in the main memory. A cache block is written back (WB) in the main memory (bus is used) when a dirty copy is evicted [6]. The bus and the main memory are also used when synchronization procedures are executed [2]. Apparently the bus can be considered as the bottleneck of the system.

In terms of the queuing theory processors can be viewed as customers (clients) and the bus can be viewed as a server.

Inter-arrival times are exponentially distributed with parameter λ . This assumption is adequate for most applications [7]. Requests are served on First Come First Served (FCFS) basis. Immediately after issuing a request for cache-to-cache transfer or synchronization procedure the customer blocks itself. The service time for blocking request has a density function $f_1(x)$. When service is completed the processor (customer) resumes processing with probability p or resumes processing and generates a new request with probability q $(p+q=1)$. Details on how to obtain the input parameters are given in [2, 3, 8, 9]. This new request has a different density function $f_2(x)$ and corresponds to WB transaction. It does not block the customer but the server is held until completion of WB transaction therefore adding to the queue. The system can be in one of the following states: 1) N: all N customers are doing internal processing; 2) ***j, 1***: j customers are doing internal processing (N-j are blocked respectively) and all requests are of type 1$(0\leq j\leq N\text{-}1)$, 3) ***j ,2:*** j customers are doing internal processing , the server is serving request of type 2, and N-j customers are waiting in the queue for service of type 1 $(0\leq j\leq N)$. The transitions between these states are illustrated in Fig. 1.

Throughout this paper we use the following notations

$P_N(t)$ Probability[all N customers are doing internal processing at time t]

$P_{j,i}(t,x)$ Probability[j customers are doing internal processing, N-j are in the queue and/or in the server, and the server is busy doing service of type i at time t and the elapsed service time lies between x and $x+dx$]

$P_{j,i}(x)$ Probability[in the equilibrium state j customers are doing internal processing, N-j are in the queue and/or in the server, the server is busy doing service of type i and the elapsed service time lies between x and $x+dx$]

$P_{j,i}(t)$ Probability[j customers are doing internal processing, N-j are in the queue or in the server, the server is busy doing service of type i at time t]

P_N, $P_{j,i}$ steady-state probabilities. $P_N = \lim_{t\to\infty} P_N(t)$, $P_{j,i} = \int_0^\infty P_{j,i}(x)dx$

$\beta_i = j\lambda$

$F_i(x)$ cumulative distribution function (c.d.f.) of the service time of type i ; $i=1,2$

$f_i(x)$ probability density function (p.d.f.) of the service time of type i ; $i=1,2$

$\delta_{m,n}$ Kronecker delta

$\frac{1}{\mu_i} = \int_0^\infty x f_i(x)dx$ $i=1,2$

$h_i(x) = \frac{f_i(x)}{1-F_i(x)}$ service rate for type i; i=1,2

$\underline{f_i}$(s), $\underline{f_i}$(s+β_n), $\underline{f_i}(\beta_n)$ Laplace Transforms (LT) of $f_i(x)$

t.u. time unit

Viewing the nature of the system, we obtain the following set of integro-differential equations

$$\left[\frac{d}{dt} + \beta_n\right] P_N = p\int_0^t P_{N-1}(t,x)h_1(x)dx + \int_0^t P_{N,2}(t,x)h_2(x)dx \qquad (1)$$

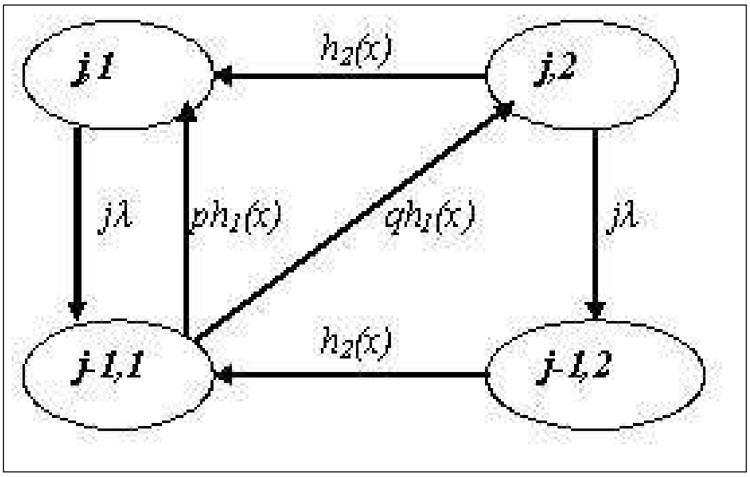

Figure 1: State-transition diagram of the model. $1 \leq j \leq N$

$$\left[\frac{d}{dt}+\frac{\partial}{\partial t}+\beta_{N-1}+h_1(x)\right]P_{N-1,1}(t,x)=0 \tag{2}$$

$$\left[\frac{d}{dt}+\frac{\partial}{\partial t}+\beta_{N}+h_2(x)\right]P_{N,2}(t,x)=0 \tag{3}$$

$$\left[\frac{d}{dt}+\frac{\partial}{\partial t}+\beta_{j}+h_i(x)\right]P_{j,i}(t,x)=\beta_{j+1}P_{j+1,i}(t,x) \tag{4}$$

for $i=1, 1 \leq j \leq N-1; i=2, 1 \leq j \leq N$

$$\left[\frac{d}{dt}+\frac{\partial}{\partial t}+h_i(x)\right]P_{0,i}(t,x)=\beta_1 P_{1,i}(t,x) \tag{5}$$

for *i=1,2*

having the following boundary and initial conditions

$$P_{j,1}(t,0)=(1-\delta_{j,0})p\int_0^\infty P_{j-1,1}(t,x)h_1(x)dx+\int_0^\infty P_{j,2}(t,x)h_2(x)dx+\delta_{j,N-1}\beta_N P_N(t) \tag{6}$$

for $0 \leq j \leq N-1$

$$P_{j,2}(t,0)=q\int_0^\infty P_{j-1,1}(t,x)h_1(x)dx \tag{7}$$

for $1 \leq j \leq N$

$$P_N(0)=1, P_{0,2}(t,0)=0, P_{j,i}(0,0)=0 \tag{8}$$

for $i=1, 1 \leq j \leq N-1; i=2, 1 \leq j \leq N$

By using Laplace transform and discrete transform [4, 8] the above equations are transformed as follows

$$(s+\beta_n)P_N=1+p\int_0^\infty P_{N-1}(s,x)h_1(x)dx+\int_0^\infty P_{N,2}(s,x)h_2(x)dx \tag{9}$$

$$\left[s+\frac{d}{dx}+\beta_j+h_i(x)\right]u_{j,i}(s,x)=0 \qquad (10)$$

for $i=1, 1\leq j\leq N-1; i=2, 1\leq j\leq N$

$$\left[s+\frac{d}{dx}++h_i(x)\right]P_{0,i}(s,x)=\beta_1 P_{1,i}(s,x) \qquad (11)$$

for *i=1,2*

where $u_{j,1}(s,x)=\sum_{n=j}^{N-1}\binom{n}{j}P_{n,1}(s,x)$, $P_{j,1}(s,x)=\sum_{n=j}^{N-1}(-1)^{n-j}\binom{n}{j}u_{n,1}(s,x)$ for $1\leq j\leq N-1$, and

$u_{j,2}(s,x)=\sum_{n=j}^{N}\binom{n}{j}P_{n,2}(s,x)$, $P_{j,2}(s,x)=\sum_{n=j}^{N}(-1)^{n-j}\binom{n}{j}u_{n,2}(s,x)$ for $1\leq j\leq N$.

Let $v_{j,i}(s,x)=\frac{u_{j,i}(s,x)}{1-F_i(x)}$ and $P'_{0,1}(s,x)=\frac{P_{0,1}(s,x)}{1-F_i(x)}$. Then from (10 and 11) we have after some transformations

$$\left[s+\frac{d}{dx}+\beta_i\right]v_{j,i}(s,x)=0$$

for $i=1, 1\leq j\leq N-1; i=2, 1\leq j\leq N$ and

$$\left[s+\frac{d}{dx}\right]P'_{0,i}(s,x)=\beta_1 P_{1,i}(s,x)$$

for $i=1,2$.

Hence the solutions of (9-11) are

$$u_{j,i}(s,x)=[1-F_i(x)]u_{j,i}(s,0)e^{-(s+\beta_i)x} \qquad (12)$$

$$P_N(s)=\frac{1+p\underline{f_1}(s+\beta_{N-1})u_{N-1,1}(s,0)+\underline{f_2}(s+\beta_N)u_{N,2}(s,0)}{s+\beta_N} \qquad (13)$$

$$P_{0,1}(s,x)=[1-F_1(x)]\beta_1 e^{-sx}\left[P_{0,1}(s,0)+\sum_{n=1}^{N-1}(-1)^{n-1}n\frac{1-e^{-\beta_n x}}{\beta_n}u_{n,1}(s,0)\right] \qquad (14)$$

$$P_{0,2}(s,x)=[1-F_2(x)]\beta_1 e^{-sx}\left[\sum_{n=1}^{N}(-1)^{n-1}n\frac{1-e^{-\beta_n x}}{\beta_n}u_{n,2}(s,0)\right]. \qquad (15)$$

By integrating (12, 14, and 15) we obtain the LT of the instantaneous probabilities

$$P_{j,1}(s)=\sum_{n=j}^{N-1}(-1)^{n-j}\binom{n}{j}\left[\frac{1-\underline{f_1}(s+\beta_n)}{s+\beta_n}\right]u_{n,1}(s,0) \qquad (16)$$

for $1\leq j\leq N-1$

$$P_{j,2}(s)=\sum_{n=j}^{N}(-1)^{n-j}\binom{n}{j}\left[\frac{1-\underline{f_2}(s+\beta_n)}{s+\beta_n}\right]u_{n,2}(s,0) \qquad (17)$$

for $1\leq j\leq N$

$$P_{0,1}(s)=P_{0,1}(s,0)\left[\frac{1-\underline{f_1}(s)}{s}\right]+\beta_1\sum_{n=1}^{N-1}(-1)^{n-1}n\left[\frac{1-\underline{f_1}(s)}{s}-\frac{1-\underline{f_1}(s+\beta_n)}{s+\beta_n}\right]\frac{u_{n,1}(s,0)}{\beta_n} \qquad (18)$$

$$P_{0,2}(s)=\beta_1\sum_{n=1}^{N}(-1)^{n-1}n\left[\frac{1-\underline{f_2}(s)}{s}-\frac{1-\underline{f_2}(s+\beta_n)}{s+\beta_n}\right]\frac{u_{n,2}(s,0)}{\beta_n}. \tag{19}$$

Taking LT of (6-7) and using (8 and 12-15) we get after some transformations the following system of linear equations

$$\sum_{n=j}^{N-1}(-1)^{n-j}\binom{n}{j}u_{n,1}(s,0)=p\sum_{n=j}^{N-1}(-1)^{n-j+1}\binom{n}{j-1}\underline{f_1}(s+\beta_n)u_{n,1}(s,0) \tag{20}$$

$$+\sum_{n=j}^{N}(-1)^{n-j}\binom{n}{j}\underline{f_2}(s+\beta_n)u_{n,2}(s,0)+\delta_{j,N-1}\beta_N P_N$$

for $2\leq j\leq N-1$

$$\sum_{n=j}^{N}(-1)^{n-j}\binom{n}{j}u_{n,2}(s,0)=q\sum_{n=j-1}^{N-1}(-1)^{n-j+1}\binom{n}{j-1}\underline{f_1}(s+\beta_n)u_{n,1}(s,0) \tag{21}$$

for $2\leq j\leq N$

$$\sum_{n=1}^{N-1}(-1)^{n-1}\binom{n}{j}u_{n,1}(s,0)=pP_{0,1}(s,0)\underline{f_1}(s)+p\beta_1\left[\sum_{n=1}^{N-1}(-1)^{n-1}n\frac{\underline{f_1}(s)-\underline{f_1}(s+\beta_n)}{\beta_n}u_{n,1}(s,0)\right] \tag{22}$$

$$\sum_{n=1}^{N}(-1)^{n-1}\binom{n}{j}u_{n,2}(s,0)=qP_{0,1}(s,0)\underline{f_1}(s)+q\beta_1\left[\sum_{n=1}^{N-1}(-1)^{n-1}n\frac{\underline{f_1}(s)-\underline{f_1}(s+\beta_n)}{\beta_n}u_{n,1}(s,0)\right] \tag{23}$$

Coefficients $u_{j,i}(s,0)$ can now be determined from the above equations. We can apply the final-value theorem to (16-19) to obtain the steady-state probabilities but it will require use of the L'Hopital rule and seems difficult and impractical [11]. Instead we set the following differential equations

$$\beta_n P_N=p\int_0^\infty P_{N-1}(x)h_1(x)dx+\int_0^\infty P_{N,2}(x)h_2(x)dx \tag{24}$$

$$\left[\frac{d}{dx}+\beta_{N-1}+h_1(x)\right]P_{N-1,1}(x)=0 \tag{25}$$

$$\left[\frac{d}{dx}+\beta_N+h_2(x)\right]P_{N,2}(x)=0 \tag{26}$$

$$\left[\frac{d}{dx}+\beta_j+h_i(x)\right]P_{j,i}(x)=\beta_{j+1}P_{j+1,i}(x) \tag{27}$$

for $i=1,1\leq j\leq N-1;i=2,1\leq j\leq N$

$$\left[\frac{d}{dx}+h_i(x)\right]P_{0,i}(x)=\beta_1 P_{1,i}(x) \tag{28}$$

for *i=1,2*. Equations (24-28) are to be solved under the following boundary conditions and normalizing condition

$$P_{j,1}(0)=(1-\delta_{j,0})p\int_0^\infty P_{j-1,1}(x)h_1(x)dx+\int_0^\infty P_{j,2}(x)h_2(x)dx+\delta_{j,N-1}\beta_N P_N \tag{29}$$

for $0 \le j \le N-1$

$$P_{j,2}(0) = q\int_0^\infty P_{j-1,1}(x)h_1(x)dx \tag{30}$$

for $1 \le j \le N-1$

$$P_{0,2}(0) = 0 \tag{31}$$

$$P_N + \sum_{j=0}^{N-1} P_{j,1} + \sum_{j=0}^{N} P_{j,2} = 1. \tag{32}$$

The solutions of (2.29-2.32) are

$$P_N = \frac{1 + p\underline{f_1}(\beta_{N-1})u_{N-1,1}(0) + \underline{f_2}(\beta_N)u_{N,2}(0)}{\beta_N} \tag{33}$$

$$P_{j,1} = \sum_{n=j}^{N-1} (-1)^{n-j} \binom{n}{j} \left[\frac{1-\underline{f_1}(\beta_n)}{\beta_n}\right] u_{n,1}(0) \tag{34}$$

for $1 \le j \le N-1$

$$P_{j,2} = \sum_{n=j}^{N} (-1)^{n-j} \binom{n}{j} \left[\frac{1-\underline{f_2}(\beta_n)}{\beta_n}\right] u_{n,2}(0) \tag{35}$$

for $1 \le j \le N-1$

$$P_{0,1} = \frac{P_{0,1}(0)}{\mu_1} + \sum_{n=j}^{N-1} (-1)^{n-j} n \left[\frac{1}{\mu_1} - \frac{1-\underline{f_1}(\beta_n)}{\beta_n}\right] u_{n,1}(0) \tag{36}$$

$$P_{0,2} = \sum_{n=j}^{N} (-1)^{n-j} n \left[\frac{1}{\mu_2} - \frac{1-\underline{f_2}(\beta_n)}{\beta_n}\right] u_{n,2}(0) \tag{37}$$

For $u_{j,i}(0)$ and $P_{0,1}(0)$ we have

$$\sum_{n=j}^{N-1} (-1)^{n-j} \binom{n}{j} u_{n,1}(0) = p\sum_{n=j}^{N-1} (-1)^{n-j+1} \binom{n}{j-1} \underline{f_1}(\beta_n)u_{n,1}(0) + \delta_{j,N-1}\beta_N P_N \tag{38}$$

for $2 \le j \le N-1$

$$\sum_{n=j}^{N-1} (-1)^{n-j} \binom{n}{j} u_{n,2}(0) = q\sum_{n=j}^{N-1} (-1)^{n-j+1} \binom{n}{j-1} \underline{f_2}(\beta_n)u_{n,2}(0) \tag{39}$$

for $2 \le j \le N-1$

$$P_{0,1}(0) = \beta_1 \sum_{n=1}^{N} (-1)^{n-1} n \left[\frac{1-\underline{f_2}(\beta_n}{\beta_n}\right] u_{n,2}(0) \tag{40}$$

$$\sum_{n=1}^{N-1} (-1)^{n-1} n u_{n,1}(0) = pP_{0,1}(0) + p\beta_1 \sum_{n=1}^{N} (-1)^{n-1} n \left[\frac{1-\underline{f_1}(\beta_n}{\beta_n}\right] u_{n,1}(0) + \sum_{n=1}^{N} n\underline{f_2}\beta_n u_{n,2}(0) \tag{41}$$

$$\sum_{n=1}^{N} (-1)^{n-1} n u_{n,2}(0) = qP_{0,1}(0) + q\beta_1 \sum_{n=1}^{N} (-1)^{n-1} n \left[\frac{1-\underline{f_1}(\beta_n}{\beta_n}\right] u_{n,1}(0) \tag{42}$$

The coefficients $u_{j,i}(0)$ can be determined from (32) and (38-42).

3 Examples

In order to obtain the transient state probabilities first we have to determine $P_N(s)$ and $P_{j,i}(s)$ from (16-19) and (20-24) and then to apply the Inverse Laplace Transform to them. We used the packages of Maple 8 on a standard PC platform under Windows XP for these computations [12]. Results were produced and printed in less than a second. For $N=4$ the instantaneous probabilities are listed in Appendix A.

Various performance characteristics can be computed using the steady-state probabilities. For example, the average number of blocked customers *(ANBC)* in the case of blocking caches will be given by

$$ANBC = \sum_{i=1}^{2} \sum_{j=0}^{N} (N-j) P_{j,i}. \tag{43}$$

In the case of non-blocking caches *ANBC* will be

$$ANBC = \sum_{j=0}^{N} (N-j-1+k) P_{j,1} + \sum_{j=0}^{N-1} (N-j) P_{j,2}. \tag{44}$$

where k is the ratio of average memory stall time [2] . k depends strongly on the application. $(1-k)$ actually refers to the fraction time the processor is consuming data while cache-to-cache or memory-to-cache transfer is in progress.

In Appendix B we list the *ANBC* for two popular service time distributions: exponential and erlangian [1], for blocking and fully non-blocking caches ($k=0$). The time to solve (33-42) and calculate ANBC was meaninglessly short.

4 Concluding Remarks

This work presented a model for a shared bus, shared memory multiprocessor with private caches and captures the whole spectrum of Invalidate type cache coherence protocols. Although we started with fairly sophisticated set of integro-differential equations, the output of the model is a set of few linear equations from which the state probabilities can be determined.

The approach eliminates the main drawbacks of the most commonly used MVA analysis: inability to deal with transients and constraint on the service time distribution. The model gives insights into the transient behaviour of the system. Moreover, the assumption of exponentially distributed service times can be dropped; any continuous distribution can be used.

The ease of obtaining performance measures in a meaningless time makes very feasible the incorporation of the model in a multiprocessor design tool.

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APPENDIX A

For $N=4$, λ=0.001[1/t.u.], $f_1(x)=0.1exp(-0.1x)$, and $f_2(x)=0.01exp(-0.01x)$ the instantaneous probabilities are

$P_4(t)$ =0 .9211361286+0.8058476879e-2*exp(-0.1248619627*t)
+0.8535072295e-2*exp(-0.1089825679*t)+0.9049529656e-2*exp(-0.9494144284e-1*t)
+0.9696074769e-2*exp(-0.8072343638e-1*t)+0.1774027054e-3
exp(-0.1510201407e-1*t) +0.1728181365e-2*exp(-0.1398702636e-1*t)
+0.5618533851e-2*exp(-0.1256085210e-1*t) +0.1211910345e-1
exp(-0.1067946234e-1*t)+0.2388149701e-1*exp(-0.8161235321e-2*t),

$P_{31}(t)$ =0.3792913471e-1-0.1093143496e-1*exp(-0.1248619627*t)
-0.1007354818e-1 *exp(-0.1089825679*t)-0.9271731350e-2*exp(-0.9494144284e-1*t)
-0.8405607569e-2*exp(-0.8072343638e-1*t)+0.2658572506e-2
*exp(-0.1510201407e-1*t)-0.2212663963e-5*exp(-0.1398702636e-1*t)
-0.3015750621e-3*exp(-0.1256085210e-1*t)-0.6739486112e-3
*exp(-0.1067946234e-1*t)-0.9276492013e-3*exp(-0.8161235321e-2*t),

$P_{21}(t)$ = 0.1420742616e-2+0.2324288902e-2*exp(-0.1248619627*t)
+0.2986557798e-3* exp(-0.1089825679*t)-0.1243034332e-2
*exp(-0.9494144284e-1*t)-0.2544948528e-2*exp(-0.8072343638e-1*t)
-0.5329230583e-2*exp(-0.1510201407e-1*t)+0.6737760872e-2
*exp(-0.1398702636e-1*t)+0.4442015626e-3*exp(-0.1256085210e-1*t)
-0.5688666731e-3*exp(-0.1067946234e-1*t)-0.1539483112e-2
*exp(-0.8161235321e-2*t),

$P_{11}(t)$ =0 .7684028624e-4-0.2290986748e-3*exp(-0.1248619627*t)
+0.3160128043e-3*exp(-0.1089825679*t)+0.2148505581e-3
*exp(-0.9494144284e-1*t)-0.3252577041e-3

*exp(-0.8072343638e-1*t)+0.3775725072e-2*exp(-0.1510201407e-1*t) -0.8400171763e-2*exp(-0.1398702636e-1*t)+0.4974831098e-2 *exp(-0.1256085210e-1*t)+0.5143708805e-3*exp(-0.1067946234e-1*t) -0.9181578239e-3*exp(-0.8161235321e-2*t),

$P_{01}(t)$ = 0.9242283829e-5*exp(0-.1248619627*t)-0.3513395647e-4 *exp(-0.1089825679*t)+0.4257071327e-4*exp(-0.9494144284e-1*t) -0.1688587212e-4*exp(-0.8072343638e-1*t)-0.9200675435e-3 *exp(-0.1510201407e-1*t)+0.2810623081e-2*exp(-0.1398702636e-1*t) -0.3183584754e-2*exp(-0.1256085210e-1*t)+0.1611954912e-2 *exp(-0.1067946234e-1*t)-0.3239077071e-3*exp(-0.8161235321e-2*t) +0.5218152790e-5,

$P_{42}(t)$ = 0.2709223908e-1+0.9859983387e-3*exp(-.1248619627*t) +0.1060558367e-2*exp(-0.1089825679*t)+0.1145474465e-2 *exp(-0.9494144284e-1*t)+0.1259769099e-2*exp(-0.8072343638e-1*t) -0.2412466943e-1*exp(-0.1510201407e-1*t)-0.1705507775e-2 *exp(-0.1398702636e-1*t)-0.2095511260e-2*exp(-0.1256085210e-1*t) -0.2029637013e-2*exp(-0.1067946234e-1*t)-0.1588776483e-2 *exp(-0.8161235321e-2*t),

$P_{32}(t)$ = -0.2421204825e-3*exp(-0.1248619627*t)-0.7509940526e-4 *exp(-0.1089825679*t)+0.9576676158e-4 *exp(-0.9494144284e-1*t)+0.3013803504e-3 *exp(-0.8072343638e-1*t)+0.7126069503e-1*exp(-0.1510201407e-1*t) -0.6135152996e-1*exp(-0.1398702636e-1*t)-0.8971987351e-2 *exp(-0.1256085210e-1*t)-0.5950006752e-2*exp(-0.1067946234e-1*t) -0.4494935895e-2*exp(-0.8161235321e-2*t)+0.9428952497e-2,

$P_{22}(t)$ =0 .2421271696e-2+0.2626333487e-4*exp(-0.1248619627*t) -.3154175021e-4*exp(-0.1089825679*t)-0.2945613244e-4 *exp(-0.9494144284e-1*t)+0.3412946115e-4*exp(-0.8072343638e-1*t) -0.8108903801e-1*exp(-0.1510201407e-1*t)+0.1349032466 *exp(-0.1398702636e-1*t)-0.4071010637e-1*exp(-0.1256085210e-1*t) -0.9622074403e-2*exp(-0.1067946234e-1*t)-0.5904604182e-2 *exp(-0.8161235321e-2*t),

$P_{12}(t)$ = -0.1765308077e-5*exp(-0.1248619627*t)+0.4800731626e-5 *exp(-0.1089825679*t)-0.4448905932e-5*exp(-0.9494144284e-1*t) +0.1599282603e-5*exp(-0.8072343638e-1*t)+0.4177917201e-1 *exp(-0.1510201407e-1*t)-0.9973555226e-1*exp(-0.139870263e-1*t +0.7256040480e-1*exp(-0.1256085210e-1*t)-0.9747995399e-2 *exp(-0.1067946234e-1*t)-0.5300997812e-2*exp(-0.8161235321e-2*t) +0.4449749927e-3,

$P_{02}(t)$ = -0.4618227199e-6*exp(-0.1248619627*t)-0.2203030325e-6 *exp(-0.1089825679*t)+0.4881890483e-7*exp(0-.9494144284e-1*t) -0.1699392257e-7*exp(-0.8072343638e-1*t)-0.8188760719e-2 *exp(-0.1510201407e-1*t)+0.2501502200e-1*exp(-0.1398702636e-1*t) -0.2833447693e-1*exp(-0.1256085210e-1*t)+0.1434663085e-1 *exp(-0.1067946234e-1*t)-0.2882912592e-2*exp(-0.8161235321e-2*t) +0.4449749927e-4.

In the above expressions e-i means 10-i for i=1,7.

APPENDIX B

Table 1: *N=8*, f_1*(x)=0.1exp(-0.1x)*, f_2*(x)=0.01exp(-0.01x)*

$\lambda[1/t.u.]$	p	*ANBC* for blocking caches	*ANBC* for fully nonblocking caches
0.001	0.9	0.154099881194466	0.075640880006411
0.002	0.9	0.441552853804251	0.290383910880334
0.003	0.9	0.822750601431095	0.607433119474025
0.004	0.9	1.253944990222998	0.984102789831906
0.001	0.8	0.230012889507952	0.152313018403034
0.002	0.8	0.729883782777377	0.584481458432927
0.003	0.8	1.382033782478873	1.183494795953230
0.004	0.8	2.063720956300253	1.826269794552253

Table 2: *N=8*, $f_1(x)=0.1^3x^2exp(-0.1x)/2!$, $f_2(x)=0.01^3x^2exp(-0.01x)/2!$

$\lambda[1/t.u]$	p	*ANBC* for blocking caches	*ANBC* for fully nonblocking caches
0.001	0.9	0.384839057891723	0.211437492029451
0.002	0.9	1.313451009452606	0.582993712839022
0.003	0.9	2.390481400874492	1.782339618354729
0.004	0.9	3.691834116720534	2.882438452093385
0.001	0.8	0.614956120345239	0.400820549913285
0.002	0.8	2.611487230549326	1.722034656332087
0.003	0.8	4.062557145097248	3.429652938504840
0.004	0.8	5.899361833023557	5.394204692051840

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COMDEVALCO framework - the modeling language for procedural paradigm

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Abstract: This work is part of a series referring to COMDEVALCO - a framework for Software Component Definition, Validation, and Composition. Its constituents are: a modeling language, a component repository and a set of tools. This is the first paper describing the object-oriented modeling language, which contains fine-grained constructions, aimed to give a precise description of software components. The current status of the language reflects the procedural paradigm constructs.
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1 Introduction

Two main forces drive the software development today: complexity and change. Software development community looks for methods and practices to deal with these challenges.

Complexity in software development [6] is the same as in mathematics, dealing with problem-solving. The usual way of solving it is its reduction by reorganization. Brooks [2] makes a distinction between essential and accidental complexity. Essential complexity belongs to the problem to be solved and cannot be reduced or eliminated. Accidental complexity belongs to its solution, being created when fine-grained, general-purpose abstractions are used to directly implement coarse-grained, problem-specific concepts. It can be reduced or even eliminated by increasing the level of abstraction, i.e. by using more coarse-grained, problem-specific concepts (classes).

The other challenge in software development is *change management*: how to build software systems able to change. Software needs to change in response to changes in its operational environment and in its requirements. Sources of change are both in the problem domain (invalidating existing requirements, adding new ones) and in the solution domain, due to technological evolution.

Both challenges can be addressed in a disciplined manner using *models*, which increase the level of abstraction and allow for the automation of the software development process. Model-driven development (MDD) processes propose the creation of extensive models before the source code is written. An example of MDD approach is the Object Management Group's Model Driven Architecture [12] standard. Agile versions of MDD approaches have been defined in order to better deal with change management. Agile MDD processes [1] create *agile models* (models "just barely good enough") that drive the overall development efforts, instead of creating extensive models before writing source code. Another agile approach, Agile MDA [8], emphasizes on complete *executable models* [9].

Our work follows the idea of executable models, proposing an object-based modeling language that fits the procedural paradigm and allows construction and execution of models. Software components considered in our approach to the procedural paradigm are *Program* (the only executable), *Procedure*, and *Function*, and the software development process is component-based and model-driven. The modeling language constructs allow both precise *definition* of these components (called *program units*), and their *verification and validation* (V & V), by *simulating* their execution. Once these components pass the V & V process, they can be stored in a component repository, ready for later use in the development process.

The structure of this paper is as follows. After this introductory section, the next one is discussing current status, problems, and ideal properties of a modeling language. The third section presents the proposed modeling language, starting with low-level constructs, followed by statements, and finally program units. The current status of our work is described in the fourth section, while the last one contains some conclusions and plans further efforts.

2 Modeling process: current status, problems, and desired features

2.1 Modeling languages

It is generally recognized that the use of models raises the level of abstraction and favors the automation of the software development process. Unfortunately, as Greenfield and Short stated in [6], the largest impediment to achieve these tasks was "the promulgation of imprecise general-purpose modeling languages as both de facto and de jure standards", namely UML.

Martin Fowler [5] identifies three different UML goals: *informal design* (sketching), *model-driven development* (blueprinting), and *direct execution* (model interpretation), noticing a similar and independent opinion made by Steve Mellor [8]. The conclusion is that UML succeeded in the first goal and failed in the others; the reasons for this failure, as they are discussed in [6], are: (1) lack of precision, (2) poor support for component-based development, and (3) weak extensibility mechanisms.

UML 2 and its Action Semantics [15] provide the foundation to construct executable models, but the standardization efforts for defining a subset of actions sufficient for computational completeness are still in progress [14]. In order to make UML a computational-complete specification language, there are some tools [3, 17, 18, 11] which have defined *non-standard* subsets of actions. Other issues related to UML 2 refer to the graphical notations and textual notations. The current version of UML does not define graphical notations for easy manipulation of UML elements. Moreover, there are UML elements (e.g. UML structured activity nodes) without a proposed graphical notation, and textual notations for behavioral elements are still in the process of standardization [14].

2.2 Component-based development and the modeling process

The process of component-based software development (or CBD for short) has two sub-processes more or less independent: component development process and system development process. Naturally, the requirements concerning the components are derived from system requirements; the absence of a relationship, such as causal, may produce severe difficulties in both sub-processes mentioned above.

The system construction by assembling software components [4] has several steps: component specification, component evaluation, component testing, and component integration. The system development sub-process focuses on identifying reusable entities and selecting the components fulfilling the requirements, while in the component development sub-process the emphasis is on component reuse: from the beginning, components are designed as reusable entities. Component's degree of reuse depends on its generality, while the easiness in identification, understanding, and use is affected by the component specification. The sole communication channel with the environment is the component's interface(s). In other words, the client components of a component can only rely on the contracts specified in the interfaces implemented by the component. Thus, it is obvious that component development must be interface-driven.

In our opinion, the main CBD challenge is to provide a general, flexible and extensible model, for both components and software systems. This model should be language-independent, as well as programming-paradigm independent, allowing the reuse at design level.

The design process of a component-based system [7] follows the same steps as in the classical methods: the design of architecture, which depicts the structure of the system (which are its parts) and the design of behavior (how these parts interact in order to fulfill the requirements). The structural description establishes component interconnections, while behavioral description states the ways in which each component uses the services provided by interconnected components in order to fulfill its tasks.

2.3 Ideal properties of a modeling language

Our discussion here follows the general uses of a modeling language identified by Martin Fowler [5] and Steve Mellor [8]: *informal design*, *model-driven development*, and *direct execution*. In order to fulfill these goals, a modeling language should have: (1) good degree of precision, (2) good support for CBD, (3) good support for Agile MDA processes, and (4) good extensibility mechanisms.

In order to be precise, a modeling language needs to have fine-grained constructs, which allow both the complete definition of computing processes and the simulation of their execution. The language elements should cover low-level constructs referring to data types, expressions, program state and behavior (body of statements).

As we stated above, in order to offer a good support for CBD, a modeling language needs to build general, flexible and extensible models for both components and software systems. The resulting models should be both language-independent and programming-paradigm independent.

In order to offer a good support for agile MDA processes, a modeling language should provide *a metamodel*, together with *graphical* and *textual notations* for easy manipulation of language constructs. The metamodel should satisfy two important properties: *computability* and *completeness*.

The extensibility of a modeling language means the extensibility of its set of constructs, like data types, expressions, statements, and program units.

3 A modeling language proposal: ComDeValCo solution

This section discusses in more detail our proposal of a modeling language, part of a framework for component definition, validation, and composition.

The proposed solution is ComDeValCo - a conceptual framework for Software COMponents DEfinition, VALidation, and COmposition. Its constituents are meant to cover both CBD-related sub-processes described in 2.2: component development and component-based system development.

The sub-process of component development starts with its definition, using an object-oriented modeling language, and graphical tools. The modeling language provides the necessary precision and consistency, and the use of graphical tools simplifies developer's work, which doesn't need to know the notations of the modeling language. Once defined, component models are passed to a V & V (verification and validation) process, which is intended to check their correctness and to evaluate their performances. When a component passes the V & V step, it is stored in a component repository, for later (re)use.

The sub-process of component-based system development takes the components already stored in repository and uses graphical tools, intended to: select components fulfilling a specific requirement, perform consistency checks regarding component assembly and include a component in the already existing architecture of the target system. When the assembly process is completed, and the target system is built, other tools will perform V & V, as well as performance evaluation operations on it.

Constituents of the conceptual framework are: the modeling language, the component repository and the toolset. Any model of a software component is described as a compound object, using the elements of the object-based modeling language. The component repository represents the persistent part of the framework and its goal is to store and retrieve valid component models. The toolset is aimed to help developers to define, check, and validate software components and systems, as well as to provide maintenance operations for the component repository.

Starting in a top-down manner, program units considered are *Program* (the only executable) and proper software components specific to the procedural paradigm - *Procedure* and *Function* (see Figure 1). Each of these software components has a *name*, a *state*, and a *body*; the *state* is given by all *Variable*s local to the component, and the *body* is, generally speaking, a *Statement*.

According to the imperative paradigm, the program execution is seen as a set of state changes, i.e. the execution of a statement changes the *Value* of a *Variable*, usually by evaluating an *Expression*.

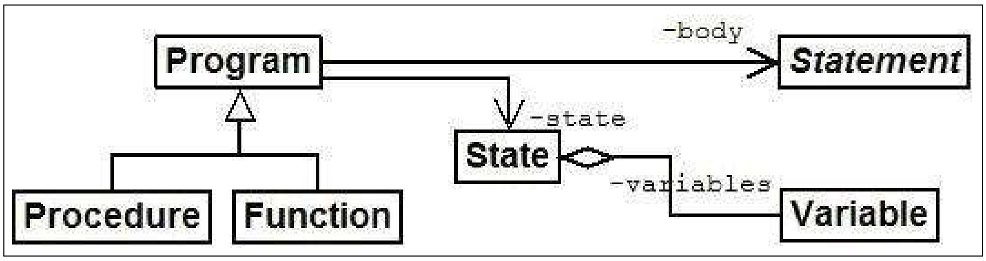

Figure 1: COMDEVALCO modeling language. Main constructs in the procedural paradigm

We describe below, in a bottom-up manner, the language elements as they are considered so far.

3.1 Low-level constructs

Basic language constructs are *Type* and *Declaration*. *Type* class abstracts the concept of data type, while a *Declaration* object is used to associate a specific *Type* object to a name (identifier). This corresponds to explicit variable declaration in imperative programming languages.

The next important concept is *Value*. Each *Value* object encapsulates a value of a specific *Type*. Values are fundamental in our model, because a variable represents an alternate name for a value stored in the memory, a function returns a value, or, more generally, the process of evaluating an expression returns a value.

Having these facts in mind, we designed the *Expression* class hierarchy shown in Figure 2. The root of the hierarchy, *Expression*, is abstract and has a single abstract operation, *getValue*(), overriden by subclasses and returning a *Value* result. The concrete specializations of *Expression* are: *Value*, *Variable*, *BinaryExpression*, *UnaryExpression*, and *DefinedFunction*.

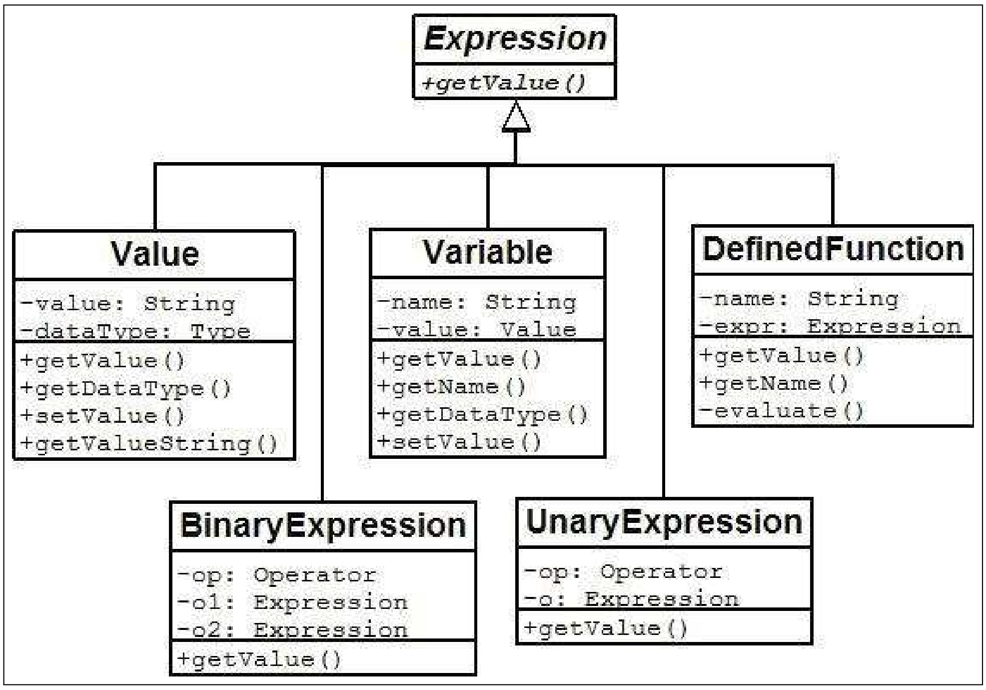

Figure 2: *Expression* class hierachy

Value is the simplest *Expression* descendant, its instances corresponding to typed literals (constants). Its proper operations are: *getDataType*(), which returns the data type of the value stored in the object, *getValueString*(), returning the value as a string, and *setValue*().

Variable is probably one of the most important subclasses of *Expression*, having multiple uses in our model: (1) a *Variable* is a simple *Expression*; (2) all *Statement* objects deal with *Variable* instances, and (3) the state of a program unit is seen as a collection of *Variable* objects. According to the general definition, each *Variable* object has a name (identifier) and a value (a *Value* object). Its own operations are: *getName*(), *getDataType*(), and *setValue*().

Specific expression classes considered so far are *BinaryExpression* and *UnaryExpression*, having an operator and two, respectively one expression operands. The extensible *Operator* class implements *evaluate*() operations for all operand types, called by *getValue*() code in *BinaryExpression* and *UnaryExpression*.

DefinedFunction object corresponds to a one-argument function call. Its instance variables are the name of the function and its actual parameter, an expression.

3.2 Statements

Statement class hierarchy employs *Composite* design pattern, with subclasses *SimpleStatement* and *CompoundStatement*. A *CompoundStatement* object contains a list of *Statement* objects; both concrete simple and compound statement objects are treated uniformly.

As Figure 3 shows, *Statement* class is abstract and represents the root of all simple and compound statement classes. Its single abstract operation is *execute*(), which usually produces a state change. *Statement*'s concrete subclasses will implement this operation accordingly.

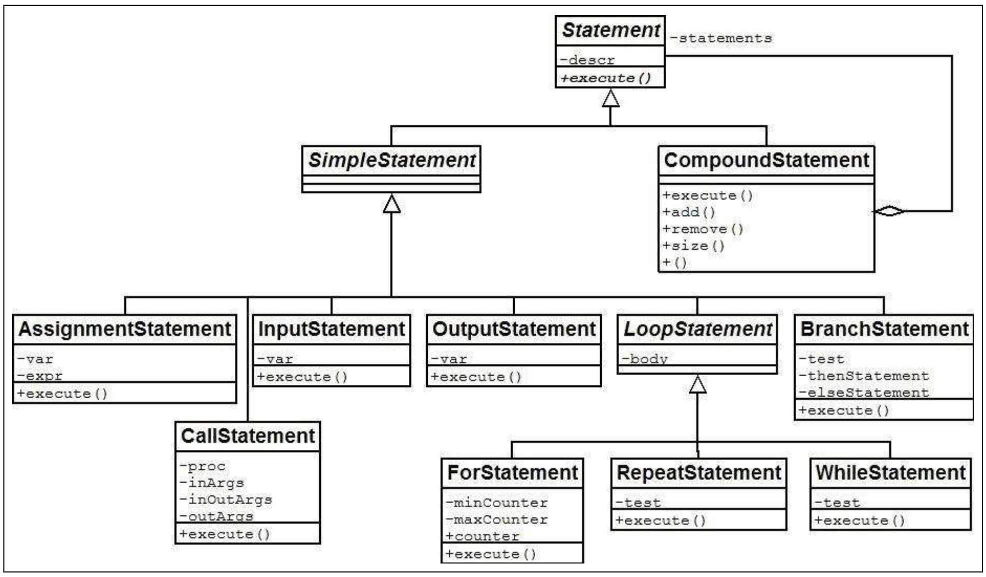

Figure 3: *Statement* class hierachy

SimpleStatement subclasses cover all important control statements in any imperative programming language: *AssignmentStatement*, *CallStatement*, *InputStatement*, *OutputStatement*, *LoopStatement*, and *BranchStatement*.

AssignmentStatement object takes an *Expression* and a *Variable*; after its execution, the variable takes the value of that expression. *InputStatement* takes only a *Variable*, being considered as a special kind of assignment: its execution means reading a value from standard input, evaluating and assigning it to the considered variable. The execution of an *OutputStatement* extracts the value of its *Variable* to standard output.

CallStatement object corresponds to a procedure call. Its instance variables are the procedure being called (the callee object) and actual (call) parameters, whose values belong to the caller object. According to the definition of a *Procedure* object (see next subsection), three different parameter lists are needed, corresponding to in-, in-out, and out parameters. The execution of this statement has five steps: (1) extracting the values of in- and in-out parameters from the caller state; (2) building the callee state; (3) running the callee object; (4) extracting the values of in-out and out parameters from the callee state and (5) updating the state of the caller object with these values.

All loop statements execute repeatedly their *body*, a *Statement* object. Three different loop statements were considered in our design, considered as subclasses of the abstract *LoopStatement*: *ForStatement*, *RepeatStatement*, and *WhileStatement*.

In the case of a *ForStatement* object, the number of iterations is known a priori, and its execution uses a counter *Variable*, with values ranging from lower to upper bounds. *WhileStatement* and *RepeatStatement* objects use a test *Expression* to continue the iterative process. Their execution differs by the test strategy, i.e. evaluate test then execute body (*while*), respectively execute body then evaluate test (*repeat*).

BranchStatement objects correspond to *if-then-else* constructs. The condition to be checked is an *Expression* object, and both branches are *Statement* objects. Its execution evaluates test expression and then, based on its value, executes the corresponding statement.

3.3 Program units

As we already stated, the program units considered so far are *Program*, *Procedure*, and *Function* (see Figure 4), specific to the procedural paradigm.

Program is the only executable software component, having a *name*, a *state*, and a *body*; the *state* is made up by all *Variable*s local to the component, and the *body* is a *Statement* object. The only operation of a *Program* object is its *run*() method, implemented by a call to the *execute*() method of its *body*.

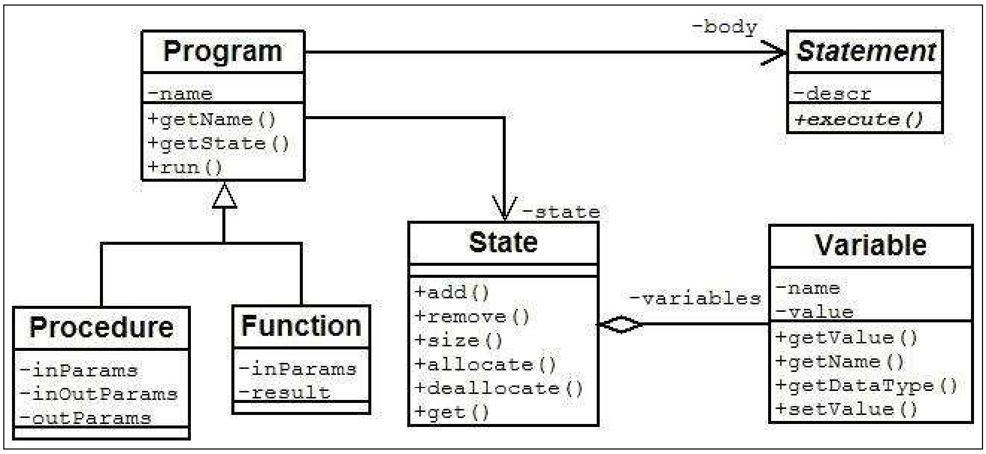

Figure 4: Program units class hierachy

Proper software components are *Procedure* and *Function*. As in the imperative programming world, a *Procedure* declaration must define its name, formal parameters, local state and procedure body. Consequently, it is easy to consider *Procedure* as a *Program* subclass; the proper instance variables of the *Procedure* class are the lists of in-, in-out, and out parameters, needed for a complete implementation of *execute*() method from *CallStatement* class, discussed in 3.2.

The concept of a user-defined function in imperative programming languages considers it without side-effects, i.e. the only result of its execution is the value it produces, without affecting the caller's state. Having this in mind, we designed the *Function* class accordingly, i.e. it has only input (*in*) formal parameters, and produces as result a *Value* object.

4 Experimental results

From a methodological viewpoint, our main concern was to model all theoretical aspects in concrete objects - constructs of the modeling language. The idea was to apply an iterative and incremental process: start with simple objects, perform checks after each modeling step, in order to be sure that things work.

Each modeling step covers both theoretical/analytical activities - the abstract model of the concept - and practical/applicative ones - coding, testing and integrating it in the already existing language.

The initial step of our work was to prove that things are working well. So we conducted first a proof-of-concept study, and then we started the development of graphical tools.

4.1 Modeling language: proof-of-concept stage

The modeling language described in Section 3 was implemented in Java. The classes containing the current implementation are included in three packages: `syntax` (`Expression` classes, `Declaration`, `DeclarationList`, `Operator`, `State`, and `Type`), `statements` (all classes in Figure 3), and `programUnits` (`Program`, `Procedure`, and `Function`). The implementations were tested by building some simple components, like solving of polynomial equations of first and second degree, or computing the integer square root (`isqrt()`) of a positive integer.

As we discuss below, in order to test a proper component `P`, two program units need to be designed: the component `P` itself and the corresponding test driver (a `Program` component). In each situation, the building process has two main steps: (1) build the state of the component and (2) build its body. As the state is a set of `Variable` objects, its creation is a sequence of `allocate()` messages. Additionally, in the case of `Procedure` and `Function` components, the parameter lists need to be also defined, in the same way. Next, the body of a component is a `CompoundStatement`, so the building process needs to create all the `Statement` objects which describe the computing process, and to include them into the body, preserving the sequence of computing steps.

Consider the simplest example of designing a component `EcGr1` which solves polynomial equations of the first degree, and its corresponding test program. The building process of `EcGr1` is defined in the following static method:

```
public static Procedure buildEcGr1() {
  DeclarationList inP = new DeclarationList();     // in params
  DeclarationList outP = new DeclarationList();    // out params
  DeclarationList inOutP = new DeclarationList();  // in-out params
  DeclarationList locale = new DeclarationList();  // local state
  // input parameters
  inP.allocate("a", Value.tDouble);
  inP.allocate("b", Value.tDouble);
  // output parameters
  outP.allocate("cod", Value.tInt);
  outP.allocate("x", Value.tDouble);
  CompoundStatement body =
      new CompoundStatement("Solves the equation a x + b = 0");
  Procedure proc =
      new Procedure("proc EcGr1", locale, body, inP, outP, inOutP);
  // body: BranchStatement(s1, s2)  (a == 0)
  Statement s11 =
      new AssignmentStatement("cod = 2", // infinite solution set
                               proc.getLocalState().get("cod"),
                               new Value(Value.tInt, "2"));
  Statement s12 =
      new AssignmentStatement("cod = 1", // no solution
```

```
                              proc.getLocalState().get("cod"),
                              new Value(Value.tInt, "1"));
    Expression e1 = proc.getLocalState().get("b");
    Expression e2 = new Value(Value.tDouble, "0");
    Expression e =
        new BinaryExpression(e1, e2, new Operator(Operator.EQ));
    // s1: BranchStatement(s11, s12)  (b == 0)
    BranchStatement s1 = new BranchStatement("b == 0", e, s11, s12);
    CompoundStatement s2 = new CompoundStatement("unique solution");
    s2.add(new AssignmentStatement("cod = 0",
        proc.getLocalState().get("cod"),  new Value(Value.tInt, "0")));
    e1 = proc.getLocalState().get("b");
    e2 = new Value(Value.tInt, "-1");
    Expression e3 = new BinaryExpression(e1, e2,
                            new Operator(Operator.TIMES)); // -b
    e2 = proc.getLocalState().get("a");
    e = new BinaryExpression(e3, e2, new Operator(Operator.DIV));  // -b/a
    s2.add(new AssignmentStatement("x = -b/a",
                proc.getLocalState().get("x"), e));
    e1 = proc.getLocalState().get("a");
    e2 = new Value(Value.tInt, "0");
    e = new BinaryExpression(e1, e2, new Operator(Operator.EQ));
    body.add(new BranchStatement("a == 0", e, s1, s2));
    return proc;
  }
```

The method builds a `Procedure` object who implements the well-known algorithm for solving first degree polynomial equations (its body being a `BranchStatement` object) and returns it when the building process is done. This object has two *in* parameters (`a` and `b`) and two *out* parameters (`x` and `cod`).

The test driver `Program` object is built as follows:

```
  public static Program buildProgEcGr1() {
    DeclarationList state = new DeclarationList();
    CompoundStatement body =
            new CompoundStatement("Test driver for EcGr1");
    Program prog = new Program("DemoEcGr1", state, body);
    state.allocate("ca", Value.tDouble);  // coefficient a
    state.allocate("cb", Value.tDouble);  // coefficient b
    state.allocate("rez", Value.tInt);    // return code
    state.allocate("sol", Value.tDouble); // the solution
    // resets state
    prog.setState(state);
    // start program
    body.add(new OutputStatement("*** Program " +
               prog.getName() + " started ***", null));
    // read coeffs
    body.add(new InputStatement("Read coeff ca", prog.getState().get("ca")));
    body.add(new InputStatement("Read coeff cb", prog.getState().get("cb")));
    // calls EcGr1
    DeclarationList pIn = new DeclarationList();
    pIn.allocate(prog.getState().get("ca"));
    pIn.allocate(prog.getState().get("cb"));
    DeclarationList pOut = new DeclarationList();
    pOut.allocate(prog.getState().get("rez"));
```

```
    pOut.allocate(prog.getState().get("sol"));
    DeclarationList pInOut = new DeclarationList();
    Procedure ecGr1 = buildEcGr1(); // create the EcGr1 procedure object
    SimpleStatement s = new CallStatement("call EcGr1", ecGr1, pIn, pInOut, pOut);
    body.add(s);
    // print results
    Statement s11 = new OutputStatement("unique solution", null);
    Statement s12 = new OutputStatement("print solution",
                                  prog.getState().get("sol"));
    CompoundStatement s1 = new CompoundStatement("Print unique solution");
    s1.add(s11);
    s1.add(s12);
    Expression e1 = prog.getState().get("rez");
    Expression e2 = new Value(Value.tInt, "1");
    Expression e = new BinaryExpression(e1, e2, new Operator(Operator.EQ));
    s11 = new OutputStatement("empty solution set", null);
                                          // cod = 1 (a=0, b<>0)
    s12 = new OutputStatement("infinite solution set", null);
                                          // cod = 2 (a=0, b=0)
    BranchStatement s2 = new BranchStatement("rez == 1", e, s11, s12);
    e2 = new Value(Value.tInt, "0");
    e = new BinaryExpression(e1, e2, new Operator(Operator.EQ));
    BranchStatement st = new BranchStatement("rez == 0", e, s1, s2);
    body.add(st);
    body.add(new OutputStatement("*** Program " + prog.getName() +
                              " terminated ***", null));
    return prog;
  }
```

This time, the body of the constructed `Program` object is a sequence of statements which: (1) read the coefficients (using a sequence of `InputStatement` objects), (2) call the `EcGr1` component (using a `CallStatement` object), and (3) print the result (using `BranchStatement` objects in which the condition tests the value of the *out* parameter `rez` while the branches are `OutputStatement` objects).

The above code also contains statements which create and build the state of the `Program` object, and prepare the call process, i.e. create and populate the actual *in*, *out*, and *in-out* parameter lists and then create the callee `Procedure` object `EcGr1` (by invoking `buildEcGr1()` method).

The `main()` method of the demo class first creates the driver `Program` object and then calls its `run()` method:

```
  public static void main(String[] args) {
    TextIO.putln("Demo Program Units");
    Program pEcGr1 = buildProgEcGr1();
    pEcGr1.run();
  }
```

The program object runs its body by executing sequentially the statements in it: (1) asks the user to enter the values of coefficients, (2) calls the `EcGr1` procedure and (3) prints an explanatory message and the unique solution (if this is the case).

Above-described component definition approach is tedious and error-prone. For example, in order to build a `BranchStatement` object, the process is bottom-up: (1) create the `Statement` objects corresponding to the branches and (2) create the `BranchStatement` object containing them.

In a real-world situation, the building process is assisted by graphical tools, as we discuss below. These tools will perform at least the following: (1) graphical or textual building of components, (2) saving and restoring component definitions to/from a component repository, (3) component testing and debugging.

4.2 The toolset

The ComDeValCo toolset proposal includes graphical tools for component definition, validation, and composition. This subsection describes current status of these tools.

As part of the ComDeValCo framework, a procedural action language (PAL) was defined and it is described in [10]. PAL contains all statements included in Figure 3, has a concrete textual syntax for UML structured activities, and graphical notations for some UML structured activity actions. The main idea for simplifying the construction of UML structured activities is to use the pull data flow for expression trees. Also, we propose new graphical notations for conditionals and loops, following the classical flowchart style.

In order to allow the exchange of executable models with other tools, a UML profile is also defined, specifying the mapping between PAL and UML constructs.

A component definition and validation tool is under development, using both graphical and textual PAL notations for building *Program*, *Procedure*, and *Function* program units. This tool is used within an Agile MDA process which includes test-first component design steps: (1) add a test (in the form of a *Program* component calling a non-existing *Procedure* or *Function*), (2) run the tests (in order to report the missing components), (3) add the production code (i.e. design the missing components), and (4) goto step (2). The process ends during the step (2), when all the tests pass. In the steps (1) and (3), developers are allowed to use either the graphical notation or the concrete syntax of PAL; the tool maintains automatically the consistency of the two views. The debugging and testing techniques employed in step (2) are defined according to Model-level Testing and Debugging Specification [14, 13].

A detailed description of this tool will be given in a separate paper.

4.3 Original elements of the proposed solution

The proposed solution brings original elements in at least the following directions:

- the object model is precise and fine-grained, because all objects are rigorously defined, and the component behavior is described at statement level. The UML metamodel has no correspondent for modeling constructs more fine-grained than *Program* and *Procedure*;
- the models are executable and verifiable because each component can be executed; moreover, one can use tools for validation and evaluation of complexity;
- the models are independent of any specific object-oriented language;
- the modeling language is flexible and extensible in the following dimensions: the statement set, the component (program units) family, the component definition, the data type definition, and the set of components;
- the modeling language allows the use of graphical tools in all the phases: building, validating, and using software component models;
- the modeling language allows automatic code generation for components in a concrete programming language, according to Model Driven Architecture (MDA) specifications. One can define mappings from the modeling elements to specific constructs in a concrete programming language in a declarative way.

5 Conclusions and further work

This paper describes the current status of the modeling language, part of the ComDeValCo framework. As we discussed above, this version implements a minimal set of elements, corresponding to the procedural programming paradigm.

The approach considered was aimed to control the complexity of the problem and of the development process. We started with the simplest programming paradigm, using simple data types and expressions and a small but complete set of statement objects. The development process consisted of small steps, meaning either the implementation of a new concept (transforming the concept into an object), or the extension of a model element. As the experiments were successful, we believe that our approach is feasible.

Future developments of the modeling language will include: extending *Type*, *Expression*, and *Operator* classes in order to define and manage structured and object types, extending the program units with constructs specific to modular, object-oriented, and component-based paradigms. These steps are considered within the planned evolution of the ComDeValCo framework, which include steps for defining the structure of component repository and developing the tools aimed to operate in the component definition, validation, evaluation, simulation, and composition.

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Virtual Training Centre for Computer Numerical Control

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Abstract:
It is a fact that virtual training has been a scope of interest for vocational training for a very long time. However, it needs more time to be more common in all specific training fields. Focusing on Computer Numerical Control (CNC) Training, new developments in the CNC machinery produce a continuous demand on enhancing the programming and technical capabilities of the involved personnel. Training on CNC should follow similar developments and in particular in their programming capabilities, automation they offer and their technical capabilities. Based on these main objectives a Virtual Training Center (VTC) for CNC has been developed and it is presented in this paper. The VTC is the main result of a multilateral Leonardo Da Vinci project witch aims to promote and reinforce Vocational Training in CNC Machines.
Keywords: Virtual training center, CNC, VET.

1 Introduction

In most Member States the past two decades there has been a growing awareness of the importance of quality in vocational education and training (VET). The changing demands of the knowledge-based society and the overall trend to increase the efficiency and effectiveness of VET systems, constitute major driving forces behind these developments. Major European funding frameworks and programmes, such as Leonardo Da Vinci (LdV) have contributed to improving education and VET systems by raising the level of the services they offer.

One of the objectives of the innovative VET systems is the transparency and distribution of information. This function concerns the potential and actual use of information. There may be different systems and structures of information distribution among the various actors, and in the public and there are preconditions for creating transparency in the VET system. To improve quality there must be systems for distributing information and certain mechanisms to ensure the circulated information can be used by the various actors in the policy process. The more widespread the distribution, the better the potential use of the data will be - and as a reversal effect, better quality data can be expected, as the actors are able to check the information against their experience and will provide feedback to the systems for gathering data.

One of the concrete future strategic objectives of education and training systems in the EU (Council of the European Union, 2001) is the improvement of the quality and the effectiveness of education and training systems in the EU. This includes improving education and training for teachers and trainers, developing skills for the knowledge society, ensuring access to ICT for everyone, increasing recruitment to scientific and technical studies, and making the best use of resources. The second strategic objective is facilitating the access of all to education and training systems. This objective includes open learning environment, making learning more attractive, and supporting active citizenship, equal opportunities and social cohesion. This paper describes the main results of a LdV project that addresses the strategic objectives mentioned above.

2 From the Blackboard to the Virtual Training Centre

During the 60's and 70's, teaching and learning tools were nothing but a piece of chalk and a blackboard eraser, teachers and students who met each other face to face inside the classroom during class.

In the 80's, videotape programs were used as teaching aids. In the 90's, one-way teaching by computer arrived. And finally today's advanced computer and information network technology has introduced radical innovative breakthroughs in our teaching and learning methods as well as in the learning environment. Students can listen to their teacher or trainers in distant classrooms through PC's and get a simultaneous view of their teachers and texts as well. They can ask questions and record the "class" for repeated viewing. Training organizations can conduct professional training directly via the computer network. These learning environments are not so different from a teacher-guided class with discussions and tests as well.

In the report "Studies in the context of the E-learning Initiative: Virtual Models of European Universities" [1] a key concern was how virtual mobility is being supported in European universities through ICT integration and e-learning. The study found that the majority of universities face major challenges in promoting ICT integration. ICT strategy is very important and those universities that have an ICT strategy are significantly ahead in integration of ICT in administration and organisation and networking. Integration of ICT and e-learning is politically important in the EU in terms of internationalisation and globalisation of education, student demand and interest in increasing the quality of education through ICT [2], [3], [4]. At the national level, integration of ICT should become a key priority with national and regional institutions making a commitment to ITC and the development of networks. There must be increased national flexibility with a commitment to support common standards of quality and assessment and to develop national and international metadata standards.

In the last 3 decades, a large number of vocational training centres and technical universities are giving priority to CNC Training. New developments on CNC machines are providing a continuous need for updated CNC training curriculum. Training on CNC should follow similar developments and in particular in their programming capabilities, automation they offer and their technical capabilities. In addition, CNC programming is becoming more and more automated through the use of CAD/CAM systems. This requires from the programmers to acquire CAD operation capabilities, on top of their CNC operation and programming knowledge. The major objective in the field of CNC training is to improve the qualifications and competences of the trainees, which is directly related to a well-designed and effective curriculum to be carried out on CNCs. The facilities for CNC training vary a lot and this has had direct impact on the experience that the trainee is acquiring during his/her apprentice. This paper presents the development and promotion of a Virtual Training Centre (VTC), an internet based e-learning facility, specifically based on Computer Numerical Control (CNC) training. This centre includes a virtual space (a CNC training portal) on the Internet which allows the constant sharing of e-learning based CNC teaching material, which is created so as to foster the further development of e-learning based CNC educational contents. This virtual training centre aims at setting the standard CNC virtual learning in vocational training systems [5].

3 Developing a common CNC Curriculum

During the first stages of the project, the equipment, methods, curriculum and techniques currently used for CNC training by the organisations in the partner countries were observed, collected and evaluated [6], [7]. The selected materials were used to create a new and common curriculum. Five important factors that contribute to learning were taken into account in order to prepare the CNC curriculum:

- Motivation
- Aptitude
- Presentation
- Repetition
- Practice with reinforcement

The approach for developing the appropriate training material was based on the following key concepts:

- Motivation
- Know your machine (from a programmer's viewpoint)
- Prepare to write programs
- Understand the motion types
- Know the compensation types
- Format your programs in a safe, convenient, and efficient manner
- Know the special features of programming
- Know your machine (from an operator's viewpoint)
- Understand the three modes of operation
- Know the procedures related to operation
- You must be able to verify programs safely

This approach combined with the important learning factors finally led to a CNC training curriculum including 28 sessions:

1. Machine configuration
2. Speeds and feeds
3. Visualizing program execution
4. Understanding program zero
5. Measuring program zero
6. Assigning program zero
7. Flow of program processing
8. Introduction to programming words

9. Preparation for programming
10. Types of motion
11. Introduction to compensation
12. Dimensional (wear) tool offsets
13. Geometry offsets
14. Tool nose radius compensation
15. Program formatting
16. The four kinds of program format
17. Simple canned cycles
18. Rough turning and boring multiple repetitive cycle
19. More multiple repetitive cycles
20. Threading multiple repetitive cycle
21. Subprogramming techniques
22. Control model differences
23. Other special features of programming
24. Control model differences
25. Machine panel functions
26. Three modes of operation
27. The key operation procedures
28. Verifying new programs safely

4 The structure of the Virtual Training Centre

To develop the virtual training centre, firstly, a communication website was developed in order to manage the activities and tasks to be carried out by the partners. Then, an interactive teaching program was developed and put into a website to form a virtual training centre (figure 1).

The common curriculum developed for this purpose was the base of this training centre. The site, along with the interactive teaching program, was divided into four main areas, "News", "Exchange of views", "Projects and Networks", and "Information Resources". With these, users would be able to access a newsletter, a bulletin board, online surveys and survey reports, information on VET networks, an electronic library with references, a bookshop with downloadable publications and a number of databases.

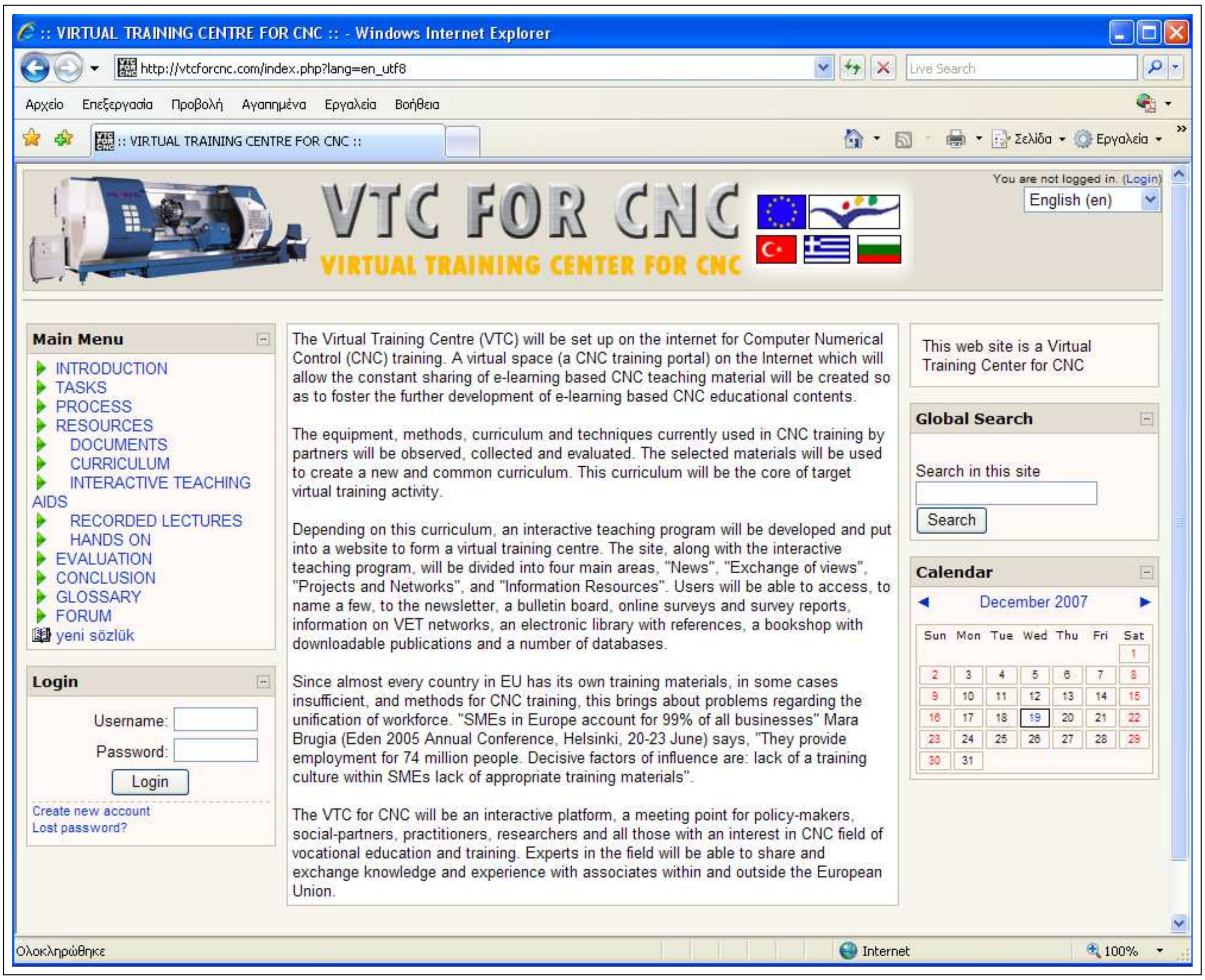

Figure 1: The interface of the interactive CNC training centre (http://www.vtcforcnc.com)

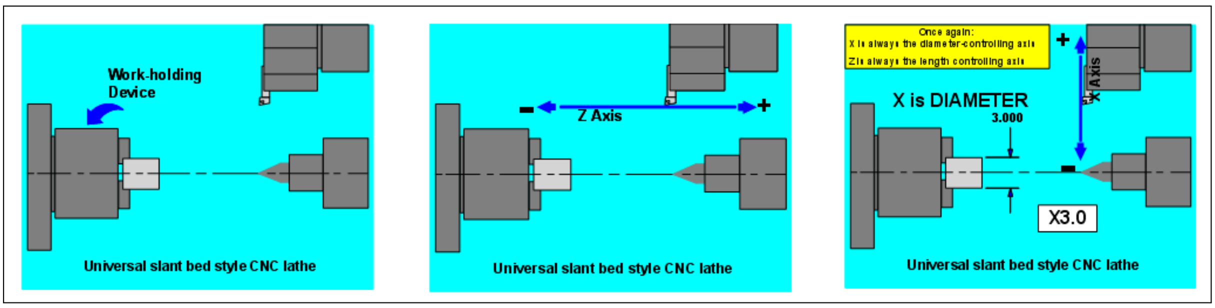

Figure 2: Example of 3- phase animated CNC training material

In the main core of the CNC training material, simulations and practical exercises are included into the interactive training centre (figure 2).

The feedback of the implementation of the VTC in training centres has been recorded and evaluated in order to produce the final version. The evaluation procedure included content (topics, language used, modules), methods (progress, different levels of difficulty, and range of resources, situations and practical cases) and technology (ease of installation, interactive nature and use without a tutor).

The main aim of the VTC for CNC aims is to be an interactive platform, a meeting point for policy-makers, social-partners, practitioners, researchers and all those with an interest in CNC field of vocational education and training. Experts in the field are able to share and exchange knowledge and experience with associates within and outside the European Union. This will foster the long-term viability of the Centre.

5 Aims and Target Groups of the VTC

The VTC aims to improve the skills and competences of people to promote and reinforce the contribution of vocational training to the process of innovation, with a view to improving competitiveness and entrepreneurship, also in view of new employment possibilities.

The specific aims of VTC can be defined as follows:

- Training the trainers, trainees, technicians and apprentices and all enthusiastic about CNC.
- Preparing technicians as intermediates having common measurable qualities the industry is seeking.
- Helping to form a labour force that can use current knowledge and technology, and thus, in search for life-long learning.
- Supporting the sectoral communication through the national centres in partners.
- Setting up a website to publish the data collected.
- Adapting the collected materials to enhance the new curriculum satisfying the requirements in a modern sense.
- Helping to improve and upgrade competences and skills of the involving institutions' didactic staff and exchange experiences over the virtual training centre.
- Enabling the participants to extend the common educational qualifications of CNC technologies, the accreditation of the skills and knowledge of CNC technologies acquired within the network created between participating institutions and organizations.
- Increase the quality of employment through qualified workers.
- Helping to increase active use of technology acquired and thus to increase the standards.
- Contributing to individuals by behaving through life long learning.
- Having a labour power in accordance with common design and production standards.
- Contributing to labour market by using the common technology and equipment effectively.

- Helping to enhance available potential of human sources.

Target groups include trainers, trainees, technicians, apprentices and all enthusiasts about CNC. The final and potential users of the project's results are the training organisations, the SMEs dealing with metal products by CNC usage, and the universities, colleges, vocational schools, training centres.

6 Conclusions

The integration of ITC in this virtual learning environment for CNC, the development of the VTC and the common training curriculum are focused on the EU goals of of internationalisation and globalisation of education, student demand and interest in increasing the quality of education through ICT. At the national level, integration of ICT should become a key priority with national and regional institutions making a commitment to ITC and the development of networks. There must be increased national flexibility with a commitment to support common standards of quality and assessment and to develop national and international metadata standards. This centre addresses the priorities expressed here. Furthermore, this Virtual Training Centre addresses the strategic objectives mentioned above: improving the quality and effectiveness of education and training systems in the EU by developing skills for the knowledge society, ensuring access to ICT for everyone, increasing recruitment to scientific and technical studies, and making the best use of resources. Facilitating the access of all to education and training systems by providing open learning environment, making learning more attractive, and supporting active citizenship, equal opportunities and social cohesion is the other strategic objective that can be achieved through this virtual training centre. The experiences and knowledge gained during the implementation of this Centre can be used in developing and improving other training programmes in particular in the area of new information technology applications in related sectors.

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eCAD System Design - Applications in Architecture

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Abstract: The rapid advances in learning technologies, computer modeling, multimedia and spatial sciences, as well as the availability of many powerful graphics PCs and workstations, make 3-D modeling-based methods for personalized e-learning with eCAD (modeling) functionality feasible. Personalized eCAD learning is a new term in engineering, environment and architecture education, related to the development of learning educational units (3-D learning objects) with re-usable digital architecture functionality, and introduced to literature for the first time within this paper. In particular, for university education courses in eCAD, digital architecture, design computing and CAAD (reagarding spatial information systems, architectures, monuments, cultural heritage sites, etc.), such a e-learning methodolgy must be able to derive spatial, pictorial, geometric, spatial, topological, learning and semantic information from the target object (a 3-D model) or scene (a 3-D landscape environment) or procedure (a 3-D simulation approach to a phenomenon), in such a way that it can be directly used for e-learning purposes regarding the spatial topology, the history, the architecture, the structure and the temporal (time-based) 3-D geometry of the projected object, scene or procedure. This paper is about the system design of such a e-learning method. For this purpose, the requirements, objectives and pedagogical extensions are presented and discussed. Finaly, a practical project is used to demonstrate the functionality and the performance of the proposed methodology in architecture.
Keywords: e-learning documentation, modeling functionality, digital photography, CAD, historical living systems

1 Introduction

The rapid advances in digital imaging sensors and scanners, off-the-shelf haptic devices, computer modeling software and the availability of many powerful graphics PCs and workstations make a method for personalized eCAD learning with 3-D modeling or 2-D drafting functionality feasible (Kalay, 2006). Personalized eCAD learning is a new term in informatics, engineering and architecture, related to digital architecture documentation with e-learning functionality, and introduced to literature for the first time within this paper.

The proposed term personalized eCAD learning is defined as a digital architecture documentation procedure with e-learning functionality based on metric and non-metric (qualitative) data, and spatial and 3-D modeling semantic information (please see next Section).

In particular, for the historical living systems (i.e. monuments, churches, basilicas, archaeological sites, etc.), such a methodolgy must be able to derive pictorial, geometric, spatial, topological, learning and semantic information from the target architectural object (historical living system), in such a way that it can be directly used for e-learning purposes regarding the history, the architecture, the structure and the temporal (time-based) 3-D geometry of the projected historical living system.

Improvements and new developments in the fields of sensor technology and computer modeling allow the acquisition of digital images in video-realtime, without developing and digitizing a photographic film (Streilein, 1996; Kazakeviciute et al., 2005).

Such a system -which is well described by Andre Streilein from the ETH Zurich- for digital photogrammetry and architectural design consists of two sub-systems: a sub-system for the digital photogrammetric station and a sub-system for the CAAD (Streilein, 1996; Streilein et al., 1992). In this domain the aim of a method for e-learning documentation is to make the photogrammetric data acquisition and processing easier and faster, to create a three-dimensional geometric and semantic object description, and to allow CAAD/multimedia data integration, haptic rendering, íisua1ization and architectural processing in an easy and user-friendly way (Vladoiu, 2004; Weber, 2004).

Therefore, such a method must be capable to acquire imagery with sufficient resolution, process the data with a big leíel of automation, and pass the results to a data structure useful for 3-D CAAD modeling (Hirschberg et al., 1996). This can be achieved using solid-state sensors and manual, semi-automatic or automatic measurement techniques. Also, for environmental management purposes, the current status of a relative methodology for such a system is described by L. Dimen et al. (2005) and a relative method is being deíeloped in a joint project of the ATEI of Thessaloniki in co-operation with the AGORA University of Oradea, Romania.

With the constant progress of multimedia technology and network bandwidth, the traditional teaching environment that based on text and pictures, will be integrated with media streams, 3-D modeling, intelligent agents, mathematics, virtual reality, haptic rendering and spatial objects (sciences)ů as described by A. Styliadis et al. (2006) for the GIS case, by Engeli et al. (1996) for the intelligent agents, by I. Dzitac (2000, 2002) and by I. Dzitac et al. (2007) for the mathematics case, and by Silva et al. (2002) for the insertion of 3-D architectural objects in photography. For this reason, in this paper, the proposed methodology shows and demonstrates an architecture (3-D model) that can support these new, rich in e-learning functionality, environments.

Recently, more and more systems come up that use any CAAD and semantic information available prior the measurement process. Such a system is the modelling-and-rendering system developed at the University at Berkeley by Debevec et al. in 1996. This system uses a rough object description in order to guide a stereo matching technique for the digital reconstruction of the primary object details with relative accuracy better than 10-3.

Another similar system (a CAAD system named "NAOS"), dealing with 3-D geometry (with relative 10-3 accuracy as well) and qualitative information for CAAD documentation, was developed in 1997 at the Aristotle University of Thessaloniki, School of Surveying Engineering and at the ATEI of Thessaloniki, Greece (Styliadis, 1997).

Also, very interested is the work at the University of Helsinki from H. Haggren and S. Mattila (1997) dealing for 3-D indoor modeling development based on videography data. In particular, in this work a functional 3-D model of indoor scenes is built first and the measurements of the geometry based on video images are performed thereafter.

Finally, an interested CAAD system under development exists at the University of Delft (Frank van den Heuvel, 2003), which makes use of a priori geometric object information in the form of parameterized object models with image lines as the main type of observations.

On the other hand, e-learning is a process that needs quite amount of mental and body strength. In order to promote the e-learning efficiency, it is important to improve the learning environment and this is the case of the proposed methodology (e-learning with CAAD functionality).

Apart from traditional design, the media stream or the virtual reality, can stimulate learner even more, reinforce the learner's motivation, attention and mentality. Some systems adopt different technology and implemented similar environment also demonstrate satisfactory results. However, they need to spend a lot of money and time to achieve that, such as VRML (Virtual Reality Modeling Language) it can establishes a virtual 3-D scene with walk-through functionality in the scene by a simple parameter, but while controlling the behaviors of the 3-D objects that enhance photorealism -such as the materials, the lights, the object scale, etc. - a script procedure must be writen in the complicated VRML markup language. Evenmore, the VRML modeling relative inaccuracy is greater than 10-3 and so, this is not acceptable for e-learning documentation applications.

The proposed method is based on a virtual learning environmental architecture that integrates synchronous, asynchronous and co-operative characteristics.

The paper is structured as follows: In Section 2 (Personalized eCAD Learning: Term Formulation) the new term Personalized e-learning is introduced and described. In Section 3 (Personalized eCAD Learning: The System Design - Learning Requirements) an overview of the proposed personalized e-learning methodology is given. The Section 4 (Personalized eCAD Learning: The Main Streams) presents the main sub-systems outline design of the proposed e-learning methodology. Finaly, in Section 5 (Personalized eCAD Learning: An Application in Architecture) a practical 3-D model based application is presented and its e-learning functionality is discussed.

2 Personalized eCAD Learning: Term Formulation

Personalized eCAD learning is a new term in engineering and digital architecture, related to digital (geometric- and semantic-based) learning with re-usable spatial functionality, and introduced to literature for the first time within this paper.

The proposed term personalized eCAD learning is defined as a digital documentation procedure with e-learning re-usable spatial functionality based on metric and non-metric (qualitative) data, and spatial 3-D modeling semantic information. At the 'heart' of this e-learning is the 3-D model (vector format) of the object (which could be any architecture, building, monument, etc.) or the process (environmental polution, weather forecast, water flood estimation, etc.) being described (Dimen, 2005).

The objectives of the personalized eCAD learning are:

- to facilitate and encourage the collaboration and the critical awareness between the design students, scientists and professionals (architects, designers, engineers and so on).
- to design virtual spaces using different representation methods and techniques for haptic rendering regarding architectures, landscapes and urban design.
- to communicate through 3-D model-based multimedia data in ways traditional CAAD, photography and video does not support.
- to support access to prior understandings regarding the 'pathology' (nature) and the characteristics of the described object or process.
- to allow ideas exchange and to support design autonomy.
- to test the efficiency of the various sub-systems involved in design and construction processes for the Architecture, Engineering and Construction (AEC) community.
- to promote self-directed reusable learning exercises which lead to a critical awareness of the learning process and the learner's empirical background.

Similarly, the pedagogical profits are:

- the establishment, through this documentation, of a new reality in education and design practice, whereby the accepted realism and the level of the 3-D modeling accuracy (or inaccuracy), of the object or the process, are not so necessary to communicate performative and reusable educational and design concepts (Martin et al., 2004).
- the real-time collaborative and reusable interactivity.
- the feedback (learning domain 3-D ontologies for semantic CAAD descriptions).
- the ability to develop manual, semi-automatic or automatic reusable CAAD learning tools that could support architectural, photogrammetric, art, historical or archaeological training and education.

The pedagogical strategy of the personalized eCAD learning is based on encouraging and facilitating the communication and ideas exchange between the personnel involved in the design, implementation and spatial analysis process. Finaly, active role, interaction, group work and design autonomy are the characteristics of the proposed personalized eCAD learning.

3 Personalized eCAD Learning: The System Design - Learning Requirements

The structure and the processing steps for the proposed personalized eCAD learning method are shown in Fig. 1. In this figure, the relation among the 3-D learning objects with modeling functionality and the available learners' (engineers, CAD personnel, architects) profiles are presented in connection with the geometric, topologic and thematic spatial data.

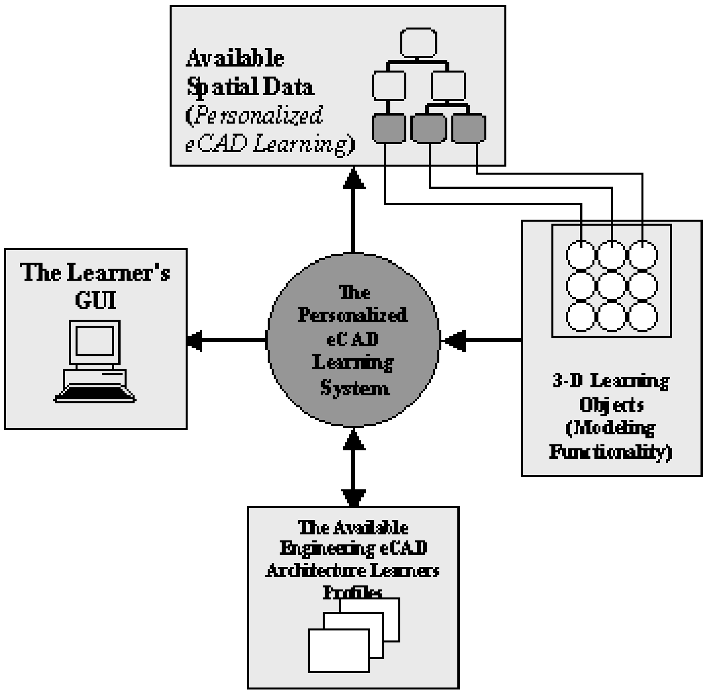

Figure 1: The Proposed eCAD System Design (Personalized eCAD Learning)

On designing the proposed methodology for the e-learning documentation, the statistical analysis results from an e-learning course in CAAD and the VRlab research project at the ATEI of Thessaloniki are examined (Tsakiris et al., 2005). So, according to students suggestion, the functional specifications for a 3-D based e-learning system are defined as follows:

- 3-D map video processing
- 2-D image processing
- Archive or historical photography, rich in geometric regularities and properties (i.e. clues, like: planarity, parallelism, orthogonality, symmetry, perpendicularity, topology, etc.), processing (Styliadis et al., 2003)
- Item-by-item 3-D modeling functionality in an e-learning CAAD environment

- Haptic rendering of the resulting virtual representations of both the 3-D maps (models) and 2-D images (drawings)
- GUI with drag-n-drop functionality
- Multimedia functionality
- Learning functionality incorporating historical and semantic data
- Force-field haptic rendering functionality
- Virtual Reality functionality
- Noting- and shared-board functionality
- Non-stop study functionality

Actually, what the learner needs is a synchronism and adaptive e-learning system which can interact in real-time with the teacher in class (Wu, 2002). In this domain an asynchronous system can let learner to study in his free time by adapting learning object selection (based on discrete and reusable 3-D modeling items) in intelligent learning systems (Karampiperis et al., 2004). Also, such as system can let learners discuss with each other through media stream. Besides, they also need 3-D virtual environment with haptic rendering functionality, which can increase learner's interest and attention.

4 Personalized eCAD Learning: The Main Streams

After defining its functional specifications the main sub-systems (streams) of the re-usable e-learning system are defined as follows:

- Media Stream Services: This is the server sub-system; for which a number of media stream servers are needed (e.g. a system or central server). These servers can provide data (photography, imagery, history, architecture, modeling) for learners on real-time. These servers can also store material in repository (i.e. material palettes) which then can be searched by researchers or learners (e.g. students in architecture, art, history, etc.).
- Virtual Learning Environment for 3-D Visualization: This is the client sub-system; which includes a user interface based on 3-D graphics, haptic equipment and virtual reality tools (Petrovic, 1996). It is the stage for the learner and it includes virtual and resource classroom, chat room, etc. This e-learning sub-system provides chatting functionality on a learner-to-learner or learner-to-teacher basis. After the learner's logon to the system, he can control the learning process on focusing: (i) on particular 3-D modeling and rendering methods supporting e-learning functionality, e.g. haptic rendering, phong shading rendering (Fig. 2) or phong rendering; and (ii) on particular details of the historical living system using a GUI input device like the keyboard, the light-pen or the mouse. Evenmore, using this stream the learner can also communicate on-line with other learners (e-students).
- Web Portal: This e-learning stream provides the learner with additional information and operates as an integration platform for the entire e-learning documentation. This stream mainly includes the system's operation manual, monument's relevant documents and teaching materials, monument's architecture, history, archive (historic) photography, digital imagery, etc.

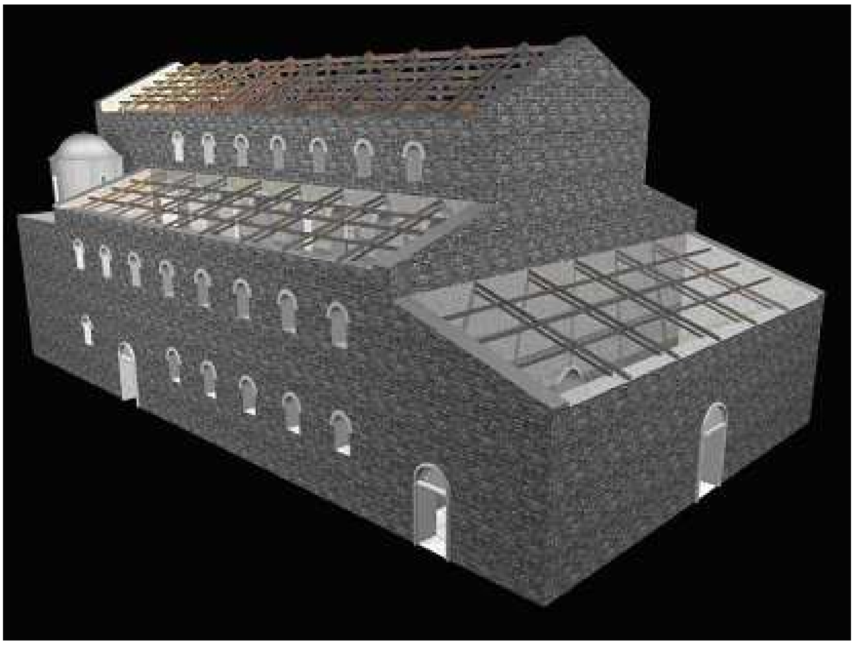

Figure 2: 3-D modeling of Aghios Achilleios basilica

5 Personalized eCAD Learning: An Application in Architecture

Beyond the thirsty coasts of Greece lies a lush heartland where a coachload of sunburnt tourists are a rarer sight than a flock of pink-backed pelicans. This is Macedonia, a land of legendary battles and untamed landscapes, more familiar for the news headlines it attracts than for its startling natural beauty.

Nestled, among Macedonia's verdant mountains, are the twin cool lakes of Prespa (North-West Greece). Declared as a National Park in 1974; these twin lakes provide a sanctuary for over 280 species of birds and the largest pelican breeding ground in the world. Though stranded on the edge of Greece, Prespa lies at the 'heart' of the Balkans. Straddling Greece, Albania and the Former Yugoslavian Republic of Macedonia (FYROM), these lakes are a smooth expanse of serenity caught in the crossfire of shifting borders. Locals are an unusual stew of immigrants and refugees from Pondos and Asia Minor, and nomadic Vlachs; many still speak their native dialects. But as with most of rural Greece, Prespa's population is dwindling.

At the turn of the century, there were 12,000 inhabitants and 21 villages. Now, only 1,200 locals and 12 villages are left; they survive now, as then, by fishing and farming. Until 1969, locals carried special ID cards and foreign visitors required a visa. Even today, tourism is just a slow trickle in this watery wonderland.

The Aghios Achilleios basilica, in lakes Prespes, was chosen to demonstrate the functionality and efficiency of the proposed method. Actually, the Aghios Achilleios basilica is located at the Aghios Achilleios island on the minor Prespes lake.

The monument is a three-aisled, wooden-roofed basilica with a narthex and domes over the parabemata (Fig. 3). It was founded in ca. 986-990 by tsar Samuel of Bulgaria. Initially, it was the cathedral of Samuel's short lived empire and later, until the middle of the 15th century, was an episcopal church.

A tomb covered with a relief tombstone is preserved in the south arm of the cruciform diaconicon; tradition say that the relics of Aghios Achilleios were kept in this tomb. Along the south wall of the south aisle, four other graves are preserved, in which important persons of the church or the local community were buried.

The few fragments of the wall paintings belong to two different layers and have been removed from

Figure 3: The Aghios Achilleios basilica at the twin lakes Prespes

the building. They are now on display in the exhibition of Byzantine and post-Byzantine art, in the Byzantine Museum of Florina. Today, only a part of the super-structure of the building is preserved, especially on the east side.

It stands to a privileged and dominating position, nearly 20 metres above the lake of Prespes at the isle of Aghios Achilleios. The monument is about 22 m in length, 16 m in width and 6 m in height. A detailed discussion about the history, architectural design and construction of this basilica is given by Prof. Emeritus of Architecture Nikolaos Moutsopoulos (1999). The monument has been under restoration since 1987, and the wall masonry will be rebuilt as long as there is available evidence of its construction.

The result of the photogrammetric processing was a 3-D geometric and semantic object description, which was passed automatically via Java-MDL programming (Java and C++ coding) to the MicroStation Masterpiece CAAD system. This system is able to pre-process the data and store it in data structures adapted to architectural purposes; allowing, as well, data transformation into other representations in an easy way.

For the personalized eCAD learning, the task of the learner is the creative finding of new modeling solutions (point or parallel perspective) as well as to evaluate the current modeling accuracy, for both the point and the parallel perspective projections, in connection with the imagery processing equipment and technique used. More for 3-D reconstruction from perspective images could be found in (Yang et al., 2005).

The e-learning documentation is important for documentation and visualization purposes, and for complex simulations, manipulations and analysis of the target architectural object. This could be used in e-learning courses about architecture, archaeology and art history, in preservation of historical monuments and sites, in regional and local planning, as well as in renovations, reconstructions and reverse engineering projects.

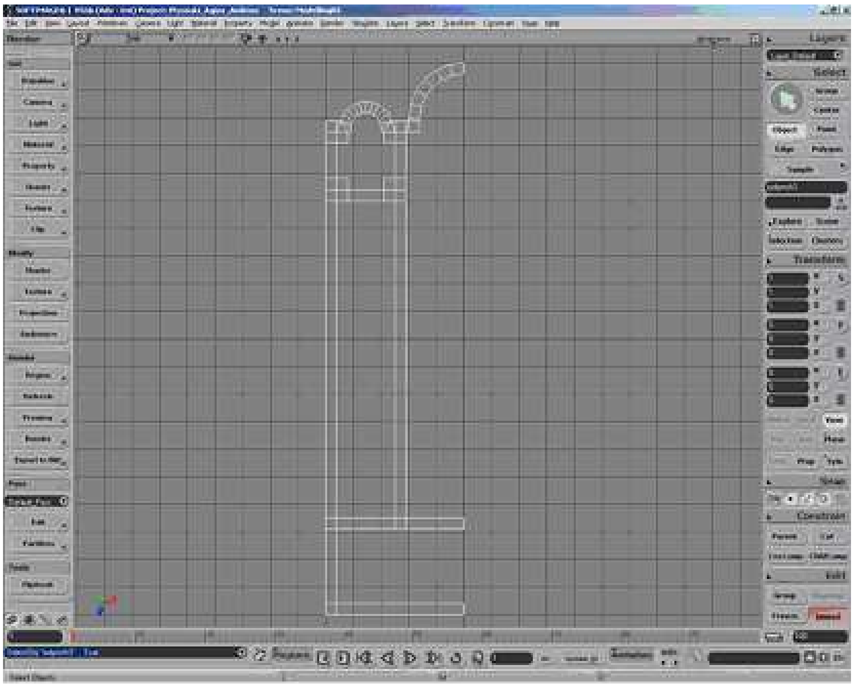

Figure 4: A top view of the east part of Aghios Achilleios basilica (architectural drawing)

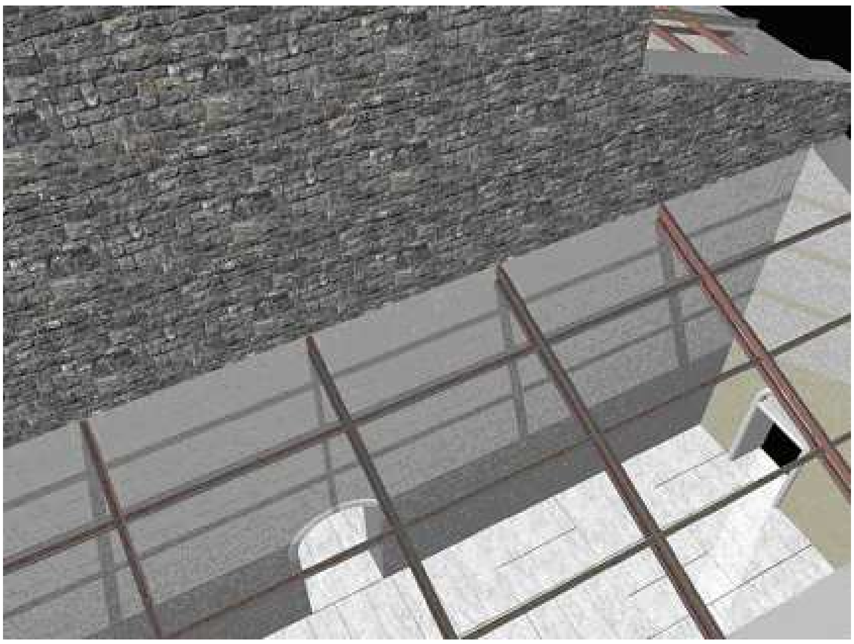

Figure 5: Phong haptic rendering: A point-perspective view of the Aghios Achilleios basilica CAAD Model (haptic representation based on digital low-resolution Canon CI-10 imagery)

Figure 6: Phong haptic rendering: A parallel-perspective view of the Aghios Achilleios basilica CAAD Model (haptic representation based on digital low-resolution Canon CI-10 imagery)

Figure 4 shows the top view of an architectural drawing regarding the east part of the Aghios Achilleios basilica, and Figures 5 and 6 illustrate two haptic rendering perspective views ïf the photogrammetric generated CAAD model of the same monument. It is important to note that haptic interaction and rendering is especially important to e-learning students and populations with disabilities, such as the visually impaired, because tactile interpretation is one of the most important modalities they can use to perceive the world and to appreciate the monuments and the cultural heritage.

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