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Methods, Models and Workflow Used in Calibration Oil Reservoirs Software

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Abstract: The scope of the present article is to present a proposal regarding the integration methods, models and workflow used in the metrology field with the Enterprise Resource Planning (ERP) systems. One of the main topics of the author's PhD research is the development methodology and the implementation of a metrology software application for the calibration of oil tanks. The developed application is integrated with an existing Enterprise Resource Planning (ERP) system used by important Oil & Gas Company. The software application was developed in the SAP (System and Applications Products) programming environment ABAP (Advanced Business Application Programming), using the latest Web Dynpro WD technology. The development methodology includes the analysis, implementation and testing of the software application.

Keywords: metrology, workflow, enterprise resource planning, advanced business application

1. INTRODUCTION

Enterprise Resource Planning or ERP is software business solution that helps integrating all divisions across a company onto a single computer system serving all needs in the company. Enterprise resource planning (ERP) software business solutions are designed for companies that work in a wide variety of areas. ERP is business process management software that allows an organization to use a system of integrated applications to manage the business and automate many back office functions related to technology, services and human resources. This concept, ERP ”Enterprise Resource Planning”, was introduced in 1990 by the Gartner Group, in order to define a new generation of manufacturing resource planning (MRP II) software, which later came to fill up the gap reflected by the evolution of application integration beyond manufacturing. The Gartner Group its client's oriented company which has as a main field of activity, IT solutions consultancy. For companies, MRP II is a method which helps, to involve the planning of all the regular resources, including without limitation, software applications, users skills and abilities, design of specific databases, and any other computer resources [3].

In order to manage accurate the resources we use the concept purpose, to increase the performance and most of the productivity of the company [1], [2]. For developing activity in a company, initially for each division where used separate software, accounting, business intelligence (BI), human resources (HR), inventory management (IM), planning, manufacturing (PP), sales and distribution (SD), marketing, later came the ERP concept and his final target were to integrate all these software applications in one single software product [4]. Overall the ERP has improved the process management of a business activity; he integrated and managed applications for all areas. SAP, Oracle and Microsoft are the more well-known companies which deliver ERP software for large enterprises. SAP started in 1972 in Germany, is the largest inter-enterprise software company in the world, and one of the largest independent software supplier. The initial purpose of SAP was to provide to his customers the possibility to interact with a common corporate database for a broad software application. ESR it's a new trend in SAP evolution, “Enterprise Services Repository is the central repository, which is part of SAP NetWeaver platform, where enterprise services, business objects, and business processes and their metadata are stored” [6].

More or less ESR is the central repository information used in entire SAP NetWeaver Platform and if we want to make our application callable by services and integrated with other applications or business partners we have to use the principles of ESR [7]. From this paper's point of view, the interesting aspect is that we create a z-homemade application inside our installed enterprise resource planning software (SAP) [8].

2. CALIBRATION OIL TANKS - METHODOLOGIES

Using Enterprise Services Repository as a new software technology, is part of daily activity inside oil companies, which try to automate processes, in order to have an accurate visibility of their innovations and to adapt several changes shortly and with better results [5], [6]. In order to achieve this, many companies create development teams dedicated to solve the problems of each specific activity. In entire group, the development team (inside Technology

Department) is dedicated for developing and providing best practices for internal processes, in order to help the daily activity of their colleagues from other departments. We store all developments in SAP Solution Manager – in fact in Development Center tool [9]. In order to have an accurate integrated database with all measurements regarding calibration of oil reservoirs, test results, conclusions after measurements, we initiate a process / case study in order to create an internal development application for metrology area, calibration reservoirs inside SAP system.

Fig 1. Vertical reservoir / tank

Our case study full fills all legal requirements regarding this subject. In exploration and production area we can use two types of reservoirs: vertical and horizontal (Figure 1 and Figure 2). In order to realize a calibration of an oil reservoir a mixed method is used. The method is based on two components: a volumetric one and a geometric one [13]. This method is used to calibrate a vertically cylinder reservoir with fixed roof. This reservoir cannot have a nominal capacity greater than 40 cubic meters [12]. In order to implement this method for the calibration purposes, two components are used:

Fig 2. Horizontal reservoir / tank

- geometric components are used for direct measurement reservoir dimensions based on measuring tapes, the final result regarding entire capacity of reservoir being determined based on measurement performed [12],[13];
- geometric components are used for direct measurement reservoir dimensions based on measuring tapes, the final result regarding entire capacity of reservoir being determined based on measurement performed [12],[13].

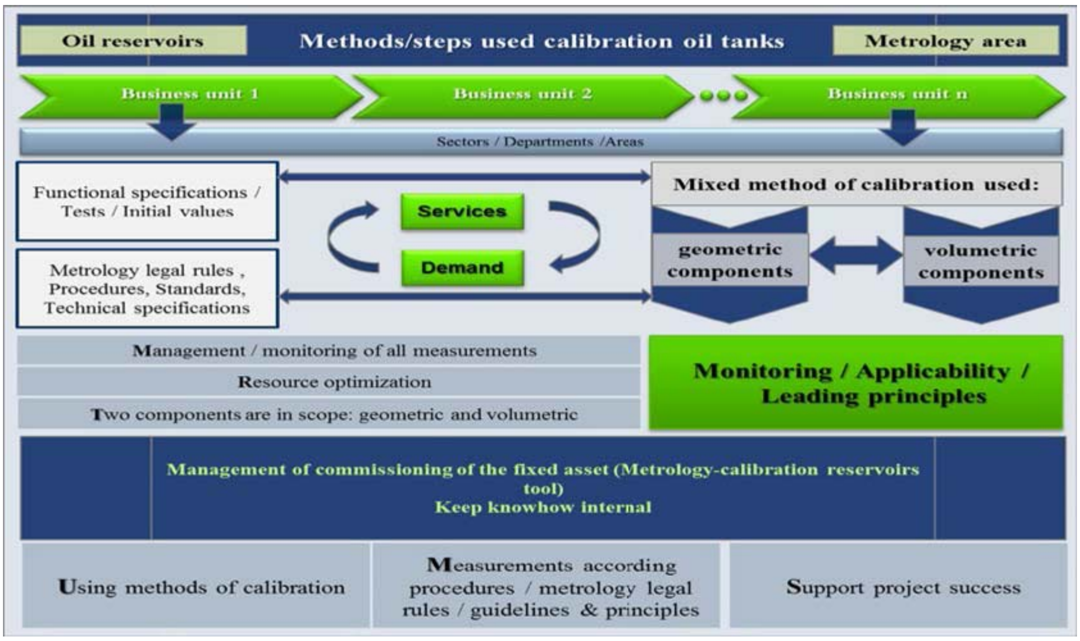

Fig.3. Example metrology procedure / connection between business areas

Mixed method cannot be applied to tanks with obvious deformity and to tanks which do not have a circular horizontal section. In order to verify and calibrate a reservoir it's used a different metal measurement unit (with overflow): 100 dm^3 (cubic decimeter), 200 dm^3, 500 dm^3 or higher than this value. If is needed to measure with other standard fraction, then we will use, a measure of 50 dm^3 [12], [13]. In order to see the underlying principles to create a software application, the Figure 3 illustrated this, so, we take into consideration the metrology standard rules, guidelines, principles, standards and indications from the internal metrology team. In the application all recorded information is stored in order to be analyzed and to be part of the mathematical computations. When the collecting measurements process is started, it is needed to create a calibration table for each reservoir. For each value of partial capacity from the reservoir, and for each integer value expressed in centimeter of the filling height of the tank, the reference temperature will be 20^0 C [10]. We notice that V_H is partial capacity, corresponding to the higher fill H (integer number recorded in centimeter), between consecutive two measured heights, h_{i-1} and h_i, and will be obtained using the linear interpolation, using the following formula [12], [13]:

$$V_H = V_{i-1} + v_i \times \frac{H - h_{i-1}}{h_i - h_{i-1}}, (i = 1,2,...n) \tag{1}$$

where:

-$k = 1, 2 \ldots i$- order number of ratio water introduced; $h_0=0$;

- v_0 = dead stock of reservoir,

- $v_1, v_2 \ldots v_i$–ratio water volume which are placed in reservoir, successively, to the height h_i,

h1, h2 … hi– each measured height, after ratio water placed.

$$V_{i-1} = \sum_{k=0}^{i-1} v_k , \tag{2}$$

For each measurement we have to take into consideration the outside temperature. In this case, regarding v_k, there are two cases:

- when it is not considered, then the amount of sum of all capacity, will be equal with all ratio water introduced in reservoir;
- or we have to adapt our calculation with one correction factor, equal with (1-e)/100 (e is the corrected error, in percentage, of the working flow meter) [12], [13].

Regarding the avoidance of water expansion effect, there are also two cases:

- when the water temperature is between 5^0 C and 10^0 C and the difference between average measure volume and the reservoir does not exceed 2^0 C,
- when the water temperature is between 10^0 C and 25^0 C and the difference between average measure volume and the reservoir does not exceed 1^0 C.

For some different water ration at t_k temperature, the relation (1) can be corrected, using the following formula [12], [13]:

$$v_k(t_k) = v_k(20) \times [1 + \beta_e (t_k - 20)], \tag{3}$$

where:

k - is the order number of ratio water,

$v_k(t_k)$ - is the ratio water volume on t_k temperature;

$v_k(20)$ - is the amount of the real conventional capacities for the water measure, which is used for the achievement water ratio;

β - is the coefficient of expansion in volume of the material volume ratio of which is made.

These corrections are also made for the dead stock v_0. In order to calculate water mass, m_k, taking in consideration volumes $v_k(t_k)$ we can use the following formula:

$$m_k = v_k(t_k) \times \rho(t_k) \text{ , } k=0,1,...,i, \tag{4}$$

where: $\rho(t_k)$ – the density of water at the t_k temperature.

The following formula is used to compute the water mass M_{i-1} till high h_{i-1}:

$$M_{i-1} = \sum_{k=0}^{i-1} m_k , \tag{5}$$

In order to calculate the water volume of our reservoir, V_{i-1}, at h_{i-1} and t_{i-1} the following formula is used:

$$V_{i-1}(t_{i-1}) = M_{i-1} / \rho(t_{i-1}), \tag{6}$$

where: $\rho(t_{i-1})$ – is water density at t_{i-1} temperature.

The capacity of reservoir, $V_{i-1}(20)$, for height t_{i-1} and reference temperature 20^0 C, will be calculated [12], [13]:

$$V_{i-1}(20) = V_{i-1}(t_{i-1}) \times [1 + \gamma_r (20 - t_{i-1})], \tag{7}$$

where γ_r = (2/3) x β_r is the dilatation coefficient of the reservoir material. A correction for temperature could be applied during the calibration of a reservoir if the water height h_i is considered. This correction could be ignored if the height is lower than 2 m or if the height is upper than 2 m and water temperature into the reservoir is between $15^0 - 25^0$ C.

The following formula is applied:

$$h_i(t_i) = h_i(20) \times [1 - \alpha (t_i - 20)], \tag{8}$$

where:

$h_i(t_i)$ – is the height at the temperature t_i, which is measured in the reservoir;

$h_i(20)$ - is the height read from measuring tape, according with the calibration certificate which is attached to the measuring tape; α - the material coefficient of linear dilatation; In order to perform the calculations, the following dilatations coefficients are used: the mild steel

– 3,3 x $(10^{-5})^0$ C; stainless steel: 5,1 x $(10^{-5})^0$ C; aluminum alloy - 3,3 x $(10^{-5})^0$ C; brass: 3,3 x $(10^{-5})^0$ C. In each measurement the calculated value of height is rounded on integer value [10], [12], [13]. As a conclusion, the calibration sheet will include the ratio water number, the reservoir/tank height water, the cumulative volumes of water rations, the volume of water ratio, the size of range, the volume/mm, the height and the corresponding volume of height as is described in the Figure 4.

3. METROLOGY SOFTWARE APPLICATION DESIGN

SAP focuses on existing integrated processes in the company, from the collecting, planning process, development/production tracking and to the purpose of managing the relationships with customers, suppliers or other business partners. SAP (System and Applications, Products) is the largest ERP (Enterprise Resource Planning) system in the world [15] [16]. SAP is based on client/server architecture and it is used in developing integrated systems. The benefits for the company, when choosing to use SAP, are as following: an integrated system (there is a single database, all components are interdependent); an open system (independent from the hardware platform and database used, allowing the correlation with other software; modification including new functions created by the user; a comprehensive system that, from an economic perspective, can cover any sector activities; a real-time system including tools and providing information based on data analysis from operational flow; a lower cost for company based on automated tools and preconfigured functionality; an integrated industry-specific solutions inside business processes; easy to integrate operations into one software in order to meet the corporate needs for standardization and control. As it was used for the application WebDynpro, other benefits come with this new technology for SAP landscapes, like: the model is used for develop professional Web UI's (Web User Interface) for business applications; the WD tools can support the application development during all phases (implementation, testing and design); a clear separation layout data and business data, thus it is possible a clear separation between layout data and business data, thus it is possible to develop WD applications with the same programming model, both for conventional PC's and mobile devices; different languages are supported; the time for implementation and the effort implementation is significantly reduced; a structured design process is supported by WD; it's easy to use the Model View Controller concept obtaining a strict separation of layout data and business data; it has more UI elements as compared to other technology; run on multiple platforms; support web service and data-binding.

In the Figure 5 is explained the WD concept and his benefits. In another train of thoughts the concept of WD are based on MVC (Model View Controller) architecture and is composed of three particular elements: model, controller and view. The MVC architecture is described in the figure below, Figure 6. As it is plotted in this figure, the MVC architecture design pattern contains a clear distinction between processing control (controller), data model (application data, connection to business functionality), and the display of the data (view) in the interface according with clear rules. As described in the

	A	B	C	D	E	F	G	H
	Ratio water number	**Reservoir heigh water**	**Cumulative volumes of water rations**	**The volume of water ratio**	**The size of range**	**The volume / mm**	**The height**	**The coresponding volume of H height**
	i	h_i	$\sum v_k$	v_i	$h_i - h_{i-1}$	$\frac{v_i}{h_i - h_{i-1}}$	H	
		mm	*dm³*	*dm³*	*mm*	*dm³/mm*	*mm*	*dm³*
1	Dead stock	0,00	21,00	21,00	0,00	0,00	0	21
2							10	31
3	1			50,1	49,40	1,01417004	20	41
4							30	51
5		49,40	71,10				40	62
6							50	75
7	2			50,1	32,90	1,522796353	60	90
8							70	105
9		82,30	121,20				80	121

Formula will be: H2 = C1 + D3 x ((H2 - B1) / E3))

Figure 4 The result of a calibration

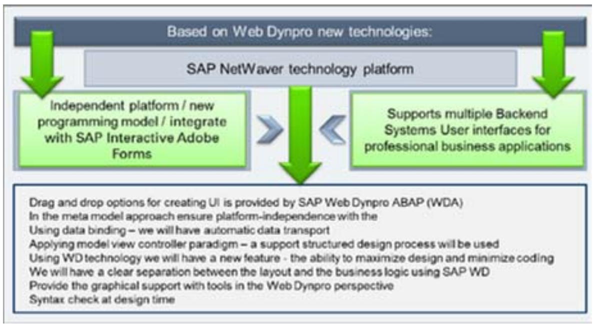

Figure 5 Web Dynpro advantages

Figure 6 different types of controllers are available: component controller, custom controller, interface controller, view controller and windows controller.

Enhancements in WD ABAP can be done easily using the functionality called Enhancement Options (ABAP WD components cannot be implemented using BADI - BADI's are ABAP object based of changes, instead of the more common subroutines/function modules). This is an explicit anchor points provided by SAP and is implemented in the source code at suitable points during the development of the WD components [10]. As an experience, using these options provided by SAP (enhancement options) it is possible to insert a separately developed BADI into the flow of the program and therefore each BADI is an explicit enhancement. For the WD components, several enhanced implementations can be created and all are independent of one another, so it is possible to add, in addition to source code, enhancements: in a view, in a controller, in a component and window. An important aspect in WD flow is the context, which is a method of storing data in a hierarchical manner. The data used by the component or a view is stored in the form of context [17].

The controller can be used to read or write data in the context, as a starting point. In order to create a WD application it is compulsory to use the normal t-code (SAP transaction) se80 and to choose in the repository browser the particular WebDynpro component/interface.

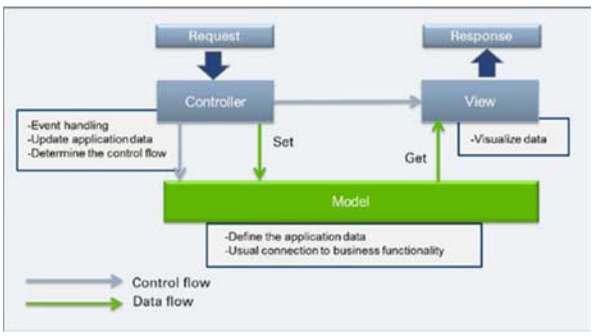

Figure 6 The MVC architecture

4. IMPLEMENTATION PRINCIPLES FOR THE SOFTWARE APPLICATION

Calibrations are part of planned activity inside companies, which try to supervise the integrity and legality of his fixed assets – here we are talking about reservoirs which are subject of metrological control. The Metrology tank calibration application structure was created based on request from Demand Management business division. In order to have an accurate process of calibration we categorize in our tool 3 models as following: dispatcher model; body-leasing model; calibration given outside (fixed price) [18]. Each model has got separate details concerning the functionalities which will be taken into consideration: dispatcher model - it is the widest used model, calibrations are achieved by means of internal experts calibration colleagues and external calibration reservoirs experts, and extended service time can be requested (putting into operation the tank, after maintenance and repairing); body-leasing model: calibration reservoirs experts leased to projects (calibration project), but all rules and QA will be achieved by a team of our company (experts certified by BRML); calibration given outside (fixed price) model: an external company will be hired in order to provide the entire calibration process of a tank for a fixed price and all rules are provided by the team of our company (experts certified by BRML), QA internally; a special note will be that all our models will be verified and certified by the legal entity BRML. In the beneficiary Oil Company, in particular Exploration & Production division, this implementation has been considered a success. The application was done based on a detailed analysis of the business environment, taking into account all requirements from exploration business and all BRML legal requirements. The application workflow from Figure 7 show, step by step, the "in house procedure" used in SAP solution for recording in our tool a calibration for a tank used in demand management business. The innovation of this development is that everything was developed in the latest technology provided by SAP, WebDynpro WD - a web application technology. Due to this development each end-user will be able to access the application via web. In order to see the content of it, this application will be published via SAP Portal servers [19]. In order to perform the oil tank calibration record in the tool, it is necessary to collect the data from the oil sectors. This data will be filled in specific forms, according to the BRML legislation. In Figure 8 it is plotted the situations used in order to perform a calibration tank. In addition to this process, all documents that have been provided from the company which sales the oil tank, are being stored in the system, in order to be viewed at any time [10].

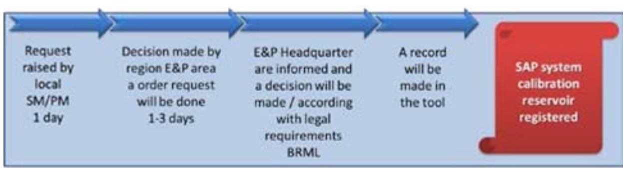

Figure 7 The workflow used in application

In E&P division, by using our tool, there are major benefits: viewing all the data for metrology calculation in one database. The data introduced in the system is accurate and can be displayed on-line.

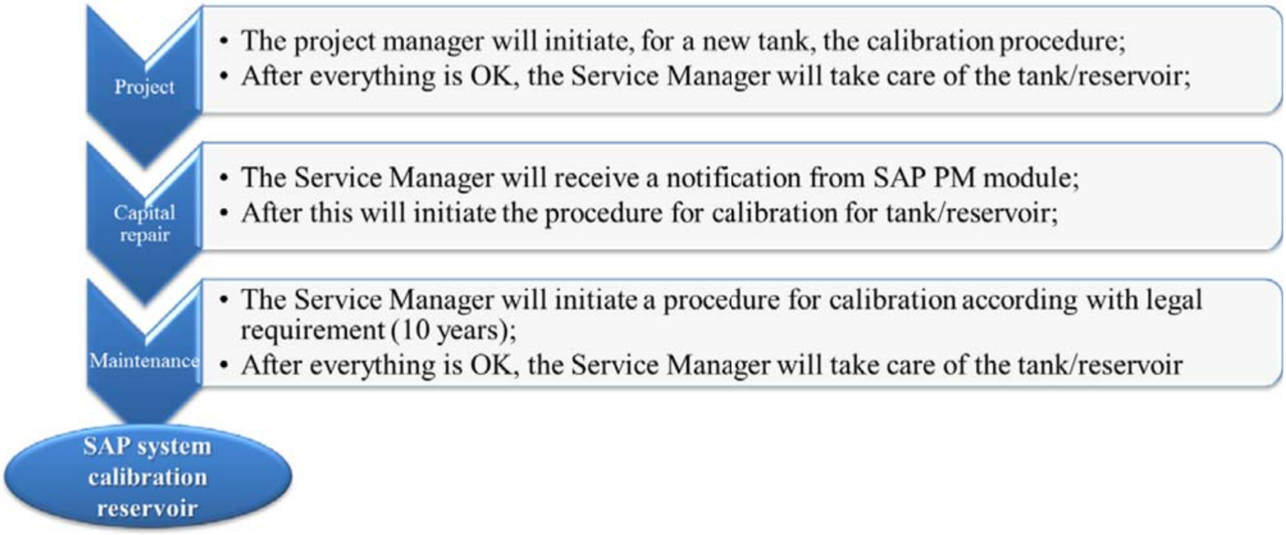

Figure 8 Metrology add new measurement

In Figure 9 are shown the steps needed to approve a calibration, the workflow used for each important decision part, in fact all these parties are involved in calibration procedure. The most important step used for calibration workflow is the decision of service manager if a calibration will be done or not. Each decision is done in E&P region based on specifications received from local department manager who take care of tanks in respective petroleum zone. The legal entities can audit the data at any time in order to verify if the algorithm used for calibration is used correctly [10]. Based on a chosen calibration method and after all technical characteristics are added / stored in the tool, we have the possibility to upload, step by step, the data provided from the oil sectors, which is based on multiple manual measurements. The data previously mentioned, can be added automatically or manually. If the data is added manually, a calibration method will be established first, and only then the measurement can be started. The data is added in the system as described in Figure 10 (the application interface). The ZMET_TANK_METROLOGY transaction (in front of the ZMETTANKMETROLOGY program) is an example of "in house" z-application (all these SAP objects are included in one application package called

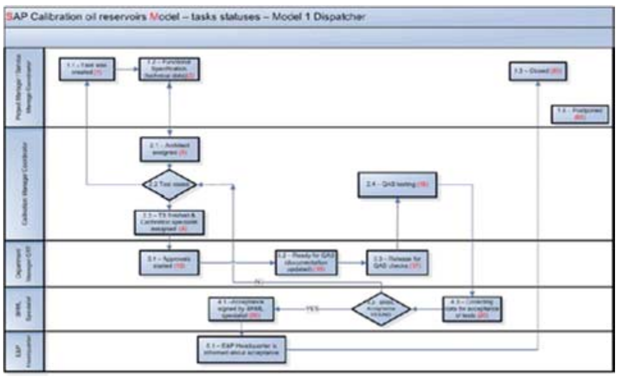

Figure 9 Steps used for calibration

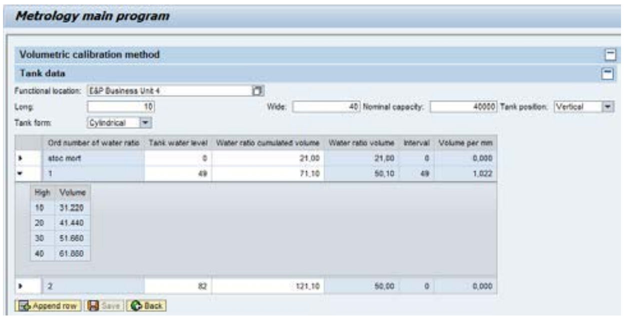

Figure 10 The application interface

ZOIL_TEST). This package contains all objects used in the SAP z-application developed by the development team: Embedded Programs, Dictionary Objects, Class Library, Programs, Function groups, Includes, Transactions, SET / GET Parameters, Message Classes, Area Menus, Test Objects, Authorization Objects, Enhancements.

The Web Dynpro content for Metrology tool processing is a collection of screens, fields, menu bars, GUI status, GUI title, transactions, includes, flow logic - all used for metrology management processing inside the MET application. Two types of tables were used: first - the SAP standard tables and z-tables inside SAP Solution Manager [14].

All the tables are connected and are used for metrology management processing. All used metrology transactions refer to the WebDynpro technology / pool and to the initial screen. All programs are written using ABAP methodology and according with the company guideline and rules using Development Center too [9], and, as a particular knowhow, the created code can be moved to other development systems, using Transport Organizer (se10 transaction), where we will create a big transport (transport of copies - because we have to add the corresponding target system) and we will include all created transports for dedicated development (report, form…etc.). The entire SAP development methodology / process comprise all activities that are part of the process for programming, documenting as well as testing SAP developments. From a high level point of view this process consists of the following phases: design, coding/testing, quality management, release transportation. In order to add / maintain / display data into system the screens is needed for helping the user. Each screen has a logic flow referring to the process before output (in order to execute the action related to this screen it is compulsory that the correspondent include to be correct), the process after input (here all existing fields containing recorded data are connected) or to the process values on request (a validation process must be performed: checking if the values entered are not out of the normal ranges and giving warnings when it is the case) [14]. All created interfaces for other SAP systems are used in the release management module, the reusability of development code is reached, time consuming reduced, software quality done – all interfaces are tested – using trusted relations between systems, TMS trusted services are activated. The transport request will be added afterwards to the correspondent transport directory, in order to be included to the queue of target SAP system and imported in all systems in order to be visible for all SAP users [11].

6. CONCLUSION

This paper is to bring one of possible alternative for using calibration methods, models and workflow processes together with ERP systems inside in Oil and Gas multinational company. The research performed, part of a PhD study, proved that a metrology system, fully and flexible auditable software tool, is a necessity for the evolution of ERP systems in an oil and gas company. The application presented in this paper is designed to solve problems (calibration reservoirs) in E&P - in the area of metrology management. For our application, we composed three models: dispatcher model, body-leasing model, calibration given outside (fixed price). The authors developed and adapted a software system for storing, monitoring and reporting metrology data inside an existing SAP ERP integrated system. The application was developed and integrated in SAP, programming environment ABAP - WD WebDynpro (a web application framework - server-side runtime environment). The metrology software application is presently being used in a large oil and gas company and handles the management of tank oil calibration. The paper started by presenting the steps used in tank oil calibration (metrology area) management and identified useful features in order to design successful software application in E&P area.

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Determination of the Maximum Straining Point on Walking at the Patients with Total Knee Arthroplasty using FEM. Modelling and Simulation Approach

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Abstract: The main cause of the premature deterioration of the knee arthroplasty is represented by the failure in restoration of the joint biomechanics with a direct effect in affecting the stability and mobility of the neo-articulation. Walking is a daily activity, which strains both the polyethylene and the bone-prosthesis interface. The determination of some parameters that can be influenced, like the maximum straining point during walking, is extremely useful in order to increase the survival of knee arthroplasties. This maximum straining point is at 15^o flexion during the stage of unipodal weight bearing and makes an overstraining in vertical plane and less in the anteroposterior and mediolateral planes. The present work uses the Finite Element Method (FEM). For modelling, image acquisition and simulation several software packages are used, such as the geometric modelling software Pro/Engineer® (Parametric Technology Corporation), Matlab (The MathWorks), and SIMI® Motion (SIMI Reality Motion Systems GmbH).

Keywords: Total knee arthroplasty, Finite element method, Walking analysis, Simulation.

1. INTRODUCTION

The walking is a repetitive activity through the alternation of two stages: the one of unipodal weight bearing, which lasts for about 0.53 seconds and the bipodal weight bearing, which lasts for about 0.15 seconds (Andriacchi and Hurwitz, 1997).

After the knee arthroplasty there are made a series of changes in the walking cycle: the travelling speed decreases at the same time with the reduction of the walking cycle duration and with the reduction of the steps frequency (Minns, 2004), being maintained however, a preoperative pattern induced during time (Bjoersson *et al.*, 2005). The reduction of the walking cycle duration is caused firstly by the reduction of the weight bearing stage duration (Benedetti *et al.*, 2003). At the same time, it is reduced also the amplitude of the flexion, both in the oscillation stage, as well as in the unipodal weight bearing stage (McClelland *et al.*, 2007). The flexion is limited at about 52^o-53^o, according to Dorr's *et al.* studies (1988) confirmed by Wilson *et al.* (1996). Dorr has assessed that the reduction of the flexion amplitude is caused both by the design of the prosthesis as well as by the muscular atrophy and change of proprioceptive sensitivity induced by gonarthrosis. Some studies concerning the flexion corresponding to middle phase of unipodal weight bearing were presented in (Georgeanu and Gruionu, 2006). The results showed that the position of flexion is the most critical position for polyethylene during the gait. At the same time with the reduction of the flexion it is produced an increase of the external rotation during the screw-home movement, especially at patients with a marked preoperative varus (Ogrodzka and Niedwiedzki, 2012).

2. MATERIAL AND METHOD

The three-dimensional reconstruction of the joint has been made through serial sections obtained through computed tomography of the patient, as well as frontal and side X-rays of the joint after the implantation of the prosthesis. Using a three-dimensional geometric modelling software, Pro/Engineer®, it has been made the import of the images in surfaces of A_{img} size, disposed on parallel planes at d_{img} distances between them (Fig. 1). On the computational geometric model of the joint thus obtained there have been added prosthesis elements taking into account also the characteristics of materials of which they are made.

For the purpose of obtaining a correct kinematics of the prosthetic joint, there have been made a series of experiments on a voluntary patient who has been subject to surgery (total knee arthroplasty) for the determination in vivo of the joint kinematics on a walking movement, using the image acquisition and analysis system, SIMI® Motion (SIMI Reality Motion Systems GmbH) belonging to the Faculty of Sport and Kinetotherapy at the University of Craiova.

The cycle of obtaining the kinematic data requires the attachment of a series of markers on the lower extremity of the subject, corresponding to the anatomical reference points, in order to obtain a coordination system for every single anatomic segment. The markers are visible to an image retrieval system with two high-speed video cameras, in two perpendicular planes.

The walking platform on which this study has been made did not have the possibility of automated, instantaneous determination of the reaction force of the ground, for which reason there were applied the literature data (Winiarski and Rutkowska-Kuchanska, 2009).

In the final stage of processing the images, the markers on each frame were automatically identified with the help of the software options and the kinematic curves have been raised, as it is shown in Fig. 2.

The calculation of the joint strainings has been made starting from the skeletal and muscular model of the lower extremities. The skeletal structure of the lower extremities, even though it is more complex in reality, is considered to be composed of 4 elements - pelvis, femur, tibia and foot. The 4 elements of the lower extremities are interconnected through 26 main muscles. The muscles are modeled in space through functional lines, obtained by connecting origin points with insertion points (Kepple *et al.*, 1997) – Fig 3. The procedure of solving the musculo-skeletal model has been made through a number of balance equations reported to the time of maximum weight bearing (the stage of unipodal weight bearing). From the various functions objectively used in the biomechanics practice, for the present paper, it has been chosen the criteria of minimizing all the forces developed by the muscles:

$$U = \sum_{i=1}^{29} F_i \qquad (1)$$

where F_i represents the forces in the muscle *i*. There are considered only the stretching forces. The entire calculation has been made with the help of an original program made in Matlab.

Following the calculations and the kinematic analysis it results a series of data, which are expressed further in graphic form, reported to the stages of the walking cycle (Fig. 4).

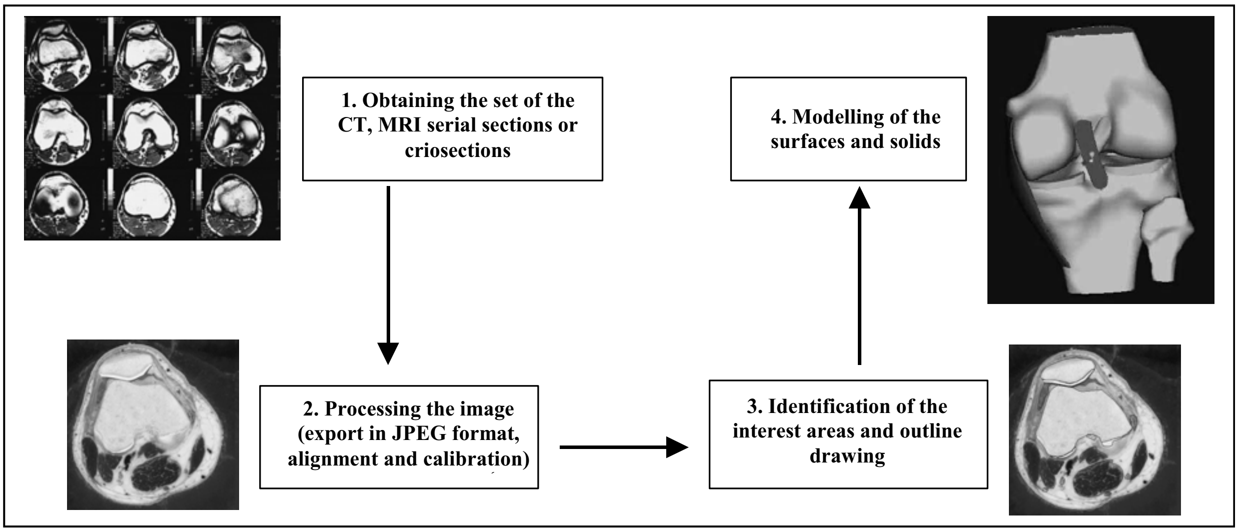

Fig. 1. Diagram of the three-dimensional reconstruction process, using serial sections.

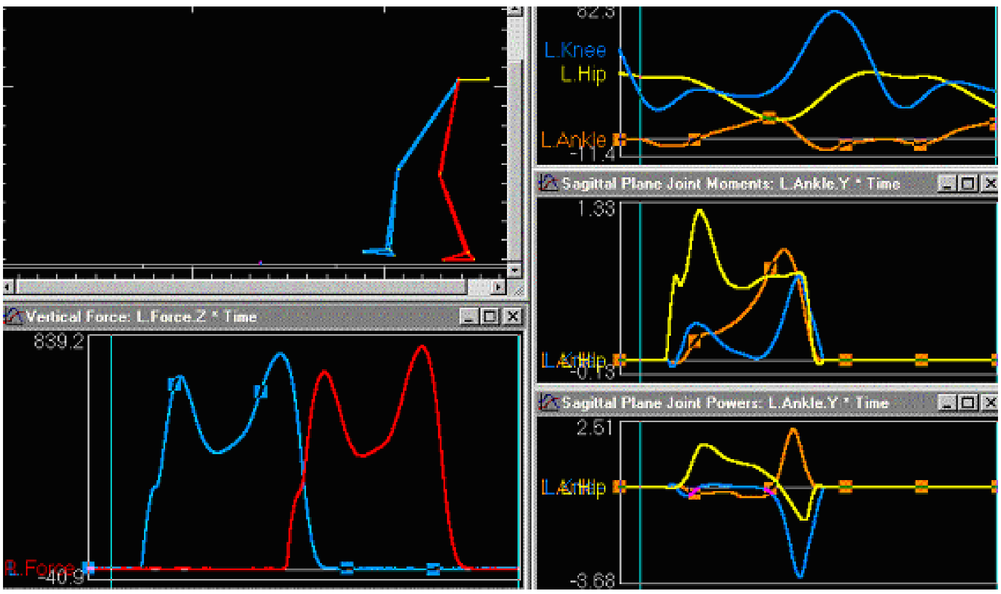

Fig. 2. The obtained kinematic curves.

3. RESULTS

Results of the analysis of the mechanical strainings at the surface of the polyethylene during walking. The surfaces of the prosthesis at contact for normal walking.

The results are presented for the position of 15^o (Fig. 5) and respectively 20^o (Fig. 6) flexion during walking, for which the axial strainings, according to the calculations, are maximal. In the medium stage of unipodal weight bearing, the knee is in flexion of about 15^o-20^o after which it reaches the extension. The main flexors of the ankle are in activity, their contraction growing progressively until immediately after the detachment of the heel of the ground.

The projection of the center of gravity of the body moves to the front of the knee, leading to its "locking" (Wu *et al.*, 2007). The contraction of the quadriceps and gluteal muscles maintains the stability of the hip and knee. All these aspects of the kinematics of the knee are responsible of the maximum strainings in flexion position of 15^o of the knee (Zhang *et al.*, 1997; Zheng *et al.*, 1998).

For the interpretation of the results it is necessary to define the three-dimensional system of evaluation of the arthroplasty. The X-axis is on the anteroposterior direction with the positive direction towards the anterior.

The Y-axis is on the craniocaudal direction with the positive direction towards the cranial, and the Z-axis is on the mediolateral direction with the positive direction from de medial to the lateral. A tensional value with positive sign means that it is developed in the above mentioned positive direction and a value with negative sign means its application in the opposite direction of the above mentioned direction.

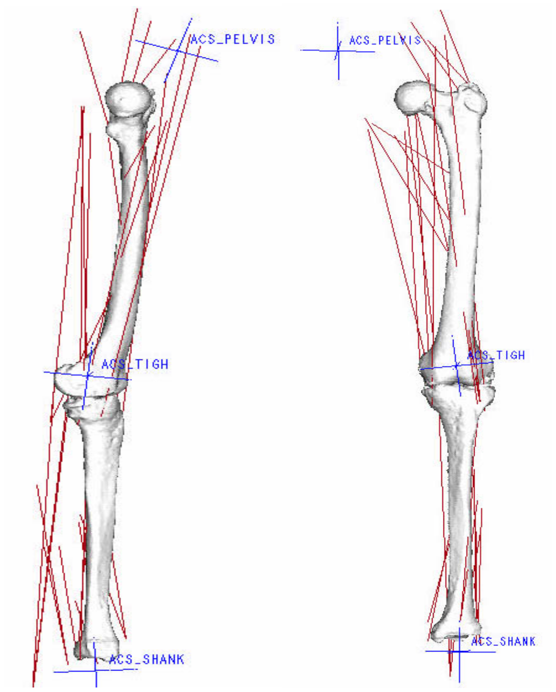

Fig. 3. 3D model of the lower extremity with the muscular action lines developed in Pro/Engineer.

For both position of flexion, in the images (a) and (b) there can be noted the values and positions of the areas with maximum contact pressure. The tangential tension is presented in the image (c). In (d), (e), (f) are presented the values and distribution of tensions according to X, Y, Z axes. For the position of 15^o flexion of the joint, the value of the axial strainings is of about 2200N, so that in the case of the 20^o flexion to decrease at about 1500N.

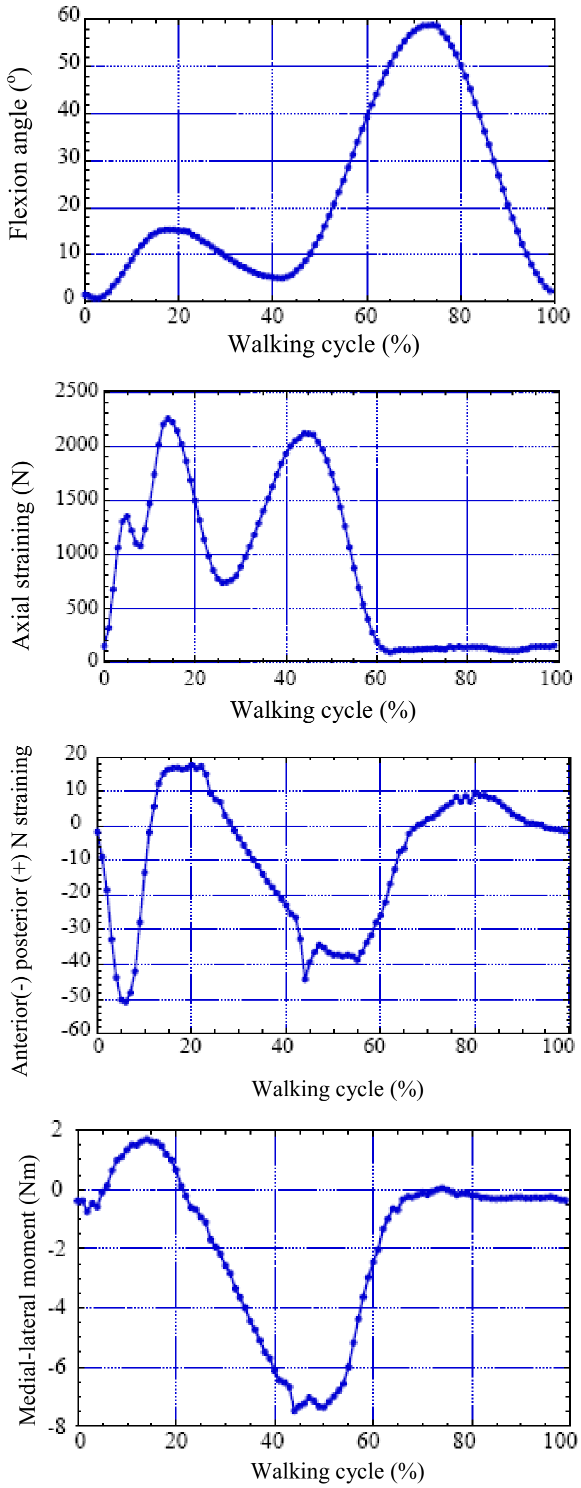

Fig. 4. The kinetic results obtained following the video analysis and analytical calculations.

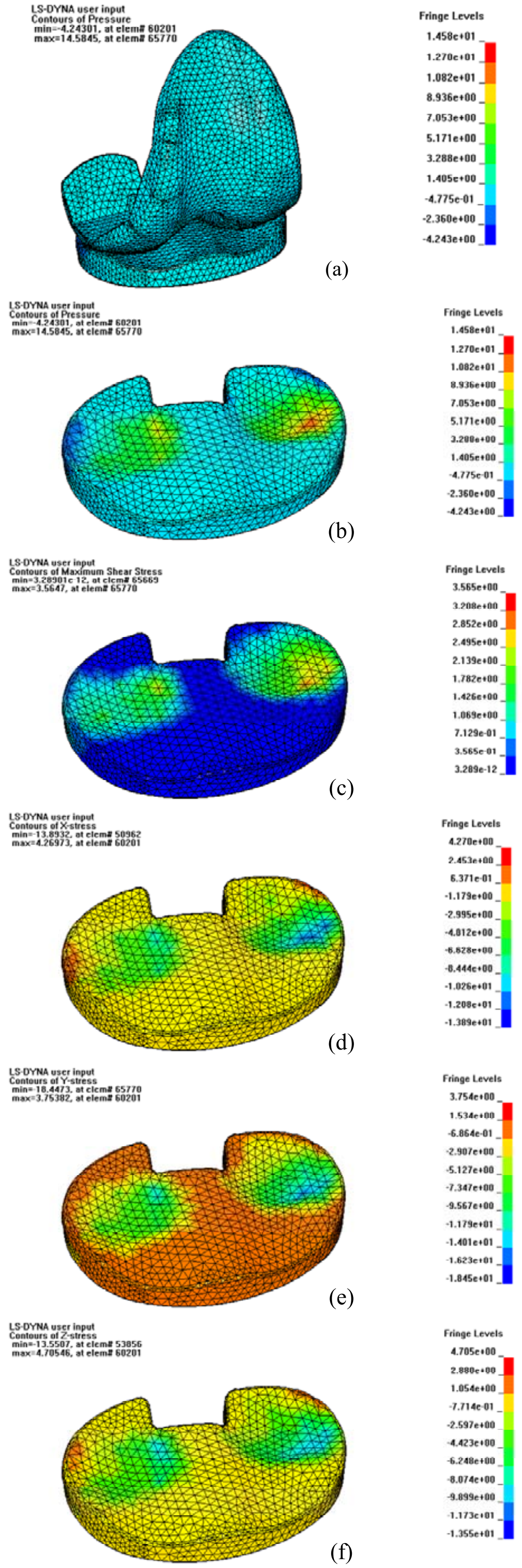

Fig. 5. The results of analysis with finite elements of the implant surface for the position of 15^{o} flexion.

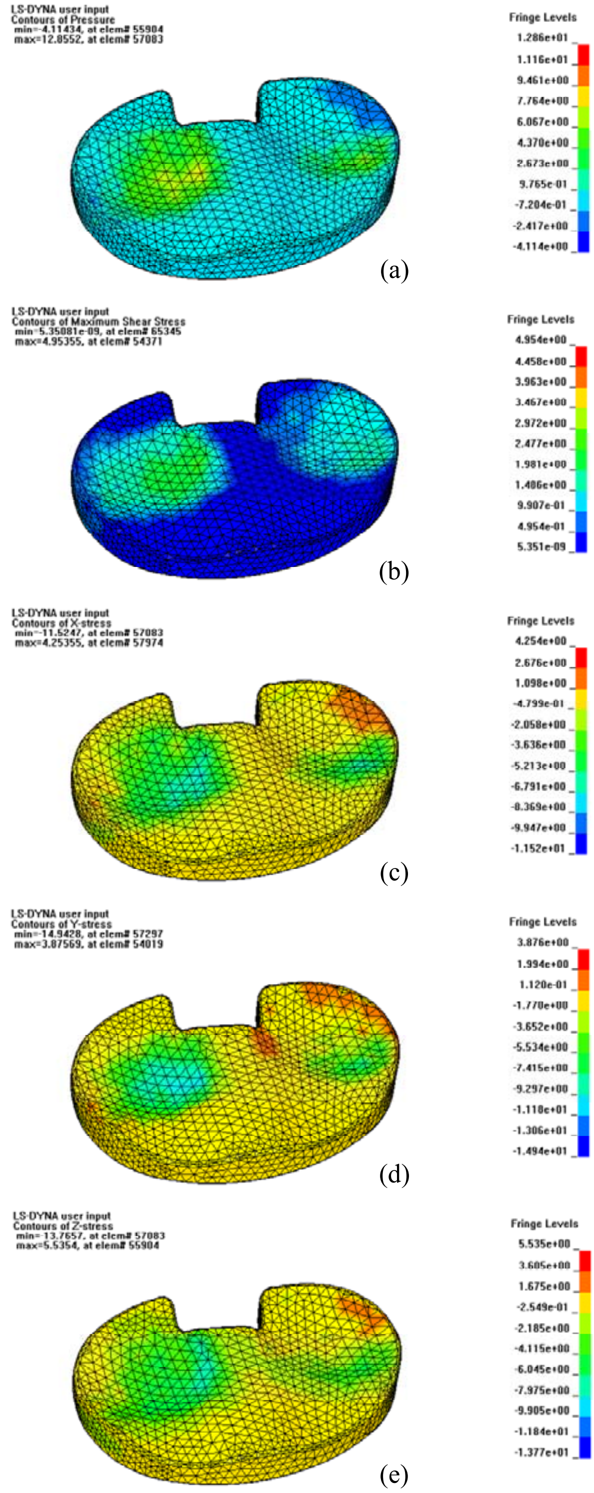

Fig. 6. The results of the analysis with finite elements of the implant surface for the position of 20^{o} flexion.

A comparative evaluation of the two positions revealed that the highest value is at the contact pressure at 15^{o} flexion at the level of the medial compartment (14.5 MPa) – Table 1. This value is correlated with the tensions of weight bearing developed in the cranio-caudal direction, corresponding to the Y-axis on the cranio-caudal direction (14.01 Mpa). This model is preserved also in the case of 20^{o} flexion, but at more reduced values.

Table 1. Tensions distribution for simulation of weight bearing for the positions of 15°, respectively 20° flexion.

		flexion 15°	flexion 20°
Contact pressure	Medial plateau	14. 5	9.46
	Lateral plateau	8.9	7.76
Tensions on the X-axis (A – P)	Medial plateau	12.8	6.79
	Lateral plateau	8.4	5.21
Tensions on the Y-axis (Cr. – Ca.)	Medial plateau	14.01	9.29
	Lateral plateau	11.7	7.45
Tensions on the Z-axis (M – L)	Medial plateau	8.07	7.97
	Lateral plateau	8.07	4.11
Marginal weight bearing	Medial plateau	7. 05	4.3
	Lateral plateau	4.24	2.4

The difference between the recorded values at the level of the two plateaus, medial, respectively lateral, is made, most likely, by adding at the level of the medial compartment, the varus moment developed at this level during unipodal weight bearing.

The tensions developed on the X-axis (anteroposterior) represent a second great category of strainings that the polyethylene bears. In case of both situations, the tensions are higher at the level of medial compartment, preserving however, the same model (in the case of 15° flexion, higher than for the 20° flexion). The value of these tensions is connected with the displacement of femur on the tibial surface (roll–back) who leads to the apparition of these high-tension areas on X-axis with direction from the anterior towards the posterior (negative values).

The tensions appeared on the Z-axis (mediolateral direction) are the most reduced, both in the case of the 15° position and in the case of the 20° flexion position and they most likely represent the expression of the external rotation of the femur on the tibia of the first degrees of flexion, the so-called unlocking of the knee.

In case of a correctly fixed component on the tibial mechanical axis (90°), the vertical weight bearing forces (Y-axis) have a significantly higher value compared with the forces developed on the X and Z axes, for which reason the wear mechanism is represented by abrasion. In practice, the delamination is the most frequently involved mechanism in the wear of the polyethylene, in which case the tangential developed forces (on X-axis) have a higher value. The combination of the two types of straining leads to the beginning of the "pitting" type of wearing, in which the cracks are propagated in a perpendicular direction on the joint surface of polyethylene.

4. CONCLUSIONS

The position of maximum straining of the knee arthroplasty during the walking cycle is during the stage of unipodal weight bearing on the operated lower extremity, at 15° flexion. The clinical result was confirmed by the result of mathematical remodelling and finite element method simulation. The shorter the duration of weight bearing at this flexion degree, the more reduced are the strainings to which the prosthesis is subject to (both the polyethylene, as well as the bone-prosthesis interference) and implicitly, the life period of the arthroplasty will grow.

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Method for the Heart Sounds Processing

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Abstract: This study show that the spectral analysis of the sounds of heart is a non-invasive method known to be useful in evaluating the state of the valves. Examples of the frequency range of heart sounds are presented with the help of conventional frequency analyses with the Fourier transform and with the Wigner-Ville distribution. The spectral analysis reveals the frequency band and may have significant clinical implication in diagnosis and in the management of the therapy.

Keywords: Heart sound, signal processing, Fourier transform, Wigner-Ville distribution, spectral analyse.

1. INTRODUCTION

The heart sounds are vibrations produced by the mechanical activity of the heart in cardiac cycle. The sources of the vibrations are generally, the follow:

- Oscillations of the muscular walls of the atrium, ventricle and the initial parts of the large arteries (aortic pulmonary) in periods of the blood filling and blood ejection.
- Oscillations produced of the movements of closure and opening valves.
- Turbulence of blood filling into the heart cavities and vessels in the periods of increased of blood pressure gradient and blood velocity movement.
- Oscillations produced in myocardium contraction and relaxations through the friction between the muscular cells.

The vibrations produced in the heart are recorded to the surface of the thoraces. These sounds go through an inhomogeneous medium and are modified by the resonance of the multiple structures found inside the thoraces cavity. Examples: pericardium, bones, muscles, conjunctive tissue, fat, skin, blood columns moving in different directions, esophagus, air columns moving in trachea and bronchia and also the lung movements, that produce the pulmonary murmurs. So, on the surface of the thoraces exist special areas for auscultation of each sound. Intensity of the heart sounds are correlated with the myocardium force of contractions, the tension developed in myocardium and the blood pressure in the heart cavities and large vessels.

Human heart sounds are very natural signals, which have been applied in the clinical auscultation for health monitoring and diagnosis (Gusti, Badea et al., 2003). The pathological states of the myocardium, valves or vessels, associated with alterations in hemodynamics parameters of the cardiovascular system induce specifically abnormality of the heart sound (splitting the heart sounds, clacments, gallop rhythms, heart sounds loud or attenuates, murmurs). These abnormalities are not clinical identifiable in the early stage of the disease or are not significant for precise diagnostic, stage or evolution of the disease.

Phonocardiogram, a non-invasive investigation, could be developed as quantitative and sensitive medical method of cardiovascular exploration by using the mathematical tools as is spectral analysis.

The phonospectrogram combines traditional phonocardiogram with the presentation of the time-frequency distribution of the signal. Recent advances in information technology systems, in acoustic signal processing and in pattern recognition methods have inspired the design of systems based on electronic stethoscopes and computers. In the last decade, many research activities were conducted concerning automated and semi-automated heart sound diagnosis.

The time plot of the heart sound phonocardiogram displays the amplitude of the sound at each instant, but no information about the energy is displayed. The best method to compute heart sound energy is to utilize the Wigner-Ville joint time-frequency distribution (*WVD*). It reflects the distribution of the signal energy in the time-frequency plane.

2. SPECTRAL ANALYSIS OF THE HEART SOUNDS

Many times, we are interested in details of the temporal process represented through $x(t)$ in certain time intervals as well as details as the spectral density in certain frequency bands. In these cases, the analysis needs to be done very specifically, in time intervals or in the frequency bands that we are interested in. Such situations can occur, for example, in the analysis of the vocal signal, in recordings of electrocardiogram signals, seismic signals and so on. Obviously, for the extraction of a window from a $x(t)$ signal we can use the windowing process with a function $w(t)$. The windowed signal:

$$x_w(t) = x(t)w(t) \quad (1)$$

is defined on a shorter time interval. In the case of analogical moving signals, the instantaneous frequency is variable in time. This is what happens, for example, in the case of frequency or phase modulated signals with a harmonic carrier. The concept of heart sound spectral display was first introduced by McKusick in 1955, (McKusick, Webb et al., 1955).

Unfortunately, this method must use various forms of the Short Term Fast Fourier Transform (*STFT*) to obtain instantaneous frequency characteristics of signals and due to this reason, it is not very accurate. As a result of this situation, a new concept has taken shape, becoming known under the name of heart energy signature (*HES*). The energy of a signal *x(t)*, including both acoustic and *PCG* signals, is proportional to the squared amplitude of the signal. The signal energy *E*, contained at the time interval [*t, t*+*T*] is computed as (Kudriavtsev, Polyshchuk et al., 2007):

$$E = \int_{t1}^{t1+T} |x(t)|^2 dt \quad (2)$$

The time plot of the heart sound (*PCG*) displays the amplitude of the sound at each instant, i.e. no information about the energy is displayed. An accepted principle in acoustics is that the energy of the single frequency acoustic signal at each instant is proportional to the squared amplitude of the signal and the squared frequency of the signal. The best method to compute heart sound energy is to utilize joint time-frequency distribution (*JTFD*). A heart energy signature is essentially a high-resolution spectrographic image of the heart sound signal that is based on the Wigner-Ville joint time-frequency distribution (Polyshchuk, Kudriavtsev et al., 2005) of recorded heart sound signal. *JTFD* reflects the distribution of the signal energy in the time-frequency plane (Cohen L., 1989), (Mertins A., 1999).

The Wigner-Ville distribution (*WVD*) has the mathematical expression:

$$WVD(t,f) = \\ = \frac{1}{2\pi} \int_{-\infty}^{+\infty} x_w(t+\frac{\tau}{2}) x_w{}^*(t-\frac{\tau}{2}) e^{-j2\pi f\tau} d\tau \quad (3)$$

The *WVD* satisfies a large number of desirable mathematical properties. In particular, the *WVD* is always real-valued; it preserves time and frequency shifts and satisfies the marginal properties. Moreover, the *WVD* conserves the energy of the signal.

For a time-series $x(n)$, the expression of the discrete-time Wigner-Ville distribution, *WD*(*n,f*) is:

$$WD(n,f) = \\ = 2 \sum_{k=-\infty}^{\infty} h_N^2(k) x(n+k) \cdot x^*(n-k) \cdot e^{-j4\pi fk} \quad (4)$$

where $h_N(k)$ is a data-window, which performs a frequency smoothing. While Fourier spectra are periodic with period equal to the sampling rate, *WD*(*n,f*) is periodic in frequency with period equal to half the sampling rate. This may cause aliasing, which can be removed either by oversampling, or by using the corresponding analytic signal. The distribution is negatively affected by important cross-terms, which limit its practical use. Cross-terms may be adequately reduced smoothing the distribution over time. The resulting smoothed Wigner-Ville, *SWD*(*n,f*) is:

$$SWD(n,f) = \sum_{m=-\infty}^{\infty} w(m) \cdot \\ \sum_{k=-\infty}^{\infty} h_N^2(k) x(n+k+m) \cdot x^*(n-k+m) e^{-j4\pi fk} \quad (5)$$

3. EXPERIMENTAL STUDY

The signals represent measurements taken from patients being suffering from different vascular diseases. The goal is to find a measure, which allows classifying the different signals according to the medical conditions.

Aortic stenosis is the obstruction of blood flow across the aortic valve. Fig. 1 represents a typical example of the murmur caused by early aortic stenosis.

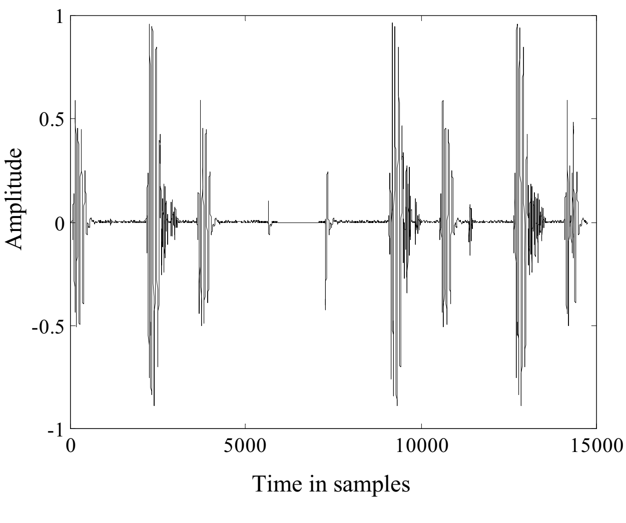

Fig. 1. The phonocardiogram for early aortic stenosis

In Fig. 2 is represented the spectral analysis using the short term fast Fourier transform and in Fig. 3 is represented the Wigner-Ville distribution (3D) for this signal. The Wigner-Ville distribution has the advantage to evidence the moment (in time) when the spectral components appear. So, is more useful for automated diagnose.

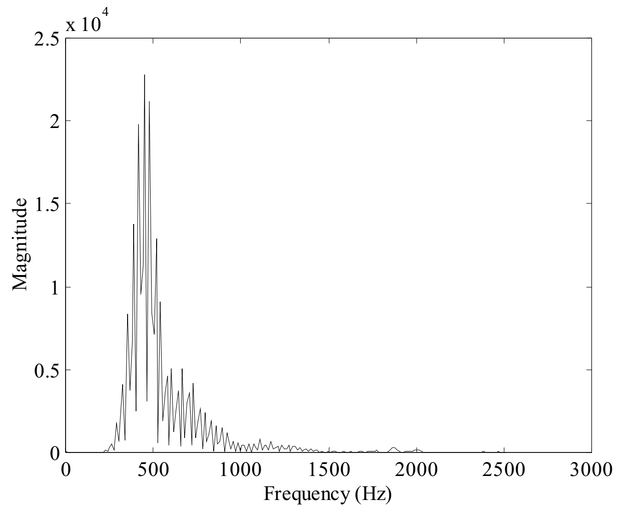

Fig. 2. The spectrum for a typical PCG in early aortic stenosis.

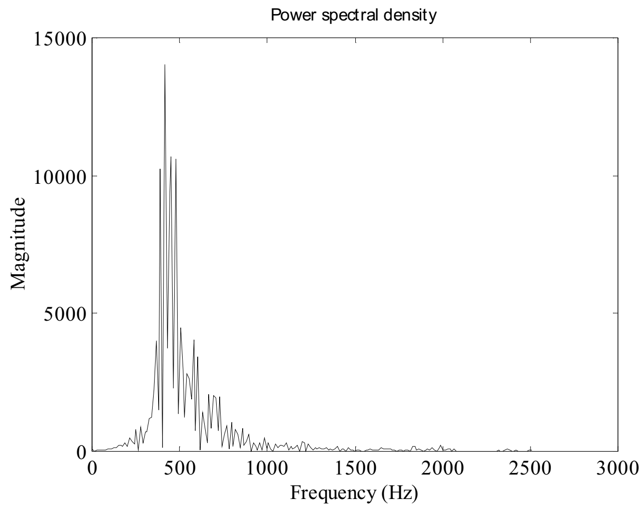

Fig. 5. The spectrum for a typical PCG in later aortic stenosis.

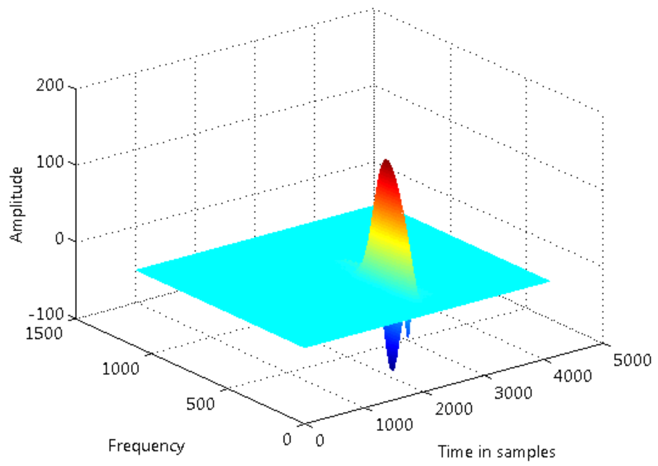

Fig. 3. The WVD for a typical PCG in early aortic stenosis.

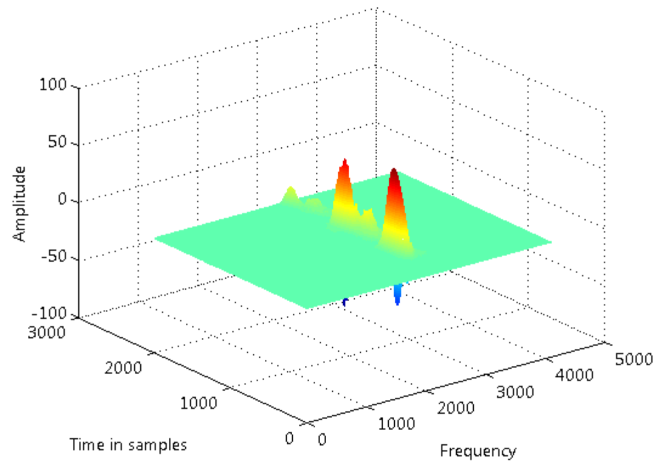

Fig. 6. The WVD for a typical PCG in later aortic stenosis.

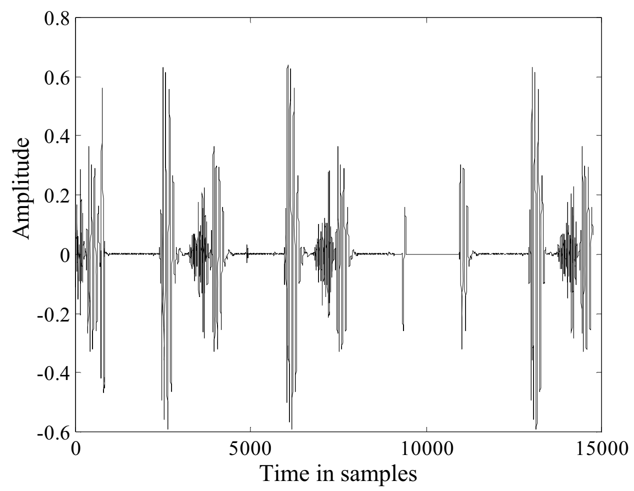

Fig. 4. The phonocardiogram for later aortic stenosis.

Aortic stenosis mainly occurs due to the buildup of calcium deposits that narrow the valve. This is called calcific aortic stenosis. The problem mostly affects older people (http://www.nlm.nih.gov/medlineplus/ency/article/000178.htm). Fig. 4 represents the murmur caused by a later aortic stenosis and in Fig. 5 we have the spectral analysis. In Fig. 6 is represented the Wigner-Ville distribution for this case.

Mitral valve regurgitation - or mitral regurgitation - is when the heart's mitral valve doesn't close tightly, allowing blood to flow backward. As a result, blood can't move through the heart or to the rest of the body efficiently (http://www.mayoclinic.org/diseases-conditions/mitral-valve-regurgitation/basics/definition/ con20022644). Fig. 7 represents the murmur caused by a mitral regurgitation and in Fig. 8 we have the spectral analysis. In Fig. 9 is represented the Wigner-Ville distribution for this case.

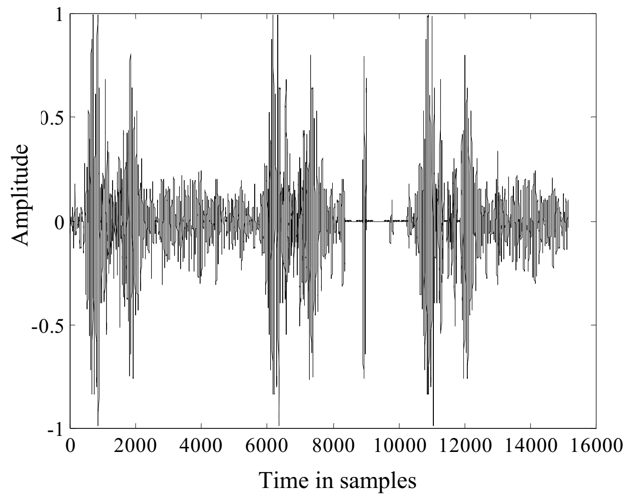

Fig. 7. The phonocardiogram for mitral regurgitation.

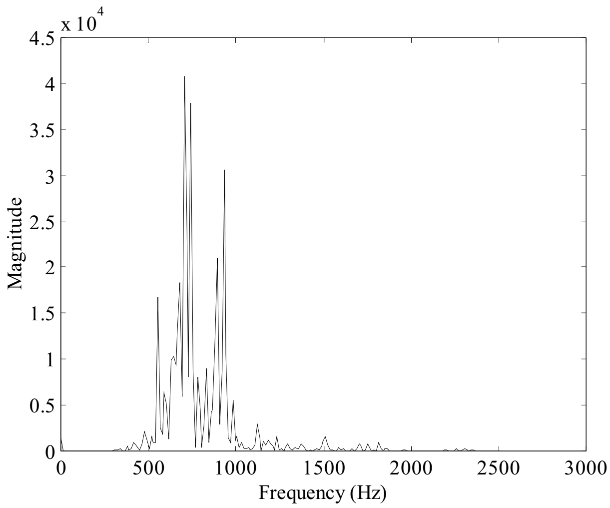

Fig. 8. The spectrum for a typical PCG in mitral regurgitation.

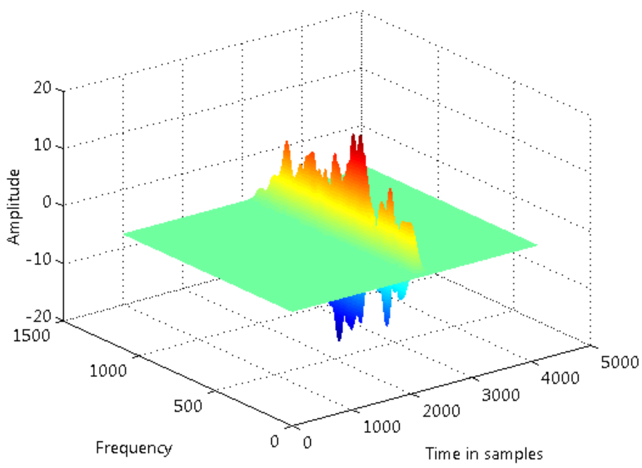

Fig. 9. The WVD for a typical PCG in mitral regurgitation.

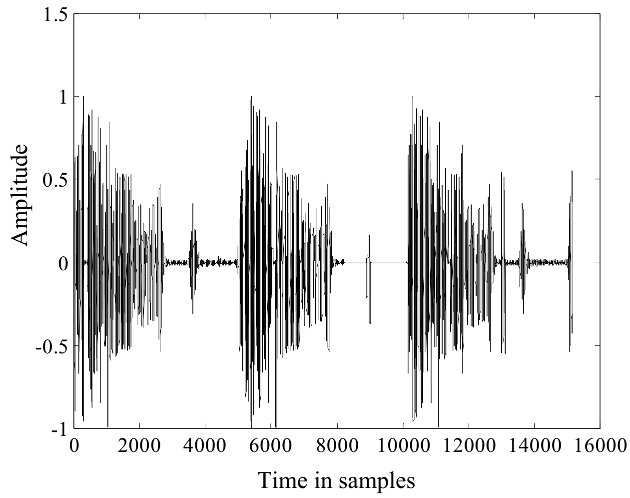

Fig. 10. The phonocardiogram for aortic regurgitation.

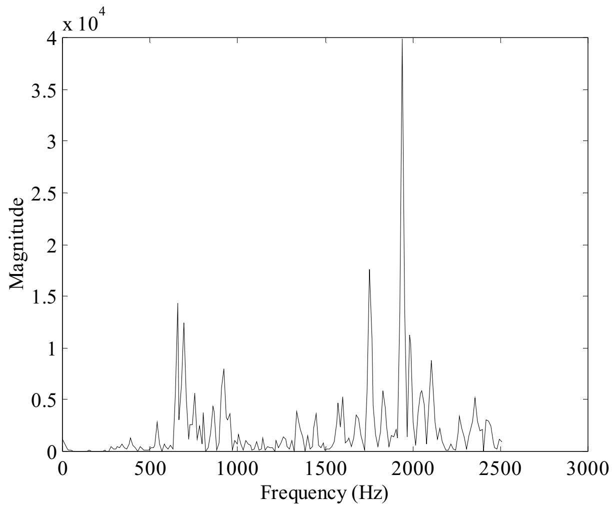

Fig. 11. The spectrum for a typical PCG of aortic regurgitation.

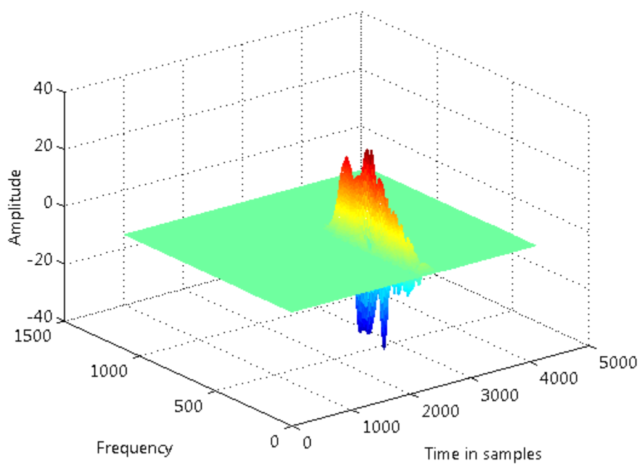

Fig. 12. The WVD for a typical PCG in aortic regurgitation.

Aortic valve regurgitation - or aortic regurgitation - is a condition that occurs when the heart's aortic valve doesn't close tightly. Aortic valve regurgitation allows some of the blood that was just pumped out of the heart main pumping chamber (left ventricle) to leak back into it (http://www.mayoclinic.org/diseases-conditions/aortic-valve-regurgitation/basics/definition/con-20022523). Fig. 10 represents the murmur caused by an aortic regurgitation and in Fig. 11 we have the spectral analysis. In Fig. 12 is represented the Wigner-Ville distribution for this case.

8. CONCLUSIONS

The proposed method is an analytical solution, which represent a new approach for the computer-assisted diagnosis. Phonocardiogram, a non-invasive investigation, could be developed as quantitative and sensitive medical method of cardiovascular exploration by using the mathematical tools as is spectral analysis.

The method can be useful in evaluating the state of the valves. The spectral analysis reveals the frequency band and may have significant clinical implication in diagnosis and in the management of the therapy.

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Distributed Architectures for Ant Colony Optimization

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Abstract: In this paper a survey on existing distributed approaches to Ant Colony Optimization(ACO) is presented. The comparison criteria that have been used are computational efficiency and speedup. This paper includes the agent-based approaches to ACO and general distribution frameworks that can be applied to ACO. The conclusion of this study is that the coarse grained master-slave model is the most studied. However, we found a large amount of papers sustaining that the island approach offers better solution quality. The added flexibility of the communication strategy between the islands makes this model preferred by the most current papers.

Keywords: Distributed Computing, Artificial Intelligence, Swarm Intelligence, ACO

1. INTRODUCTION

ACO (Dorigo, 2004) refers to a family of optimization algorithms that get their inspiration from the metaphor of real ants searching for food. During their searching process, ants secrete pheromone to mark their way back to the anthill. Other colony members sense the pheromone and become attracted by marked paths; the more pheromone is deposited on a path, the more attractive that path becomes.

The pheromone is volatile so it disappears over time. Evaporation erases pheromone on longer paths as well as on paths that are not of interest anymore. However, shorter paths are more quickly refreshed, thus having the chance of being more frequently explored. Intuitively, ants will converge towards the most efficient path, as that path gets the strongest concentration of pheromone.

In ACO, artificial ants are programmed to mimic the behavior of real ants while searching for food. The ants' environment is modeled as a graph while the path to the food becomes the solution to a given graph search problem. Artificial ants originate from the anthills that are vertices of the graph and travel between vertices to find optimal paths, following ACO rules. When a solution path is found, ants mark its edges with pheromone by retracing the path. An ant chooses the next edge to follow towards an unvisited vertex with a probability that increases with the quantity of pheromone deposited on that edge.

1.1 Speedup and Efficiency

Performing a fair comparison of the different approaches for distributing various ACO algorithms requires the use of general and meaningful quantitative measures that are independent on the distribution model. For this reason we introduce the classical notions of speedup and computational efficiency.

The speedup metric S_c of a distributed application measures how much the application is faster when running on more computing nodes as compared to running on a single computing node. We define the term *computing node* as abstraction of a computer or machine, physical or virtual, with its own or allocated processor and memory. This term is used in the literature on distributed applications (Santoro, 2006) and adopted by distributed computing support systems. Very often the short version "node" is used in the literature, but this can be confused with "vertex" from graph theory (Coremen, 2009). Therefore we prefer to use the longer version "computing node" to avoid confusions.

The computational efficiency metric e_c normalizes the value of the speedup to the number of computing nodes. The equations for computing the two metrics are:

$$S_c = \frac{T_1}{T_c} \qquad e_c = \frac{S_c}{c} \tag{1}$$

Where: c is the number of computing nodes; S_c is the speedup of the application; T_1 is the execution time of the application on a single computing node; T_c is the execution time of the application on c computing nodes; e_c is the efficiency of running an application on c computing nodes.

Due to lack of access to actual code of the distributed approaches, the study presented in this paper is based on the values reported by the authors of the various cited works.

2. BACKGROUND

A very recent overview and classification of parallel computing approaches to ACO was reported by (Pedemonte, 2011). The authors propose an interesting and novel classification scheme for parallel ACO algorithms. The classification includes: master-slave model, cellular model, independent runs model, island model and hybrid models. However, the authors do not include in their analysis the agent based approaches by arguing that they are usually not designed to take advantage of multi-processor architectures in order to reduce execution time. The cellular model mentioned in (Pedemonte, 2011) is actually based on the author's own work (Pedemonte, 2010a) which proposes the splitting of ACO search space into overlapping neighborhoods, each one with its own pheromone matrix. The good solutions gradually spread from one neighborhood to another through diffusion. This approach requires the partitioning of the search space such that each set contains a continuous part of the optimal solution. However, this condition is almost never met in practice, so an optimal solution is hardly reachable. The authors are the only ones that have ever implemented and tested this model.

In the following subsections we identify and describe the research done using master-slave model, independent runs model, island model, hybrid models and the agent-based models. But because these terms are not standardized we must first define what we mean by them.

2.1 The Basic Taxonomy of Distributed ACO Approaches.

The master-slave model of distributing ACO employs a central "master" computing node that manages a global best-so-far solution while multiple "slave" computing nodes find candidate solutions. This model can be further divided into: fine grained master-slave model, where the slaves do atomic actions such as move one ant or find one solution, coarse grained master-slave model, in which the slaves do complex actions such as find multiple solutions and communicate the best one to the master.

In the fine grained version the slaves have to communicate with the master after each tiny task they are asked to execute and then they wait for new requests from the master. This overloads the master computing node and introduces large wait times when many slaves are used. In the coarse grained version the slaves find whole solutions or even sets of solutions before reporting to the master. Since that is the sole purpose of the slaves in most implementations, they actually do not need to be explicitly told what to do next. Evidently the coarse grained master-slave model puts less stress on the master and therefore is a lot more scalable.

The independent runs model uses many instances of the ACO algorithm that solve the problem independently and the best solution is chosen. ACO approaches are inherently heuristic therefore they cannot guarantee finding the optimal solution; however, running an ACO algorithm multiple times increases the chances of getting a very good quality solution. The fact that no communication is used but more than one instance of the algorithm is executed entails three consequences: (i) faster execution time and implicitly better efficiency than any other implementation that requires communication, but only if the same number of solutions are explored in all considered implementations, (ii) better quality of solutions than a single sequential run, (iii) less qualitative solutions than implementations that use communication.

The island model of distributing ACO requires running a separate group of entities, referred to as an "island", on each available computing node. Each group has its own instance of the search graph and ant population therefore can be considered a sequential implementation of the ACO algorithm. The islands communicate solutions to each other and the best solution over all is marked on all graphs as required by the ACO algorithm. Solutions can be communicated asynchronously or synchronously. This type of decentralized collaboration between the islands sets this model apart from the master-slave model and the independent runs model. This model is also called the "multi-colony model". Intuitively, this model is even more scalable than the coarse-grained master-slave since there is no master computing node to cause a communication "bottleneck". The existence of a master would decrease performance when too many slaves try to communicate at once.

The hybrid model is a combination of the island and the master-slave model.

3. FINE GRAINED MASTER-SLAVE MODEL

Implementing a scalable fine grained master-slave model is not trivial. The authors of (Middendorf, 2010) analyze the amount of communication needed by the fine grained model of ACO, concluding that it is not feasible. In the paper (Randall , 2002) a fine grained master-slave model of ACO is analyzed and the maximum efficiency, of 0.8, was obtained when using only two processors. In the paper (Delisle, 2005a) the authors used a shared memory machine in their experiments. In such an architecture the access to the memory is concurrent, i.e. there is a shared memory and each process uses it one at a time in order to centralize its knowledge. The authors continue their work in (Delisle, 2005) by comparing their approach from (Delisle, 2001) that uses synchronized messages instead of a shared memory. The access to the shared memory proved to be much faster than messaging. This allows the ants to benefit sooner from the improvements found by the other population members. The conclusions were that their shared memory implementation offers better solutions in less time. The authors obtained a speedup of 5.45 using 16 nodes, therefore resulting in an efficiency of merely 0.34. The most recent approach we could find on the fine-grained master-slave model is (Fu, 2011). The authors of this paper used up to 240 GPUs to solve TSP using ACO and they succeeded in obtaining speedups of up to 30 ($e = 0.12$).

4. COARSE GRAINED MASTER SLAVE MODEL

The coarse grained master-slave model, unlike the fine grained one, is not plagued by conflicting opinions about its effectiveness. In the paper (Talbi, 2001) the authors present their approach to the coarse grained master-slave model called "ANTabu" which offers high quality solutions to the Quadratic Assignment Problem (QAP) (Burkard, 2009). Peng et al. presented their experiments with the coarse grained model (Peng, 2006) that offered better quality solutions than evolutionary algorithms in the case of two different problems. In the paper (Lv, 2006) groups of ants are used on each slave resulting in better performance than sequential ACO. However, no comparison was made with the case of using only one ant per slave. Although these experiments used more than one computing node, these papers did not study the computational efficiency of their approaches.

We found several papers describing scalable implementations of the coarse grained master-slave model. In (Li, 2007) the authors present experiments showing that the coarse grained master-slave model is more efficient than the independent runs model. Their approach obtained efficiency of 0.8 using up to 16 processors. Paper (Gao, 2010) present experimental results where this model offers a speedup of up to 1.72 on dual core computers when running the slaves on separate threads, which means 0.86 efficiency. The implementation from paper (Chintalapati, 2010), which uses asynchronous centralization to the master computing node boasts 0.9 efficiency on 8 nodes. Top efficiency of e=0.8 was obtained when using 25 computing nodes.

5. VARIATIONS OF THE MASTER-SLAVE MODEL

Some approaches to the master-slave model use the slaves only to perform local search on the solutions generated by the master. In (Lopez-Ibanes, 2009) this idea is implemented for ACO using one thread per slave on two dual-core machines. The authors obtained speedup in their experiments, however, the hardware used did not facilitate detailed testing of their approach. The paper (Tsetsui, 2007) tested a multithreading implementation of ACO on two quad-core computing nodes. The experiments showed significant improvement in execution time. Continuing their work in (Tsutsui, 2008) using two dual core machines, they obtained better results than a synchronous communication island model and an independent parallel runs model. (Weiss, 2009) experimented with this model of ACO on 47 non-dedicated machines, they concluded that larger problems generate better speedup values. In the paper (Craus, 2002) the authors used their parallel framework for master-slave approaches to implement similarly asynchronous ACO. They achieved very good speedup values up to 25 computing nodes, however, efficiency decreased directly proportional to the resources used.

6. INDEPENDENT RUNS MODEL

The independent runs model is found to be used rarely. Experiments in (Rahoual, 2005) confirm that the independent runs model is more efficient than the coarse grained approach and offers slightly better solution quality than sequential implementations. The papers (Alba, 2005) and (Alba, 2007) also concluded that it is more efficient than coarse grained master-slave, synchronous and asynchronous island model. However, at the same time they confirm the fact that the independent runs model offers less qualitative solutions than implementations that use communication. Therefore the implementations that require communication on top of constructing and validating solutions will automatically have longer execution times. However, the models that use communication offer better solutions sooner than the independent runs model. Thus, it is our conclusion that better alternatives to the independent runs model have already been developed.

7. THE HYBRID MODEL

The hybrid model was implemented and studied in a reduced number of publications. In the papers (Delisle, 2005) and (Liu, 2008) each colony, from the island model, becomes the master of multiple slaves. The papers reported slight improvements in quality of solutions when compared to other models. On the other hand, papers such as (Iimura, 2005) and (Roozmand , 2008) propose that the solutions of island models should be collected and processed by a master computing node. All reviewed papers of this model lack efficiency analysis.

The hybrid models and other variations of the master-slave model are isolated attempts to improve the execution time of the existing approaches. Although they sometimes boast better results taking advantage of hardware architecture such as multiple GPUs they are not widely accepted as best approach to distributing ACO.

8. THE ISLAND MODEL

The paper (Xiong, 2008) presents experimental data on island model ACO tests on up to 64 computing nodes, however, they do show a dramatic decrease in speedup for more than 8 nodes. In (Lee, 2002) the island model experiments show better runtimes and higher quality of solutions than sequential models of ACO. In the paper (Chu, 2010) the authors experimentally show that multi-colony is faster than the master-slave model. Their approach was tested on up to 5 computing nodes. The paper (Yang, 2007) confirms that multicolony is more efficient than sequential ACO when using up to 8 computing nodes. However, the authors of the paper (Jovanovic, 2010) found that adding more ant colonies will not necessarily yield better efficiency. The experiments show that for given TSP problem sizes there is always a number of colonies above which efficiency decreases. Many authors noted that island model offers an increase of solution quality compared to sequential implementations. In (Twomey, 2010) it is stated that the island model consistently offers better solutions than the sequential implementations of the same ACO algorithm. On the other hand, (Yu, 2011) found that the island model offers just *competitive* solutions when compared with other approaches. In the paper (Sameh, 2010) the authors experiment with exchanging full pheromone matrices instead of just one best-so-far solution. Their conclusion was that this greatly affected the execution time of the approach but slightly improved the quality of the solutions. (Taskova et al, 2010), implemented a typical island approach and tested it on a cluster of 8 nodes obtaining a speedup of up to 2.98 using all the available processors.

No significant differences in the solution quality were found when compared with a sequential implementation. Chen and Zhang (Chen, 2005) tested an island approach that used an adaptive frequency of information exchanges.

9. AGENT-BASED APPROACHES

The authors of (Ridge, 2006) present a multi-agent system (Bellifemine, 2007) implementation of ACO applying their solution to TSP. In their approach, graph vertices and ants are implemented as JADE (Bellifemine, 2007) agents. Ants centralize the information about pheromone deposits and vertices' best tour cost through a single message exchange per vertex. Each ant has to notify the vertex about its next hop and the cost of its tour for the vertex to be able to update its pheromone levels. When an ant completes a tour, it compares the tour cost with the collected best tours from the vertices. A best tour synchronization is triggered for all the vertices if a better tour has been found. Unfortunately, the authors provide no experimental data to support their claim of "good results".

In (Fattahi , 2009) the authors compare a distributed form of ACS with the flooding algorithm applied to resource discovery problem using ns2 network simulation tool (see reference ns-2, 2010). They show that ACS is the better approach in terms of: best success rate, least number of hops and least traffic. The detailed algorithm and ACO parameters are not presented in order to duplicate their approach for a realistic comparison. The main characteristics of their approach are: (i) resource queries are handled centrally at a single computing node, (ii) they do not take edge weights into account as they are trying to solve the resource discovery problem, and (iii) ants are implemented as ns2 mobile agents. In the article (Al Dahoud, 2010) the authors present a fully distributed approach to ACO that models both vertices and ants as agents. Their proposal uses multiple vertices that play the role of anthills, generating ants modeled as mobile agents. They test their proposal on the problem of load balancing in distributed systems and compare it with the work-stealing approach. The article concludes that the proposed architecture is more efficient in terms of the number of busy vertices and the elapsed time until a load distribution of 50% is reached. No efficiency study is made on the approach. In the article (Chira, 2010) the authors present an agent-based distributed approach to the fine grained master-slave model where agents have learning capabilities. These papers' main goal is to improve the solution quality by the use of a knowledge base. As a consequence, this approach inherits the efficiency shortcomings of its predecessor. The paper (Xiang , 2008) proposes a multi-agent environment for dynamic manufacturing scheduling that combines intelligent techniques of ACO and multi-agent coordination.

There is no globally accessible map, hence each agent needs to manage their own map and pheromone deposits. However, the focus in (Xiang, 2008) is to evaluate the impact of ACO intelligence on multi-agent coordination, rather than to utilize multi-agent middleware for improving ACO.

We are aware of only one agent-based approach that was studied in terms of computational efficiency: the "ACODA" approach from (Ilie, 2011). The authors model subsets of the search graph vertices as agents and execute them on separate computing nodes. Ants are modeled as software objects passed from one vertex to another via a local queue or agent message. The authors boast an e=0.98 efficiency value on 11 computing nodes.

10. GENERAL-PURPOSE DISTRIBUTED FRAMEWORKS

During our review of the work done on distributing ACO we have also found a few general-purpose distributed frameworks designed for any algorithms.

Paper (Czarnowski, 2009) proposes JABAT (JADE-Based A-Team) a JADE (Bellifemine, 2007) based middleware for collaborative problem solving using asynchronous teams known as Ateams. JABAT supports distributed implementation and collaboration of population based optimization algorithms. JABAT agents represent sequential improvement algorithms that cooperate in order to solve a given problem in a distributed manner. Unfortunately, we could not find scalability studies of the JABAT distributed architecture. Earlier, a similar approach was introduced in (Craus, 2005) using an object oriented approach to run several sequential algorithms in parallel. In this case the authors impose a master-slave organization system between the processes. The framework is tested for image processing using ACO.

The scalable distributed constraint architecture called DisChoco is described in the paper (Ezzahir, 2004). In this approach, agents manage parts of the problem domain as well as the constraints specific to their partition. The agents propose, propagate or refuse partial solutions to each other.

The paper (Holvoet, 2009) proposes a purely theoretical framework for multi-agent systems. No experiments or implementations are mentioned in this work. The authors present a distributed form of ACO based on so called smart messages approach to multiagent systems. Agent mobility is used to implement complex communication over dynamic networks. They use delegate multi-agent systems to manage these smart messages in order to design a multi-agent approach for ACO. No ways of modeling the environment, determining convergence or stopping condition of ACO experiments are presented.

The frameworks presented in papers (Barbucha, 2006), (Czarnowski, 2009) and (Craus, 2005) are designed for the coarse grained master-slave approach. The (Holvoet, 2009) approach is much better suited for the distribution of the search space then migrating entities in the form of messages, according to the particular ACO rules. However, this does not motivate the use of code mobility since all entities are governed by the same behavioral rules.

11. PARTITIONED SPACE APPROACHES

A novel way to distribute ACO is to partition the search graph allocating each subset of the graph on a separate computing node. One such approach, briefly mentioned at the beginning of this section, is the cellular model from (Pedemonte, 2010) which proposes splitting ACO search space into overlapping neighborhoods, each one with its own pheromone matrix. The good solutions gradually spread from one neighborhood to another through diffusion. The authors obtained the efficiency of 0.9 on 4 nodes.

Another approach that divides the search space called "D-ant" is presented in (Doerner, 2006) which was reported to outperform a multi-colony and a coarse grained implementation of ACO. The efficiency of the approach peaked at 0.7 when using 8 computing nodes.

Similarly the *ACODA* approach from (Ilie, 2011) also distributes the environment instead of the ants. However, unlike the other papers, ACODA allows the ants to migrate freely between subsets, resulting in less reliance on an optimal partition in order to achieve optimal solutions while preserving scalability.

12. CONCLUSIONS

The independent runs model is rarely used by the scientific community. When many instances of the ACO algorithm solve the problem independently and the best solution is chosen in the end increases the chances of getting a higher quality solution. We draw two conclusions from the work on the subject: i) this model is faster, however, it offers worse solutions than any other distribution model and ii) it provides better quality of solutions than a single sequential run.

The hybrid models and other variations of the master-slave model are isolated attempts to improve the execution time of the existing approaches. Although they sometimes boast better results taking advantage of hardware architecture such as multiple GPUs they are not widely accepted as best approach to distributing ACO.

In the case of fine grained master-slave model the communication overhead that is necessary to exchange solutions is too large. The small amount of research using this model and the conflicting opinions about its effectiveness suggests that it is being abandoned as a viable model and is not, in fact, the state of the art approach to distributing ACO.

Most authors focus on the coarse grained master-slave model or the island approach, obtaining top efficiency when distributing their implementations on 8 to 25 nodes distribution. The approaches that were tested on TSP generally used graphs from the benchmark library TSPLIB (Reinelt, 1991) consisting of up to 500 vertices. The exception is the work presented in (Xiong, 2008), where an island model was tested on a 15 000 vertex TSP instance of TSPLIB. However, efficiency peaked at 8 nodes. The most scalable approach in all the considered papers was presented in (Chen, 2008), an island model that reached peak efficiency at 25 nodes. This was tested on a 318 vertex TSP instance. However, the peak efficiency was inferior to the maximum efficiency (of 0.9) we encountered, obtained in the paper (Chintalapati, 2010) using 8 computing nodes. We found significant research sustaining the superior asynchronous communication for the island model. It is our conclusion supported by the large number of papers written on the subject and the outstanding results, that the island approach is the current state of the art model of distributing ACO. These distributing models may be criticized for not being especially designed for ACO approaches. Therefore they do not take advantage of the inherently distributed nature of the ACO approaches they are using.

In the case of agent-based approaches to distributed ACO, the authors model entities and vertices as agents. Although this type of modeling is fully distributed, the separation of ACO entities and search environment results in a large amount of messaging. All the necessary actions are done through messages: visiting a vertex, current solutions update any other ACO specific action.

The novel partitioned space approaches present a simple, intuitive way of distributing ACO by mapping subsets of the search graph vertices to each computing node and allowing the ants to move in this distributed virtual environment. These approaches show a lot of promise in simplicity as well as solution quality however only a few papers have been written on a subject and even less offer efficiency analysis.

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Adaptive and Robust-adaptive Control of a Bio-dissimilation Continuous Process

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Abstract: This paper deals with adaptive and robust-adaptive control applied to a bio-dissimilation continuous process of glycerol to 1, 3-propanediol. Firstly, an indirect adaptive control structure is achieved by combining a linearizing control law with a state observer and a parameter estimator used for on-line estimation of the bioprocess unknown kinetics. Secondly, under the realistic assumption that the bioprocess kinetics are unknown and time-varying and the influent flow rates are time-varying and uncertain, but some lower and upper bounds of these uncertainties are known, a robust-adaptive control structure is designed by combining a linearizing control law with an appropriately interval observer able to estimate lower and upper bounds of the unknown states and a parameter estimator able to estimates the unknown reaction rates. The effectiveness and performance of the designed control algorithms are illustrated by numerical simulations.

Keywords: Nonlinear processes, Adaptive control, Robust-adaptive control, Glycerol fermentation bioprocess.

1. INTRODUCTION

The biotechnology, whose applications can be found in many domains, is one of the fields that in the last decades have a high development. An important issue of biotechnology is the synthesis of some products by using fermentation processes. These processes that are carried out in perfectly stirred tank reactors are commonly described by a set of ordinary differential equations expressing mass and energy balances.

A basic difficulty for the application of modern control techniques to these processes lies in the fact that, in many cases, the models include kinetic parameters, which are highly uncertain and time varying. These uncertain factors can deteriorate the performance of a bioprocess and lead to the instability of the process. Therefore, the control of biotechnological processes has been and remains an important problem attracting wide attention, the main engineering motivation being the improvement of the operational stability and production efficiency of these processes (Bastin and Dochain, 1990; Bernard and Bastin, 2004; Dochain and Vanrolleghem, 2001; Dochain, 2008; Petre, 2008; Xu, 2010).

Another important challenge in the monitoring and control of such living processes is finding adequate and reliable sensors to measure the important state variables of the plant (Bastin and Dochain, 1990; Dochain and Vanrolleghem, 2001; Bernard and Bastin, 2004). Even if several on-line sensors providing state information are available today at industrial scale, they are still expensive, especially in the field of biological processes (Bastin and Dochain, 1990; Dochain and Vanrolleghem, 2001; Bernard and Bastin, 2004; Dochain, 2008).

To overcome these difficulties, several strategies were developed, such as linearizing strategy (Bastin and Dochain, 1990; Dochain, 2008; Petre, 2008, Proll and Karim, 1994), adaptive approach (Bastin and Dochain, 1990; Dochain, 2008; Petre, 2008; Petre et al., 2013), robust control (Petre et al., 2013; Xu, 2010), optimal control (Bastin and Dochain, 1990; Xu et al., 2008), sliding mode control (Selişteanu et al., 2007), neural strategies (Petre and Răsvan, 2000; Hayakawa, 2008; Petre et al., 2010) and so on. Some of these approaches imposed the use of the so-called "software sensors" – combinations between hardware sensors and software estimators that can be used not only for the estimation of concentrations of some components but also for the estimation of kinetic parameters or even kinetic reactions (Bastin and Dochain, 1990; Bernard and Bastin, 2004; Dochain and Vanrolleghem, 2001; Dochain, 2008).

However, in all previously cited schemes, the knowledge of all the inputs of the process, including, for example, the substrates input concentrations, is needed. Unfortunately, there are many bioprocesses for which the complete knowledge of inputs is not available and classical observer schemes cannot be used. For these situations, in the last ten years it was developed and analyzed a special class of observers called *set-observers*, which allows the user to reconstruct a guaranteed interval on the unmeasured states instead of reconstructing their precise numerical values. The only requirement is to know an interval in which the process unmeasured inputs evolve (Alcaraz-González et al., 2000, 2003, 2005; Aviles and Moreno, 2009; Mazenc and Bernard, 2009, 2011; Moisan and Bernard, 2005; Petre et al., 2013; Rapaport and Dochain, 2005).

This paper presents the design of some adaptive and robust-adaptive control schemes, able to deal with the model uncertainties in an adaptive way, for a bio-dissimilation process that is carried out in a continuous stirred tank bioreactor. This bioprocess is characterized by strongly nonlinear, time varying and not exactly known dynamical kinetics. Also, some kinetic parameters will be considered uncertain and time varying. Much more, the concentration of the influent substrate will be considered completely unknown, but some intervals in which this unmeasured concentration evolve are known.

The indirect adaptive control structure is achieved by combining a linearizing control law with a state asymptotic observer which plays the role of a software sensor for on-line estimation of process biological states of interest, and with a parameter estimator for on-line estimation of uncertain or unknown bioprocess kinetic rates.

In the following, under the assumption that the bioprocess kinetics are unknown and time-varying and the influent flow rates are time-varying and uncertain, but some lower and upper bounds of these uncertainties are known, a new robust-adaptive control structure is proposed by combining a linearizing control law with an appropriately parameter estimator able to estimates the unknown reaction rates. The proposed robust algorithm uses the same estimator designed is the first case but its structure is modified so that to use the known lower and upper bounds of the influent flow rates but also the estimated lower and upper bounds of the unknown state variables.

The effectiveness and performance of the developed control algorithms are illustrated by simulations applied in the case of a bio-dissimilation continuous process of glycerol to 1, 3-propanediol for which kinetic dynamics are strongly nonlinear, time varying and completely unknown, and not all the state variables are measurable.

The rest of the paper is organized as follows. In Section 2 a brief description and mathematical modelling of a continuous bio-dissimilation process of glycerol is presented. An indirect adaptive and a robust-adaptive control structure for this bioprocess is presented in Section 3. Simulations results presented in Section 4 illustrate the performance of the proposed control algorithms and, finally, Section 5 concludes the paper.

2. BIOPROCESS DESCRIPTION AND MODELLING

The bioprocess under consideration is a continuous bio-dissimilation process of glycerol to 1, 3-propanediol by *Klebsiella pneumonias* (Xu, 2010). Since the 1, 3-propanediol has considerable demand in the market, especially as a monomer for the production of polyesters or polyurethanes, of late, much attention has been paid to its microbial production, for its low cost, high production rate and no pollution (Xu et al., 2008). The mathematical model of this bioprocess is described by the following set of differential equations (Xu et al., 2008, Xu, 2010):

$$\dot{X} = \mu(\cdot)X - DX \ , \tag{1}$$

$$\dot{C}_S = -q_S(\cdot)\cdot X + D\cdot\left(C_{Sin} - C_S\right) , \tag{2}$$

$$\dot{C}_P = q_P(\cdot)\cdot X - DC_P \ , \tag{3}$$

$$\dot{C}_{Ac} = q_{Ac}(\cdot)\cdot X - DC_{Ac} \tag{4}$$

$$\dot{C}_{Et} = q_{Et}(\cdot)\cdot X - DC_{Et} \tag{5}$$

where X and C_S are the biomass concentration and the substrate (glycerol) concentration inside the reactor, and C_P, C_{Ac} and C_{Et} are the concentrations of the three mainly products obtained by bioconversion of glycerol, namely: 1, 3-propanediol, acetic acid and ethanol, respectively. C_{Sin} is the influent substrate concentration, and D is the dilution rate.

The variables μ, q_S, q_P, q_{Ac} and q_{Et} are the specific growth rate of biomass, specific consumption rate of substrate, specific formation rate of products 1,3-propanediol, acetic acid and ethanol, respectively, that are described by the following nonlinear inhibited models (Xu, 2010):

$$\mu(\cdot) = \mu_{\max}\frac{C_S}{K_s + C_S}\left(1 - \frac{C_S}{C_S^*}\right)\left(1 - \frac{C_P}{C_P^*}\right)\left(1 - \frac{C_{Ac}}{C_{Ac}^*}\right)\left(1 - \frac{C_{Et}}{C_{Et}^*}\right), \tag{6}$$

$$q_S(\cdot) = m_S + \frac{\mu}{Y_S^m} + \Delta q_S^m \frac{C_S}{C_S + K_S^*} , \tag{7}$$

$$q_P(\cdot) = m_P + Y_P^m\cdot\mu + \Delta q_P^m\frac{C_S}{C_S + K_P^*} , \tag{8}$$

$$q_{Ac}(\cdot) = m_{Ac} + Y_{Ac}^m\cdot\mu + \Delta q_{Ac}^m\frac{C_S}{C_S + K_{Ac}^*} , \tag{9}$$

$$q_{Et}(\cdot) = q_S\left(\frac{b_1}{c_1 + DC_S} + \frac{b_2}{c_2 + DC_S}\right), \tag{10}$$

where $\mu_{\max}$ is the maximum specific growth rate, K_s is the saturation constant for glycerol, C_S^*, C_S^*, C_S^*, C_S^*, are the critical concentrations in glycerol, 1, 3-propanediol, acetic acid, and ethanol, respectively, K_S^*, K_P^*, K_{Ac}^* are inhibition constants, Y_S^m, Y_P^m and Y_S^m are yield coefficients, and m_S, m_P, m_{Ac}, b_1, b_2, c_1, c_2 are constant kinetic parameters.

The highly nonlinear model (5) takes into account both substrate, propanediol, acetic acid, and ethanol inhibition on the growth rate and the fact that growth and products interact. In fact if a substrate inhibition takes place in a bioreactor (like in our case), it can be find out not only that the process can exhibit unstable behaviour but also that it can led to wash-out steady-states, for which the microbial life has completely disappeared (Bastin and Dochain, 1990). Taking into account these inhibition aspects, it follows that for the bio-dissimilation process of glycerol to 1, 3-propanediol it is necessary to design some control algorithms to stabilize the process in face of the parametric variations in the model. More exactly, considering that the process model (1)-(10) is incompletely known, its parameters are time varying and not all the states are available for measurements, the *control goal* is to make the system to have a favourable robust tracking performance in the presence of set-point variations. Therefore, in this paper, to stabilize the bio-dissimilation process of glycerol to 1, 3-propanediol into its components via fermentation it will regulate the substrate concentration C_S inside the bioreactor at a set point C_S^* by acting on the feeding substrate rate, or equivalently on the dilution rate *D*.

3. CONTROL STRATEGIES

In this section, under the assumptions formulated in Sections 2, for the bio-dissimilation process of glycerol to 1, 3-propanediol described by dynamical model (1)-(10) we will develop an adaptive and a robust-adaptive control algorithm for controlling the substrate concentration C_S inside the bioreactor.

3.1 Exact linearizing feedback control

Consider the ideal case where maximum prior knowledge concerning the process is available, that is in model (1)-(10) the specific reaction rates μ, q_S, q_P, q_{Ac} and q_{Et}, even if they are time varying, are assumed completely known, while all the state variables and the inflow rate are available for on-line measurements. It can be seen that the equation (2) in the process model (1)-(10) is an input-output model with relative degree (Isidori, 1995) equal to 1. Assume that for closed loop system we wish to have the following first order linear stable dynamical behaviour:

$$(\dot{C}_S^* - \dot{C}_S) + \lambda_1 (C_S^* - C_S) = 0\,,\ \lambda_1 > 0\,. \qquad (11)$$

Then, from (2) and (11) we obtain the following exact linearizing feedback control law:

$$D(t) = 1/\left(C_{Sin} - C_S\right)\cdot\left(\lambda_1 (C_S^* - C_S) + q_S(t)\cdot X\right), \qquad (12)$$

The control law (12) leads to a linear error model $\dot{e} = -\lambda_1 e$, where $e = C_S^* - C_S$ represents the tracking error, which for $\lambda_1 > 0$ has an exponential stable point at $e = 0$.

The controller (12) will be used in order to develop the adaptive and robust-adaptive controllers as well as a benchmark in order to compare its behaviour with the behaviour of the designed adaptive and robust-adaptive controllers.

3.2 An indirect adaptive control strategy

In the previous subsection, it was assumed that the functional forms of the nonlinearities as well as the process parameters are known. Since such prior knowledge is not realistic, in this subsection we consider that the specific reaction rates are completely unknown and time varying and some state variables are not accessible. More exactly, we will design an indirect adaptive control strategy under the following conditions:

- reaction rate μ is time varying and completely unknown;
- the state variables *X*, C_P, C_{Ac} and C_{Et} are not accessible;
- the on-line available measurements are C_S and C_{Sin};
- all the other kinetic and process coefficients are given.

The main *control objective* is to make the output C_S to asymptotically track a specified reference $C_S^* \in \Re^+$ despite the unknown kinetics and the time variation of C_{Sin} and of some process parameters.

The unmeasured variable *X* used in control law (12) can be estimated by using an asymptotic observer (Bastin and Dochain, 1990; Petre, 2008). For that, let us define the auxiliary variable $\hat{z}$ as follows:

$$\hat{z} = X + Y_S^m C_S\,, \qquad (13)$$

whose dynamics derived from model (1)-(5) are independent of the unknown growth rate μ:

$$\dot{\hat{z}} = -D\,z - Y_S^m\left(m_S + \Delta q_S^m \frac{C_S}{C_S + K_S^*}\right)\left(z - Y_S^m C_S\right) + Y_S^m D C_{Sin}\,. \qquad (14)$$

Then, from (13) the estimate $\hat{X}$ of X is given by:

$$\hat{X} = \hat{z} - Y_S^m C_S\,. \qquad (15)$$

Under the first above condition, the reaction rate $\mu(\cdot)$ also used in control law (12) can be expressed as follows:

$$\mu(C_S, C_P, C_{Ac}, C_{Et}) = \rho(t)\,, \qquad (16)$$

where ρ is a completely unknown time-varying parameter. The estimates $\hat{\rho}$ of ρ can be on-line calculated by using a linear regressive parameter estimator (for details, see Bastin and Dochain, 1990; Petre, 2008), that for this bioprocess is described by the following equations:

$$\begin{cases} \dot{\Psi} = -\omega\Psi + \hat{X} \\ \dot{\Psi}_0 = -\omega\Psi_0 + \omega C_S + D\left(-C_S + C_{Sin}\right) \\ \dot{\hat{\rho}} = \Gamma\Psi(C_S - \Psi_0 - \Psi^T\hat{\rho}) \\ \dot{\Gamma} = -\Gamma\Psi\Psi^T\Gamma + \lambda\Gamma, \quad \Gamma(0) > 0,\ 0 < \lambda \le 1 \end{cases} \qquad (17)$$

where Ψ and Ψ_0 are the state variables of some linear and stable filters, Γ is a positive and symmetric gain matrix, and $\lambda \in (0, 1]$ named forgetting factor and $\omega > 0$ are design parameters which can be choose to control the stability and convergence properties of the estimator (see Bastin and Dochain, 1990; Petre, 2000; Sastry and Bodson, 1989).

Finally, the full indirect adaptive controller is made up by combination of (14), (15) and (17) with the control law (19) rewritten as follows:

$$D(t) = 1/\left(C_{Sin} - C_S\right)\cdot\left(\lambda_1 (C_S^* - C_S) + \hat{\rho}(t)\cdot\hat{X}\right). \qquad (18)$$

A block diagram of the designed indirect adaptive control system is shown in Fig. 1.

3.3 A robust-adaptive control strategy

Now, for the analyzed bioprocesses, we will develop a robust-adaptive controller under more realistic conditions:

- the influent concentration C_{Sin} is not measurable, but some lower and upper bounds, possible time-varying, denoted by C_{Sin}^- and C_{Sin}^+, respectively, are given;
- the specific reaction rate μ is time-varying and completely unknown;
- the state variables *X*, C_P, C_{Ac} and C_{Et} are not accessible;
- the on-line available measurement is C_S;

▪ all the other kinetic and process coefficients are known.

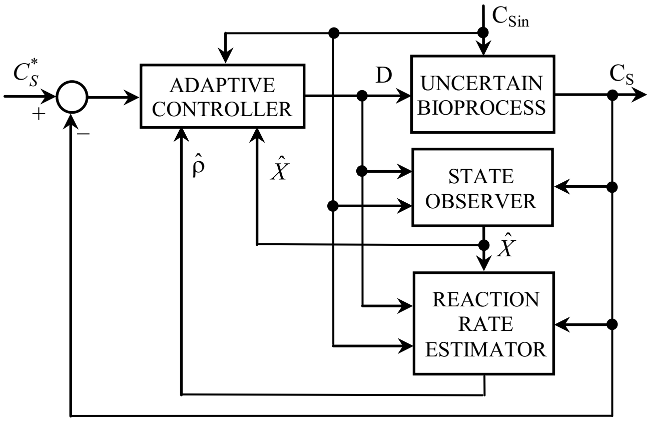

Fig. 1. Structure of indirect adaptive controlled bioprocess

The *control objective* is the same as in the previous case i.e. to maintain the output C_S at a desired level $C_S^* \in \Re^+$ despite the unknown variation of C_{Sin}, the unknown kinetics and time variation of some process parameters.

Since C_{Sin}, is unmeasurable, to estimate the unknown state X from (12), we cannot use the asymptotic observer (14), (15). But, since we assumed that some lower and upper bounds of C_{Sin} are known, then, depending on these known bounds, we can estimate lower and upper bounds of X by using an appropriately state *interval observer*.

Remark 1. The design of interval observers is based on properties of monotone dynamical systems or cooperative systems (Alcaraz-González et al., 2003, 2005; Rapaport and Dochain, 2005; Smith, 1995). Such systems have the property to keep the partial order between two trajectories depending on the bounds of the uncertainties in the model: if the (unknown) initial condition of the real system can be bounded between two known values, the trajectories of the system starting from these bounds will enclose the real trajectory (Alcaraz-González et al., 2003, 2005; Aviles and Moreno, 2009; Mazenc and Bernard, 2011; Moisan and Bernard, 2005; Petre et al., 2013; Rapaport and Dochain, 2005; Smith, 1995). □

The proposed interval observer is based on the asymptotic observer (14), (15). So, by using the cooperativity property (Smith, 1995) of the equation (14), to calculate lower and upper bounds of the unknown state X, a robust interval observer for the state X can be formulated as follows:

$$\begin{cases} \dot{\hat{z}}^+ = -D\hat{z}^+ - Y_S^m\left(m_S + \Delta q_S^m \dfrac{C_S}{C_S + K_S^*}\right)\left(\hat{z}^+ - Y_S^m C_S\right) + Y_S^m D C_{Sin}^+ \\ \hat{X}^+ = \hat{z}^+ - Y_S^m C_S \end{cases}$$
$$\begin{cases} \dot{\hat{z}}^- = -D\hat{z}^- - Y_S^m\left(m_S + \Delta q_S^m \dfrac{C_S}{C_S + K_S^*}\right)\left(\hat{z}^- - Y_S^m C_S\right) + Y_S^m D C_{Sin}^- \\ \hat{X}^- = \hat{z}^- - Y_S^m C_S \end{cases} \quad (19)$$

where $\hat{X}^+$ and $\hat{X}^-$ are the upper and lower bounds of the estimated variable X corresponding to the known upper C_{Sin}^+ and lower C_{Sin}^- bounds of the influent concentration C_{Sin}. The interval observer (19) works as a bundle of two observers: an upper observer, which produces an upper bound of the unknown state X, and a lower observer producing a lower bound, providing by this way a bounded interval in which the unmesurable states is guaranteed to evolve.

Under these conditions, we propose an indirect robust-adaptive controller derived from (18), which uses a linearizing control law coupled with the interval observer (19) used for the reconstruction of unmeasured states, and with the parameter estimator (17) for the unknown kinetics of the process. The control law takes the form:

$$D = \frac{1}{\left(\dfrac{C_{Sin}^+ + C_{Sin}^-}{2} - C_S\right)} \cdot \left(\lambda_1 (C_S{}^* - C_S) + \hat{\rho} \cdot \frac{(\hat{X}^+ + \hat{X}^-)}{2}\right) \quad (20)$$

It must be noted that in the equations of linear regressive parameter estimator (17), the variable $\hat{X}$ is replaced by the arithmetic mean of its lower and upper estimated bounds, and the unmeasurable variable C_{Sin} is replaced by the known variable $(C_{Sin}^- + C_{Sin}^+)/2$, as:

$$\begin{cases} \dot{\Psi} = -\omega\Psi + (\hat{X}^- + \hat{X}^+)/2 \\ \dot{\Psi}_0 = -\omega\Psi_0 + \omega C_S + D\left(-C_S + (C_{Sin}^- + C_{Sin}^+)/2\right) \\ \dot{\hat{\rho}} = \Gamma\Psi(C_S - \Psi_0 - \Psi^T\hat{\rho}) \\ \dot{\Gamma} = -\Gamma\Psi\Psi^T\Gamma + \lambda\Gamma, \quad \Gamma(0) > 0,\ 0 < \lambda \le 1 \end{cases} \quad (21)$$

Then the adaptive control structure presented in Fig. 1 is modified as a robust-adaptive scheme given in Fig. 2.

4. SIMULATION RESULTS AND DISCUSIONS

The performance of adaptive controller (17) and of robust-adaptive controller (19), by comparison to the exact linearizing controller (12) (which yields the best response and can be used as benchmark), has been tested by performing extensive simulation experiments. For a proper comparison, the simulations were carried out by using the process model (1)-(10) under identical conditions.

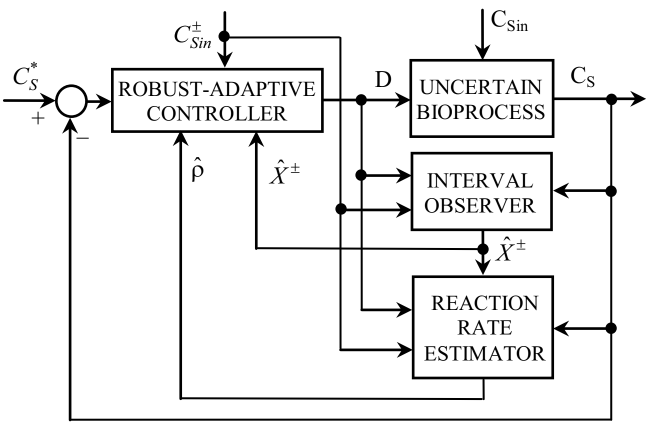

Fig. 2. Structure of the robust-adaptive system

The values of the yield and of the kinetic coefficients are (Xu, 2010):

$\mu_{\max}^0 = 0.67 \ h^{-1}$, $K_S^0 = 0.28 \ mmol/l$, $C_S^* = 2039 \ mmol/l$, $C_P^* = 939.5 \ mmol/l$, $C_{Ac}^* = 1026 \ mmol/l$, $C_{Et}^* = 360.9 \ mmol/l$, $m_S = 2.20 \ mmol/gh$, $m_P = -2.69 \ mmol/gh$, $m_{Ac} = -0.97 \ mmol/gh$, $Y_S^m = 0.0082$, $Y_P^m = 67.69$, $Y_{Ac}^m = 33.07$, $\Delta_S^m = 28.58$, $\Delta_P^m = 26.59$, $\Delta_{Ac}^m = 5.74$, $b_1 = 0.025 \ mmol/lh$, $b_2 = 5.18 \ mmol/lh$, $c_1 = 0.06 \ mmol/lh$, $c_2 = 50.45 \ mmol/lh$, $C_{Sin}^0 = 730.8 \ mmol/l$, $D^0 = 0.2857 \ h^{-1}$.

Two simulation scenarios were taken into consideration:

Case 1. In this case we analyse the behaviour of closed-loop system using the indirect adaptive controller (17), by comparison to exactly linearizing control law (12) under the following conditions and characteristics of the bioprocess: the states X, C_P, C_{Ac} and C_{Et} are unmeasurable; the specific growth rate μ is completely unknown and time varying; the influent concentration C_{Sin} is time varying, as in Fig. 3, but it is assumed measurable; the variable C_S is measurable; the kinetic coefficients $\mu_{\max}$ and K_s are time varying upon some sinusoidal patterns as:

$$\mu_{\max}(t) = \mu_{\max}^0 (1 + 0.1\sin(\pi t/10)), \qquad (22)$$

$$K_s(t) = K_s^0 (1 - 0.1\cos(\pi t/25)), \qquad (23)$$

and all the other kinetics and process coefficients are constant and known.

The behaviour of closed-loop system using adaptive controller (17), by comparison to exact linearizing control law (12) is presented in Fig. 3-8. Because in real operation the bioprocess behaviour can be influenced by noisy measurements, we considered that the measurements of controlled variable C_S as well as of the influent substrate concentration C_{Sin} are corrupted with an additive white noise with zero average (2.5% from its nominal values). The graphics plotted in Fig. 3 correspond to the controlled variable C_S, and graphics plotted in Fig. 4 corresponds to the control inputs D.

To verify the regulation properties of the controllers, for the reference variable C_S^*, a piece-wise constant variation was considered.

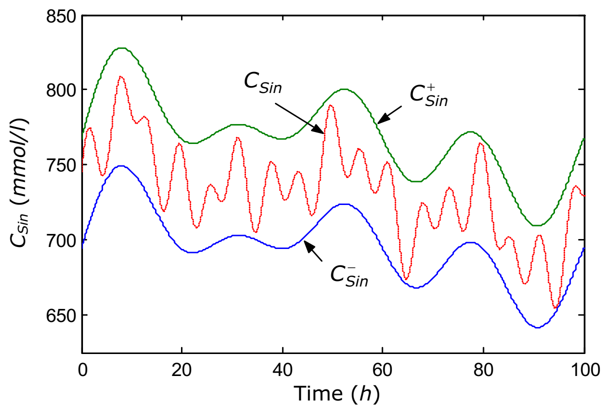

Fig. 3. Time evolution of C_{Sin} and of its bounds

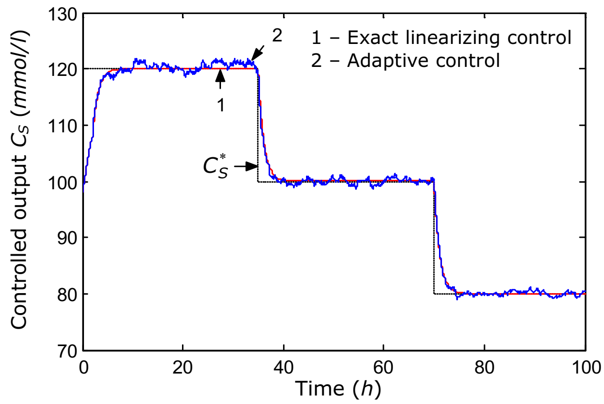

Fig. 4. Time evolution of output C_S – case 1

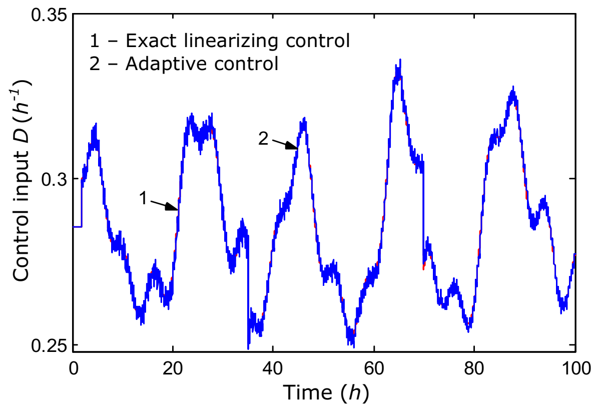

Fig. 5. Profile of control input D – case 1

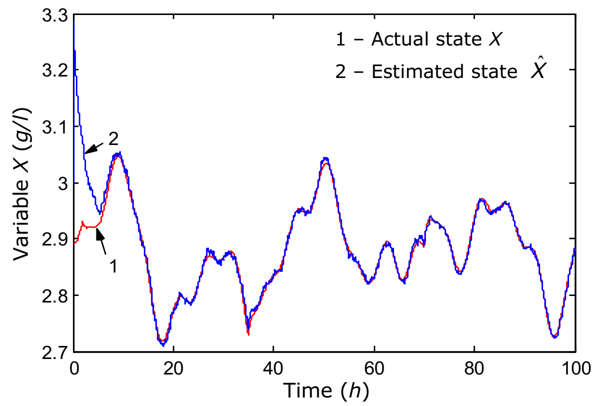

Fig. 6. Profile of estimate of unmeasurable variable X – case 1

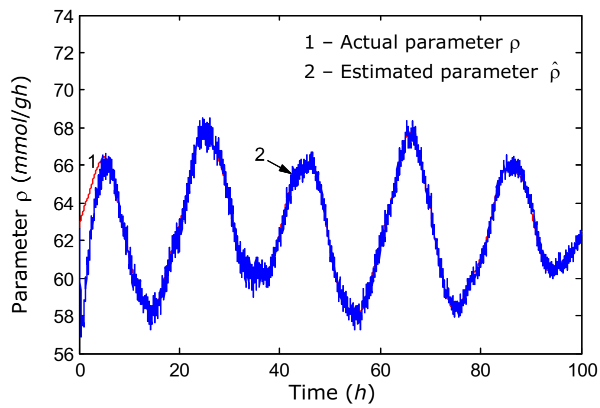

Fig. 7. Profile of estimate of unknown parameter ρ – case 1

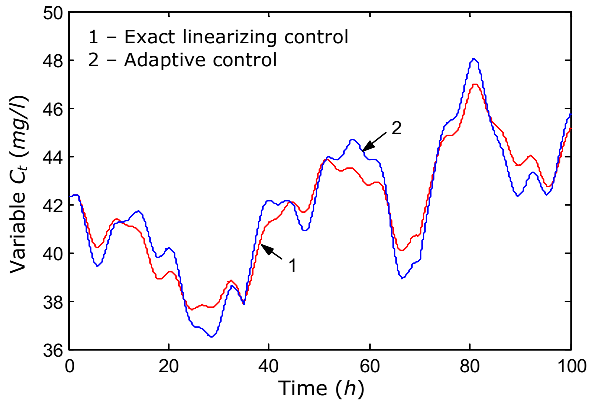

Fig. 8. Time evolution of variable C_t – case 1

It must be noted that initial the process is considered as evolving in open loop (with a constant input $D = 0.286\ h^{-1}$), and after 2 hours the loop is closed by using the control law (12), respectively (17).

From Fig. 4 and Fig. 5 it can be observed that the substrate concentration C_S tracks the reference profile C_S^*, and the control inputs D is kept in the physical limits required by the process. The gain of control laws (12) and (17) is $\lambda_1 = 0.9$, the tuning parameters of adaptive controller have been set to the values $\omega =$ 20 and $\lambda = 0.65$, and for the updating gain Γ it was considered the initial value $\Gamma(0) = 10.5$.

The time evolution of the estimates of unmeasured variable X provided by the asymptotic observer (14)-(15) is plotted in Fig. 6, and the time evolution of estimates of unknown parameter ρ provided by the linear regressive parameter estimator (17) is presented in Fig. 7. From these figures, it can be noticed that both state observer and parameter estimator provide properly results.

From graphics in Figs. 4-8 it can be seen that the behaviour of overall system with adaptive controller (17) is correct, being very close to the behaviour of closed loop system in the ideal case obtained by using the linearizing controller (12) when the process model is completely known. Note also the regulation properties and ability of the controller to maintain the controlled output C_S very close to its desired value, despite the high variation of C_{Sin}, and time variation of some process parameters. However it must be noted that both the control input and parameter estimator are more affected by noisy measurements than the state observer.

Case 2. In this case we analyse the behaviour of closed-loop system obtained by implementing the robust-adaptive controller (20), by comparison to exact linearizing control law (12) under the following conditions of the bioprocess: the influent concentration C_{Sin} is not measurable but some lower and upper bounds, denoted by C_{Sin}^- and C_{Sin}^+, respectively, as in Fig. 3, are given; the specific reaction rate μ is completely unknown and time-varying; the state variables X, C_P, C_{Ac} and C_{Et} are not accessible; the only on-line available measurements are the values of the output C_S; the kinetic coefficients $\mu_{\max}$ and K_s are time varying upon the same sinusoidal patterns as in the Case 1, and all the other kinetic and process coefficients are known (given).

The behaviour of closed-loop system using robust-adaptive controller (20) by comparison to the exact linearizing control law (12) is presented in Figs. 9-13. In order to test the robustness of the controller (20), like in the first case, we considered that the measurements of controlled variable C_S are corrupted with an additive white noise with zero average (2.5% from its nominal values). Also, like in Case 1, initial the process evolve in open loop (with a constant input $D = 0.286\ h^{-1}$), and after 2 hours the loop is closed by using the control law (12), respectively (20). The graphics shown in Fig. 9 correspond to the controlled output C_S, and graphics in Fig. 10 correspond to the control input D.

The gain of control laws (12) and (20) has the same value as in the case 1, $\lambda_1 = 0.9$, the tuning parameters of robust-adaptive controller have been set to the values $\omega =$ 20 and $\lambda = 0.95$, and for the updating gain Γ it was considered the initial value $\Gamma(0) = 10.5$.

The estimates of lower and upper bounds of the unmeasured variable X are presented in Fig. 11. The estimated values $\hat{X}^{\pm}$ are obtained by using the interval observer (19), which contain the known bounds C_{Sin}^+ and C_{Sin}^-, respectively. The state initial conditions are unknown but some guaranteed lower and upper bounds are assumed as $2.4 = X^-(0) \le X(0) \le X^+(0) = 3.4$ (g/l).

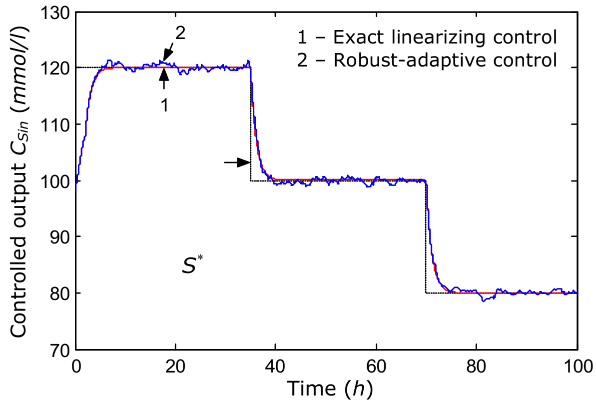

Fig. 9. Time evolution of controlled output C_S – case 2

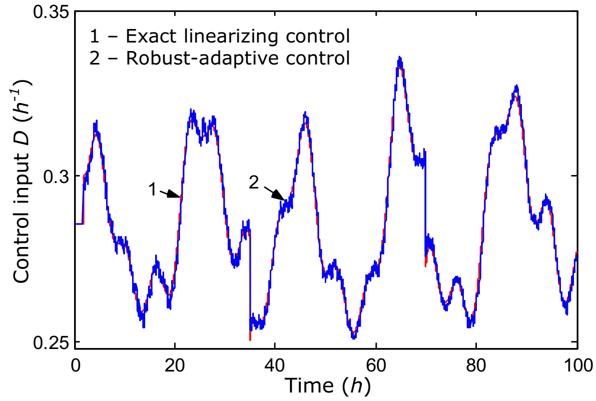

Fig. 10. Profile of control input D – case 2

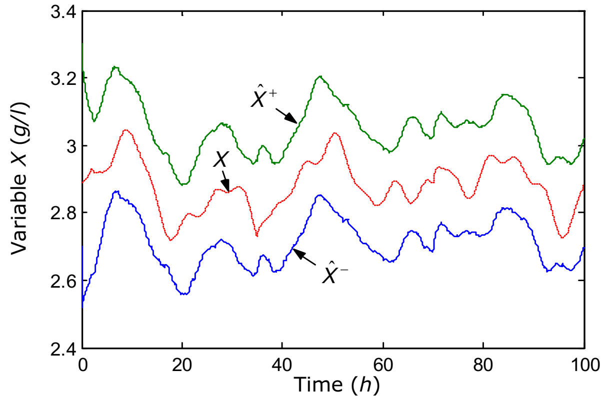

Fig. 12. The time evolution of variable *X*– case 2

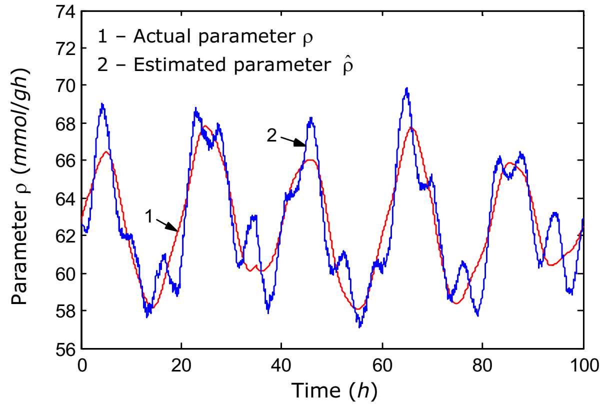

Fig. 11. Profile of estimate of unknown parameter ρ – case 2

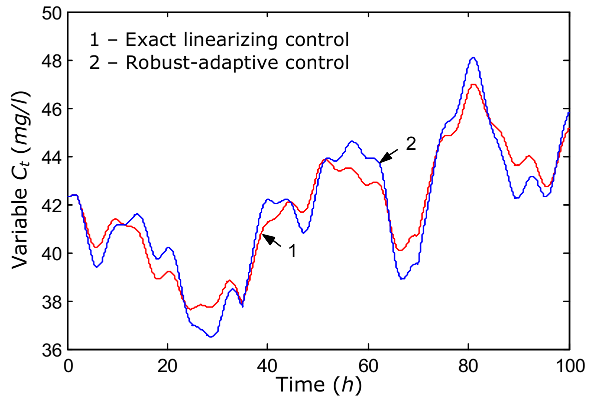

Fig. 13. Time evolution of variable C_t – case 2

The time evolution of estimates of unknown parameter ρ provided by the linear regressive parameter estimator (21) is presented in Fig. 7.

From graphics in Figs. 9-10 it can be seen that the behaviour of closed-loop system with robust-adaptive controller (20), even if this controller uses much less a priori information, is good, being close to the behaviour of closed loop system with adaptive controller (18) as well as to the behaviour of closed loop system in the ideal case obtained using the linearizing controller (12) when the process model is completely known. The controller is able to maintain the controlled output C_S close to its desired value C_S^*, despite the unknown high variation of the unmeasurable concentration of C_{Sin} and time variation of some process parameters. Also, as in the first case, the control inputs D is kept in the physical limits required by the process.

However the behaviour of the robust-adaptive controlled system is affected by the noise, and the behaviour of the parameter estimator (21) is not so good as of estimator (17), it remains satisfactory. It should be mentioned that the noise influence upon the estimates of upper and lower bounds of unknown variable X is negligible. Also both the control input and parameter estimator (21) are less affected by noisy measurements than in the Case 1. The reason is that in this case only the controlled variable C_S are corrupted with noise not and the influent substrate concentration C_{Sin} as in the first case.

It must be noted that the time evolutions of the three mainly products obtained by bioconversion of glycerol, namely propanediol, acetic acid and ethanol, respectively are properly in the both cases, and they are not presented here.

5. CONCLUSION

In this paper some indirect adaptive and robust-adaptive control structures for a continuous bio-dissimilation process of glycerol were designed and analyzed.

The indirect adaptive control structure was achieved by combining a linearizing control law with a state asymptotic observer and a parameter estimator used for on-line estimation of process unknown kinetics. This control structure was developed under the assumption that the bacterial growth rates were unknown but the influent flow rate was measurable.

In order to be close to practical situations, a robust-adaptive control strategy was designed under the realistic assumptions that the bacterial growth rate is time-varying and completely unknown, some kinetic parameters are uncertain and time varying, and the influent substrate concentration is also completely unknown, but some lower and upper bounds of this influent organic load (possibly time varying) are known. The robust-adaptive control structure was developed using a linearizing control law combined with an interval observer able to estimate a lower and an upper bound of unmeasurable states and with a parameter estimator for the process unknown kinetics. The obtained results are properly, being close to the behaviour of closed-loop system that uses the adaptive controller, despite the heavy uncertainties and disturbances that affect the process.

The performance of the designed algorithms was validated by numerical simulations, by using noisy measurements of the available state variables. Taking into account all the uncertainties, disturbances and noisy data acting on the process, the conclusion is that the robust-adaptive controller can constitute a good option for the control of such fermentation bioprocesses.

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Real, Virtual, Simulated and Remote Experiments for Robotics Education

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Abstract: Robotics is a multidisciplinary science and involves a variety of topics ranging from mechanics to electronics, automatic control and informatics. Therefore, training in robotics is a difficult problem. Considering the importance of practices in robotics education and training, the paper presents the real robotic systems from University of Craiova and several implemented training methods like an interactive teaching system useful in modelling and control of robotic structures, virtual systems, on-line (remote) systems. The developed systems help students to understand robotics and to compare different training methods. Also, the paper presents implemented activities to motivate the students and attract secondary school students.

Keywords: Engineering education, Robotics, On-line systems, Simulation, Virtual systems.

1. INTRODUCTION

Robotics education at the university level has appeared in Romania after 1989. Before this moment there were many researchers who worked in the field of robotics. But in the communist period, the president Ceausescu didn't want to introduce in the curricula of Engineering the Robotics specialization. He lived with idea that robotics means unemployment. However, it can be asserted that despite all the impediments, the Robotics field was sustained by some personalities. Beginning with the sixties of past century, several researchers have worked in theoretical and/or practical areas of Robotics. From 1981, the Romanian researchers have organized a National Symposium on Industrial Robots. The general constitutive meeting of the "Romanian Association of Robotics" (ARR) was organized on December 1990. In the next years 15 annual National Symposia on Robotics were organized by ARR, with national and international participants. From 2002, due to the increased interest for this scientific and research field, the national meetings have been organized as "conferences", and in 2012 the 21st Conference will be organized. ARR was renamed as Robotics Society of Romania (SRR), it has 12 branches and it publishes the journal "Robotics & Management".

The robotics education is a field of wide interest among the teachers and researchers around the world. A lot of works were reported in the last decade concerning several teaching methods used in robotics (such as [1–11]). Different approaches were derived from literature and from the teaching practice in colleges and universities. However, concerning the practical aspects related to laboratories and projects, the robotics teaching material can be classified as: simulators, self-made robots, real robots, virtual and on-line robots. Essential practical details can be lost if robotics teaching is reduced only to lectures and digital simulations, bypassing physical experiments because of their relatively high costs [12, 13]. Therefore, most of universities try to purchase or to develop real robots; thus the laboratories can be achieved by using real equipments (see for example the pedagogical overview presented in [4], or other experiments and robotic platforms in [9,14,15]). In other cases, some simulators are used in order to avoid the cost of real robots [16,17]. Related to this approach, in the last period a lot of interactive, on-line and remote robotics teaching systems were reported. In several works such as [2,3,18–23] web-based and remote laboratories are widely described. Another direction is dedicated to virtual reality based applications in robotics education: [3,23–26].

An interesting approach in robotics education is related to team-based projects and competitions in the field of mobile robots, manipulators, etc. [27–30]. For example, many small-to-medium projects and competitions are related to the use of some commercial packages and equipments such as LEGO Mindstorms [31–33].

As a generic conclusion, in order to achieve a good practical training of the students in the field of robotics is interesting and useful to combine the real robot experiments with simulation, virtual and remote facilities (we named ReViRoLab Concept).

This paper is organized as follows. First, some issues regarding the Robotics education at the University of Craiova are presented. Next, the real robotic systems installed in the laboratories are described. The subsequent section deals with some innovative virtual experiments and an interactive teaching system useful in modelling and control of robotic structures. Then, the web based telematics applications implemented in our laboratories are presented. The following sections approach several aspects concerning competitions and team-based projects in robotics, and the promotion activities in robotics. The final section collects the concluding remarks.

2. ROBOTICS EDUCATION

Robotics with all its aspects definitely belongs to one of the most multidisciplinary domain with knowledge from plenty of diverse fields. The fields are classical mechanical engineering, mechatronics, electronics and control engineering and end up with the information technology. Study of Robotics could be very difficult for the students entering the faculty with different background. In the first two years traditional study of theoretical disciplines without any clear relevance to practical problems decreases motivation of many students, who feel disappointed when they have to learn two years theory since they want to study robotics, not mathematics. Robotics Education in the universities should give to graduates expertise in: mechanical and electrical design, advanced robot control, robot programming and artificial intelligence.

As modern robotics desires expertise from diverse fields, which is very difficult to be efficiently maintained by a single engineer, it becomes reasonable to reflect this specific fact also in educational programmes in the robotics domain. At the University of Craiova, the Robotics specialization is studied in the frame of the Faculty of Automation, Computers and Electronics. We developed a four-year B.S. program in Robotics Engineering and two-year M.S. program in Robotics Control Systems. Both are recognized (have accreditation) by ARACIS (Romanian Accreditation Association for Higher Education) as a distinct engineering discipline at the University of Craiova. Both programs include a balance of theory and practice in a project-oriented framework.

The students begin to study robotics in the fourth semester with Robotic systems fundamentals discipline, and then in fifth semester study disciplines such as Sensory systems, Actuators, Microcontrollers and Control systems for robots. In the sixth semester the students continue with Robotics course, which consists of fourteen theoretical lectures, one lecture per week (100 minutes each) and fourteen lab/project sessions (one per each semester week). One lab/project session lasts 120 minutes.

The core objective of our subject Robotics is to explore, in friendly way, students' independent thinking, creativity and work in team. For Robotics lectures multimedia presentations are used. Robotics course integrates and extends the knowledge and skills gained in previous courses. The course has been composed having the mission to be a motivation for further deeper studies of robotics. The aim of this course is to combine and extend theoretical knowledge and practical skills with the ability to use and develop robots operating in real environments. The students are expected to understand processing of uncertain information and decision making processes and will be able to design, develop and implement these to robots. On the other hand, this course addresses issues of mechanical, electrical or electronics design of the robot or its parts. It concentrates on building skills, how to interpret the obtained data, at being only aware of possible constrains from real environment. The course targets the planning and decision making processes necessary to ensure objective-oriented behaviour of robots.

The course aims to create an interest in the ideas and possibilities of robotics. It should motivate students to ask questions themselves, think over solutions of robotic problems and to look forward to further advanced and specialized courses. The course should mediate practical skills in the area of robot planning or navigation, from design of robot architecture, sensor data processing and model building.

To fulfil the aforementioned aims, the emphasis is given to individual and team student's work under teacher's supervision in the laboratories while the role of lectures is to provide a theoretical background to the tasks the students solve. Evaluation of the course consists of two parts: an examination for the course and an assessment for the project. The examination has a form of a written exam, where a theoretical topic presented in the lecture has to be presented by the student, a quiz has to be filled and a problem has to be solved. To get the project assessment the students have to present the working (functioning application) done during the project work.

Our assessment rationale is clear – we assess each student against clear set of learning outcomes. On completion of this course, the student should be able to:

• Demonstrate a comprehensive understanding of the principles and techniques used in building and controlling robots by the design and implementation of adaptable controllers for robots on a real robot system.

• Demonstrate a comprehensive understanding of the theoretical principles of the techniques used in building and controlling robots and of the advances in this field.

To pass, a student must demonstrate that they have met the learning outcomes.

Training in robotics is a difficult problem, involving a variety of topics ranging from mechanics to electronics, automatic control and informatics. In the design and the achievement of a robotic course, significant issues are the modelling of the robots and understanding of classical and advanced control methods for robots. Another important problem is the choice of teaching system to pass from theory to practice. Of course, it is essential to apply the theory on real robots, but in most cases the use of this method is expensive. For this reason, the use of simulators is common and it constitutes an alternative to real robots. On-line robots offer a good platform to share experimentation through Internet. To achieve a good practical training in the field of robotics is very interesting and useful to combine the real robot experiments with simulation, virtual and on-line facilities. Virtual Reality (VR) offers good potential for presenting in education theory and practical experiments in an interesting and economical way.

3. ROBOTICS LABORATORIES – REAL EXPERIMENTS

The robotic systems which are used at the University of Craiova are composed by some different manipulators and didactical, industrial or mobile robots. Some of robots work stand-alone to do some manipulations and another robots work in two flexible manufacturing systems. For example, one robot works in the Flexible Manufacturing System FMS-200 for unloading-storage-palletization of completed assembly (Fig. 1).

The Flexible Manufacturing System Eshed Robotech comprises a flexible automation cell that carries out unloading-processing-storage operations involving a number of predetermined parts (Fig. 2). Some of the robots are didactical robots, like RD5E robot, RIP 0.2 robot (Fig. 3), PD5NT manipulator but some of the robots are industrial robots like RIP 6.3 robot (Fig. 3), ABB IRB 1440, Mitsubishi, Adept, or Yamaha robots.

Some manipulators and tentacle robots were built in Robotics laboratory with the contribution of the students. There are some mobile robots built in the Robotics laboratory or some didactical mobile robots, too (Fig. 4).

All these manipulators and robots are used in the training activities of the students to Robotics laboratory or to other courses from B.S. or M.S. programs. For majority of these robots, virtual and simulation experiments were developed, some of them with students' contribution.

4. VIRTUAL ROBOTICS AND SIMULATED EXPERIMENTS

In order to understand better how the manipulator and robots work it were developed the virtual reality (VR) simulation of the manipulators and robots from laboratories. First time VRML (Virtual Reality Modelling Language) was used to create virtual systems. The simulation respects the order and the speed of the robots movements. Then 3DSMax was used to create better virtual simulations that were exported in VRML in order to be portable on the website of laboratory. For example all the FMS-200 systems (Fig. 5) have virtual simulations [22].

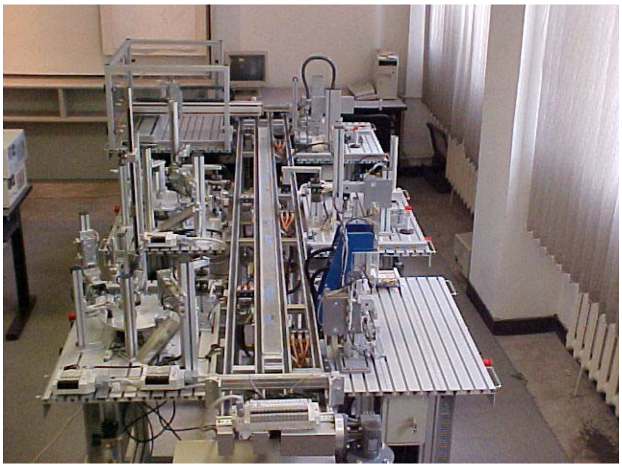

Fig. 1. SMC FMS-200.

Fig. 2. Eshed Robotech FMS.

Fig. 3. RD5E robot, RIP 0.2 robot, and RIP 6.3 robot.

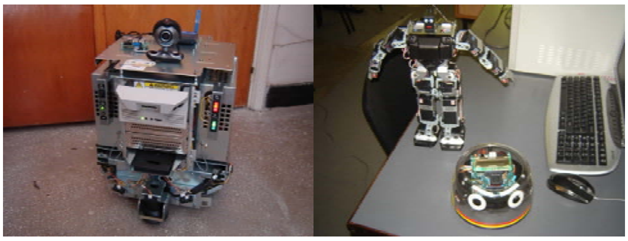

Fig. 4. Mobile robots.

Now the students can work off-line with our manipulators and robotic systems. All achieved VR applications there are on the website of laboratory. In this way the students can understand how these systems work and it is easier to develop Programmable Logic Controllers (PLC) programs for these manipulators and robots.

Another solved task was to create the possibility to write programs for the Mitsubishi PLC and to test them off-line on virtual model of the robotic system. It was developed an interface between PLC and computer, and the software that can simulate the robotic systems (another software, not VR simulation, Fig. 6). The student will write a PLC program to control the robotic systems in desired way. He will see on computer's display if his PLC program is design correctly and the movements of the manipulator or robot are well (Fig. 6). After the student tested his PLC program on simulated process he can test his PLC program on real robotic system.

Before to work with real experiments, in order to train the students some simulations were developed. Students can control and program a simulated robot on the computer. In this way the student can understand more things about that robot before he works with the real robot.

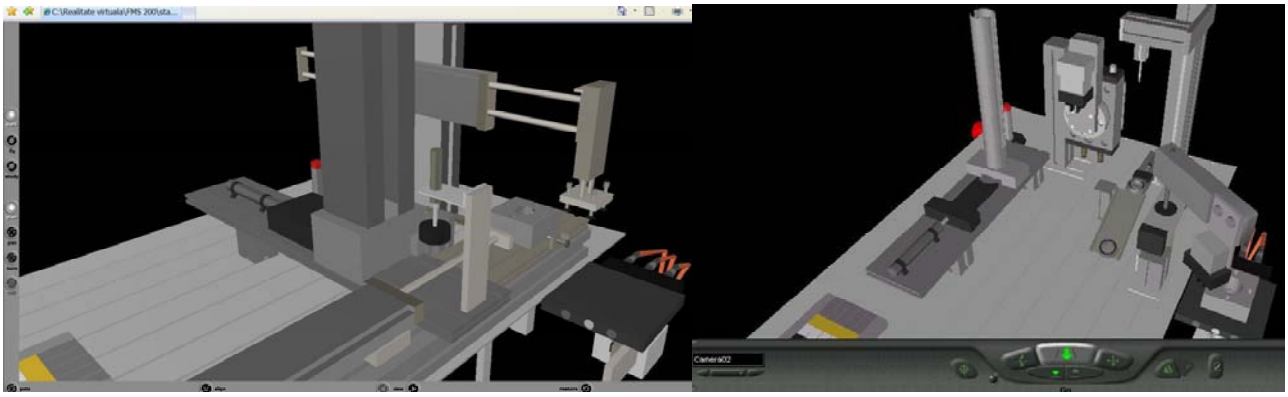

Fig. 5. Virtual robotic systems.

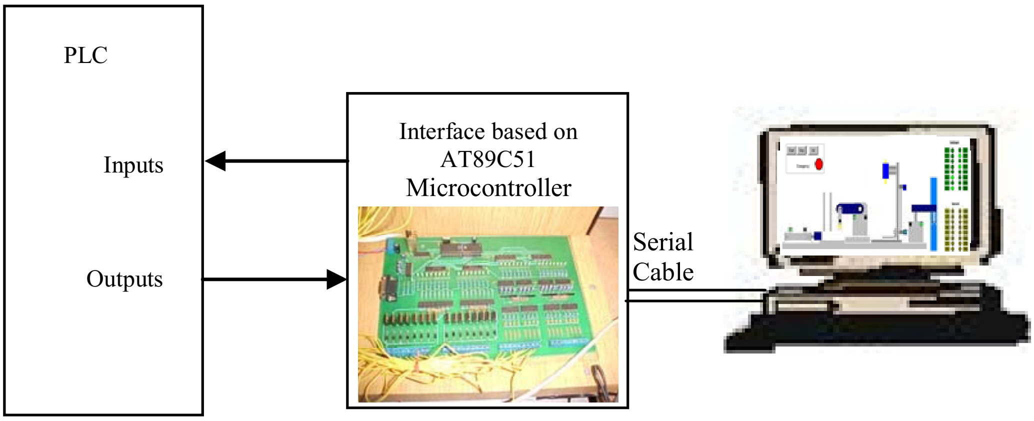

Fig. 6. The structure of the virtual robotic system controlled by a PLC.

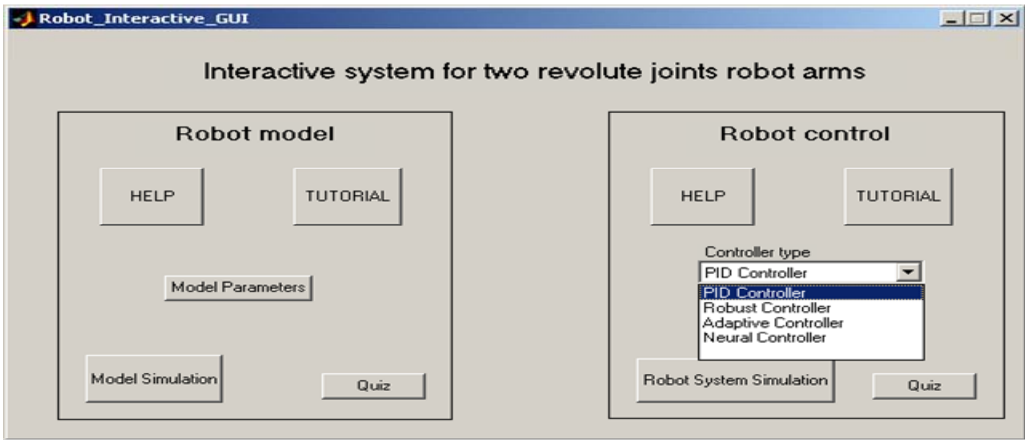

Fig. 7. GUI for simulator of two revolute joints robot arm.

First goal of the Interactive Teaching System was to develop a set of simulation experiments with a planar robot arm model (Fig. 7). This goal was achieved by designing a graphical user interface (GUI) in MATLAB, which allows to access different tasks such as: body experiments, tutorials, help-files, small quiz and so on. By acting some push-buttons or pop-up menus from this graphical user interface, students can choose different experiments for modelling or control of the robot arm.

A set of experiments with different types of robots was designed. These exercises allow students to learn about: working space, Denavit-Hartemberg parameters, transformation matrix, joints coordinates, Cartesian coordinates, direct kinematic model, inverse kinematic model, PID parameters, robust controller, adaptive controller, neural controller, training of robot, path tracking (Fig. 8), spline interpolation and so on.

The student can understand and compare some control methods (adaptive, robust, PID, neural). For example, the student can compare the errors for the final joint of a robot arm with PD controller and neural controller. They can understand how each controller's parameter changes the response of the robot. The use of MATLAB is suitable especially for control and advanced robotics [34].

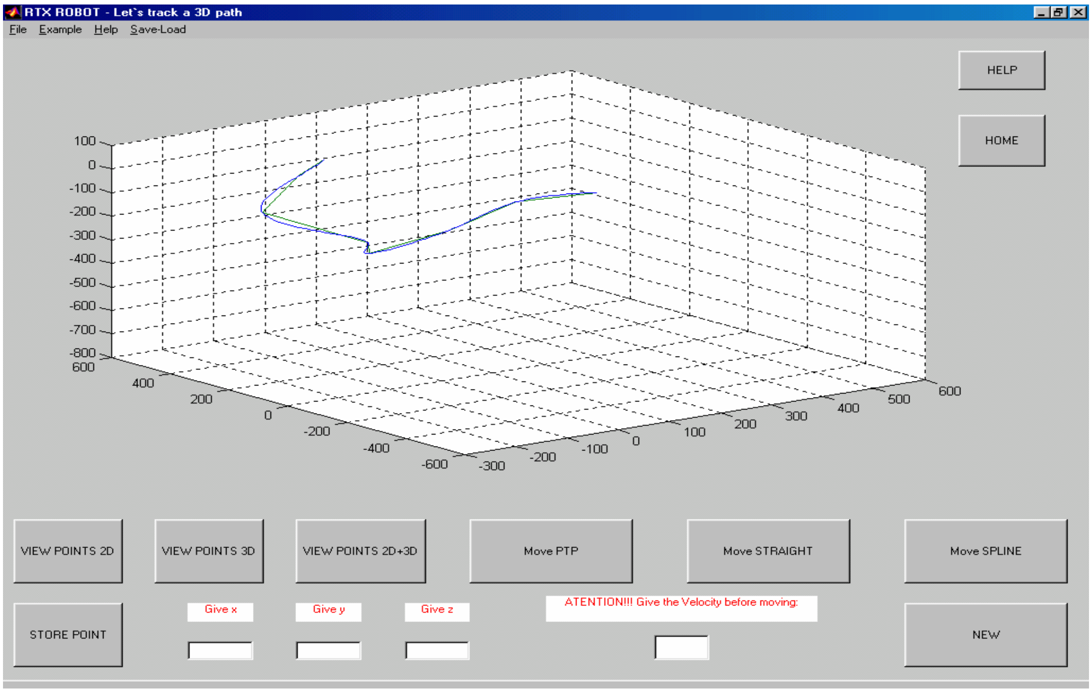

Fig. 8. Path tracking.

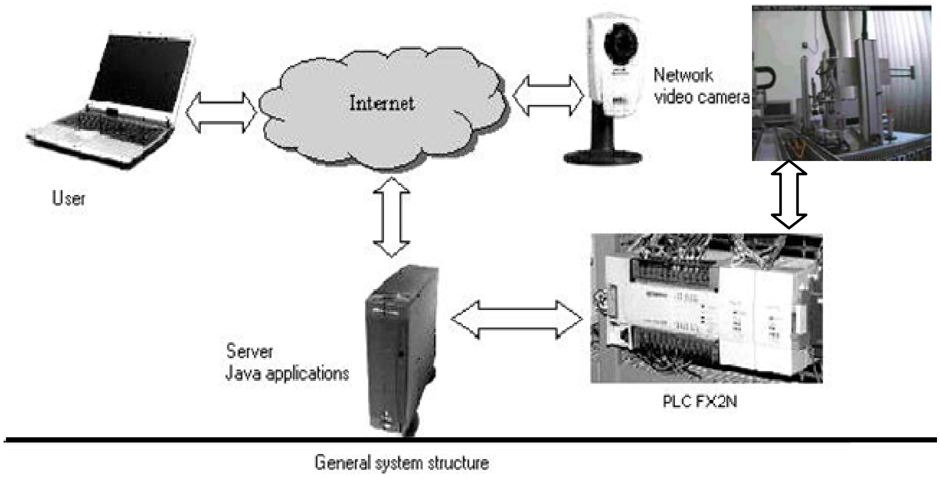

Fig. 9. General system structure.

5. WEB BASED TELEMATICS APPLICATIONS FOR ROBOTICS

The use of Internet technology for remote programming application offers the advantage of low-cost deployment. There is no longer a requirement for expensive purpose built equipment at each operator's location. Almost every computer connected to the Internet can be used to control a tele-operable device. The downside is the limitation of varying bandwidth and unpredictable time delays. These Internet features should be considered before designing an efficient remote programming system.

5.1 Web based Telematics Application for Robotic Systems

This web-based application allows users to perform own experiments remotely from another computer. Using a standard web browser and a connection to the Internet, the user can write his program for the PLC, used to control a robot system. Application contains two modules: the client and the server. The client application is an applet hosted by website department. The server application is hosted by a computer connected to Mitsubishi PLC. The server application uses COMM API for connection with PLC. Java was chosen for the application development.

In order to speed up the development process, additional open source libraries and APIs have also been used. In the general system structure (Fig. 9) the Java server application is responsible for the administration module that involves users' management, communication with PLC and program editor. The user can write his PLC program using the client window (Fig. 10). An AXIS network camera is used for sending live video of robot system to the user's browser. This camera includes a built-in WEB server running under Embedded Linux that transmits the video stream either via an ActiveX control or a Java applet.

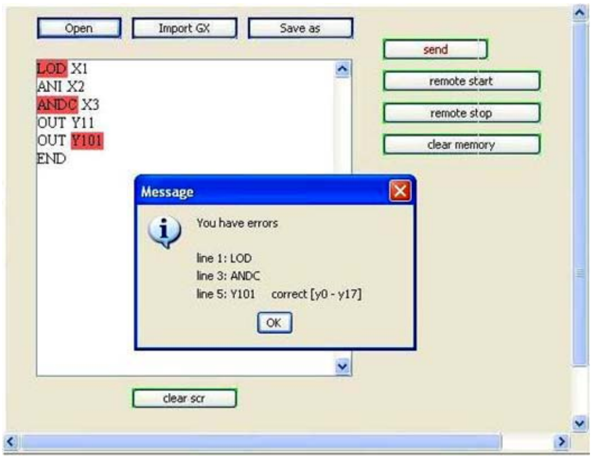

Fig. 10. Client window.

5.2 Remote Learning Environment for Visual based Robot Navigation

The most effective way to make theoretical aspects comprehensible to the students is to put them into practice on real robots. However, because high costs of the robots, a good teaching alternative is the use of an e-laboratory system that enables the students from different universities to share one or more robots situated in a remote location. The laboratory structure is shown in Fig. 11. The main component of the e-learning system is the web server that manages the students, stores the documentation and provides access to the laboratory top camera and the on-board video camera.

The MySQL database stores the information about the users and the laboratory schedule. The first step that the student must complete is to create an account for further access into the system. The user ID and password will be asked whenever the student wants to access the robot documentation, or to schedule a reservation on one of the available robots. After logging into the system, one or more of the available robots is chosen and the experiment's date, start time and duration need to be specified on the reservation form. In addition, the student can specify the type of experiment and the environment setup, which may include different targets and their positions. The web interface allows uploading the selected program to the remote robot and starting it.

A network video camera located above the experiment scene is displayed on the laboratory web browser for watching the robot in action. By selecting a robot from those available in the right side of the laboratory page (Fig. 12), a remote connection to the robot's on-board computer is initialized in a new browser window.

The C# development environment allows the student develop his own programs. During the experiment session the student can open an existing program or upload a new one. The student may also benefit of the debugging capabilities that Visual Studio offers. The visual information coming from the web camera can be used by the student in his program for obstacle detection, building the environment map or path following. Some software libraries are installed on the robot's computer.

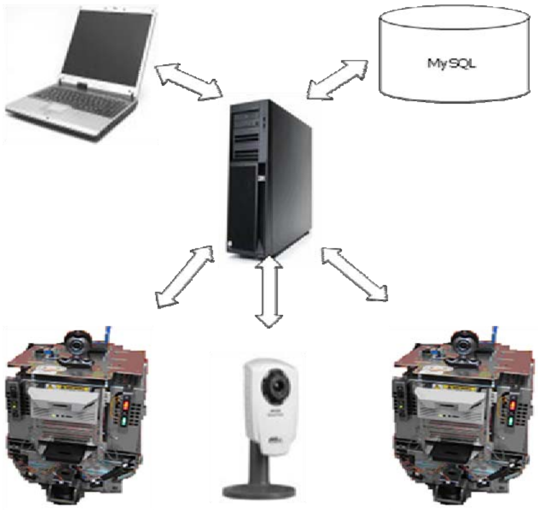

Fig. 11. The learning environment.

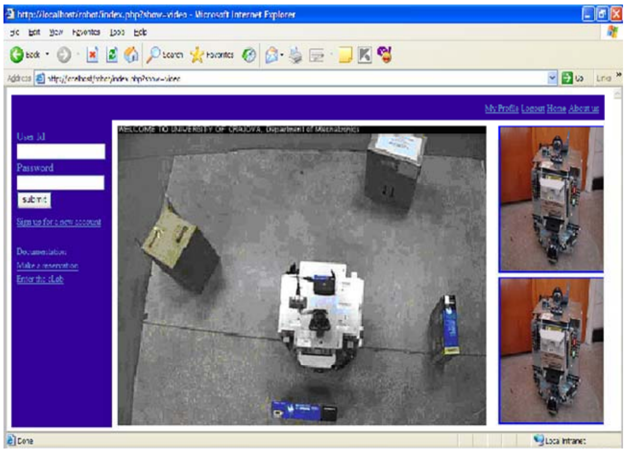
Fig. 12. The network video camera view.

5.3 Development of Online Experiments for a Mobile Robot via Internet

The telematics system is composed of mobile robot, USB webcam, computer for server application and website. The developed telematics application is a client-server application.

This first version of our implementation uses an application client-server that it consisted of two programs: the server runs on the local computer (connected to the mobile robot) whereas the client runs on any Internet-linked computer.

Required main features of the client-server application were: chat functionality; editor for BasicStamp microcontroller with syntax checker; file transfer to server and download to microcontroller; video acquisition; online video transmission. Fig. 13 presents the client window for a small mobile robot, and Fig. 14 depicts the server window but using another mobile robot (bigger) developed in laboratory.

All these (real, virtual and simulated) facilities are used at the Robotics laboratory or to other related disciplines.

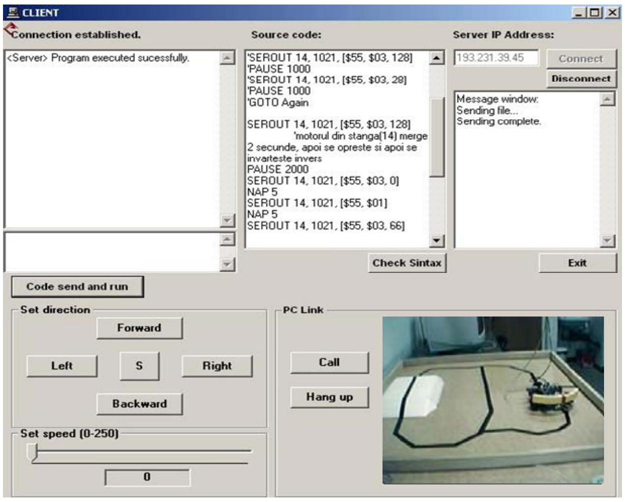

Fig. 13. The client interface.

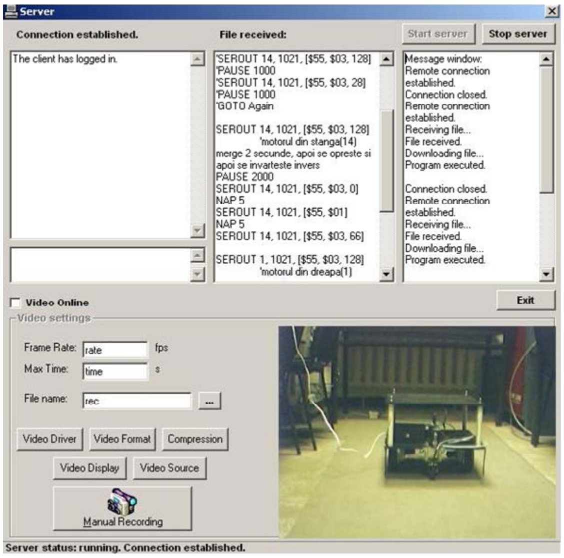

Fig. 14. The server interface.

6. COMPETITIONS

At the beginning of the semester the students are asked (via a small questionnaire) about what they want to do to the Robotics project work from some options. If the student can choose want he/she likes to do the work will be better done and the student will win more practical skills. For example, some of them can choose to work in a small team with LEGO Mindstorms, or to build small mobile robots to participate in national competitions, or to develop manipulator robots with electro-pneumatic actuation. Depending on their choice the students are divided into small teams (2 to 4 students). Each team uses the basic set of the LEGO Mindstorms. The teams design and develop the mobile robot with implemented control and program it to fulfil the specified tasks. The ”brain“ of the robot is the central control unit (LEGO® NXT Brick). Up to 3 servomotors can be connected to the LEGO ® NXT brick which can be used as sensors for rotational speed measurement as well. The touch sensor, the light sensor, the sound sensor or ultrasonic sensors can be connected as well.

The students can use different programming languages. They can use one of recommended programming languages (NXT-G or LeJOS) or use other ones (e.g. MATLAB toolbox developed at the University of Aachen, RobotC, LeJOS OSEK, or another one). NXT-G is used by students with little experience in programming. Many students chose the LEGO MINDSTORMS LeJOS NXJ (due to widespread expansion and knowledge of Java) with its extensive libraries, which support interesting robot functions. The drawback is the necessity to change the firmware NXT which includes Java Virtual Machine replacing the standard LEGO firmware.

The students have to solve two specific tasks: follow the line and labyrinth. The aim of the students in the “follow the line” task was to build and program a robot that would independently, without any further assistance, pass along the black line marked on the mat as quickly as possible and stop at its end. Students do not know the path; they know only the basic parameters of the path. The students are completely free to design the robot. Two weeks of preparation, testing and software debugging are followed by two-rounded competition.

The aim of the second task (“Labyrinth”) was to build and program a robot that would independently, without any further assistance and external control, pass through the maze from its beginning to its end as quickly as possible. In the case of rules violation the team will be immediately suspended from the competition. The choice of using sensors and control strategy depended solely on the individual teams. For the sake of orientation in labyrinth the robots could touch the walls. Four weeks of preparation, testing and software debugging will be again followed by a two-rounded competition. The students solved the passage through labyrinth using different ways.

The following problems occurred during solving the task: low computing power, long reaction time of the ultrasonic sensor, small light sensor resolution, changing light conditions and big gap in the motor gear. Tuning the controller was possible only visually according to the behaviour of the robot.

We believe that without any doubt the subject makes learning more attractive. The Lego Mindstorms competition represents a playful way how to learn the basic ideas of sensors, actuation, robotics, measurement, etc. The initiative is raised by themselves during solving the practical tasks. Right at the beginning of study the students recognize the principles of the creative engineering and research work.

A national event in the field of robotics is the Romanian Students Mechatronics Competition where our students from Robotics specialization participated in 2010 and 2011. The competition had two tests, one about programming of a PLC to control a mechatronics station and another test about mobile robots. The test with mobile robots had three sub-tests where the tasks were to find a line, follow a line and to navigate through a labyrinth. The faculty team had good results and won the third prize in 2010.

7. PROMOTION OF THE ROBOTICS TO THE TEENAGERS

The research activity has motivated significant promotion of robotics to the citizens in general and the teenagers in particular. Romania, as other European countries, is suffering from a lack of attractiveness to science and technology by young people, namely high school students. Though job offers are high in these areas, students consider the subjects somewhat too hard, and they frequently show a considerable information deficit about what is taught in engineering programmes. Robotics is an ideal vehicle for changing that attitude, due to the multidisciplinary and hands-on nature of the involved work. In Craiova the first steps to introducing robotics to high school students as an attractive and involving way of learning were taken in 2008 when we organized a robotics competition for them based on Lego Mindstorms.

Some big boom in the schools' interest in robots were caused by the organization of robotics festival, Craiova Robotics Days 2011, where recent research results from university and industrial groups were presented, together with competitions involving students (Fig. 15). This event was organised by us in the framework of 2011 European Robotics Week. The NAO presentation (Fig. 16) creates a big interest in robotics for everybody. By designing, constructing and programming robots, students can experience that working with technology is an interesting but not a trivial process.

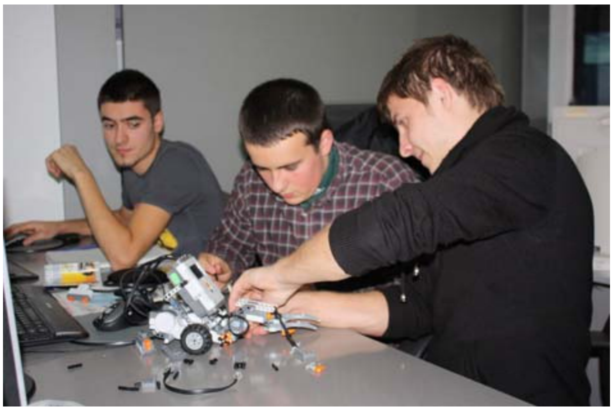

Fig. 15. High school students' competition.

Fig. 16. NAO presentation.

Additionally, constructing and programming robots in a teamwork setting is an ideal instrument to train those types of competences and soft skills that are essential for dealing with technical development processes. Many educational robotics activities - robot courses or robot competitions - rely on the fascination of mobile robots.

Another interesting initiative in our university consisted in an informal context learning through competitions, which was organized with pupils from secondary schools to attract them to technical higher education. Two consecutive years (2008, 2009) a robotics competition using Lego Mindstorms kits was organized. In the first year (2008), the competition was organized only for two secondary schools (48 teenagers), but in the second year (2009) the competition had two phases. The first phase was organized for each secondary school (six schools in total, 108 teenagers); thus, six teams with 3 pupils participated to this first phase of the competition. The winner team of each school participated in the second phase. Many of the pupils participated enthusiastically and later we found them as students of our faculty at the Robotics specialization.

We asked the participants on their future interest in robotics competition and got the following figures: 92% enjoyed the robotics competition; 84% would recommend it to friends; 76% would attend further robotics competition.

8. CONCLUSIONS

Today, the robotics industry is booming just like the personal computer business was 30 years ago. While some of ideas behind the ReViRoLab Concept are new, many of them were adopted from and inspired by outstanding projects like those described by references. We acquired early experience by running robotics workshops for secondary schools and university students in Germany and running workshops for high school students in Romania or by participating to competition as RoboCup Jr. (Netherlands).

With our achieved and future developments the students will have new possibilities to understand and work with manipulators, robots and flexible manufacturing systems. We tried to use different types of experiments: virtual, simulated, on-line and real experiments. Virtual and simulated experiments are used to understand the theory by the students, in order to provide the basics in the field of robotics; these approaches are not expensive, but have some limitations. The remote and real experiments are used to give the students a taste of real situations.

The practical activities drawn up from the modular concept of the robotic systems allow the development of skills such as: analysis, installation, assembly, implementation, maintenance, diagnosis, fault repair, start-up, set-up, design, programming, definition of procedures, measuring, etc. The use of real experiments with simulated and virtual experiments changed the students' attention and interest in robotics.

Table 1. Questionnaire - Methods used in robotics training

	Before Robotics course			After Robotics course		
	High	Medium	Low	High	Medium	Low
Interest in Robotics	37%	55%	8%	73%	24%	3%
Understanding of theoretical problems previously studied	43%	42%	15%	72%	21%	7%
Understanding of practical problems previously studied	37%	43%	20%	70%	24%	6%
Interest in real experiments	79%	21%	0%	86%	14%	0%
Interest in simulated experiments	40%	40%	20%	46%	40%	14%
Interest in virtual experiments	32%	58%	20%	42%	50%	8%
Interest in on-line experiments (via Internet)	29%	52%	19%	51%	40%	9%

It was created a questionnaire about new methods used in robotics training. Some of the questions was about their interest in robotics, understanding of theoretical and practical problems, their interest in real, simulated, virtual and on-line experiments before and after Robotics course and so on (Table 1; for 2008-2011). The students' interest in Robotics and all types of experiments increased; the understanding of theoretical and practical problems increased too.

As it can see in Table 1, the highest interest is in real experiments, but the difference between real experiments and simulated, virtual and on-line experiments decreased. Once the new methods of Robotics training were used, the students' results are better both during the semester and at the exam.

Robot competitions were also presented; even though these are not part of the curriculum, and thus no credits can be earned for it, every year a huge number of enthusiastic students build a robot and participate in competition. There are two reasons for this success:

(1) students are fascinated by robots and they feel the urge to build one,

(2) the competition has been made as accessible as possible by organizing guided hands-on workshops.

This is useful because students acquire relevant technical competences by building a robot. Moreover they learn to work as a team and are challenged to use their creativity. So, by giving students the opportunity to participate in robot competitions, they can acquire skills that are useful for their future career.

ACKNOWLEDGMENT

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Mathematical Model of a Robotic Joint with a Damper with Smart Fluids

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Abstract: In this paper the mathematical model of a damper with smart (electro-rheological-ER) fluids used to robot joins is presented. The torque generated by the ER damper has two components: a torque due to the viscous damping and a torque due to the ER fluid. The viscous damping torque is the output of the damper with non-applied electric field. The ER torque is the torque due to an applied electric field. The magnitude of the ER torque is much larger than the viscous damping torque. Using the ER damper to robot joins from a robot system, undesirable join vibrations can be efficiently compensated.

Keywords: dynamic model, electro-rheological fluids, damping process.

1. INTRODUCTION

If any vibration appears while the robot realizes a technological task, it will negatively affect the accuracy of position and orientation operations of end-effector device and the stability of mechanical structure during the robot's displacement. These undesirable effects cannot be completely eliminated not even for the flexible and lightweight structures robots, which developed an increment lately. Many researchers focused upon the study of vibrations and control methods which will result in eliminating or, at least, reducing acceptably their effects. The main two sources for the apparition of robots' vibrations are given by the inherent flexibility of the joints and by the dynamics of the control system of the joints. A set of studies and experiments (Nicolo et al, 1983), (Sweet et al, 1984) proved that the main source is given by the flexibility of robotic joins caused by the transmission subsystems for movement and control of joint system.

In specialized literature the control methods for the vibrations in robotic joins are classified in three categories: passive, semi-active and active (Seto, 1992). For *the passive method* the control is obtained based upon some structures having as component elements mass, resorts and dampers (e.g.: cylinders that move with a piston in a fluid), configured in different ways. These structures do not dispose of closed loop system based on sensors and transducers, thereby they cannot compensate for the system's vibrations.

Passive type device used for vibrations control is called *dynamic absorber.* Due to the fact that it is equipped with external sensors and actuating elements, an *active control* is obtained, which can result in reducing undesired vibrations, but it can increase significantly the price of the device, therefore the necessity of an appropriate power for the actuators appears.

Semi-active control is a method that, on one hand keeps the advantages given by the characteristic from a resort and from a passive dynamic absorber damper, and, on the other hand, eliminates the disadvantages caused by supplementary power requirements and by the increasing system's complexity level. Most of the vibrations attenuation systems frequently use this kind of control. Using unconventional methods (e.g. incorporating smart fluids like electro-rheological or magneto-rheological fluids in actuation systems structure) lead in obtaining extremely positive results.

2. ER FLUIDS BASED DAMPER

The torque generated by the ER fluids based damper consists in two components: a torque caused by the viscous attenuation and a torque caused by ER fluid. ER torque is caused by the presence of electrical field and will be used for vibration control. The size of ER couple is much bigger than that of viscous attenuation torque.

Viscous attenuation is produced due to the absence of electrical field; it permanently exists during the device operation (functioning) and can not be controlled. Under the influence of an electrical field, the rheological state of the fluid is changing. The size of ER couple can be easily modified by an appropriate adjustment of the electrical field. ER torque corresponds to a Coulomb attenuation couple. Maximal value of ER joint depends on ER fluid characteristics and on the size and configuration of the space where it is stored. ER fluid should have a low viscosity and a high limit of stress shearing in its gel state.

2.1 Phisical structure

Vibrations that affect the robot joins can be rapidly diminished or eliminated by assembling properly an ER damper. A simple constructive solution of such a kind of damper is presented in Fig. 1. Main elements are: a cylinder divided in two chambers by a separating wall - these two chambers are filled with ER liquid – and a rotation valve fixed upon the articulation axis. Both the valve and the cylinder are built of insulating materials, and the internal side of the cylinder and the external side of the valve are covered with a layer of conducting material (e.g. copper) in order to be used as electrodes. By applying a high value voltage (e.g. 6kV) upon the two electrodes, an electrical field with a high voltage is generated.

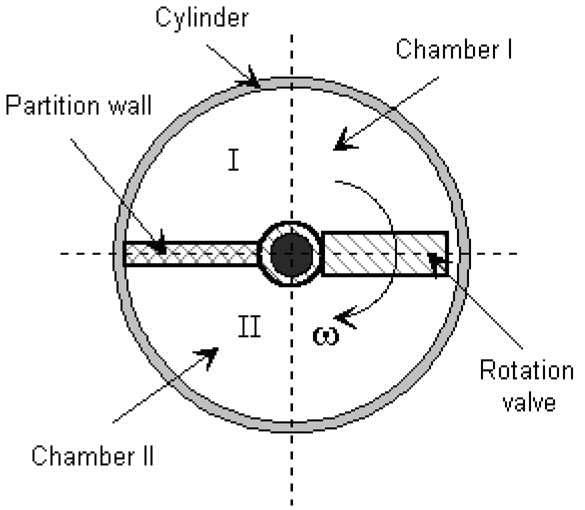

Fig. 1. A constructive solution of a damper

Due to the electrical field action, ER fluid shear increases. Therefore, by controlling the size of the field, strength in flow can rapidly be adjusted for modifying the attenuation. We can say that the system presented in the above figure represents the variant for angular motion of the valve with plate electrodes (like a capacitor) from the translation motion of the fluid. Damper functioning is based upon a very simple principle: during the valve rotation, liquid volumes in the two chambers become uneven, the two pressures suffer modifications and the difference of the pressure resulted will lead to an attenuation torque that opposes to the angular motion.

2.2 Dynamic model

For determining dynamic model of the damper system, the elements subject to movement must be considered and forces and torques that action during the functioning must be analysed.

For simplicity the following are considered:

- Coulomb type friction forces are neglectable;
- The pressure in every enclosure is uniform;
- Fluid flow in interstices is laminar;
- The influence of hydraulic shocks („hammer fight") of the fluid are neglectable;
- The fluid is incomprehensible.

The fluid behaves like a plastic material respecting Bingham law. As we previously presented, the stress shearing is given by the relation:

$$\sigma = \sigma_y + \eta\dot{\gamma} \tag{1}$$

where σ_y is the stress correspondingly to the passing from the elastic deformation to plastic deformation, η is plastic viscosity, and $\dot{\gamma}$ is the apparent shear rate.

The following forces action upon the mobile element of the valve (its form can be approximated with a rectangular parallelepiped – Fig. 2): the force given by the pressure in chamber I actions upon the $B_1B_2B_3B_4$ side, the force given by the pressure in chamber II actions upon the $A_1A_2A_3A_4$ side, the stress shearing generated by ER fluid flow in damper's interstices actions upon $A_1A_2B_2B_1$, $A_2A_3B_3B_2$, $A_3A_4B_3B_4$ sides ($A_1A_4B_4B_1$ being the side through which valve's blade is embedded in its bearing box).

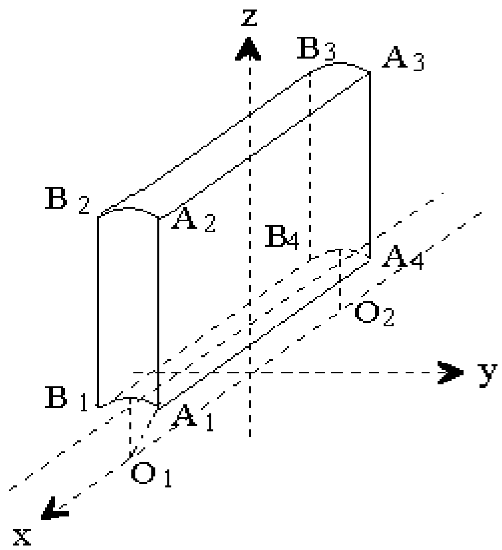

Fig. 2. Approximated mobile element of the valve

Considering these forces, attenuation torque has the following expression:

$$M_A = M_P + M_\sigma \tag{2}$$

where M_P is the torque caused by the pressure difference between the two chambers of the damper, and M_σ ιs the torque caused by the stress shearing in interstices. The torques M_P and M_σ are calculated as following:

$$M_P = \int_{(A_1A_2A_3A_4)} \Delta P \cdot r \cdot ds \tag{3}$$

$$M_\sigma = \int_{(A_1A_2B_2B_1)} \sigma \cdot r \cdot ds + \int_{(A_2A_3B_3B_2)} \sigma \cdot r \cdot ds +$$

$$+ \int_{(A_4A_3B_3B_4)} \sigma \cdot r \cdot ds \tag{4}$$

where "ds" represents the elementary surface.

The pressure difference ΔP has two components:

$$\Delta P = \Delta P_o + \Delta P_{ER} \tag{5}$$

Where ΔP_o is pressure difference on the interstice caused by the fluidic resistance where it introduces, and ΔP_{ER} is pressure difference caused by the electro-rheological effect.
In (Yeaple, 1984) we can see the expression of the fluid flow Q with a stable flow between electrodes (Fig. 3):

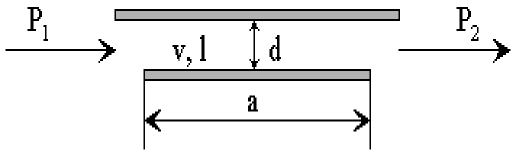

Fig. 3. Electrode system and the main variables

$$Q = \frac{(P_1 - P_2) d^3 l}{12 \eta a} - \frac{vdl}{2} \tag{6}$$

where: Q – flow, P_1 – input pressure (admission), P_2 – output pressure (evacuation), l – the length of the common side between the two electrodes, a – the width of the interstice zone, d – the distance between the two electrodes, v – motion speed of mobile electrode, η - fluid viscosity. Because, on the A_1A_2 and A_3A_4 sides tangent speed depends on the radius (it is constant on A_2A_3), relation (6) becomes:

$$Q = \frac{(P_1 - P_2) d^3 l}{12 \eta a} - \int_l \frac{v(z)\, d}{2} dz \tag{7}$$

From relation (7) the pressure difference $\Delta P_o = P_1 - P_2$ can be determined due to the fluid moving within the interstice between the two electrodes:

$$\Delta P_o = \frac{12 \eta a}{d^3 l} (Q + Q_v) \tag{8}$$

where Q_v represents the expression:

$$Q_v = \int_l \frac{v(z)\, d}{2} dz \tag{9}$$

and the value of l is:

$$l = A_1A_2 + A_2A_3 + A_3A_4 = 2\, A_1A_2 + A_3A_4 \tag{10}$$

The values of Q and Q_v are calculated below:

$$Q = v_{med} \cdot A = (\varpi R_{med}) \cdot (A_1A_2 \cdot A_2A_3) =$$

$$= \frac{\varpi}{2} \cdot A_2A_3 \cdot A_1A_2 \cdot (2\, O_1A_1 + A_1A_2) \tag{11}$$

where v_{med} is the fluid average speed and A is the sectional area covered by the fluid.

$$Q_v = \int_l \frac{v(z)\, d}{2} dz = 2 \int_{O_1A_1}^{O_1A_1 + A_1A_2} \frac{\varpi z d}{2} dz +$$

$$+ \int_{-\frac{A_2A_3}{2}}^{\frac{A_2A_3}{2}} \frac{\varpi (O_1A_1 + A_1A_2) d}{2} dz =$$

$$= \frac{\varpi d}{2} \left[(O_1A_1 + A_1A_2)^2 - (O_1A_1)^2 \right] +$$

$$+ \frac{\varpi d}{2} A_2A_3 \cdot (O_1A_1 + A_1A_2) =$$

$$= \frac{\varpi d}{2} \left[(O_1A_1 + A_1A_2)^2 - (O_1A_1)^2 + \right.$$

$$\left. + A_2A_3 \cdot (O_1A_1 + A_1A_2) \right] \tag{12}$$

By (10), (11) and (12) the expression of ΔP_o is:

$$\Delta P_o = \frac{6a\left((O_1A_1 + A_1A_2)^2 - (O_1A_1)^2\right)(A_2A_3 + d)}{d^3 (2A_1A_2 + A_2A_3)} \eta \varpi +$$

$$+ \frac{6a \cdot A_2A_3 \cdot (O_1A_1 + A_1A_2)}{d^2 (2A_1A_2 + A_2A_3)} \eta \varpi \tag{13}$$

In this case the size noted "a" is the distance A_1B_1. Finally, the pressure difference generated by the existence of electro-rheological fluid, (ΔP_{ER}), is calculated. In many papers of the researchers in this domain the effect of applying an electrical field upon an ER fluid is presented: a limit of stress (σ_y) appears where the transition of material state from the elastic to plastic deformation. Physical effect consists in introducing a resistance to fluid flow. Therefore, if stress shearing produced by the pressure difference in this case, does not exceeds the proper level, flow capacity in vane remains stationary.
The pressure difference correspondingly to the limit level of stress (σ_y) is (Bullough et al, 1987):

$$\Delta P_{ER} \cdot A_I = \sigma_y \cdot A_F \tag{14}$$

where A_I is the area where the fluid is transferred from one chamber to another (interstice area), $A_I = d(2A_1A_2 + A_2A_3)$ and A_F is the area that limits the interstice in the upper side and in the lower side, $A_F = 2a(2A_1A_2 + A_2A_3)$.
It results the following:

$$\Delta P_{ER} = \frac{2a}{d} \sigma_y \tag{15}$$

From (13) and (15) it results:

$$\Delta P = \frac{6a\left((O_1A_1 + A_1A_2)^2 - (O_1A_1)^2\right)(A_2A_3 + d)}{d^3 (2A_1A_2 + A_2A_3)} \eta \varpi +$$

$$+\frac{6ad\cdot A_2A_3\cdot(O_1A_1+A_1A_2)}{d^3(2A_1A_2+A_2A_3)}\eta\varpi+\frac{2a}{d}\sigma_y \qquad (16)$$

Based on the calculus effectuated above, the torque caused by the pressure difference between the two chambers of the damper (M_P) can be determined:

$$M_P=\int_{(A_1A_2A_3A_4)}\Delta P\cdot r\cdot ds=$$

$$+\int_{O_1A_1}^{O_1A_1+A_1A_2}\Delta P\cdot x\cdot A_2A_3\cdot dx=$$

$$=\Delta P\cdot A_2A_3\int_{O_1A_1}^{O_1A_1+A_1A_2}xdx=\Delta P\cdot A_2A_3\cdot\frac{x^2}{2}\Bigg|_{O_1A_1}^{O_1A_1+A_1A_2}$$

$$=\frac{A_2A_3\cdot\left[(O_1A_1+A_1A_2)^2-(O_1A_1)^2\right]}{2}\Delta P=$$

$$=\frac{3aA_2A_3\left[(O_1A_1+A_1A_2)^2-(O_1A_1)^2\right]^2(A_2A_3+d)}{d^3(2A_1A_2+A_2A_3)}\eta\varpi+$$

$$+\frac{3ad\cdot A_2^2A_3^2\cdot\left[(O_1A_1+A_1A_2)^2-(O_1A_1)^2\right](O_1A_1+A_1A_2)}{d^3(2A_1A_2+A_2A_3)}\cdot$$

$$\eta\varpi+\frac{a\cdot A_2A_3\cdot\left[(O_1A_1+A_1A_2)^2-(O_1A_1)^2\right]}{d}\sigma_y \qquad (17)$$

If we note:

$$k_{P1}=\frac{3aA_2A_3\left[(O_1A_1+A_1A_2)^2-(O_1A_1)^2\right]^2(A_2A_3+d)}{d^3(2A_1A_2+A_2A_3)}$$
$$+\frac{3ad\cdot A_2^2A_3^2\cdot\left[(O_1A_1+A_1A_2)^2-(O_1A_1)^2\right](O_1A_1+A_1A_2)}{d^3(2A_1A_2+A_2A_3)} \qquad (18)$$

and

$$k_{P2}=\frac{a\cdot A_2A_3\cdot\left[(O_1A_1+A_1A_2)^2-(O_1A_1)^2\right]}{d} \qquad (19)$$

Then $M_P=k_{P1}\eta\varpi+k_{P2}\sigma_y$ (20)

In order to calculate the torque M_σ caused by the stress shearing on the valve, relation (4) will be used considering the expression of the stress in (1):

$$M_\sigma=\int_{A_1A_2B_2B_1}\sigma\cdot r\cdot ds+\int_{A_2A_3B_3B_2}\sigma\cdot r\cdot ds+\int_{A_4A_3B_3B_4}\sigma\cdot r\cdot ds$$
$$=2\int_{A_1A_2B_2B_1}(\sigma_y+\eta\dot\gamma)\cdot r\cdot ds+\int_{A_2A_3B_3B_2}(\sigma_y+\eta\dot\gamma)\cdot r\cdot ds$$

Considering the mode of defining $\dot\gamma$ (apparent shear rate):

$$\dot\gamma=\frac{v}{d} \qquad (21)$$

we have:

$$M_\sigma=2\int_{A_1A_2B_2B_1}\left(\sigma_y+\eta\frac{\varpi r}{d}\right)\cdot r\cdot ds$$

$$+\int_{A_2A_3B_3B_2}\left(\sigma_y+\eta\frac{\varpi r}{d}\right)\cdot r\cdot ds=$$

$$=2\int_{O_1A_1}^{O_1A_1+A_1A_2}\left(\sigma_y+\eta\frac{\varpi z}{d}\right)\cdot z\cdot a\cdot dz$$

$$+\int_{-\frac{A_2A_3}{2}}^{\frac{A_2A_3}{2}}\left(\sigma_y+\eta\frac{\varpi(O_1A_1+A_1A_2)}{d}\right)(O_1A_1+A_1A_2)adx=$$

$$=2a\sigma_y\frac{z^2}{2}\Bigg|_{O_1A_1}^{O_1A_1+A_1A_2}+2\frac{\eta\varpi a}{d}\cdot\frac{z^3}{3}\Bigg|_{O_1A_1}^{O_1A_1+A_1A_2}+$$

$$+\sigma_y a(O_1A_1+A_1A_2)x\Bigg|_{-\frac{A_2A_3}{2}}^{\frac{A_2A_3}{2}}+$$

$$+\frac{\eta\varpi(O_1A_1+A_1A_2)^2a}{d}x\Bigg|_{-\frac{A_2A_3}{2}}^{\frac{A_2A_3}{2}}=$$

$$=a\sigma_y\left[(O_1A_1+A_1A_2)^2-(O_1A_1)^2\right]+$$

$$\frac{2}{3}\frac{\eta\varpi a}{d}\left[(O_1A_1+A_1A_2)^3-(O_1A_1)^3\right]+$$

$$+\sigma_y(O_1A_1+A_1A_2)a\cdot A_2A_3+$$

$$+\eta\varpi\frac{(O_1A_1+A_1A_2)^2a\cdot A_2A_3}{d}=$$

$$=\frac{A_1B_1}{d}\left[\frac{2}{3}\left[(O_1A_1+A_1A_2)^3-(O_1A_1)^3\right]+\right.$$

$$\left.+(O_1A_1+A_1A_2)^2\cdot A_2A_3\right]\eta\omega+$$

$$+A_1B_1\left[(O_1A_1+A_1A_2)^2-(O_1A_1)^2+\right.$$

$$\left.+(O_1A_1+A_1A_2)\cdot A_2A_3\right]\sigma_y$$

(22)

Considering the notations:

$$k_{\sigma1}=\frac{A_1B_1}{d}\left[\frac{2}{3}\left[(O_1A_1+A_1A_2)^3-(O_1A_1)^3\right]+\right.$$

$$+(O_1A_1+A_1A_2)^2 \cdot A_2A_3\ ] \tag{23}$$

respectively:

$$k_{\sigma 2} = A_1B_1\left[(O_1A_1+A_1A_2)^2 - (O_1A_1)^2 + \right.$$

$$\left. +(O_1A_1+A_1A_2)\cdot A_2A_3\ \right] \tag{24}$$

we have:

$$M_\sigma = k_{\sigma 1}\eta\varpi + k_{\sigma 2}\sigma_y \tag{25}$$

Let

$$k_1 = k_{P1} + k_{\sigma 1} \tag{26}$$

$$k_2 = k_{P2} + k_{\sigma 2} \tag{27}$$

Damping torque of ER damper results:

$$M_A = k_1 \cdot \eta\varpi + k_2 \cdot \sigma_y = K_A\,\varpi + M_C =$$

$$= M_{A0} + M_C \tag{28}$$

where

$K_A = k_1\eta$ is viscosity damping coefficient generated from the ER damper, (29)

$M_{A0} = K_A\omega$ is viscosity damping torque (30)

$M_C = k_2\sigma_y$ is ER damping torque correspondingly to Coulomb damping (31)

If the sign of the variable ω is considered, the final expression of M_A is obtained:

$$M_A = K_A\,\varpi + M_C \mathrm{Sgn}(\varpi) \tag{32}$$

where function Sgn(u) has the well-known expression:

$$\mathrm{Sgn}(u) = \begin{cases} 1 & \text{if} \quad u > 0 \\ -1 & \text{if} \quad u < 0 \end{cases} \tag{33}$$

3. CONTROL SYSTEM

The dynamic equations for a robot arm with joints with ER damper are represented by the next relation:

$$M(q)\,\ddot{q} + C(q,\dot{q})\,\dot{q} + B(\dot{q}) + G(q) + \tau = T \tag{34}$$

where;

$M(q)$ is inertia matrix of the robot,

$C(q,\dot{q})$ is the matrix of Coriolis forces (the term $C(q,\dot{q})\dot{q}$ represents the vector of Coriolis and centripetal forces),

$B(\dot{q})$ represents friction forces,

$G(q)$ is the vector of potential type forces (gravitational forces) which belong to the external forces that take actions upon the robot,

τ symbolizes the forces resulted in articulations following the application of some forces in the end-effecter when the technological task implies an interaction with the environment,

- T represents the vector of the generalized forces (forces or moments) through which actuators generate the movements to joints.

In this case, considering the expression of the couple generated by the damper (32), considering we have rotation joints at the robot and considering $\tau = 0$ (considering that the robotic arm moves freely in the environment) and the load is implicitly included in the physical description of the last segment of the robot, equation (34) becomes:

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + B(\dot{\theta}) + G(\theta) + M_A = T \tag{35}$$

$$M(\theta)\ddot{\theta} + \left[C(\theta,\dot{\theta}) + k_1\eta\right]\dot{\theta} + \left[B(\dot{\theta}) + M_C \mathrm{Sgn}(\dot{\theta})\right] + G(\theta) = T \tag{36}$$

$$M(\theta)\ddot{\theta} + A(\theta,\dot{\theta},\eta)\dot{\theta} + f(\dot{\theta}) + G(\theta) = T(t) \tag{37}$$

where:

$$A(\theta,\dot{\theta}) = C(\theta,\dot{\theta}) + K_A \tag{38}$$

$$f(\dot{\theta}) = B(\dot{\theta}) + M_C \mathrm{Sgn}(\dot{\theta}) \tag{39}$$

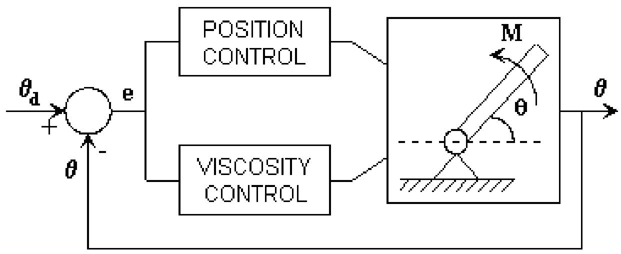

Fig. 4. Control system

In the control process, robot's controller must suddenly or gradually change systems' parameters. We will consider a controller with a variable structure having the possibility o modifying fluid viscosity (Ivanescu et al, 1995), (Ivanescu et al, 1996). Control system contains two sub-systems (Fig. 4): a position control system with a conventional feedback loop determined by the second Lyapunov method for the pressure control and a control sub-system (a non-conventional control) with a variable structure based on viscosity control of the electro-rheological fluid. The main characteristics of this last controller are determined by the dynamic performances of the ER fluid valve. The basic idea for the second control is that the controller can change abruptly or gradually the parameters of the system. This control can be obtained by using the ER fluid properties. The apparent viscosity of the fluid can be easily modified by the electric field (Stevens, 1988):

$$\eta = \eta_o + T(\varepsilon)/\dot{\gamma} \tag{40}$$

where η_0 is the viscosity at zero voltage, $\dot{\gamma}$ is the apparent, shear rate and $T(\varepsilon)$ is the shear stress as a function of the electric field ε. From (Stevens, 1988), $T(\varepsilon)$ can be approximate as a linear function,

$$T(\varepsilon) = a + b\varepsilon. \quad (41)$$

The transfer function of the (37) is

$$H(s) = \frac{k_0 \omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \quad (42)$$

and the gain k_0, the undamped natural frequency ω_n and the damping ratio ξ are presented in (Ivanescu et al, 1995). For a variable structure control, we define the switching line in Fig. 5:

$$\sigma(e, \dot{e}) = \dot{e} + pe = 0 \quad (43)$$

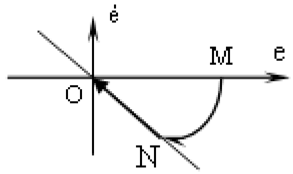

Fig. 5. The DSMC method

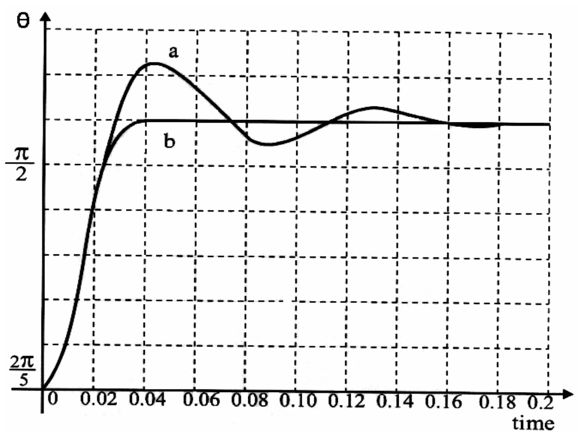

Fig. 6. The evolution of the system with and without a variable structure control

The objective is to obtain a control law τ=f(e) which will drive the system to the switching line in a finite time and then will constrain the system to stay on the switching line. Our system starts from the initial point towards the switching line (segment MN) and then it evolutes directly on the switching line, towards the origin. This evolution requires the variation of the damping ratio ξ abruptly from a small values $\xi < 1$ to high value $\xi > 1$ (the Direct Sliding Mod Control (DSMC) method). In (Stevens, 1988) it is proven that an evolution on the switching line (the segment NO) is always possible if

$$\xi = \frac{p^2 + \omega_n^2}{2\omega_n p} > 1 \quad (44)$$

In this case it is necessary to estimate the moment of intersection with the switching line,

$$t_{switch} \le \frac{|\sigma(e, \dot{e})|}{\gamma} \quad (45)$$

where γ is presented in (Ivanescu et al, 1995). The control does not require a high performance of the driving system. It is imposed a single switching of the viscosity η by the electric field at the moment t_{switch} which can be easily determined off-line. In a numerical simulation the initial conditions of the proposed trajectory are $\theta(0)=2\pi/2$, $\dot{\theta}(0) = 0$. The switching moment is obtained from (45): $t_{switch} \le 0.025$s. The evolution of the system is presented in Fig. 6. The curve "a" is the trajectory for a step input without a variable structure control. The curve "b" has 2 segments: the first segment is for a damping ratio ξ=0.51 and on the second segment the damping ratio is switched to value ξ=1.57.

4. CONCLUSIONS

The paper presents the dynamic model of a damper used for the robotic articulations that offer the advantage of rapid vibrations compensation. The torque generated by ER damper presents two components: a torque caused by viscous damping and a torque caused by the electro-rheological fluid. The viscosity damping torque represents the damper's output value in case of not applying an electrical field. The torque caused by ER effect appears when electrical field is activated, its amplitude is much bigger than that of the torque caused by the viscosity damping. Control system contains two loops: one for position control and one for viscosity control.

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