SYNTHESIS REPORT

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TITLE : **Powerful SYstems for identification and Control of Highly nOn-linear processes using neural networks** (PSYCHO)

PROJECT COORDINATOR : **Universidad Carlos III.** Madrid

PARTNERS : University of Wales College of Cardiff

Universidad de Valladolid

RIKS

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1. Title

Powerful SYstems for identification and Control of Highly nOn-linear processes using neural networks **(PSYCHO)**

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3. Abstract

PSYCHO project has succesfully shown the feasibility of some types of neural networks to deal with strongly non-linear identification and control of dynamical systems, and also has shown the difficulties of other kinds of neural network models for the same purpose. The project has an aditional and important aspect related with the normalized test used with all the neural network models, which is a key point in order to decide which models are adequate to deal with a certain problem.

Avery ambitious objective of PSYCHO was related to the elaboration and testing of a synergistic control scheme among the different neural paradigms used by each member of the consortium. Different synergistic controllers have been deveoped with the aim of getting a joint point among all proposed techniques(Recurrent Networks, Reinforcement Learning, Genetic Algorithms, Neural Group Selection, Fuzzy ART and FasArt)

It has been demonstrated to be very difficult to generalise what kind of identification models or control schemes are suitable for all industrial plants: the criteria for models are different depending upon the purpose of the application so the control and identification results are used as a starting point or foundation to solve future particular problems. Besides that, the definition of common testbeds and evaluation criteria would allow an easy and immediate comparison of the results obtained with the different techniques, and the convergence in the search of the best solutions,

This project has determined many fields that might be undertaken in the future. Summarizing, it has been revealed that there are real problems of non-linear control "which were not satisfactorily solved using present control techniques, at the same time that alternative control schemes have been developed. First experimental results so far obtained indicate that these schemes allow to undertake those problems, leaving for future projects the practical development of software tools in order to make products useful for industrial purposes.The next proposal of an industrial version of the PSYCHO project will lead to a deeper and competitive know-how of this non-linear control and identification methods and will permit a real dissemination of the experience gained by the researchers during the last three years, in order to reach real industrial experiences with the models succesfully tested during the PSYCHO project.

4. Introduction

The objective of PSYCHO has been the study of control of non-linear systems by means of the development and testing of neural models and techniques for the control of industrial plants. Five groups of models are to be studied (Reinforcement Learning, NGST -Neural Group Selection TheoV-, Value Repertoires, Reinforcement Learning, Artificial Life Models, Jordan and Elman neural networks, ART - Adaptive Resonance Theory), as well as their use in two specific fields (identification and control) both, separately and integrated. The study should be done starting from preliminary research work performed by the partners.

The challenge for applying neural networks, genetic algorithms and artificial life techniques to dynamic systems control is to meet real time requirements of the system and at the same time to enhance robustness and performance. Such systems can be trained to model the inverse dynamics of an unknown plant and then be applied as its controller. The net model performs a specific form of adaptive control and is therefore well suited to address the problems associated with mm-linear and stochastic control problems.

The proposed project will study the relative merits of several research lines already undertaken by the partners. This research focuses on the use of other architectures of neural networks, genetic algorithms and artificial life models for identification and control of dynamic systems.

An ambitious objective of PSYCHO was related to the elaboration and testing of a synergistic control scheme among the different neural paradigms used by each member of the consortium. These paradigms should be tested, generalized and extrapolated on a number on real case studies provided by the industrial endorsers.

5. 'Technical description "

The main technical tasks of this project can be arranged into nine groups as follows

1. Filtering and selection of suitable case studies of control in advanced production environments, with typical features of non-linear systems; extraction of one or more typical examples, i.e. test-data sets; evaluation of existing tools and techniques for identification and control employed in testbed.

2. Design of advanced architectures for identification using different neural net paradigms (Recurrent nets, ART, NGST models, Reinforcement Learning, Value Repertoires, Genetic Algorithms).

3. Design of advanced architectures for control using different neural net paradigms (Recurrent nets, ART, NGST models, Reinforcement Learning, Value Repertoires, Genetic Algorithms).

4. Application of the advanced architectures for identification to testbed data. Evaluation of the performances of dynamic neural nets for identification. Evaluation of the Imitations and prerequisites of the approach. Demonstration that the result can be generalized to the whole area to which the testbed belongs.

5. Application of the, advanced architectures for control to testbed data. Evaluation of the performances of dynamic neural nets for control. Evaluation of the limitations and prerequisites of the approach, and extrapolation to application of non-linear system control outside the testbed. Demonstration that the result can be generalized to the whole area to which the testbed belongs.

6. Use of the deliverables of the previous tasks for the design of controllers based on synergy between the different architectures. Testing of the integrated paradigm on tile testbed data set. Comparison of the results with conventional tools, as well as with the implementations of task 3.

7. Extrapolation to applications of non-linear systems identification outside the testbed.

8. Extrapolation to applications of non-linear systems control outside the testbed.

9. Recommendations for a subsequent industrial project.

PSYCHO project has developed, generalized and extrapolated a wider set of non-linear identification and control schemes than initially expected, based on the following algorithms:

Identification algorithms:	*MLP, Modified Elman Networks, RBF (Radial Basis Functions), Genetic Algorithms, NGST, Reinforcement Learning, FasArt ('Fuzzy Adaptive System ART-based), Genetic Algorithms.*
Control Algorithms:	*NMPC (Non-linear Predictive Control), MRNC (Model Reference Non-linear Control), Reinforcement learning, NGST, FasArt, FasBack, Genetic Algorithms.*

The models developed are highly oriented towards industrial applications. All these identification and control models have been tested with data from the proposed theoretical testbed plants, with simulated data from the testbed plants (including a binary NEREFCO petroleum distillation column), real data of penicillin fermentation from *ANTIBIOTICS* and data based on other biochemical models.

The models have been generalized and extrapolated for an important number of industrial applications. Other industrial and theoretical testbeds have been incorporated by the consortium with the aim of demonstrating the applicability of these models in a broader number of industrial testbeds than initially expected:

Testbeds for Generalization of identification models:	*SHELL Crude Distillation Unit, Catalytic Reformer Debutaniser Column, 3 theoretical systems*
Testbeds for Generalization of control models:	*Baker's yeast fed-fatch fermentation, NEREFCO distillation column, 3 theoretical systems.*
Testbeds for Extrapolation of identification models:	*Waste water neutralization plant, ROCCO mobile robot.*
Testbeds for Extrapolation of control models:	*Mobile robot, Traffic control in ATM Networks, NEREFCO distillation column, Batch Chemical Reactor Temperature Control*

6. Results

The results of PSYCHO are summarized in the next list of software developments and technical know-how.

- A set of new identification and control schemes based on the former schemes (see table in next page)
- Algorithms for traning the neural networks, including genetic algorithms and stochastic methods.
- Comparisons between classical and advanced neural controllers.
- Software implementation and test of neural controllers for specific industrial applications defined by the endorsers (see table in next page)
- Specifications for an industrial research project to be carried out by the endorsers

The foreground of the PSYCHO project belongs, as stated in EC Contract Annex II, to the contractors generating it. The leader of this consortium is Univ. Carlos III.

The next page shows all the developed and tested schemes.

The next table shows the identification and control algorithms evaluated, generalized and extrapolated in PSYCHO, and the testbeds used in each case.

Partner working on the scheme	Schemes	Evaluated (*)	Generalized Identification	Extrapolated Identification	Generalized Control	Extrapolated Control
Univ. Carlos III	Reinforcement Learning	X			Nerefco distillation column	Mobile robot
	NGST "/ Value repertoires / AL	X				
RIKS / Univ. Carlos III	CGA / Genetic Algorithms	X	3 theoretical systems	Mobile robot		
Univ. Wales C, Cardiff	Jordan, Elman networks	X				
	Modified Elman networks		Crude Distillat. Unit	Waste water neutralization plant		
	MLP		Crude Distillat. Unit Catalytic Ref. Debutaniser Column	Waste water neutralization plant		
	RBF		Catalytic Ref. Debutaniser Column	Waste water neutralization plant		
	NMPC				3 theoretical systems	
	MRNC				3 theoretical systems	
Univ. Valladolid	FasART	X		ROCCO mobile robot (**)	Bakers yeast fed-batch fermentation	Mobile Robot Traffic control in ATM networks
	FasBack	X				Nerefco distillation co1. Batch Chem. reactor temperature control

(*) The evaluation of the models (signs ed with an in the table below) has been performed with theoretical testbeds proposed in the literature, as well as" for the Antibióticos Penicillin production problem, for the Nerefco "Stabiliser and the Shell Crude Distillation Unit.

(**) Performed bu Univ. Carlos III

Next follows a descript ion of the results obtained from **PSYCHO,** for each of the models considered

Reinforcement **Learning**

The results obtained during the PSYCHO project using *reinforcement /earning* paradigms in the control of continuos systems show that the reinforcement controllers are reasonably robust. The knowledge required for reinforcement learning can be seen to be quite minimal. When you develop a control algorithm by existing techniques, you have to decide what an appropriate process model will be (perhaps by experimentation) and estimates the coefficients of the model. You also have to pick the type of controller to mesh with the model or the process. This phase of development can take considerable amount of time. When no objective function is available other than the concept of success or failure, the modeling and controller design is even more complex. One can extract knowledge about a process via ordinary modeling or an ANN (which is really an empirical model); the knowledge picked up about the responses of the process will be approximately the same no matter what the modeling technique is if the modeling is carried out to the same degree of accuracy. But the preliminary knowledge that a human has to have about a process for the development of a control strategy is definitely more than a human has to have to implement an ANN for control. we are not suggesting that reinforcement learning should be used in general, or than an ANN should be used in general for control, but simply that the combination can be one way to treat problems in which a quantitative model and objective function are absent.

Another point to keep in mind is that an ANN "learns" a region for the input-output response of the Controlled System . However, "learns" does not *mean* it is easy to extrapolate, scale up, or transfer the "learning" to other regions of operation as you can with a model composed of differential equations. The control actions can only be as an empirical approximation of some complex physical principles embodied in an unusual form, but certainly no more unusual form than a computer code for to the nonexpert. Consequently, convergence, stability,etc. have yet to be (may never be) demonstrated theoretically, but currently must be examined by simulation. Generalization (prediction from new starting points} can only take place by having sufficient data sets (in our case trials) to cover the domain of interest in quite the same as required in nonlinear regression for models having error in all of the variables.

One of the difficult subproblems of using reinforcement rather than supervised learning is that the criteria on which to base the reinforcement are qualitative. To apply reinforcement learning for intelligent control an engineer must apply his or her engineering knowledge to specify subgoals or additional appropriate criteria, and quantitative mathematical statements are not essential (although desirable).

TNGS

Concerning *TNGS*, the theory of neural group selection is a theorical aproximated moderation of the mind. It has been developed by Gerald M. Edelman. This theory is a biological theory in which the author study the mind dynamics at a low level. Such is the case that he has developed a series of equations with those which attempts modelizate the operation of the neurons. Due to this set of-equations has been developed to a low level.

Its detail level is very large, with something which the necessary time for its computation is very high. Because of this it has been accomplished a study of the dynamics of these equations and it has been accomplished a simplification. Attempting above all that after this simplification is not lost large part of the functionality that provide the initial equations.

Yet with these simplifications, the necessary time for the execution of a system as this is very high, with what is not found to it very appropriate to employ it currently in real environments.

Elman Network

The Elman network has been widely used in speech processing. Its main advantage is the compact size due to recurrence. The common training algorithm for a neural network, error backpropagation algorithm, is not proven to converge when training a network with recurrence. Modifications were made onto the error backpropagation algorithm which requires more computation time. In this project, the structure of the Elman network is modified to enable the original error backpropagation algorithm be used. The structural modification is very simple and requires very little additional computation power. The modified Elman network has been shown to have better modelling ability on high order systems.

Jordan Network

The Jordan network has also been structurally modified. The original Jordan network does not have enough diversity in the state layer in order to model complex non-linear system if the network has single output. By an addition of a feedback loops, the modelling ability of the modified Jordan network is greatly elevated.

NMPC

Attempts have been made previously to implement inverse control using neural network as the controller. Theoretically, inverse control can achieve perfect control which is not obtained in practice. On the other hand, inverse control suffers a few important disadvantages: lack of robustness, sensitivity to the plant and inability to reject disturbances. Moreover, training a neural network to behave as the inverse dynamics of the plant is difficult and time consuming. Consequently, a new control scheme is proposed which does not require the control to have an accurate inverse dynamics performance. So the training of the controller is easier. With the addition of a modified internal model, the output disturbance is rejected very effectively. The robustness and control accuracy at the proximity of the original plant is greatly improved. This control scheme has been tested with S1S0 and MIMO, linear and non-linear plants.

There are a few non-linear model predictive(NMPC) schemes published. Some of them use successive linearisation approach which can only be applied to certain limited plants. Most of them tackle the non-linear programming (NLP) problem with gradient descent method which can only arrive at the nearest local optimum. Moreover the computation demand is high, So the control and prediction horizons are short. The result control actions may be erratic and the plant may even be unstable. Theoretically, stochastic optimisation of the NLP problem can arrive at the global optimum. However the computation demand is too high and no successful real-time implementation has been reported. A new approach is taken in this project. A directional stochastic search has been adopted to optimise the future control actions. Owing to its effectiveness, the control and prediction horizon are an order of magnitude longer than those reported in literature. The computation time is less than 1/1 O of the time step, even on a modest computer. So real-time implementation is not an issue. This control scheme is simple and possesses the properties of the widely used linear model predictive control.

MRNC

Another new control scheme, model reference neural control (MRNC), is proposed. It consists of an outer-loop feedback PID controller. The neural network controller is trained directly on-line to minimise an error evaluation function. The error signal is calculated as the difference between the reference model output and the actual plant output. After training, the control system can achieve the performance defined by the reference model. It is does not require much prior knowledge on the plant. Some MIMO non-linear plants have been put under control using this scheme without much difficulties.

In the above NMPC and MRNC control schemes, the non-linear optimisation algorithm used is the Chemotaxis algorithm. This algorithm has been enhanced in two areas: the ability to escape from local optimum and the reliability during initialisation.

FasArt

Several features of this project can be considered very innovative. The first one is the definition of the control of the penicillin production process, which still lacks of a solution which might be feasible from the industrial point of view, as it is proved by the fact that this control is carried out by experts who decide the values of the input variables. Control is still, in a sense, a "craftsmanship".

During this project, work has been carried out on neuro-fuzzy systems for the definition and control of non-linear systems. The main contribution in this field has been the proposal of a new neuro-fuzzy architecture called FasArt, which synergistically combines the main properties of artificial neural networks and fuzzy logic systems.

This new architecture allows a double interpretation both as a neural or as a fuzzy system. This fact makes it a very interesting one in order to produce fuzzy controllers in a self-organized way from the numeric data collected during the system performance.

At the same time, FasArt can be embedded in other controlling systems where there might be a need for a system identification as, according to the theoretical results obtained during the development of this project, it is able to approximate any function uniformly.

FasArt-based control schemes have been applied to different control problems proposed in the literature, with good results. The incremental on-line learning property of the FasArt model is specially interesting, since it allows to undertake control problems with variable parameters in the plant to be controlled. Several tests have been carried out by changing the conditions in the plant to be controlled; results demonstrated that FasArt based control schemes were able to undertake any variation as well as to learn it in order to keep the performance of the control system.

A FasArt fuzzy controller has been applied to biomass control in batch reactors for penicillin production, using conditions (knowledge of variables) close to industrial reality. The obtained results clearly show the feasibility of this solution.

A very important feature of FasArt, due to its neuro-fuzzy duality, is its capability to provide a confidence degree to the predicted output at a certain time instant. This confidence degree is based upon the experience learned by the system, being greater when the FasArt input is closer to input areas already sampled. The decrease of this confidence degree means that the system is working in areas so far unknown. This can be an indicator of a failure in the data collection module or of a wrong operation of the whole system. This effect has been showed using real data from the penicillin production process.

FasBack

In a second step, a new model, called FasBack, has been proposed in order to simplify the structure of FasArt as well as to improve it with new features. This new model introduces the goal of minimization of the prediction error in the FasArt architecture. Therefore, it is a system able to comprise learning through matching and learning through error. This system can be used in Model Reference Adaptive Control (MRAC) schemes. A similar scheme has been used to control a black-box system, a neural network trained with data from a fuel distillation plant. Controlling this system brings a really difficult problem, as it is a non-linear system, with time delays and totally unknown dynamics. The obtained results show that the MRAC scheme used together with FasArt can, in fact, control the system.

Another synergistic control system has also been proposed, using a predictive control scheme, in which a FasArt unit works as a system model and a Genetic Algorithm is used as an optimization system for non-linear problems. This controller has been applied to the black-box system already described above.

FasBack based control systems have been tested in other types of problems such as temperature control in batch chemical reactors. Control schemes known from the literature have been used, where a FasBack unit has been embedded as an identifier.

FasArt model has also been applied to control of a mobile robot and the traffic in an ATM network. In both cases, obtained results were considered satisfactory and led to accept the hypothesis according to which both FasArt and FasBack are useful units in situations where a system is needed to make identification from numeric examples of its performance without any need for previous knowledge of the system.

This last feature is the main technological innovation of the system: the formalization ofa new model with a neuro-fuzzy dual character which allows its application in different control problems depending on the needs of the designer.

Genetic Algorithms

[n what concerns the work on genetic algorithms, there have not been accomplished many projects on this type of approximations with them. It exists a comparable area with this kind of work that could be the genetic programming which attempts to generate optimization and searchs in the code of a given program for its better performance.

Due to the projects shortage accomplished with this type of procedures and the few experience that was found in this area, the obtained results have not been as good as it was expected. Due to the amount of computer time needed for the performance of a task of this type, it makes no sense its implementation in the training stage of a real system.

One of the most important points in this type of systems is the capacity of generating a neural network architecture much faster than the one which could be obtained from any other type of neural networks to those which have not been accomplished with this optimization.

Other point to take into account, it is the possibility of adapting the system generated to the employment of any kind of neural network, and the different dynamics generation for each one of the functional components of the neural network. This is an idea that has been taken from the Theory of Neural Group Selection, in which the microscopical structure of the brain this genetically coded.

Coevolutionary Genetic Algorithms (CGA)

The combination of coevolution and life-time fitness evaluation (LTFE) is new. The most important innovative aspect of CGAS is their fine-grained fitness testing resulting from (LTFE). A CGA concentrates on the subproblems it has not solved yet. In this way, it avoids spending time on uninformative, already solved, subproblems. It has been shown that the combination of LTFE and coevolution outperforms traditional GAs.

Hill is (1992), provided the basic inspiration for the work presented here. He coevolved (using predator-prey interactions) sorting network architectures and sets of lists of numbers on which the sorting networks are tested. Through the introduction of LTFE, CGAs are more robust and fine-grained. This incorporation of LTFE is an important difference with Hillis' work. Moreover, we defined” a large, abstract class of problems which can be solved with a CGA. In addition, the CGA can easily be extended to incorporate symbiotic interactions as well.

Furthermore, CGAS are able to incorporate new developments in GAs in an easy way. This because the code of the traditional single population GA is an integral subpart of the code of CGA. Over the last years there has been a growing interest in extending GAs to deal with constraints or other forms of background knowledge. Recently, Paredis (1993) proposed GSSS, a general method for introducing domain knowledge - through the use of constraint programming -10 guide the evolutionary search when solving constraint problems. Michalewicz and Janikow (1991) define genetic operators designed to tackle problems involving numerical linear (inequalities. Fortunately, a CGA can incorporate domain knowledge just in the same way as a GA. Hence, all extensions to the genetic representation or operators of a GA can be incorporated in a CGA as well.

Finally, it has been shown that CGAs can be smoothly integrated with other NN learning techniques. Again, this allows to profit from advances in other technique; and to keep up with with future evolution of the state-of-the-art.

7. Conclusions

The horizontal nature of the PSYCHO research will allow to adapt the developed solutions to some specific control problems during an industrial phase later to the end of PSYCHO. Several fields have been identified as very interesting

1. **Applications to fermentation or enzymatic processes**

- Obtaining 6APA
- Obtaining the acilasa enzym
- Obtaining Amoxycillin and Ampicillin.

2. Applications to other fermentations

- Penicillin fermentation for penicillin production.
- Baker's yeast fermentation.
- Cephalosporium fermentation for cephalosporine production.

3. **Applications to the chemical sector**

Temperature and other variables control in the chemical reactors

4. Applications to power generation

5. Applications to waste water treatment

6. Applications to cement production

7. Applications to telecommunication networks **(ATIM)**

- High-Speed networks.
- Metropolitan networks.
- Integrated services digital networks (lSDN).
- Wideband integrated services digital networks (B-ISDN), in the near future.

8. Applications to Mobile robotics

- Substitution of traditional assembling line for AGV. The pieces involved in the assembling process are placed aboard the AGV and they both transport the pieces and act like assembling units.
- Transport units to communicate the fabrication cells in the Computer Integrated Manufacturing (CIM) systems.
- Managing and transporting material in the warehouse.
- Communication and transport units between the different areas of storage and factories, stores, expedition areas, etc.
- Other applications with less users involve transport in hospitals, offices, or their use as cleaning units.

In this subsequent phase, companies or endorsers specialised in the control of industrial processes could lead the adapation and integration of PSYCHO whith other existing control tools in order to develop advanced control products ready to be installed and commercialised.

Further work has to be done in order to confirm the simulation results in industrial plants. Initially, both systems (old and newly proposed) would work in parallel, leaving the expert free to choose among the suggested actions. In a later phase the new control scheme would control completely the process. The first phase could be performed in a pilot plant that would provide sufficient information for the required modifications. In other cases, further study of the specific industrial problem would be necessary in order to design the appropriate control scheme, in with the developed modules could be embedded.

The main risk is the need for further development, since algorithms and control systems have been main ly treated as academic problems. However, in certain cases (i.e. penicillin production, distillation column,..) several industrial aspects were taken into account but their applicability to real industrial plants still need further study and testing in real conditions. This type of controllers are clearly oriented towards control of higher loops, that is when control references are used.

The main benefits of the new project proposed for further applications will lie in its focus on quality and cost improvement of non-linear process control from some specific sectors. As can be seen later on in this document, investment in this technology can be very profitable for european companies specialised in process control. For this reason, this companies should play a essential role in the new consortium.

Due to the industrial experience of all partners and excellent degree of collaboration within PSYCHO, the consortium is in a very good situation in order to maintain the initiated communication strategy.

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