INTERNATIONAL JOURNAL

of

COMPUTERS, COMMUNICATIONS & CONTROL

With Emphasis on the Integration of Three Technologies

Year: 2007 Volume: II Number: 3 (September)

CCC Publications

Licensed partner: EBSCO Publishing

www.journal.univagora.ro

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Editor-in-Chief

Prof. Florin-Gheorghe Filip, *Member of the Romanian Academy*
Romanian Academy, 125, Calea Victoriei
010071 Bucharest-1, Romania, ffilip@acad.ro

Executive Editor
Dr. Ioan Dziţac
Agora University
idzitac@univagora.ro

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Publisher & Editorial Office

CCC Publications, Agora University
Piata Tineretului 8, Oradea, jud. Bihor, Romania, Zip Code 410526
Tel: +40 259 427 398, Fax: +40 259 434 925, E-mail: ccc@univagora.ro
Website: www.journal.univagora.ro
ISSN 1841-9836 (print version), 1841-9844 (online version)

Founders of IJCCC: I. Dziţac, F.G. Filip and M.J. Manolescu (2006)

This publication is co-financed by:

1. Agora University
2. The Romanian Ministry of Education and Research / The National Authority for Scientific Research

CCC Publications, powered by Agora University Publishing House, currently publishes the "International Journal of Computers, Communications & Control" and its scope is to publish scientific literature (journals, books, monographs and conference proceedings) in the field of Computers, Communications and Control.

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60 Years from Birth of Academician F.G. Filip

Ioan Dziţac, Mişu-Jan Manolescu, Horea Oros, Emma Văleanu

"To whom it may concern ...
Dr. Filip has shown himself to be a very innovative and productive researcher whose papers are equivalent in quality and cutting-edge findings to those from the best research organizations of the world. Witness his publications in Automatica, Computers in Industry and other leading journals in the field. The establishment of Dr. Filip's stature as an internationally recognized researcher in his field and the acceptance of his work are shown by the large number of international conferences where he has served as session chairman and/or program committee member and many invited seminars he has presented in other countries... [1]"

1 Introduction

Born in Bucharest on the 25^{th} of July 1947, the academician Florin Gheorghe Filip, Editor in Chief of our journal (IJCCC), turns 60, this is why the operative/executive editorial staff of IJCCC wants to

[1]Prof. Theodore J. Williams
Professor of Engineering and Director, Purdue Lab. for Applied Industrial Control, Purdue University;
Former President of Instrument Society of America;
Former President of the American Federation of Information Processing Societies;
Chairman of IFAC/IFIP Task Force on "Architecture for Enterprise Integration" (August 1994)

dedicate this short biographical-sketch in order to pay him homage.

His life is under the sign of creation in science, of generosity in his relationship with his co-workers, of his innovative courage in the coordination of the projects he has worked on, of the stimulating energy in the community he has worked for a longer period of time or just collaborated occasionally, and under the sign of modesty in his relation with other people with whom he was in contact.

Most of the people who know him through their work acknowledge his good and stimulating effects on their work or career. In order to show him respect, lots of similar journals dedicated him special numbers in this period.

Not willing to be in competition with other journals, we would like to dedicate only this short biographical sketch, but in No 4/2007 of IJCCC, we are going to publish some of the scientific articles of authors who expressed their wish to dedicate them to Academician Filip when he turns his 60.

We will present in this paper a short digest of the biography and work of F.G. Filip

2 Opera omnia

Prof. F. G. Filip is author/coauthor of *6 monographs* published in Ed. Tehnica (http://www.edituratehnica.ro/) and he is editor/coordinator of *9 contribution volumes* published in Ed. Tehnica, Romanian Academy Editing House (www.ear.ro), Ed. Expert and Elsevier.

Also, he publish more than *200 scientific papers* in several international journals (Computers in Industry, IFAC J. Automatica, IFAC J Control Engineering Practice, Large Scale Systems, J. of Human Systems Management, Systems Analysis, Modeling and Simulation, Studies in Informatics and Control etc.) and some contribution volumes printed in the Publishing Houses: Pergamon Press, North Holland, Chapmann and Hall, Springer, Kluwer, Ed. Tehnica and Ed. Academiei Române. More than 50 articles of F.G. Filip are registered in Thomson ISI Web of Knowledge Database and 22 in SCOPUS and ELSEVIER Databases.

3 Academic qualifications, scientific titles and professional positions

F.G. Filip graduated the Faculty of Automatics, University Politehnica of Bucharest, obtaining the Engineer Diploma in 1970 and received his Ph. D (1982) in Automatics (Electrical processes automation field).

Later on, he participated at several courses of professional forming and improvement: "Complex informatics systems, tele-processing systems" (Sweden, at the Universities from Goeteborg, Uppsala, Malmoe, Stockholm 1974); "Research and technology management" (Germany, Fraunhofer IITB Karlsruhe, 1995); "Decisional systems" (Germany, Fraunhofer FIRST, Berlin, 1998) etc.

F.G. Filip is Corresponding Member of the Romanian Academy since 1991 and Full Member of the Romanian Academy since 1999. since 2000 acad. Filip is Vice- President of the Romanian Academy.

Last professional titles obtained by F.G. Filip are First Degree Researcher (1990) and University Professor (1998).

He jobs and positions held is following: Engineer (1970-1976); Scientific researcher (1976-1979); Main researcher III-(1979-1990); Head of the research laboratory (1985-1991); Main researcher I (1990); Director- through contest at ICI (1991-1997); Scientific Director- responsible with the international cooperation (1997-2001); President of the Scientific Committee (1995-2003); Vice-President of the Romanian Academy (2000-now).

4 Awards, diplomas and distinctions

F.G. Filip received the following award, diplomas and distinctions:

1. “Grigore Moisil” Award and the Diploma “Man of the Year 1999” granted by INFOREC (The Association of Economical Informatics).

2. Doctor Honoris Causa of "Lucian Blaga" University, Sibiu (2000).

3. The Award “COPY RO for informatics” for the year 2003 for the monograph “Computer aided decision: base methods and techniques” (Ed. Tehnica, Bucharest, 2002, in Romanian).

4. Honorary professor of “Dunarea de Jos” University, Galati (from 2003).

5. Excellency Diploma “The most prominent Romanian personality of the decade in IT&C” granted by ARIES (Romanian Association for the Electronically and Software Industry).

6. Honorary member of the Romanian Technical Sciences Academy - ASTR (www.astr.ro) (from 2006).

7. Honorary member of Moldavian Academy of Science (from 2006).

8. Decorated with the National Order “Loyal Service” in rank of “Great Cross” (granted by the Romanian President on 30.11.2000)

9. Honorary Citizen of Campeni City(2002).

5 Research activities

Research projects coordination regarding:

- The elaboration of the dimensioning methods for the equipments configurations;

- Participating on projects regarding the informatics systems in industry;

- Researches regarding the designing of discrete automate systems;

Research projects coordination regarding:

- Hierarchical leadership methods and hierarchical compute methods;

- Real time hierarchical informatics systems;

Applicative projects coordination regarding:

- Implementation and design of real time informatics systems and decision support systems (DSS);

- Contribution to the design of the DISPECER SSD (exported in 1996)

Researcher leadership in conceiving SSD with combined knowledge (numerical models and artificial intelligence elements)

ICI Teams coordination participating to projects/networks of excellence (“Network of excellence”-NOE) or international “Working group”-WG:

- For the EC-PECO program: ESATT + (“European Science and Technology Transfer Network+”),

- For the INCO program: a) NOE AMETMAS (CP 96-26), b) INIDS (“Information Dissemination in European RTD”- IC-1030)

- For the ESPRIT program: ORBIT ("Object-oriented Decision Assistance for Continuous Operations Scheduling and Coordination"-24487), NOE ICIMS (9251), Si E (Simulation Europe) WG (cod: 8467)

General coordination of the research activities from ICI.

Coordination of the RNC (National computer network for research) *Project Accomplishment*, the first Romanian network connected to the Internet (1993).

Coordination of the projects for introducing the informatics in the cultural institutes (libraries, museums).

Founding (in 1989) and coordination of the international journal "Studies in Informatics and Control-SIC" (http://www.ici.ro/ici/revista/sic.html) (registered from 1995 the IEEE INSPEC Database, indexed in ISI Web of Knowledge, the first Romanian journal that had an on-line version from 1992).

Founding (in 2006) and coordination of the international journal "International Journal of Computers, Communications and Control-IJCCC" (http://www.journal.univagora.ro).

Participating to some ICI international projects: a) INTERBIT ("Interbalkan Net of Technology"-IST 1999-14022), b) MobiTech ("European SME Challenge in Mobile Telecom Technologies"-IPS-1999-50125), c) IDEALIST 5FP, d) PROLEARN (as "associated partner")

Coordination of the following Romanian Academy Sections:

- Technical sciences
- Geological sciences
- Sociological, juridical and economical sciences
- Informatics Science and Technology

Managerial coordination of the Romanian Academy Library (BAR)

Supervision of the Construction Activities at the Romanian Academy Library

Coordination of two fundamental projects of the Romanian Academy

- Informational Society - Knowledge Society (2001-2002) http://www.academiaromana.ro/pro_pri/pag_com01socinf_prpri.htm
- Inter-disciplinary Program for preventing the major risks phenomenon at a national scale (2004-2005) http://www.icmpp.ro/institute/P_Fundam_AR.htm

Coordination of four international projects of the Romanian Academy:

- ForSociety - "Laying the Foundations for an ERA-NET on Foresight and Society" (contract ERAS-CT-2003-003231)
- ROINTERA - "Romanian Research Community Integration in the European Research Area" (contract INCO-CT-2003-510469), (www.rointera.ro)
- ROMOB - "Romanian Mobility Center" (contract FP 6 - 513461)
- ForSociety - "Transnational Foresight ERA Net" (http://195.251.117.130/ForSociety/partners/index.html)

Coordinator of projects: The programs EC-PECO, ESPRIT, COPERNICUS, IST of UE

The responsible of the Romanian teams from ICI at 10 projects/networks of excellence/workgroups (1993-2000: see the above no. 8) and at 2 projects of the Romanian Academy in FP6 (2003-): a) ROINTERA (NCO-CT-2003-510469), b) ForSociety (ERANet 011832)

Evaluator: 1992 (in the first team with invited experts from the Central and East Europe), 1996, 1999, 2004, 2005.

Member in :

- Program Committee of the IST ("Information Society Technologies") research program of UE (1999-) national representative - named.
- Consultative Committee of the European Committee in the priority domain IST from FP6 (ISTAG-Information Society Technologies Advisory Group) (invited directly by the European Committee) (2003-2004)

NATO Science for Peace

- Associate member of the Sub-Committee Computer Networking (2000-2001) (selected by NATO)

CDI National Program

- Member of the Consultative Board for Research - Development - Innovation (1992-) and General Secretary (1998-) Member of the "Informatica" 5th Committee of the Consultative Board (from 1991), president of the "Informatica" 5th Committee (1993-1994) and vice-president (from 1995)

Romanian Academy Grants (GAR)

- Vice-President of the GAR Committee (1995-2007)

Romanian Academy priority and fundamental programs

- Coordinator of the project "Informational Society - Knowledge Based Society" http://www.academiaromana.ro/pro_pri/pag_com01socinf_prpri.htm (2001-2002)
- Leadership of the program "Major risk phenomenon and processes at national scale" http://www.icmpp.ro/institute/Contributii_stiintifice.htm (2004-2005)

6 Didactical activities

Doctorate guidance at

- UPB (University Politehnica of Bucharest), Faculty of Automatics - specialization "Automatics" (from 1993) - 8 finalized doctorates from which one is made in association with Franche Conte University)
- Romanian Academy - specialization "Computer Sciences" (from 2002)

Professor of "Applied informatics" at "Valahia" University, Targoviste (1998-2001) courses of:

- "Artificial Intelligence"
- "Computer aid decision"
- "Computer aid enterprise engineering" (master level)

Visiting Professor at

- University POLITehnica of Bucharest, Faculty of Mechanics (Mecatronica Department). Course: "Expert Systems" (1998)
- Hyperion University of Bucharest (1999-2003). Courses of: a) "Computer aided decisions" and b) "Artificial Intelligence"
- Agora University (2006- now) "Decision Support Systems"

Master courses at:

- “Lucian Blaga” University Sibiu. Course: “Industrial Management” (1998)
- UPB-CPRU: Course: "Enterprise re-engineering" (1998) and "Computer aided Decision"(2005, 2006)
- University of Bucharest, Faculty of Letter. Course: “Computer aided Decision” (2004)
- ASE Bucharest. The modules “Computer aided Decision” from the course “Project Management” (2000)
- Ecole Centrale de Lille (France, 2006)

7 Member in the editorial staff of some scientific journals/conferences

Member in *International program committees* (IPC) at more than 50 international conferences and congresses from Europe, SUA, South America, Asia and Africa.

Member in the editorial board of the following journals:

1. SAMS (Systems Analysis, Modeling and Simulation) (Taylor and Francis) (1993-2004)
2. International J. of Critical Infrastructures (Interscience Publishers: www.interscience.com) (2004)
3. Computer Journal of Moldova , Chisinau (1993), Information Technologies and Control (ISSN 1312-2622), Sofia (din 1998)
4. Information Technologies and Control, Sofia (2003)
5. ROMJIST (Romanian Journal of Information Science and Technology) of the Romanian Academy
6. Studies in Informatics and Control -SIC (founder and chief-editor, from 1989)
7. International Journal of Computers, Communications and Control (http://www.journal.univagora.ro/)-chief-editor (from 2006)
8. Control Engineering and Applied Informatics (http://www.upg-ploiesti.ro/srait/publicatii.html)
9. Romanian Journal of Informatics and Automatics (http://www.ici.ro/ici/revista/ria.html): founder
10. Romanian journal of automatics (http://www.ipa.ro/web3-8RE.html)

Invited at conferences and seminars at universities and research institutes from: England (1984), Austria (1996), Brazil (1995), Chile (2004), China (1983, 1988, 2006), France (1992, 2006), Germany (1991), Kuwait (1986), Moldova Republic (1995, 2006), Sweden (1970), Tunisia (1998).

8 Member in professional organizations

- IFAC (“International Federation of Automatic Control”): Vice-President of the Technical Committee (TC) 5.4 “Large-Scale Complex Systems”, http://www.academiaromana.ro/ifac/ifac_tc54.htm), (1998-2002), President of TC 5.4 (2002- 2005), confirmed for a new mandate (2005-2008)
- Founder Member of SiE (Simulation Europe) (1993-1997)

- Honorary member of ATIC (Association for communication and informatics technology, from 1996) (www.atic.ro)
- Romanian forum for the informational society - Committee of the Romanian Academy, Executive president (from 1997)
- http://www.academiaromana.ro/forum_info/fpsc.htm
- SRAIT (Society of automatics and technical informatics), founder member (1992), Vice-President (1992-2001), now member of the Director Committee (http://www.upg-ploiesti.ro/srait/comitet.html)
- Member of IFAC - IFIP ("International Federation of Information Processing") Task-Force "Architectures for Entreprise Integration" (from 1995)
- Honorary Member of PITCH ("Association For the Promotion of International Technological Cooperation for Humanistic Ends"-) (2000-2006)

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Ioan Dziţac
Executive Editor of IJCCC
Agora University
Piata Tineretului 8, 410526 ORADEA
ROMANIA
idzitac@univagora.ro

Mişu-Jan Manolescu
Managing Editor of IJCCC
Agora University
Piata Tineretului 8, 410526 ORADEA
ROMANIA
rectorat@univagora.ro

Horea Oros
Technical Editor and editorial secretary of IJCCC
University of Oradea
Universitatii St. 1, 410087, ORADEA
ROMANIA
horos@uoradea.ro

Emma Văleanu
Webmaster and editorial secretary of IJCCC
Agora University
Piata Tineretului 8, 410526 ORADEA
ROMANIA
evaleanu@univagora.ro

International Journal of Computers, Communications & Control
Vol. II (2007), No. 3, pp. 217-228

Reactive Control Using Behavior Modelling of a Mobile Robot

Imen Ayari, Abderrazak Chatti

Abstract: This paper deals with the reactive control of an autonomous robot which should move safely in a crowded unknown environment to reach a goal. A behavior based approach is used to realize obstacle avoidance within a neural model conceived from a set of examples of perception/action relations; supervised learning is used for the aim; while goal-reaching task is realized using a fuzzy rule-based system. A task activation module is used to generate the overall command, resulting from the fuzzy controller and the neural model. Real time simulation examples of generated path with proposed techniques are presented.
Keywords: reactive control, mobile robots, neural networks, learning,fuzzy control.

1 Introduction

One of the major challenges in the development of intelligent mobile robotic systems is endowing them with an ability to plan motions and to navigate autonomously in a crowded environment avoiding any type of obstacles. Different kinds of the path planning problem can be illustrated; the simplest one is to find a continuous path from a starting position to a goal position given the exact description of the environment. Different global approaches were applied for the purpose such as decomposition, road-map, and retraction methods.

When dealing with unknown environment, much fewer approaches are used; obstacles in that case are either detected locally during the robot movement and dynamically incorporated into the path generation process, or approximated in the workspace (Miura, Uozumi, and Shirai [9]; Yu and Su [10]; Bennewitz, Burgard and Thrun [11]). [12]
A way to deal with the navigation problem is within behavior based navigation approaches. The main idea is to subdivide the navigation task into small subtasks. Several behavior-based control schemes have been achieved inspired by the subsumption architecture of Brooks[13][14]such us reactive behaviors defined by Arkin using motor schemes (Arkin [15][16][17]); DAMN architecture presented by Rosenblatt et al.[18][19][12] in which a centralized module of votes provided by independent behaviors combines into a voted output and fuzzy logic approach to manage behaviors used by Saffiotti [13], Seraji et al. [14][15] and others [16][17].[18]

This framework provides an overview on the contribution of soft computing to the field of behavior based robot control, a hybrid approach is adopted using both neural and fuzzy logic methods to realize the specified task of reaching a goal with obstacles avoiding in a crowded unknown environment. A neural model is conceived to synthesize avoiding obstacle behavior from a set of examples representing the perception/action relation using a supervised learning strategy. Goal-reaching task is realized using a fuzzy rule-based system. A task activation module is used to generate the overall command, resulting from the fuzzy controller and the neural model. Simulation examples of generated path with proposed techniques are presented.

2 Neural networks in robotics

Historically, robots for industrial purposes involved little or no learning. Recently, a growing interest in unstructured environments has encouraged learning intensive design methodologies. The emerging class of robots must be able to interact responsively with people and other robots providing assistance and service that will increasingly affect everyday life. Robots may learn by adjusting parameters, building environmental models such as maps, exploiting patterns, evolving rule sets, generating entire behaviors, devising new strategies, predicting environmental changes, recognizing the strategies of opponents or exchanging knowledge with other robots.

Essentially, neural networks deal with cognitive tasks such as learning, adaptation, generalization and optimization. Indeed, recognition, learning, decision-making and action constitute the principal navigation problems. To solve these problems fuzzy logic and neural networks are used. They improve the learning and adaptation capabilities related to variations in the environment where information is qualitative, inaccurate, uncertain or incomplete. Artificial neural networks (ANNs) are algorithms based very loosely on the neural phenomenon of spreading activation. ANNs can encode knowledge and skill implicitly as associative connections between nodes. Stimulation introduced to the input nodes of a neural network travels between layers of the network to produce some output on the other end. This output is evaluated by a trainer who applies supervised or unsupervised learning to alter the weights of synaptic connections and thereby change the way the network will respond. In this way, ANNs allow human knowledge and guidance to orchestrate the learning process. Such techniques, where learning is applied by a knowledgeable teacher, are often referred to as robot shaping.

Usually robot shaping involves symbolic interaction between a human and robot and may even involve a high-level tasking language. Such an interface allows humans to supply high-level assistance and allows the robot to accomplish the low-level learning necessary to achieve the goal. [19]

3 Robot description

The robot used in this work has been conceived in our laboratory [20][21] around a hardware architecture that facilitates the communication with a remote computer in different ways. It was based on different modules as shown in Figure (1). Every module has processing capabilities that allows updating the type of the low level current controller for the motor driver (2), test different dead reckoning approximations for the wheel encoders that determines the position (3) or compute different averaging methods for the infrared sensors (4). The robot can be totally free with an embedded master controller while transmitting wireless information to a computer, or the computer can be its master taking inputs and giving orders.

A mechanical structure handling this architecture was based on two DC motors controlling through gears two differential wheels. Wheels are provided with encoders that allows after processing determining an approximate relative position of the robot. Eight Infrared sensors are placed on a circle every 45°, they sense for obstacles by measuring the reflected light.

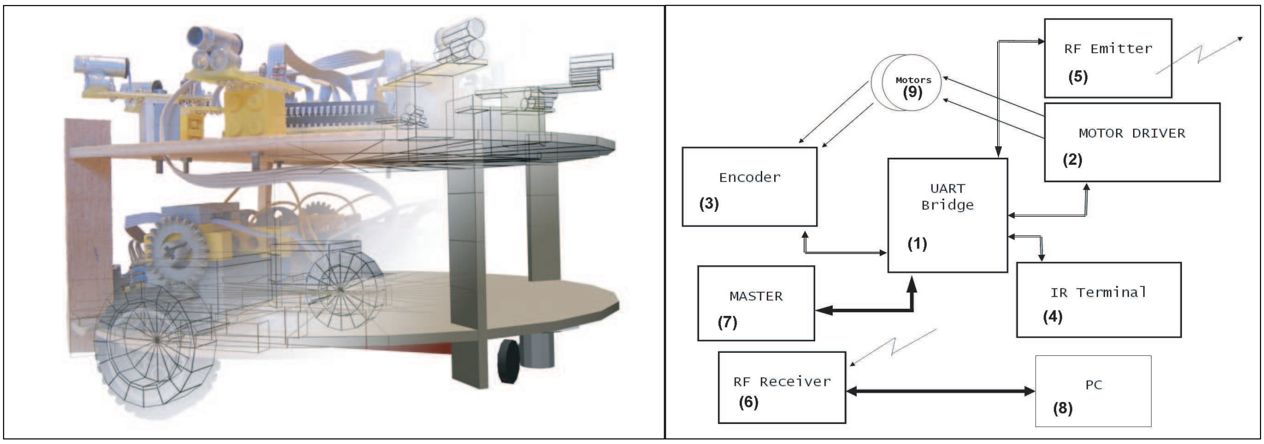

Figure 1: Robot Architecture

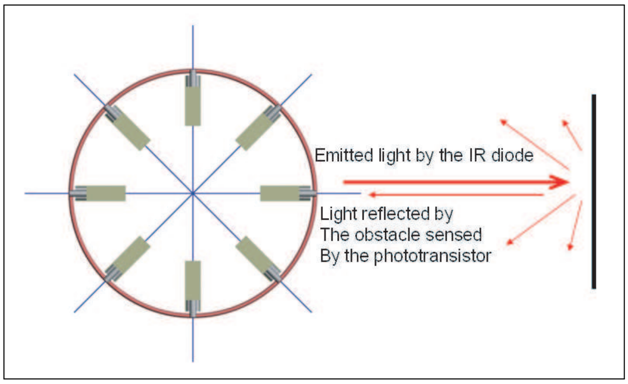

Figure 2: IR sensors (IR diode + Phototransistor)

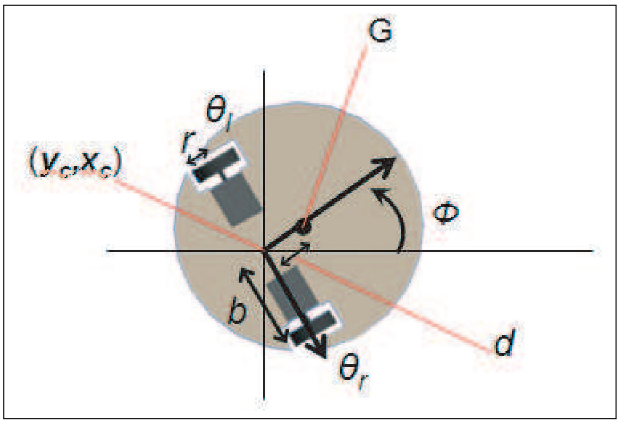

Figure 3: Robot parameters

The figure (3) shows the robot parameters where C is the center of the wheels and G is the gravity center, d separate these two centers as the in the general case d is always different than zero.

The movement vector q containing variables of the robot has the Cartesian coordinates of the center, the orientation and angle of each of left and right wheels:

$$q = (x_{c,}y_c, \phi, \theta_r, \theta_l) \tag{1}$$

Given the kinematics equations of this model:

$$\dot{y}_c \cos\phi - \dot{x}_c \sin\phi - d\dot{\phi} = 0$$

$$\dot{x}_c \cos\phi + \dot{y}_c \sin\phi - b\dot{\phi} = r\dot{\theta}_l$$

$$\dot{x}_c \cos\phi + \dot{y}_c \sin\phi + b\dot{\phi} = r\dot{\theta}_r$$

We can obtain the Pfaffian kinematics constraint:

$A(q)\dot{q} = 0$ With

$$A(q) = \begin{bmatrix} -\sin\phi & \cos\phi & -d & 0 & 0 \\ -\cos\phi & -\sin\phi & -b & r & 0 \\ -\cos\phi & -\sin\phi & b & 0 & r \end{bmatrix}$$

Deriving the Kinetic energy equation and considering the system with the Pfaffian constraint, we obtain the matrix differential system:

$$M(q)\ddot{q}+V(q,\dot{q})=E(q)\tau-A^{T}(q)\lambda$$

$A(q)S(q)=0$

$$S^{T}(MS\dot{\upsilon}(t)+M\dot{S}\upsilon(t)+V)=\tau$$

The resulting system is based on non-stationary matrices that will be re-computed every simulation step:

$$\dot{x}=\begin{bmatrix} S\upsilon \\ 0 \end{bmatrix}+\begin{bmatrix} 0 \\ I \end{bmatrix}u$$

Thus we have an approximate model of the robot dynamics. Matrices of this differential equation have parameters measured on the real robot and some others are variables computed on the run with the simulation like position and speed.

The input of this equation is the torque applied on every wheel. Resolving theses equations provide the speed and position of the robot.

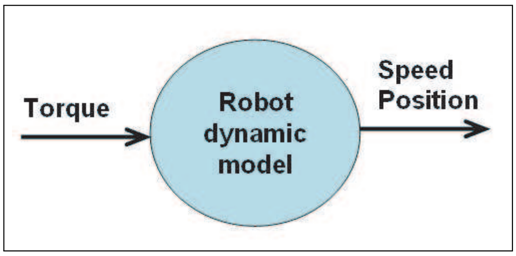

Figure 4: Robot dynamic model input output

4 Proposed approach

A hybrid approach is adopted using both neural and fuzzy logic methods to realize the specified task of reaching a goal point while avoiding obstacles. The control structure is made of two tasks as seen in the figure (5), a task for reaching the goal and a second one for avoiding obstacles; the input of the control system is sensors data and the outputs are the actuators command.

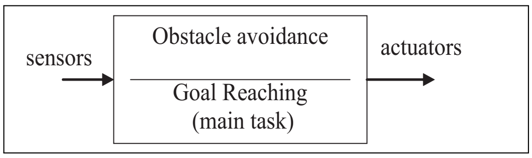

Figure 5: Control structure

5 Goal reaching task

The Goal Reaching task is expected to align the robot's heading with the direction of the goal; goal is the orientation difference between the robot axe and the goal.

A fuzzy controller is used to accomplish the task as shows the figure (7), with FC-lw and FC-rw the fuzzy command respectively of the left wheel and the right wheel.

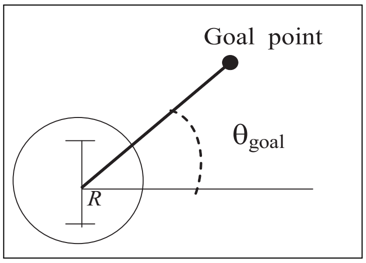

Figure 6: Goal orientation resolving

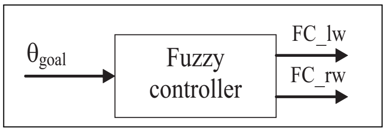

Figure 7: Goal reaching controller

Fuzzy sets

The variable ’ goal ’ has 8 fuzzy sets: (left, front left, front, front right , right, right back, back, left back)

The variables FC-lw and FC-rw have 6 fuzzy sets: (go ahead, go more on left, go more on right, quick turn left, quick turn right, go back)

Fuzzy inference system

The inference system id defined by the following rules:

- If goal is on front then go ahead
- If goal is on left then go more on left
- If goal is right then go more on right
- If goal is back then go back
- If goal is on front left then quick turn left
- If goal is left back then go back and go more on left
- If goal is on right back then go back and Go more on right
- If goal is on front right then quick turn right

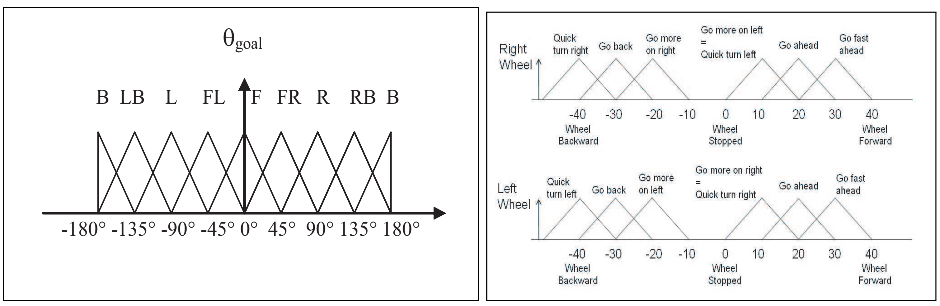

Figure 8: Inputs and Outputs membership functions

6 Obstacle avoidance task using neural robot behavior modelling

For the task of avoiding obstacles, a neural model is utilized, reproducing the robot behavior in the used environment in order to avoid obstacles. It is a way of learning the environment with obstacle existence by affecting command values to each vector data from sensors. In our application the model inputs are the 8 infrared sensors data and the outputs are the commands of each wheel motor.

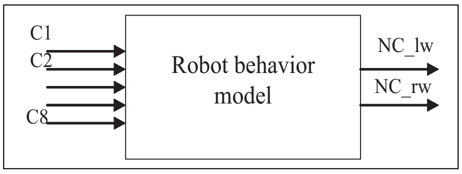

Figure 9: Obstacle avoidance strategy

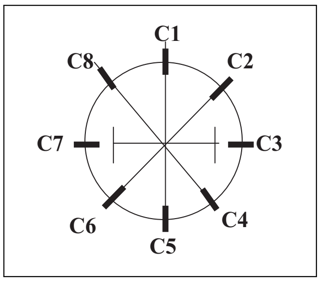

Figure 10: Infrared sensors position

The corresponding neural network model is a normalized multilayer perceptron (MLP) composed of 5 hidden neurons with sigmoidal activation functions and two output linear neuron representing wheels command. The training algorithm used is the backpropagation algorithm with simple gradient. The simple gradient version consists in modifying the weights w according to the following formula:

$w(k) = w(k-1) + \Delta w(k)$ with :

$$\Delta w(k) = -\mu \frac{\partial J}{\partial w}$$

where

$$\mu$$

is the training step.

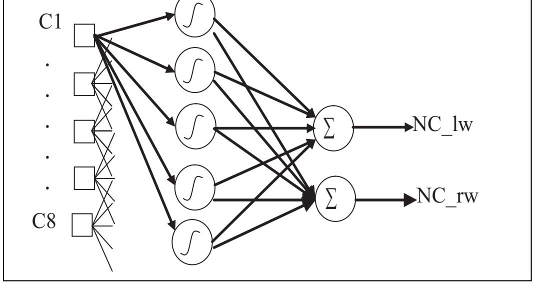

Figure 11: Neural network architecture

The network training is made using a conceived indoor environment with many obstacles of different shapes. The training data was collected using a joystick to guide the robot navigation in the environment

while avoiding obstacles. A sequence of the 8 sensors data and the corresponding wheels command is registered in a file used for the training and test of the achieved model.
The model validation is made by computing the prediction error and by testing the robot behavior in the same environment after its training. The training examples describing the obstacle avoiding behavior should be chosen carefully in order to be representative and can be generalized for other environments. A first training was made in a learning environment endowed with simple obstacles shape; we use a more type of the learning environment. The training principle is to learn the robot how to dodge obstacles; the robot goes forward, its front should be free otherwise it turns and follows the obstacle border as seen in figures (12) and (13). As a basic environment was used the one shown in the figure1.a; the test result was satisfactory in the same environment but collisions were detected when adding particular shapes of obstacles like corners or U traps. A second training is then achieved to learn avoiding this particular type of obstacles as seen in figure (13); the navigation test was satisfactory for corners but not for U traps; the robot begins to oscillate between the right and left side without having an outlet, in fact the same command is alternately applied for left and right wheel which causes the oscillation behavior. This situation was treated in the task activation module that gives the overall command for reaching goal and avoiding obstacles tasks.

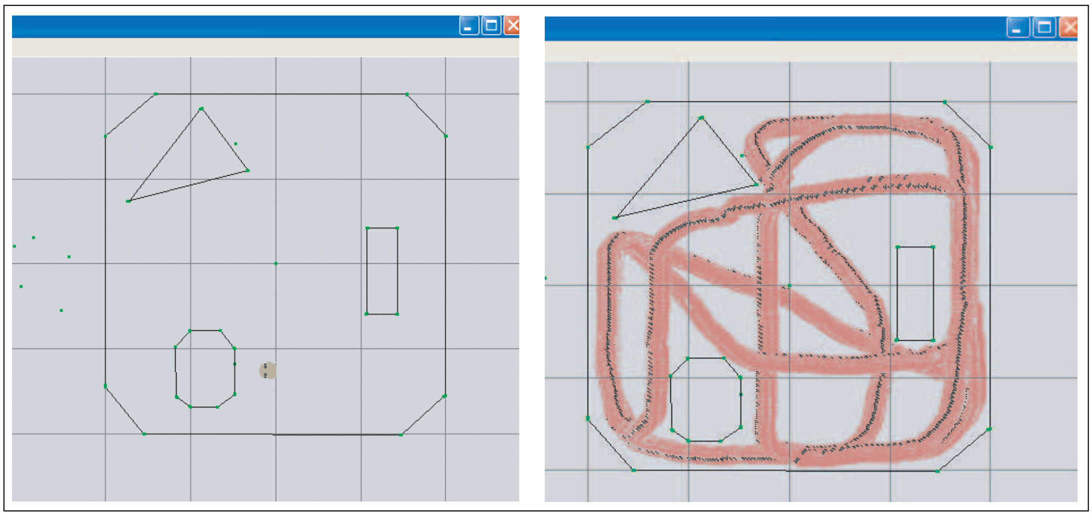

Figure 12: Behavior robot learning in simple environment

7 Task activation

The overall command, resulting from the fuzzy controller for reaching goal and the neural model for avoiding obstacles, is computed by a task activation module as shows the figure (14). A third unit is used at the input of the task activation module; it determines the situation (context) concerning the robot localization. Three situations are considered according to sensors data giving information about obstacles existence.

S1: IF C1 is far AND C2 is farĚAND C8 is far THEN obstacle is far

S2: IF C1 is near OR C2 is nearĚOR C8 is near THEN obstacle is near

S3: IF C1 is near AND C2 is near AND C4 is near AND C6 is near AND C7 is near AND C8 is near THEN trap situation

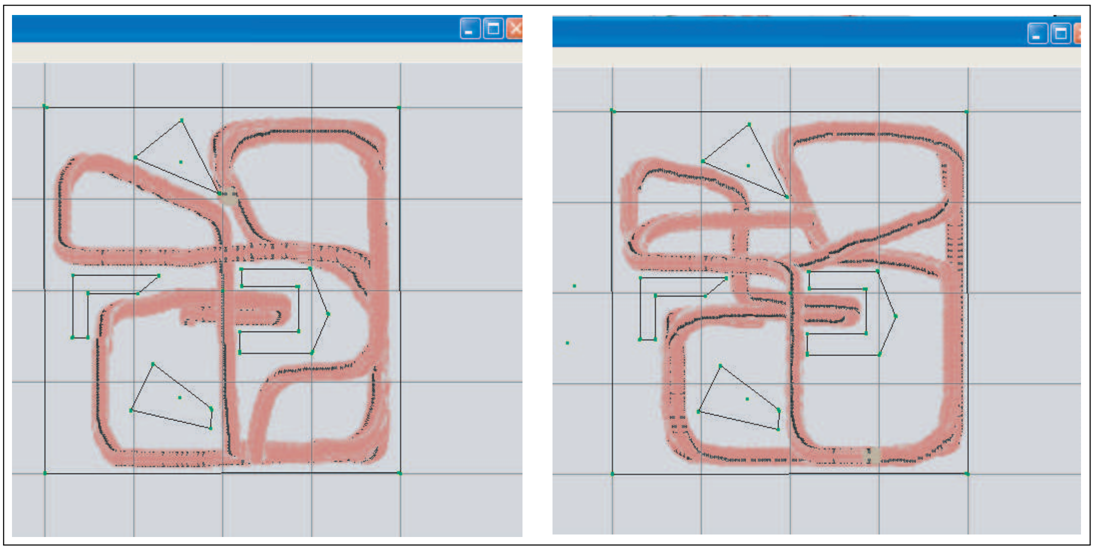

Figure 13: Behavior robot learning in complex environment (particular shaped obstacles)

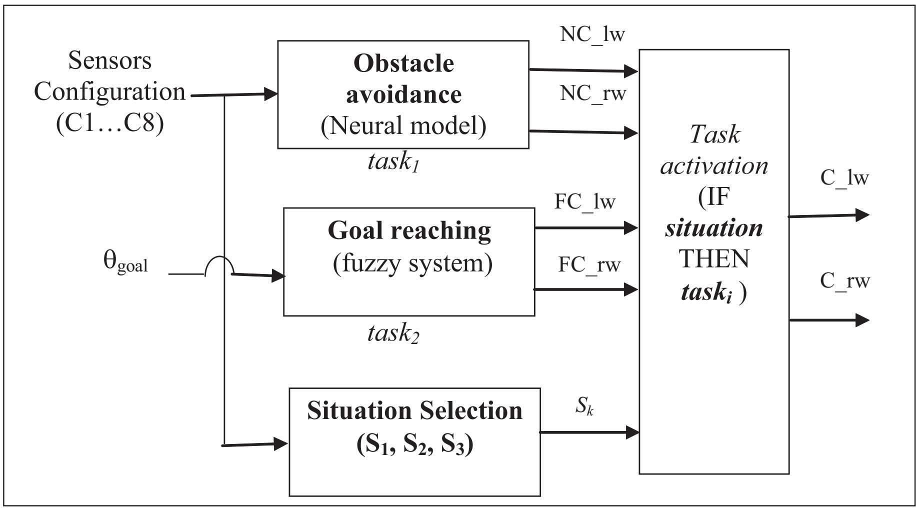

Figure 14: Task activation module

The input fuzzy sets describing the distances of each sensor to the nearest obstacle is defined in the figure (15).

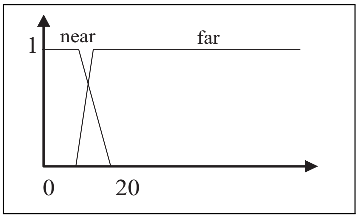

Figure 15: Membership functions for distance to obstacle

Trap situation is activated when the robot is trapped in a narrow corridor; the neural controller gives in this case a bad behavior; the robot begins to oscillate between the right and left side without having an outlet. The figure (16) shows an example of a trap situation.

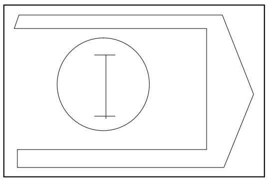

Figure 16: Example of a trap situation

The task activation module is made up of a fuzzy rule base:
IF situation THEN task i Three rules are considered as follows:

- IF obstacle is far THEN Goal reaching
- IF obstacle is near THEN obstacle avoidance
- IF trap situation AND 0 < goal < pi THEN turn left ELSE turn right

8 Simulation results

To verify the validity of the proposed approach, some cases were illustrated using a real time simulation of the upper presented robot; it has to move from a given current position to a desired goal position in an unknown environment endowed with different obstacle shapes: simple shapes as seen in figure (17) and particular ones depicted by figure (18.2). The learned environment and a new one were both tested for the robot navigation depicted respectively by figures (18) and (17). The robot is any case, able to reach the goal placed behind obstacles while avoiding obstacles successfully.

9 Summary and Conclusions

This framework presented a behavior based approach making use of the neural network and fuzzy control to realize the task of reaching goal in a crowded environment. A neural network modelling the robot behavior when encountering obstacles is conceived using supervised learning. Different shapes of obstacles were learned; the neural model should associate a particular sensor data to a given action. The goal reaching task was achieved using a fuzzy rule-based system; coordination of the two tasks was addressed using a task activation module giving the overall action depending on the context. The simulation examples of the generation of the collision free path with goal reaching show that designed strategy is acceptable as solution of this problem.

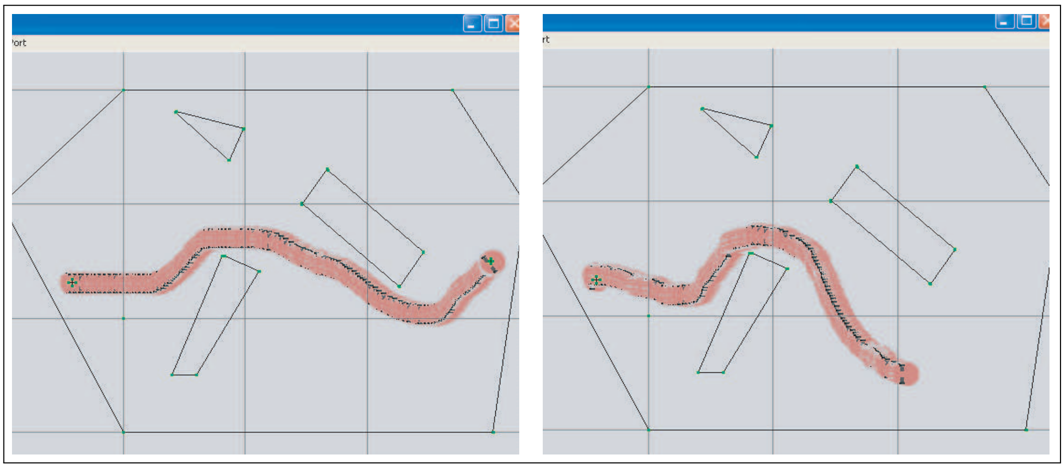

Figure 17: Collision free goal reaching in an unlearned environment

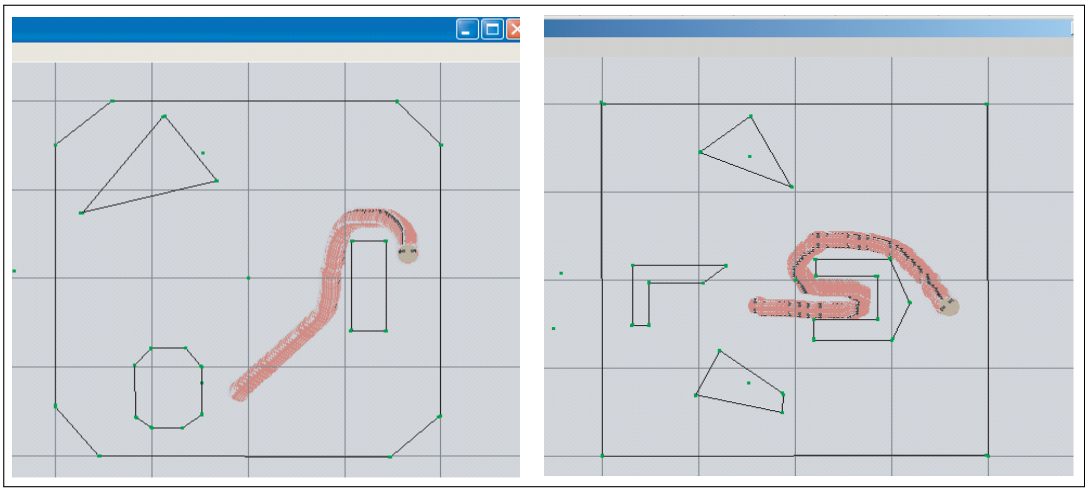

Figure 18: Collision free goal reaching in a learned environment

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Imen Ayari, Abderrazak Chatti
Institut National des Sciences Appliquées et de Technologie (INSAT)
Centre Urbain Nord, BP. 676, 1080 Tunis Cedex, Tunisie
E-mail : ayari.imen@gmail.com, abderrazak.chatti@insat.rnu.tn
Received : February 12, 2007
Revised : June 26, 2007

Imen Ayari (born on July 10, 1979) received the Engineer Diploma degree in 2003 and the master degree in 2005, both in Automatic and Industrial Computing from the "Institut National des Sciences Appliquées et de Technologie", Tunisia. She is currently preparing the Ph.D. degree in automatic and computer science within the framework of LAGIS-EC-Lille and LARA-ENIT (Tunisia) cooperation. Her research is related to the appliance of soft computing methods especially neural networks for mobile robots control.

Abderrazak Chatti received the Master of Science degree in 1988 from Polytechnical School of Saint-Pétersbourg from Russia and the PhD degree in Technical Sciences in 1994 from Polytechnical University of Saint-Pétersbourg, Russia, both in Automatics and Industrial Computing. Presently he is associate professor in the "Institut National des Sciences Appliquées et de Technologie", Tunisia. His research interest includes topics such as modelling and control of non linear dynamic processes, robust and intelligent control.

International Journal of Computers, Communications & Control
Vol. II (2007), No. 3, pp. 229-240

A Proposed Genetic Algorithm Coding for Flow-Shop Scheduling Problems

Hela Boukef, Mohamed Benrejeb, Pierre Borne

Abstract: A new genetic algorithm coding is proposed in this paper to solve flow-shop scheduling problems. To show the efficiency of the considered approach, two examples, in pharmaceutical and agro-food industries are considered with minimization of different costs related to each problem as a scope. Multi-objective optimization is thus, used and its performances proved.
Keywords: genetic algorithm, operations coding, flow-shop problems, multi-objective optimization, pharmaceutical industries, agro-food industries.

1 Introduction

In shop scheduling, there are three basic models classified according to the structure of a processing route:

- the job-shop scheduling problem is an operation sequencing problem on multiple machines subject to some precedence constraints among the operations,
- the flow-shop scheduling problem is a set of jobs that flow through multiple stages in the same order,
- the open-shop scheduling problem is a problem where the workshop has several resources and the routing of all the operations is free.

In pharmaceutical and agro-food industries, the tasks execution needs the use of several resources in a single order. It is thus about a flow-shop problem.

Flow-shop problems have received considerable attention from researchers during the last decades and the scheduling criterion most frequently used was the maximum completion time [3],[7], [4], [21], [15], [26]...

However, the analysis of the performance of a schedule often involves more than one aspect and therefore requires a multi-objective treatment [8], [17], [25]. The aim of multi-objective optimization is to deal with many criteria at the same time.

This paper is focused on minimizing the total costs related to manufacturing and delivery processes. To solve this kind of problems, the exact methods and the approached methods can be applied.

The exact methods, such as branch and bound [1] and linear programming methods [23], concern small size problems at the contrary of approached methods, such as tabu search [10], simulated annealing [16], genetic algorithms [13] and ants colony methods [6], that concern big size ones [14]. In this paper, we focus on the use of genetic algorithms method.

The principle scope of this method, based on natural selection mechanism, is the improvement of robustness and balance between cost and performance [11].

The genetic algorithms became famous due to their efficiency in solving combinatory optimization problems [19]. Their application fields are very important. They vary from complex real application such as pipelines flow control or robot planning path to theoretical combinatory problems.

The paper is organized as follows. First, the notations are introduced. Section 2 deals with the presentation and formulation of pharmaceutical and agro-food scheduling problems. Section 3 tackles the choice of the use of multi-objective evaluation. Section 4 handles with the presentation of genetic algorithms and the proposed structured coding of list operations. In section 5, two examples, concerning agro-food and pharmaceutical industries scheduling, are treated by using this algorithm.

Notations :

P_i : finished product after operation O_i
p_{ik} : conditioning time of O_i on machine k
$C_{P_{ik}}$: ending processing time ofP_i on machine k
$d_{P_i}^{liv}$: delivery date of P_i
$C_{P_i}^{stk}$: storage cost by time unit of P_i

For pharmaceutical industries:

tp_{ik} : preparation time on machine $k$before O_i
t_{ik}^{arr} : stoppage time during $O_i$on machine k
C_{prod}^{tot} : total production cost
C_k^u : production cost by time unit on machine k
DO_{ik}^{nett} : cleaning operations time on machine k
DO_{ik}^{chf} : size changing operations time on machine k
Crd_i : costs of distribution delays of P_i
Cf_i : manufacturing cost of P_i

For agro-food industries:

t_i : effective start time of manufacturing O_i
r_i : earliest start time of O_i
γ_i : effective end time of O_i
c_{ik} : k^{th}component from the whole components of O_i
v_{ik} : limit validity date of a component c_{ik}
DV_{P_i} : lifespan of P_i
DR_{P_i} : back delay of P_i
P_{ik}^{rev} : income of a component c_{ik}
$P_{P_i}^{ven}$: unit sale price of P_i

2 Presentation and formulation of pharmaceutical and agro-food scheduling problem

2.1 Pharmaceutical industries scheduling case

In pharmaceutical industries, many problems can appear in production workshop. Several operations of cleaning and format changes have to be managed jointly with the manufacturing operations. The unproductive times generated by these operations are rather significant, taking into account the fact that the time launching of a product manufacturing depends on that which precede it. From a product to another, the change involves certain modifications on the level of each machine. These problems can brake the beginning of the production and delay its end.

Moreover, stoppage time due to machines break down, and production time are as many factors that breed important production costs [2].

Costs of distribution delays can also be calculated taking account of storage costs, date of production and end delivery date.

Let consider objective functions f_1 and f_2. They represent the minimization of total cost of production, C_{prod}^{tot}, and the minimization of distribution delays cost of the product P_i, C_{rd_i}.

The total cost of production has the following global expression:

$$C_{prod}^{tot} = \sum_{1<j<N} Cf_j$$

N is the number of manufactured products [22].

In pharmaceutical industries, this expression becomes:

$$f_1 = C_{prod}^{tot} = \sum_k C_k^u \sum_i w_{ik}(p_{ik} + tp_{ik}^{arr}) \tag{1}$$

with:

$$tp_{ik}^{arr} = DO_{ik}^{nett} + DO_{ik}^{chf}$$

w_{ik} : the coefficient of use of the machine k for the production of the product i, $w_{i,k} = \{0,1\}$

The distribution delays penalties has the following expression:

$$f_2 = C_{rd_i} = \max(0, d_{P_i}^{liv} - C_{P_{ik}})C_{P_i}^{stk} \tag{2}$$

2.2 Agro-food industries scheduling case

Among the different problems occurring in agro-food industries let distinguish products perishability and distribution discount.

Products perishability is a major problem in agro-food industries because of products short expiry dates. The distribution discount contains penalties applied to sellers and storage costs of final products before their delivery. This criterion depends on the end-products storage's period of time before its expedition to the distribution areas [9].

Generally, expired product's costs, g_1, and distribution discount costs, g_2, are expressed by the following expressions:

$$g_1 = \sum_k P_{ik}^{rev} \left(\frac{\max(0, t_i - v_{ik})}{(t_i - v_{ik})} \right) \tag{3}$$

$$g_2 = \max\left(0, d_{P_i}^{liv} - C_{P_i}\right) \times \left(\frac{P_{P_i}^{ven}}{DV_{P_i} - DR_{P_i}} + C_{P_i}^{stk} \right) \tag{4}$$

Usually, resolution approaches take account of one criterion at once. In this paper, we want to optimize a trade off between several criteria at the same time and to find a mean of global evaluation of these criteria.

3 Multi-objective evaluation

Weighting sum function method, one of the different multi-objective methods, consists in combining linearly the different functions applying a weighted coefficient to each of them and summing them [5]. We can also say that it is a weighted linear combination of the objectives and it is used to aggregate the considered objectives in a single one.

Pharmaceutical industries case [3]

The weighted sum of functions f_1 and f_2 gives the following function f_{eq}:

$$f_{eq} = \alpha_1 f_1 + \alpha_2 f_2 \tag{5}$$

then:

$$f_{eq} = \alpha_1 \left(\sum_k C_k^u \sum_i w_{ik} (p_{ik} + tp_{ik} + t_{ik}^{arr}) \right) + \alpha_2 \left(\max\left(0, d_{P_i}^{liv} - C_{P_i}\right) C_{P_i}^{stk} \right) \tag{6}$$

where α_i are the coefficient that privilege one function instead of another, $\alpha_1 + \alpha_2 = 1$.

Agro-food industries case [24]

The weighted sum g_{eq} of functions g_1 and g_2 is expressed as following:

$$g_{eq} = \beta_1 g_1 + \beta_2 g_2 \tag{7}$$

then:

$$g_{eq} = \beta_1 \sum_k P_{ik}^{rev} \left(\frac{\max(0, t_i - v_{ik})}{(t_i - v_{ik})} \right) + \beta_2 \max(0, d_{P_i}^{liv} - C_{P_i}) \times \left(\frac{P_{P_i}^{ven}}{DV_{P_i} - DR_{P_i}} + C_{P_i}^{stk} \right) \tag{8}$$

where β_i are the coefficients that privilege one function instead of another, $\beta_1 + \beta_2 = 1$.

Genetic algorithms are adapted from natural systems and are successfully used in artificial systems. They proof themselves in optimization fields and in multiple other application fields [17]. That's why they are adopted and then proposed for our scheduling problems resolution.

4 Proposed operations coding used in genetic algorithms application

Genetic algorithms are parts of evolutionary algorithms that are composed of three essential elements:

- a population made up of several individuals representing the potential solutions (configurations) of a given problem,
- an evaluation mechanism of each individual adaptation regard to his external environment,
- evolution operators allowing the elimination of certain individuals and the creation of new ones [12].

4.1 Genetic algorithms

Genetic algorithms are iterative algorithms whose aim is to optimize a function called fitness [13]. They are exploration algorithms based on natural selection mechanisms and genetics and use at the same time survival of the best adapted structures principles and pseudo-random exchanges information, to form an exploration algorithm which has certain characteristics of human exploration. With each generation, a new set of individuals is created by using best elements parts of the precedent generation as well as innovating parts.

The genetic algorithms are not purely random. They effectively exploit information obtained previously to speculate in the position of new points to explore, with the hope to improve the performance [11].

To realize this scope, they use a set of points, called individual population, where each individual represents a possible solution of the given problem and contains different elements, called gene, which can take multiple values [20]. The different operators used in genetic algorithms are selection, crossover and mutation.

The aim of selection operator is to pick individuals that can survive and/or reproduce themselves to transmit their characteristics to the next generation. The selection operator is based on conservation principle of the most adapted individuals and elimination of the less ones [12]. No selection operator is absolutely perfect; a risk of favouring a number of individuals always exists and it could be a real drawback.

The crossover operator ensures the combination of parental genes to form new descendants with new potentials. This operator works randomly according to a probability fixed by the user keeping count of the optimization problem [20].

The mutation operator consists in a random changing for an individual certain gene's values [12]. Without this operator, a uniform population is produced.

A suitable coding choice is an important task that can guarantee the success of the genetic algorithms application.

The classic coding introduced by Holland [13] corresponds to the binary alphabet (0/1) where the chromosome is simply represented by a finite 0-1 array. More generally, genes can be real, characters or any expressions or elementary entities [14].

4.2 Structured list operations coding

In the case related to pharmaceutical industries scheduling, cleaning and size changing operations as well as stoppage and preparation times generate very high production costs. Distribution delays can also occur and generate significant costs.

In the case of agro-food industries scheduling, products expiry dates and storage time before delivery have to be taken into account for perishability costs and distribution discount costs evaluation.

Coding to be implemented must thus be able to deal with management time problems, precedence constraints, assignment resources, and the different costs that result from these problems.

SLOC's presentation

Inspired by Parallel Machine Coding CPM [20] and List Operations Coding CLO [14], the proposed Structured List Operations Coding SLOC, offers to solve the previously quoted problems.

The *one point crossover* operator for the SLOC, selects two individual parents (according to the technique of the caster) and a crossover point. First child receives from first parent the chromosomes preceding the crossover point (same thing for second child and second parent) and it receives from the second parent chromosomes following the crossover point (same thing for second child 2 and first parent). Updates are then carried out.

The *two points crossover* operator for the SLOC chooses two individual parents and two crossover points. First child receives from first parent the chromosomes preceding the first crossover point and following the second crossover point (same thing for the second child and second parent) then, it receives from the second parent chromosomes located between the two crossover points without redundancy (same thing for second child and first parent). Updates are then carried out.

When it is about only one machine, the *mutation operator* chooses one individual parent and two mutation points, the permutation of the two chromosomes produces a new individual.

When they are two (or more) machines, this operator chooses one individual parent and a mutation point, the operation thus consists in changing for the individual concerned the number of the machine and making the necessary updates.

The use of these operators has as principle concern the improvement of robustness and the balance between costs and performances.

Algorithm

The genetic algorithm steps, applied to pharmaceutical and agro-food scheduling, is given in figure 1.

SLOC's structure

In the case of only one machine, an individual is composed of a list of products, and for each product a cost function is associated in table 1 where List $_i$ is a set of products placed in a well defined ordered

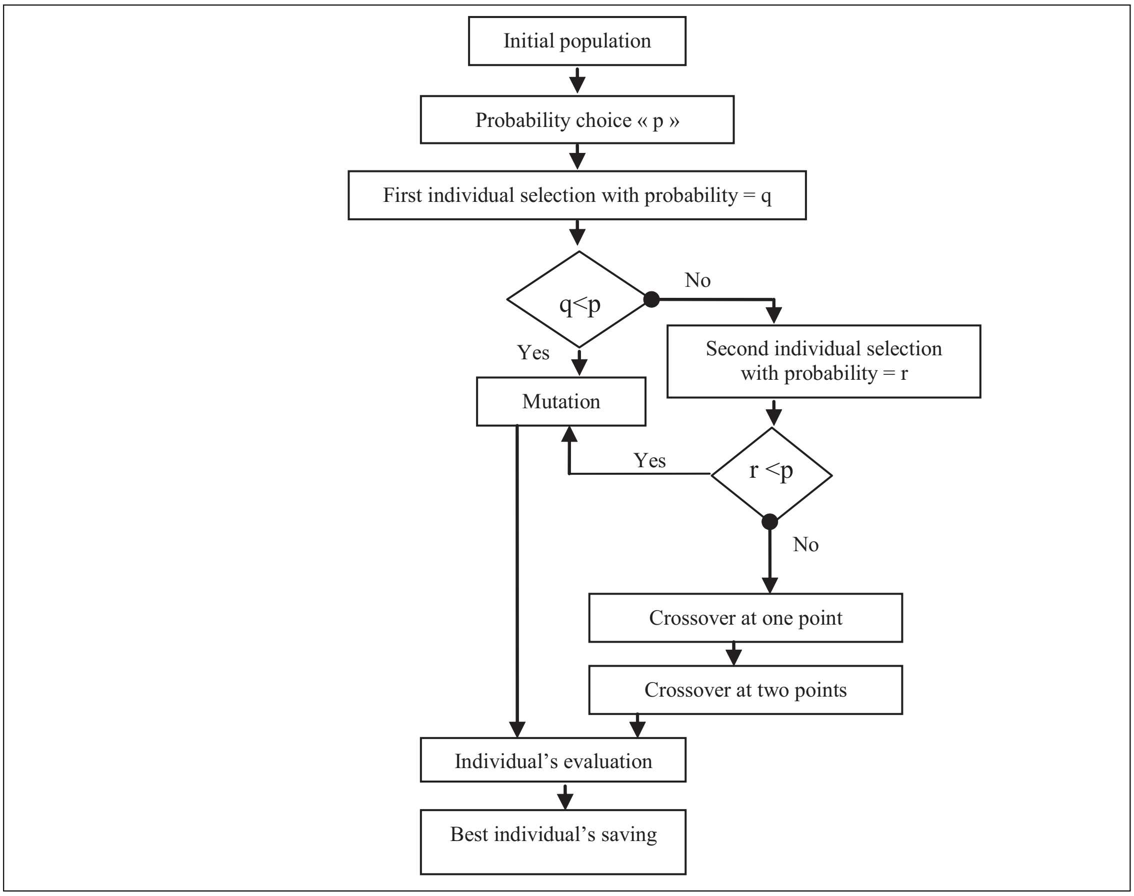

Figure 1: Genetic algorithm steps

passage, $i = 1, 2, \ldots, n$ and $f_{eq}(List_i)$ is an equivalent function corresponding to the weighted sum of the two considered cost functions, $i = 1, 2, \ldots, n$.

Table 1: : Scheduling data in agro-food industries

List of products	f_{eq}
$List_1$	$f_{eq}(List_1)$
$List_2$	$f_{eq}(List_2)$
...	...
$List_n$	$f_{eq}(List_n)$

In the case of two or several machines, an individual is also composed of a list of products but, in this case, to each product corresponds a data structure taking into account the number of the machines on which the product is manufactured, of its beginning execution time and of its end time.

As in the case of only one machine, to each individual (list of products) is associated the function corresponding to the weighted sum of both or several cost functions, showed in table 2 and using the following notations:

nM_i : machines number in which the product P_i is manufactured
t_i : beginning time of product P_i manufacturing
C_i : time ending of product P_i manufacturing
f_{eq} : equivalent function to optimize
ind_i : given individual of a given generation

Table 2: SLOC coding for n machines and m products for a given individual and a given generation

$Product_1$	nM_1	t_1	C_1	$f_{eq}(ind_i)$
...				
$Product_j$	nM_j	t_j	C_j	
...				
$Product_n$	nM_n	t_n	C_n	

5 Agro-food and pharmaceutical scheduling resolution

In this section, we propose to solve a single machine flow-shop problem in agro-food industries and a two-machines flow-shop problem in pharmaceutical industries. The scope is the minimization of different costs, appropriate to each scheduling problem.

5.1 First example: Resolution of a flow-shop scheduling problem in agro-food industries

The flow-shop scheduling problem data in agro-food industries in the case of one machine is presented in the following table 3. Taking into account the data presented in this table, products perishability and distribution discount costs can be calculated following expressions 3 and 4.

Starting from g_{eq} function, the genetic algorithms are applied to solve the scheduling problem in order to obtain the products best list which minimizes this function, by using structured lists operation coding. Indeed, for 200 generations and a 20 individuals population per generation, mutation and crossover operations are carried out, thus generating, new individuals whose new costs are calculated. Then, the best individual is progressively generated and saved.

Table 3: Scheduling data in agro-food industries

Operation name	Component name	r_i	p_i	v_{ik}	p_{ik}^{rev}	P_{Pi}^{ven}	DV_{Pi}	DR_{Pi}	d_{Pi}^{liv}	C_{Pi}^{stk}
Op1	C11	1	3	3	8	4	5	11	10	6
Op1	C12	1	3	8	10	4	5	11	10	6
Op1	C13	1	3	2	7	4	5	11	10	6
Op2	C21	2	5	5	13	5	12	10	19	2
Op2	C22	2	5	12	11	5	12	10	19	2
Op2	C23	2	5	11	4	5	12	10	19	2
Op3	C31	2	3	5	6	6	15	12	22	7
Op3	C32	2	3	20	2	6	15	12	22	7
Op3	C33	2	3	3	9	6	15	12	22	7
Op4	C41	3	2	17	11	8	11	15	11	14
Op4	C42	3	2	10	2	8	11	15	11	14
Op4	C43	3	2	4	5	8	11	15	11	14
Op5	C51	3	2	11	14	7	8	10	15	18
Op5	C52	3	2	15	12	7	8	10	15	18
Op5	C53	3	2	4	23	7	8	10	15	18

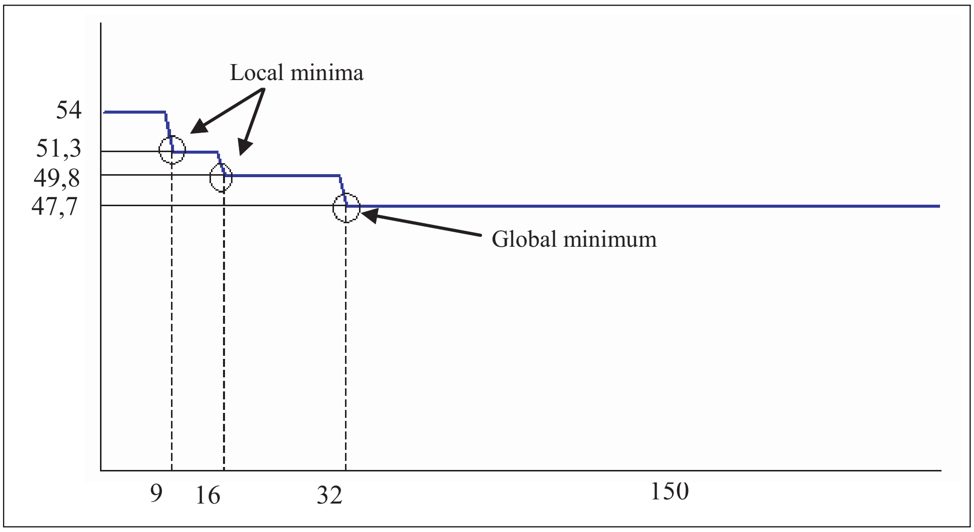

Figure 2: Total cost evolution through the generations in agro-food industries

The figure 2 shows that the cost of the best individual of the initial population is 54, then, the first local minimum observed shows that the cost of the best individual passed to 51,3 and this in the nineth generation. For the second local minimum, the total cost passes to 49,8 in the sixteenth generation to stabilize itself in the thirty second generation with 47,7 which is the observed global minimum.

5.2 Second example: Resolution of a flow-shop scheduling problem in pharmaceutical industries

The flow-shop scheduling problem data in pharmaceutical industries, in the case of two machines M1 and M2, is presented in the following table 4.

Table 4: Scheduling data in pharmaceutical industries

Product name	p_{i1}	t_{i1}^{arr}	tp_{i1}	p_{i2}	t_{i2}^{arr}	tp_{i2}	d_{Pi}^{liv}
P01	1800	240	120	2880	100	100	3
P02	2400	310	150	—	—	—	20
P03	2250	240	135	2100	115	100	14
P04	1950	175	130	2300	135	115	11
P05	2800	300	120	—	—	—	10
P06	1750	150	100	1500	115	110	25
P07	—	—	—	2400	120	110	15
P08	3500	315	180	3000	250	110	25
P09	2200	270	120	2500	110	150	45
P10	1000	115	165	—	—	—	32
P11	1850	155	180	1650	155	130	12
P12	2120	180	200	2400	160	120	56
P13	3300	210	140	—	—	—	15
P14	4500	190	175	3800	150	190	60
P15	—	—	—	1600	100	100	35
P16	6750	180	120	7000	220	100	45

Times of manufacturing, stoppage and preparation are indicated in minutes and the various dates are calculated compared to an initial time t_0.

Times and dates comprising the symbol " — " indicate the impossibility of manufacturing the concerning product on the corresponding machine.

Taking into account the data presented in the table 4, the production cost and the distribution delays penalties can be calculated while following expressions 1 and 2.

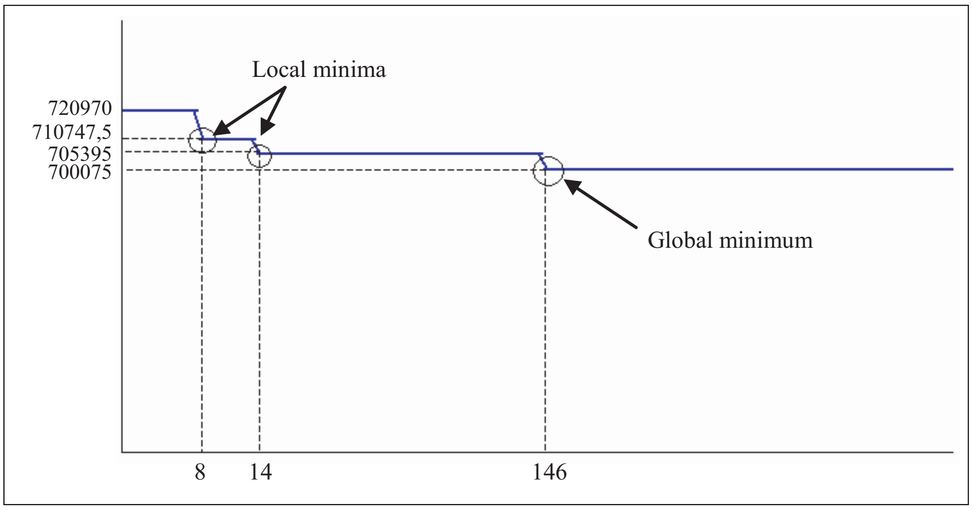

Figure 3: Total cost evolution through the generations in pharmaceutical industries

Starting from function f_{eq}, the genetic algorithms are applied to solve the scheduling problem in order to obtain the products best list which minimizes this function, by using proposed structured lists operation coding. Indeed, for 200 generations and 20 individuals population per generation, mutation and crossover operations are carried out, thus generating, new individuals whose new costs are calculated. Then, the best individual is progressively generated and saved.

The figure 3 shows that the cost of the best individual of the initial population is 720970, then, the first local minimum observed shows that the cost of the best individual passed to 710747,5 and this in the eighth generation. For the second local minimum, the total cost passes to 705395 in the fourteenth generation to stabilize itself in the hundred forty sixth generation with 700075 which is the observed global minimum.

6 Conclusion

In this paper, a multi-objective approach was adopted for the flow-shop scheduling problems resolution in agro-food and pharmaceutical industries. The proposed structured list operations coding and its use to implement genetic algorithms showed the capacity of this type of algorithms to find the global minimum aimed. It is interesting to make a comparison of the effectiveness of the choice of this suggested coding with other codings.

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Hela BOUKEF[1,2], Mohamed BENREJEB[1], Pierre BORNE[2]

[1]Ecole Nationale d'Ingénieurs de Tunis
Unité de recherche LARA-Automatique
BP 37, Le Belvédère, 1002 Tunis, Tunisie

[2]Ecole Centrale de Lille, Cité scientifique
Laboratoire d'Automatique, Genie Informatique et Signal

BP 48, 59651 Villeneuve d'Ascq Cedex, France

E-mail: hela.boukef@yahoo.fr, mohamed.benrejeb@enit.rnu.tn, pierre.borne@ec-lille.fr

Hela Boukef was born in Carthage, Tunisia in 1981. She graduated from "Institut Supérieur de Gestion de Tunis" in 2003 and obtain the Master of automatic and signal treatment in 2006 at the "Ecole Nationale d'Ingénieur de Tunis". She is currently preparing the Ph.D. degree in automatic and computer science within the framework of LAGIS-EC-Lille and LARA-ENIT cooperation. Her research is related to optimization methods for discrete events systems, computer science and operational research.

Mohamed Benrejeb was born in Tunisia in 1950. He obtained the Diploma of "Ingénieur IDN" (French "Grande Ecole") in 1973, The Master degree of Automatic Control in 1974, the PhD in Automatic Control of the University of Lille in 1976 and the DSc of the same University in 1980. Full Professor at "Ecole Nationale d'Ingénieurs de Tunis" since 1985 and at "Ecole Centrale de Lille" since 2003, his research interests are in the area of analysis and synthesis of complex systems based on classical and non conventional approaches.

Pierre Borne was born in Corbeil, France in 1944, he received the Master degree of Physics in 1967, the Masters of Electronics, of Mechanics and of Applied Mathematics in 1968. The same year he obtained the Diploma of "Ingénieur IDN" (French "Grande Ecole"). He obtained the PhD in Automatic Control of the University of Lille in 1970 and the DSc of the same University in 1976. He became Doctor Honoris Causa of the Moscow Institute of Electronics and Mathematics (Russia) in 1999, of the University of Waterloo (Canada) in 2006 and of the polytechnic University of Bucarest (Romania). He is author or co-author of about 200 Journal articles and book chapters, and of 34 plenary lectures and of more than 250 communications in international conferences. He has been the supervisor of 66 PhD thesis and is author of 20 books . He has been President of the IEEE/SMC society in 2000 and 2001. He is presently Professor "de classe exceptionnelle" at the Ecole Centrale de Lille and director of the french pluriformations national group of research in Automatic Control.

International Journal of Computers, Communications & Control
Vol. II (2007), No. 3, pp. 241-251

Hybrid Control Accommodation for Water-asset Management of Hydraulic Systems Subjected to Large Operating Conditions

Eric Duviella, Pascale Chiron, Philippe Charbonnaud

Abstract: The Hybrid Control Accommodation (HCA) strategy was proposed to improve the water-asset management of hydraulic systems by resource allocation and setpoint assignment. Hydraulic system dynamics are taken into account during the setpoint assignment step which consists in controlling gates for large operating conditions. For hydraulic systems subjected to strong disturbances, transfer delays are variable, thus different operating modes must be considered. A multimodelling method, associated to a selection technique of transfer delay, allowing for the determination of the number of models, is proposed. The simulation results on the first reach of the Neste canal show the effectiveness of the HCA strategy.
Keywords: Hybrid control accommodation, resource allocation, setpoint assignment, multimodelling, water management.

1 Introduction

Hydrographic networks naturally convey water quantities upstream to downstream. They are equipped with dams, catchment areas, channels, etc., and are instrumented for water resource management and satisfaction of human activity needs. Several control methods have been designed [9], and are still designed [8, 2], to supply hydraulic systems with water quantities corresponding to the management objectives and rejecting disturbances. Other techniques, such as LPV regulation [10] or supervised internal multi-model controller [3] were recently proposed in order to consider these systems for different operating points. These control methods are accurate for a local control. However, they are not designed to allocate water quantities in excess towards the catchments areas, and water quantities in lack amongst the users. An original proposition for the management of such situations consists in recalculating setpoints according to the resource value (continuous dynamics) and to the resource state (discrete events) of the hydrographic systems. The supervision and hybrid control accommodation strategy by resource allocation and setpoint assignment proposed in [4] allows the water-asset management to take into account the management constraints. The strategy efficiency has been shown by simulation, in the case of an open-channel hydraulic system considering large operating conditions.

The problem addressed in this paper deals with the water-asset management of a hydraulic system subjected to scenarii with large disturbances. In the second section, the supervision and hybrid control accommodation strategy, well adapted to consider large operating conditions, is presented. In the third section, a multimodelling method is proposed for determining the number of Operating Modes (OM) necessary to represent open-surface hydraulic system dynamics, accurately. For each OM, the transfer delay identification is done in the fourth section. Finally, the effectiveness of this proposed strategy is shown by simulation on the first reach of the Neste canal.

2 Hybrid control accommodation

Hybrid Control Accommodation (HCA) strategy (*see* figure 1) allows the computation of new setpoints for each gate G_j of hydraulic systems according to data measured on the measurement points M_i (*see* figure 2). The setpoints are computed according to the resource state e_i, and taking into account management objectives $q_{j\,obj}$, λ_j and μ_j weekly fixed by the Management Objective Generation module.

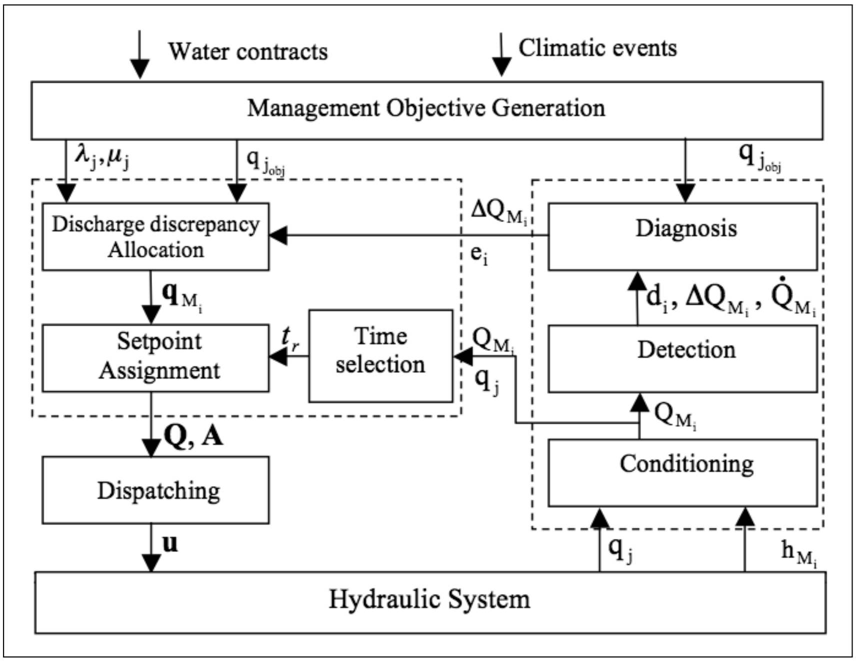

Figure 1: HCA strategy scheme.

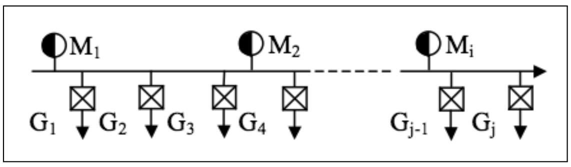

Figure 2: Open-surface hydraulic system equipped with measurement points M_i and gates G_j.

The resource state e_i determination is carried out at the detection period T_e by concurrent hybrid automata (*see* figure 3) designed for each measurement point M_i [4]. The five pertinent states retained correspond respectively to no-discrepancy state e_0, two states where the discharge discrepancy is either positive ($e+$) or negative ($e-$) and constant c, and two states where the discharge discrepancy is either positive ($e+$) or negative ($e-$) and no constant $\neg c$. Transitions between states are defined as conditions on the measured discharge value and variation:

$$\begin{cases} d_i : [|\Delta Q_{M_i}| > th_i], \\ \psi_i : [\Delta Q_{M_i} < 0], \\ \omega_i : \left[\left|\dot{Q}_{M_i}\right| < dth_i\right], \end{cases} \tag{1}$$

with $\Delta Q_{M_i} = Q_{M_i} - \sum_{j=n_i}^{n} q_{j\,obj}$, where Q_{M_i} is the measured discharge, $q_{j\,obj}$ is the management objective of the gate j, n_i the index of the first gate downstream the i^{th} measurement point M_i, n the number of gates, $\dot{Q}_{M_i}$ the estimate derivative of Q_{M_i}, th_i and dth_i respectively the detection and diagnosis thresholds.

The discharge discrepancy allocation is carried out according to the resource state. When the state is e_0, the gate setpoints correspond to their discharge objective $q_{j\,obj}$. When the state is $e \pm \wedge c$, the discharge discrepancy ΔQ_{M_i} is allocated amongst gates, according to their weights λ_j and μ_j, by optimizing, for each measurement point, a cost function. Finally, when the state is $e \pm \wedge \neg c$, the discharge discrepancy is allocated on gate each one on its turn [4]. At each detection date kT_e, the discharge discrepancy allocation leads to the allocation vector $\mathbf{q}_{M_i}^k$:

$$\mathbf{q}_{M_i}^k = \begin{bmatrix} 0\ 0\ \dots\ 0\ q_{n_i}^k\ q_{n_i+1}^k\ \dots\ q_n^k \end{bmatrix}^T \ , \tag{2}$$

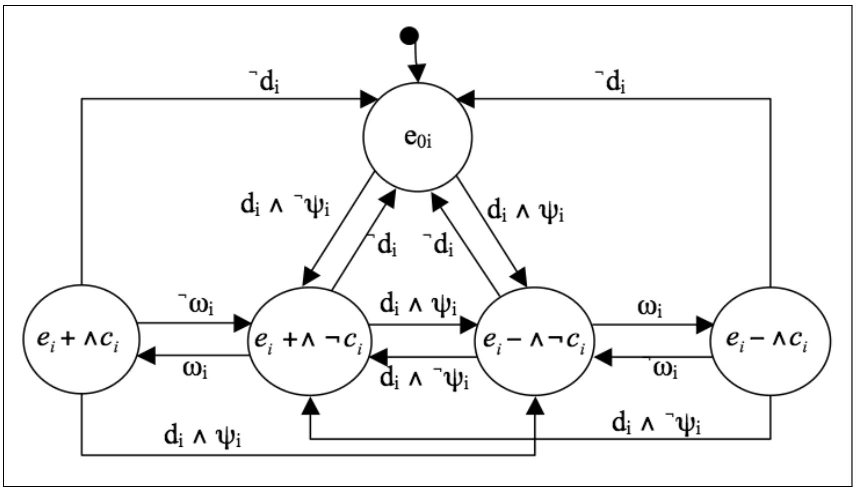

Figure 3: Hybrid automata for the measurement point M_i.

Then, to synchronize the control of the gate with the appearance of lacks or excess of the water due to the disturbances, the setpoints must be assigned at a date taking into account the transfer delays $T_{M_i,j}$ between the measurement point M_i and the gate G_j. It is computed according to the relation (3):

$$T_{M_i,j} = T_{M_i,n_i} + \sum_{r=n_i+1}^{j} t_r \ , \tag{3}$$

where t_r is the time necessary for the water quantity to go from gate G_{r-1} to gate G_r (*see* Figure 4).

The delay t_r depends on the physical characteristics of the hydraulic system and on the discharge value Q_r. Thereafter, the allocation vector $\mathbf{q}_{M_i}^k$ is associated with an allocation dates vector $\mathbf{T}$ arising

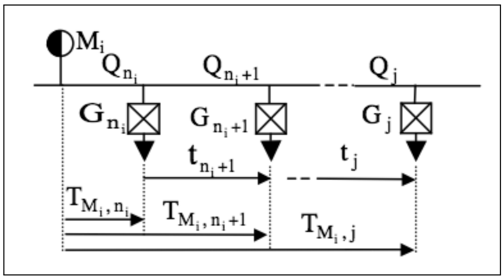

Figure 4: Time delays between M_i and G_j.

from the transfer delay values $T_{M_i,j}$. Finally, taking into account the allocation date, the setpoints are sent to gates periodically. The control period T_c is chosen as a multiple integer of T_e. In the next section, a multimodelling method is proposed to identify the system dynamics for several OM.

3 Multimodelling steps

The modelling of the free-surface hydraulic system dynamics is generally carried out starting from the diffusive wave equation (4) which is obtained by simplifying Saint Venant equations [1].

$$\frac{dQ}{dt} + C\frac{dQ}{dx} - D\frac{d^2Q}{dx^2} = 0 \ , \tag{4}$$

where C and D are respectively the celerity and diffusion coefficients.

The diffusive wave equation can be linearized according to an operating discharge Q_e [7], and the identified celerity and diffusion parameters, denoted C_e and D_e, are expressed as:

$$\begin{cases} C_e = \frac{1}{L^2 \frac{\partial J}{\partial Q_e}} \left[\frac{\partial L}{\partial x} - \frac{\partial JL}{\partial z} \right], \\ D_e = \frac{1}{L \frac{\partial J}{\partial Q_e}}, \end{cases} \tag{5}$$

where L is the surface width, z is the discharge depth, J is the friction slope expressed with the Manning-Strickler relation as $J = \frac{Q^2 P^{\frac{4}{3}}}{K^2 S^{\frac{10}{3}}}$ where K is the Strickler coefficient, P is the wetted perimeter and S the wetted surface. The open-channel systems dynamics can be modelled by transfer functions, as:

$$F(s) = \frac{e^{-\tau s}}{1 + w_1 s + w_2 s^2} \ , \tag{6}$$

where the coefficients w_1, w_2 and the pure delay τ are computed according to the coefficients C_e, D_e, to the open-channel system length X, and to the adimensional coefficient $C_L = \frac{2C_eX}{9D_e}$; if $C_L \leq \frac{4}{9}$, $w_2 = 0$ and $\tau = 0$, if $\frac{4}{9} < C_L \leq 1$, $w_2 = 0$.

This modelling method allows the identification of the free-surface hydraulic system dynamics with good accuracy only around an operating point. However, setpoint assignment must be done for hydraulic system subjected to large operating conditions. Thus, the hydraulic system dynamics must be identified for different OM. Based on the previous modelling method, the multimodelling approach consists in determining the number of OM and their corresponding operating points.

The celerity coefficient C is a very relevant parameter of the hydraulic system dynamics. The model identified for each OM is available as soon as the error on the celerity coefficient is less than a predefined percentage Π_C. Thus, a validity domain is defined for each OM, and the number of OM which are necessary to identify the dynamics with a good accuracy, is determined. To limit the switching between two OM, an interval Δ_C is shared by two successive OM validity domains. The selection of parameters Π_C and Δ_C is carried out taking into account the system dynamics. The multimodelling steps are described

Table 1: Multimodelling algorithm.

Input: C_{min}, C_{max}, Π_C, Δ_C,
Output: C_{id_r}, C_{inf_r}, C_{sup_r},
$C_{med} = \frac{C_{min}+C_{max}}{2}$,
$r = 1$,
For i: $\left\lfloor \frac{ln\frac{C_{min}}{C_{med}}}{ln\frac{1+\Pi_C}{1-\Pi_C}} \right\rfloor + 1$ to $\left\lfloor \frac{ln\frac{C_{max}}{C_{med}}}{ln\frac{1+\Pi_C}{1-\Pi_C}} \right\rfloor$,

$$C_{id_r} = \left(\frac{1+\Pi_C}{1-\Pi_C}\right)^i C_{med} - \frac{sign(i)\Delta_C}{1-sign(i)\Pi_C} \sum_{j=1}^{|i|} \left(\frac{1+\Pi_C}{1-\Pi_C}\right)^{i-sign(i).j},$$

$$C_{sup_r} = (1+\Pi_C)\left(\frac{1+\Pi_C}{1-\Pi_C}\right)^i C_{med} - sign(i)\frac{(1+\Pi_C)\Delta_C}{1-sign(i)\Pi_C} \sum_{j=1}^{|i|} \left(\frac{1+\Pi_C}{1-\Pi_C}\right)^{i-sign(i).j},$$

$$C_{inf_r} = (1-\Pi_C)\left(\frac{1+\Pi_C}{1-\Pi_C}\right)^i C_{med} - sign(i)\frac{(1-\Pi_C)\Delta_C}{1-sign(i)\Pi_C} \sum_{j=1}^{|i|} \left(\frac{1+\Pi_C}{1-\Pi_C}\right)^{i-sign(i).j},$$

$r++$,
EndFor

by an algorithm (*see* Table 1), where the OM are determined starting with C_{med}. This one is computed with the parameters C_{min} and C_{max} corresponding respectively to the minimum and maximum discharges of the system. The algorithm requires the definition of $\lfloor x \rfloor$ which corresponds to the integer part of x, and $sign(x)$ such as $sign(x) = \frac{|x|}{x}$.

Then, according to C_{id_r}, the water elevation z_{id_r} of each r^{th} OM is determined, with one millimeter accuracy, using the digital resolution of the relation (7) with the Newton method.

$$C_{id} = \frac{\sqrt{J}KS^{\frac{5}{3}}}{P^{\frac{2}{3}}L^2}\left[-\frac{1}{2}\frac{\partial L}{\partial z} - \frac{L}{3P}\left(2\frac{\partial P}{\partial z} - 5\frac{P}{S}\frac{\partial S}{\partial z}\right)\right] \ . \tag{7}$$

Then, the water elevation z_{id_r} value is used to compute the discharge Q_{id_r} with the relation (8). The same steps are used for parameters C_{inf_r} and C_{sup_r} to obtain the domain validity boundaries of the OM: $[Q_{inf_r}; Q_{sup_r}[$.

$$Q_{id_r} = \frac{\sqrt{J}KS^{\frac{5}{3}}}{P^{\frac{2}{3}}} \ . \tag{8}$$

Finally, the celerity and diffusion coefficients C_{id_r} and D_{id_r} (5), and the transfer function parameters w_1, w_2 and τ (6) are computed according to the discharge Q_{id_r}. These parameters allow for the computation and the selection of the transfer delays of each OM. This is described in the next section.

4 Transfer delay identification

The hydraulic systems consist of several reaches, *i.e.* a part between two measurement points (*see* Figure 5.*a*), each reach being composed of Open-Channel Reach Section (OCRS), *i.e.* a part between two gates, or between a measurement point and a gate or between a gate and a measurement point. Thus, the reach dynamics are modelled with a concurrent Hybrid Automaton cHA (*see* Figure 5.*b*) composed of several HA defined for each OCRS. This representation is directly inspired from the concurrent hybrid automata proposed in [5, 6]. In the study case, the cHA is deterministic. The input of the first automaton HA_{o_i} of the first OCRS following M_i is the discharge measured on M_i. The input of the second automaton, HA_{o_i+1} is the discharge downstream HA_{o_i} minus q_{n_i}, the discharge setpoint assigned to the gate between this two OCRS.

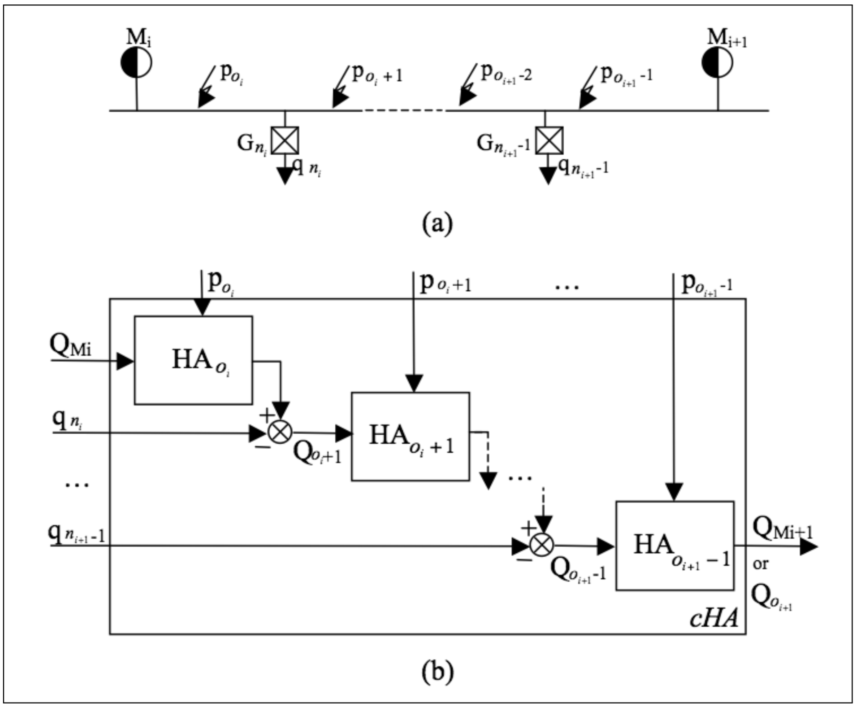

Figure 5: (a) A canal reach and (b) its modelling by concurrent hybrid automaton (cHA).

The OCRS dynamics (*see* Figure 6.*a*) are modelled using the multimodelling method described in the previous section, and are represented by a HA (*see* Figure 6.*b*). Each state corresponds to one OM identified as transfer function F_l given by the relation (6). The transition conditions are defined according to the upstream discharge Q_o and the l_{th} OM boundaries Q_{inf_l} and Q_{sup_l}.

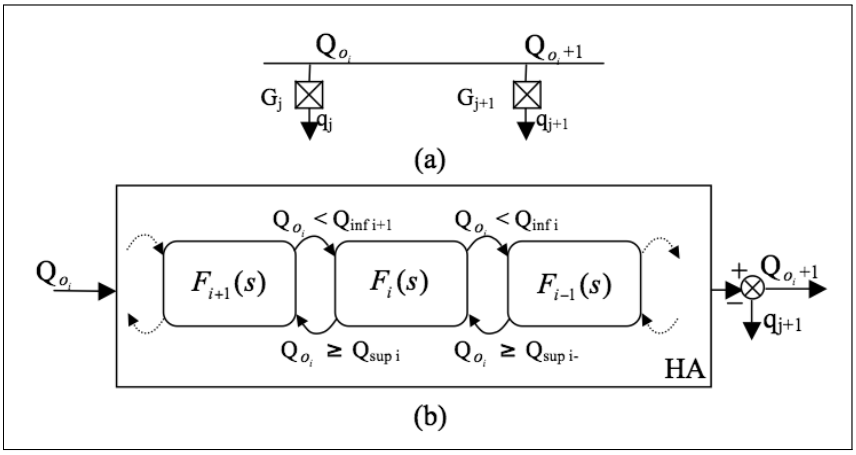

Figure 6: (a) OCRS with index o and (b) its modelling by Hybrid Automaton (HA).

For each OM, the transfer delay t_r is obtained from the step response of the corresponding transfer function. It is chosen as the time value for which Π_Q percent of step is reached. The percentage Π_Q can be tuned from simulation. In the next section, the HCA strategy is used to valorize water quantities of a hydraulic system subjected to large operating conditions.

Table 2: Geometrical characteristics of each OCRS.

OCRS	$B\ [m]$	f	$X\ [m]$	$J\ [rad]$	$Q_{min}\ [m^3/s]$	$Q_{max}\ [m^3/s]$
1	5.73	0.79	204	7.10^{-4}	0.8	10
2	5.09	0.96	702	7.10^{-4}	0.8	9
3	5.21	0.95	562	6.10^{-4}	0.7	7
4	3.72	0.94	1360	5.10^{-4}	0.6	5

5 Simulation results

The effectiveness of the proposed strategy is shown by simulation on the first reach of the Neste canal located in Gascogne, a french southwestern region. It is composed of one measurement point M_1, three gates G_1 to G_3 and one output considered as a non-controlled gate G_4 (*see* Figure 7). This canal reach is composed of four OCRS with trapezoidal profile characterized by the bottom width B, the average fruit of the banks f, the profile length X and the reach slope I (*see* Figure 8). The geometrical characteristics and operating conditions of each OCRS are detailed in Table 2. The fourth OCRS, between G_3 and G_4, is not modelled, because gate G_4 is not locally controlled. In the case of a trapezoidal profile, celerity and diffusion coefficients C and D are expressed by the following relation:

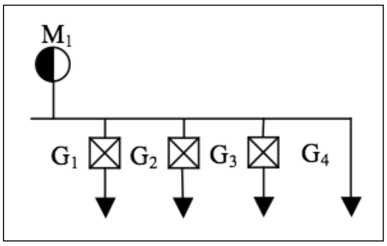

Figure 7: First reach of the Neste canal.

$$\begin{cases} C = \frac{Q}{L^2}\left[-f + \frac{L}{3}\left(\frac{2B}{Pz} + \frac{5L}{S} - \frac{2}{z}\right)\right] \\ D = \frac{Q}{2LJ} \end{cases}, \quad (9)$$

where $L = B + 2fz$, $S = zB + fz^2$, $P = B + 2z\sqrt{1+f^2}$.

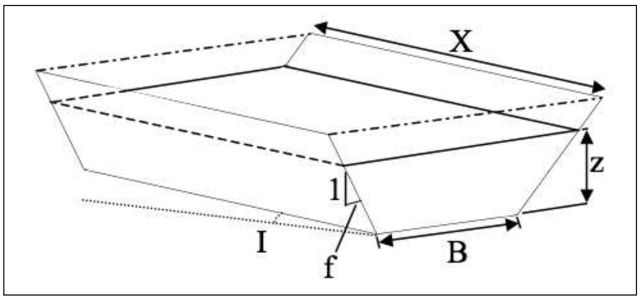

Figure 8: Geometrical characteristics of a trapezoidal profile.

The multimodelling steps which are carried out with $\Pi_C = 15\,\%$ and $\Delta_C = 0.1$, lead to the determination of three OM for each OCRS. Their corresponding transfer function parameters are given in Table 3. The transfer delays t_r are computed with a value $\Pi_Q = 63\,\%$. This value, chosen by simulation, leads to the best water quantity valorization.

Table 3: Multiple models of each OCRS.

OCRS	Q	Q_{min} $[m^3/s]$	Q_{max} $[m^3/s]$	w_1	w_2	τ	t_r $[s]$
	1.6	0.8	2.4	161	0	0	160
1	3.2	1.9	5.2	128	0	0	130
	7.7	4.3	10	100	0	0	100
	1.4	0.8	2.2	424	24331	145	575
2	3	1.7	4.9	364	0	89	450
	7.4	4.1	9	355	0	0	355
	1.2	0.7	1.9	377	0	129	505
3	2.4	1.5	4	357	0	29	385
	5.8	3.2	7	320	0	0	320

The Neste canal is supplied with water corresponding to an objective discharge equal to $7\,m^3/s$. The objective discharges and the weights of each gate are displayed in Table 4. The canal is subjected to strong withdrawals of $3\,m^3/s$ and $4.5\,m^3/s$ upstream to M_1 (*see* Figure 9.*a*). This scenario was selected among several simulated scenarii, because it reveals accurately the inversion phenomenon of the discharge tendency. The HCA strategy goals consist in the allocation of the water resource amongst the gates according to their weights, and in the minimization of the discharge discrepancy at gate G_4. The detection and control periods are selected as $T_e = 12\,s$ and $T_c = 120\,s$. In Figure 9, the simulation results are shown in continuous line when the transfer delay selection method is used, and in dashed line when the transfer delays are fixed to $100\,s$ for the first OCRS, to $355\,s$ for the second and to $320\,s$ for the third. These transfer delay values are selected according to the operating point of each OCRS, *i.e.* $7\,m^3/s$, $5\,m^3/s$ and $4\,m^3/s$. They correspond to the third OM of each OCRS.

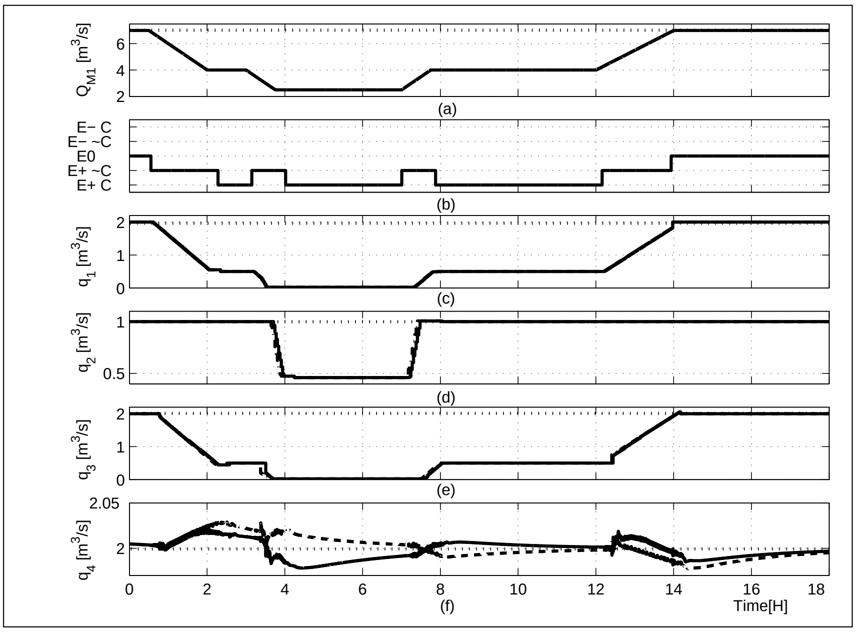

Figure 9: Discharge Q_{M_1} (continuous line) and objective discharge Q_{M_1obj} (dotted line) (a), resource states (b), setpoints assigned q_j (continuous line when the delay selection method is used, dashed line in other case) and objective discharge q_{jobj} (dotted line) to G_1 (c), G_2 (d), G_3 (e) and discharge at G_4 (f).

Table 4: Gate objective discharges q_{jobj}, gate weights λ_j and μ_j, and minimum and maximum discharges $q_{j_{min}}$ and $q_{j_{max}}$.

Gate	G_1	G_2	G_3	G_4
q_{jobj} $[m^3/s]$	2	1	2	2
λ_j	10	10	4	–
μ_j	10	4	10	–
$q_{j_{min}}$ $[m^3/s]$	0.02	0.1	0.02	0.15
$q_{j_{max}}$ $[m^3/s]$	3.6	4.5	3.5	3

Table 5: Criteria computed when the transfer delay selection method is or not used.

Criterion	min(q_4 $[m^3/s]$)	max(q_4 $[m^3/s]$)	V $[m^3]$
With selection method	1.9778	2.0451	541
Without selection method	1.9763	2.0455	602

Figure 9 displays the discharges Q_{M_1} in (a), the corresponding discharge states in (b), the setpoint assigned at gate G_1 in (c), G_2 in (d), G_3 in (e) and the resulting discharge at G_4 in (f). The resource in lack measured on M_1 is allocated on gates G_1 and G_3, as long as their setpoints are upper than their respectively minimum discharge characteristics $q_{j_{min}}$, otherwise it is allocated on gate G_2 (*see* Figures 9.*c*, 9.*d* and 9.*e*). Thus, the gates G_1 and G_3 are controlled between the 1^{st} and 4^{th} hours, and the gate G_2 between the 4^{th} and 7^{th} hours.

During all the simulation time, the discharge on G_4 is close to the objective value of $2\,m^3/s$ (*see* Figure 9.*f*). However, when the transfer delay selection method is not used, the setpoints are always assigned too early. Consequently at G_4, the discharge is in excess when the water resource decreases on M_1, and the discharge is in lack when the water resource increases on M_1. The tendency of Q_{M_1} discharge is inverted at G_4 the end of the canal reach.

The use of the transfer delay selection method improves the performances of the HCA strategy and maintains the tendency. The maximum and minimum discharges reached at G_4 and the water volume V which was not allocated, are displayed in Table 5. The maximum discharge discrepancy at G_4 corresponds to 2.26 % of the objective discharge q_{4obj} when the transfer delay selection method is used and to 2.28 % in the other case.

6 Conclusion

The HCA strategy is adapted to valorize the water resource by allocation and setpoint assignment of open-surface hydraulic system submitted to strong disturbances. A multimodelling method is proposed to identify by a determined number of linear models the open-surface hydraulic systems. Then, a transfer delay selection method is proposed to take into account variable transfer delays by the selection of the right setpoint assignment date according to the system dynamics and to the measured discharge. Finally, the HCA strategy performances are shown by simulation on the first reach of the Neste canal subjected to large operating conditions and to strong disturbances. The study of control stability proof of the HCA strategy is a future goal.

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Eric Duviella
Ecole des Mines de Douai
Département Informatique et Automatique
941, rue Charles Bourseul, BP 10838, 59508 Douai Cedex, France
Phone: 33.3.27.71.21.02 ; Fax : 33.3.27.71.29.80
E-mail: duviella@ensm-douai.fr
Pascale Chiron
Laboratoire Génie de Production
Ecole Nationale d'Ingénieurs de Tarbes
47, Avenue d'Azereix, BP1629, 65016 Tarbes Cedex, France
Phone: 33.5.62.44.27.69 ; Fax : 33.5.62.44.27.08
E-mail: pascale.chiron@enit.fr
Philippe Charbonnaud
Laboratoire Génie de Production
Ecole Nationale d'Ingénieurs de Tarbes
47, Avenue d'Azereix, BP1629, 65016 Tarbes Cedex, France

Phone: 33.5.62.44.27.34 ; Fax : 33.5.62.44.27.08
E-mail: philippe.charbonnaud@enit.fr
Received: January 29, 2007
Revised: May 22, 2007

Eric Duviella was born in France in 1978. In 2001, he received the Diploma in engineering from the National Engineering School, Tarbes, France. He received the Ph.D. degree from the Institut Polytechnique, Toulouse, France, in 2005. Since 2007, he has been an Assitant Professor in the Department Informatic and Automatic of the Ecole des Mines, Douai, France. He has published around 15 papers in journals or international conferences. His research interests include modelling, hybrid dynamical systems, supervision, reactive control strategy.

Pascale Chiron was born in France in 1961. She is assistant professor at the Ecole Nationale d'Ingénieurs de Tarbes, France since 2000. She has obtained his PhD in 1989 at Ecole Centrale in Nantes on 'matching and similarity criterion in medical imaging'. Now, she is involved in the theme 'Planning, Control, Supervision and Distributed Simulation' in the 'Automated Production' Group of Laboratoire de Génie de Production. Her domains of interest are modelling and simulation for system control.

Philippe Charbonnaud was born in France in 1962. Since 2003, he is full Professor at the Ecole Nationale d'Ingénieurs de Tarbes. He is coordinator of the Spanish-French project GEPREDO dealing with the management of hydrographical networks and the predictive management of the water resource. The main contribution lies in the development of a hybrid control method applied to distributed systems. His main topic of interest concerns the real-time decision support systems, and more particularly supervision and control accommodation of distributed systems.

International Journal of Computers, Communications & Control
Vol. II (2007), No. 3, pp. 252-268

Extraction of Critical Scenarios in a Railway Level Crossing Control System

Malika Medjoudj, Pascal Yim

Abstract: This paper deals with the safety of the level crossing control system. We propose one way of the safety evaluation witch consist on the extraction of feared scenarios in the Petri net model of the system. We use ESA_PetriNet tool (Extraction Scenarios & Analyzer by Petri Net model) that was developed in the aim of extraction of feared scenarios in computer-controlled systems. These scenarios characterize the sequences of actions leading to dangerous situations. The taking into account of the failures, the temporal constraints and partially the continuous dynamic (by temporal abstraction) of the system makes it possible to respect the order of appearance of the events in the generated scenarios.
Keywords: Critical scenarios, hybrid dynamic, level crossing control system, safety, temporal Petri net

1 Introduction

One way to evaluate the safety [2] of complex system such as a level crossing control system (*lccs*) is the extraction of critical scenarios leading to the feared states. A qualitative analysis method of safety, aiming the extraction of all the critical scenarios from a Petri Net model [5] of computer-controlled systems was developed by [3]. This approach witch is an extension of a method developed by [6] but which operated only on the discrete aspect of the system, takes into account the continuous aspect of the system and the temporal specifications. This approach based on linear logic [7] determines more precisely the exact conditions of the occurrence of the feared event, i.e what has led the system to leave its normal operation and to evolve into the feared state. The originality of this approach is that the order of occurrence of the events is taken into account, and impossible scenarios with respect to continuous dynamics and temporal specifications of the system are eliminated. The automation of all stages of the process has led to the development of ESA_PetriNet tool (Extraction & Scenarios Analyser by PetriNet model) [4] that has been interfaced with TINA tool (Time Petri Net Analyzer) [8].We will use in this paper ESA_PetriNet tool to extract dangerous scenarios from the level crossing benchmark published by [10].

We will present the method of extraction of feared scenarios and the basic of the algorithm in section 2, the level crossing control system in section 3, its Petri Net modelling in section 4, the use of ESA_PetriNet tool to generate the critical scenarios in the section 5 and we will end by a conclusion.

2 Method of extraction of feared scenarios

The application of this method requires the modelling of the system by a time Petri Net model and identifying the places of nominal behaviour. The appropriate Petri net modelling of computer-controlled systems is a Predicate Transitions Differential Stochastic Petri net (PTDS Petri net) as they are generally hybrid (discrete and continuous dynamics) and there safety analysis require taking into account failures. A temporal abstraction is necessary to translate this model to a time Petri net by associating to the transitions a temporal interval of firing corresponding to the time which the system can spend to reach the state in question. A preliminary analysis will refine fields of variables according to various accessible markings by reasoning on the invariants of places. Indeed, the invariants of places determine the possible dynamics, and which other places can be simultaneously marked when a token is present in a given place.

2.1 Principal

The method of extraction of feared scenarios is made up of two steps [3]: a backward reasoning and a forward reasoning. The backward reasoning takes as an initial marking in the reversed Petri net model (the initial Petri net in which all the arcs are reversed), the only target state (feared) and seeks exhaustively all the scenarios making it possible to consume the initial marking (feared state since forward reasoning) and reach a final marking composed only of places associated to the normal operation. The forward reasoning takes as an initial state these places of normal operation in the initial Petri net model. The objective is to locate the junctions between the feared behaviour and the normal operation of the system as well as the conditions implied in these junctions. Thus we have not only the explanation of the dangerous behaviour but also of strategies allowing its avoidance. A significant point of the method is that the context in which occurred the feared event is enriched gradually. The enrichment (of marking) consists on putting tokens in empty places in the Petri net model when it is necessary to make evolve the system and generate scenarios. The invariant of places are used as a mechanism of checking the coherence of the enrichment of marking. Indeed the new tokens added are removed if they do not respect the dynamics of the system.

Each scenario is given in form of a partial order between the events necessary to the appearance of the feared event what differs from a failure tree, which gives a whole of static combinations of the partial states necessary for obtaining the feared state.

2.2 Dealing with continuous dynamics by temporal abstraction

This method takes into account the conditions associated to the firing of certain transitions. These conditions are thresholds involving continuous variables. By temporal approximation of the hybrid dynamics, these thresholds are transformed to durations, which correspond to time that the system puts to reach when the transitions are enabled. From a qualitative point of view, the objective is to determine the firing order of the transition. Thus, when we enrich the marking, we can find situation where two transitions *t1* and *t2* are enabled if only the ordinary Petri net is considered, but whose are such as *t1* will be always fired before *t2* if the temporal abstraction is also considered. In the generation of the scenarios only the firing of *t1* will be considered since that of *t2* before *t1* would be in fact incoherent with the continuous dynamics. This appears in the form of a priority: if *t1* and *t2* are enabled, only the case of *t1*, priority, is examined. The taking into account of these precedence relations coming from the continuous dynamics and not specified by the ordinary Petri net allows to reduce the number of scenarios generated by eliminating a certain number of incoherent scenarios with respect to continuous dynamics.

Let us consider an example. In Figure 1 we suppose that the differential-algebra system associated to the place *P1* guarantees that the variable x is increasing. We associate to the transition *t1* the threshold $x = v1$ and to the transition *t2* the threshold $x = v2$ with $v1 < v2$. Finally, we suppose that when the token arrives in the place *P1* we have always $x < v1$. So, if the place *P3* is marked, the transition *t1* will be fired before *t2* since the threshold associated to *t1* is lower than that of *t2*. In this case we don't consider the scenario associated to the firing of *t2*. On the other hand, if *t3* is already fired for example if we consider that *t1* is a stochastic transition corresponding to a failure (place *P3* empty) and if the place *P2* is marked, *t1* cannot be fired and then *t2* will be fired.

In the example above, finally only one type of scenarios is examined, those for which the transition *t2* is fired after *t3*. So, there is a precedence relation between the firing of *t3*, which empties the place *P3* and that of *t2*, however there is no place connecting *t3* to *t2*. This precedence relation is so, a consequence of continuous dynamics and thresholds associated to transitions *t1* and *t2*. We are talking in this case about indirect precedence relation and about indirect causality. The direct precedence relations and causality are those that are highlighted by the only Petri net, i.e. by the only discrete aspect.

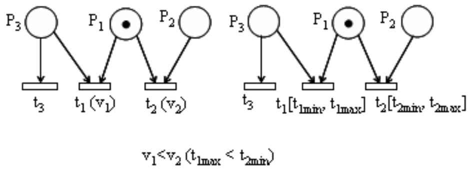
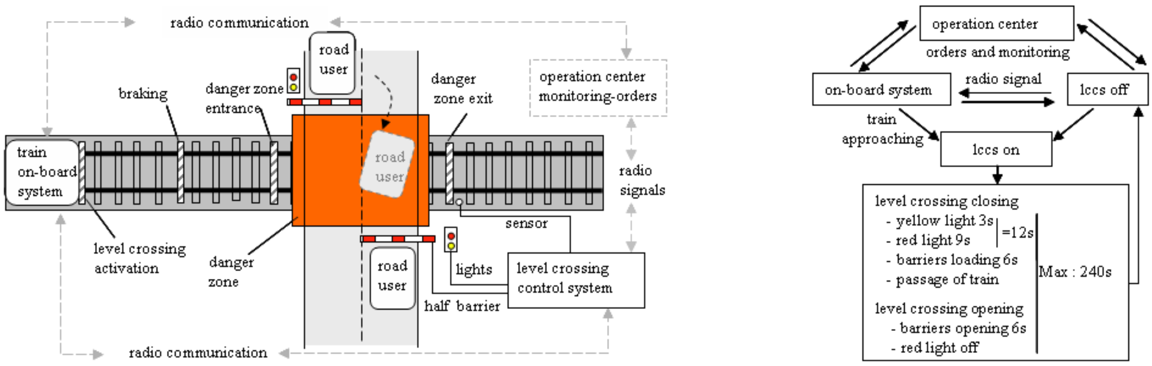


Figure 1: Temporal abstraction and priority due to thresholds of transitions

2.3 ESA_PetriNet tool

ESA_PetriNet tool uses two output files of TINA tool as input files. The first file is a textual description of the Petri net model of the system and the second contains the invariant of places. The indirect precedence between certain transitions firing resulted by the temporal abstraction of continuous dynamics, is expressed in the algorithm in the form of rules of priority (a certain transition is not fired if another is enabled). The transition time interval of TINA tool permits to express this rule of priority. If we take the example of Figure 1, if there is an intersection between the time interval associated to transitions *t1* and *t2*, they will have the same priority of firing and the two scenarios will be generated. We note that only one execution of the algorithm generates automatically several scenarios. All the possible and coherent scenarios with respect to the continuous dynamics and the temporal constraints of the system are generated.

3 Level crossing control system case study



(a) General view (b) Nominal behaviour

Figure 2: Railway level crossing

3.1 General description

This case study concerns a decentralized radio-based railway level crossing control system taken from a realistic specification of a new radio-based train control system, which has been developed for the German Railways. It is presented by [10] and studied by [9] using a transformation of a p-time Petri net model of the system to automata in the purpose of avoiding forbidden states. This modelling is of a high level of abstraction and does not take into account the failures of the system.

Although, simplification has been made in the presentation of this example, it remain especially interesting as it is well known by the railway specialists, takes into account software and hardware specification, hybrid dynamic and temporal constraints. Our aim is a whole modelling of the system using a Petri nets model by taking into accounts the hybrid dynamic, temporal constraints and failures. Then, applying the method described above to extract critical scenarios.

3.2 Composition of the system and specification

The radio-based level crossing control system is used in an intersection area between a single track railway line and a road as illustrated in Figure 2a. To avoid collision, trains and road traffic must not enter at the same time this crossing zone called danger zone. The level crossing is controlled by means of signals radio communication between a train-borne control system (on-board system), a level crossing control system and an operation centre which supervises interactions between the two preceding components. It is important to note that transmission times on the network may vary and radio telegrams may be lost.

The railway crossing is equipped with half barriers, a red and a yellow road traffic light. Road users shall stop at the level crossing if possible when the yellow light is shown and must stop when the red light is shown as the level crossing is closed for road users in this case. The yellow light and the red light never must be shown together and when both are off the danger zone can be crossed by road users. The traffic lights and barriers at the level crossing are controlled by the level crossing control system which will be activated (turn on) with the approach of a train to the level crossing. When the level crossing control system is activated, it carries out a sequence of actions at a specific timing to ensure a safely closing of the crossing and the danger zone to be free of road traffic. First, the yellow light is switched on, then after 3 seconds it is switched off and the red light is switched on. After 9 seconds the barriers are started to be lowered within a maximum time of 6 seconds. If the barriers have been completely lowered within this time, the level crossing control system signals the safe state of the level crossing and the train can cross it. When the train has completely passed the danger zone, the level crossing may be opened for road traffic. In the level crossing opening phase, the barriers are first opened then the red traffic light and the level crossing control system are switched off.

The half barriers are used to block the entry lane on either side of the level crossing. As there are no barriers for the exit lanes, imprudent road users may enter the crossing area on the opposite lane if the closure time of the level crossing exceeds 240 seconds. A general view of the normal operating of the level crossing control system is given in Figure 2b. The train is equipped on board by a route map which contains the positions of danger points at level crossings and provides information for the train (lineside equipment or signal staff) when or where to send an activation order to the corresponding level crossing control system. The train on-board system sends so a radio message to the level crossing control system in order to close the level crossing in time and let the train pass through without any delay or braking action. It will also set a breaking curve for speed supervision making the train stop at the danger point in a failure situation. The level crossing control system acknowledges receipt of the activation order to the train. After receipt of the acknowledgement the on-board system waits the necessary time for the closing of the level crossing, then sends a status request to the level crossing control system. If the level crossing is in a safe state it will be reported to the train which allows cancelling the breaking curve and safely pass over the level crossing. The vehicle sensor at the rear of the level crossing will be triggered allowing the opening of the level crossing.

3.3 Possible Failures

A main cause of failures is the malfunctioning of sensors or actuators. The main physical structures, communication systems and the control systems themselves may be failed. Failure may occur at any time. Defective devices will be repaired after some time but will not take place when a train approaching or passing the level crossing in case of non recoverable failure. In this case study, only a limited number of failures are taken into account:

- Failure of the yellow or the red traffic light
- Failure of barriers (actuators)
- Failure of vehicle sensor
- The delay or loss of telegrams on the radio network

The traffic lights and the vehicle sensor are constantly supervised and defect is immediately reported to the level crossing control system. Failure of the barriers can only be detected by time-out when barriers fail to reach upper or lower end position in time or at all.

3.4 Behaviour of the control system under failure

The level crossing control system detects the occurrence and repair of failures of traffic lights and vehicle sensor and immediately reports them as an event to the operations centre. Train operation is not suspended on the affected track section until repair.

When the train sends a status request, if in the sequel it does not receive the status report with the safe state of the level crossing before entering its breaking curve the on-board system will apply the breaks until the status report will be received or the train has come to a stand still. If the status report is received before stand still, breaks are released and train can continue its run. If not a request is prompted on the driver's display to make sure that the level crossing can be passed safely and to confirm the safe state on the display. If meanwhile the status has been received the message is cancelled from the display, the break are released and the driver does not need to confirm anymore. Otherwise the driver has to confirm the safe state of the level crossing in order to release the breaks and continue its run.

The train supervises a maximum arrival time of 240 seconds to avoid long waiting times of road users. If the train detects that it cannot arrive at the level crossing within a specified time and still is able to stop before the danger point it cancels the activation order by sending a deactivated order to the level crossing. In this situation the train discards any information received from the level crossing and supervises a breaking curve ending at the danger point. The level crossing will be opened upon receipt of the deactivation order. The driver has to confirm as described above the safe state before passing unclosed level crossing.

The level crossing control system will not be activated if the red traffic lights or the vehicle sensor are defective and it will not send an acknowledgment to the train. If the level crossing control system has been activated, a minimum green time is considered since the last deactivation of the level crossing before switching on the yellow light for 3 seconds. If the yellow traffic light becomes defective either before or during the yellow light period, the traffic lights are switched to red and the red light period of 9 seconds is extended correspondingly by the messing time of the yellow light period. If the red traffic light fails after activation of the level crossing control the closing procedure has to be cancelled unless the barriers have yet begun to be lowered. The failure state of the level crossing must be reported if the barriers fail to be completely lowered within a maximum duration of 6 seconds or if in the meantime the red traffic light has become defective. The current status of the level crossing will be reported to the train upon request.

If the vehicle sensor becomes defective the level crossing control system can not be deactivated anymore by passing train. Consequently the barriers remain lowered and the red traffic light remains switched on. However, the level crossing control system supervises a maximum closure time starting from the red light be switched on. The exceeding of the maximum closure time will be reported to the operation centre by the level crossing control system. The operation centre finds out, whether the train has yet passed the level crossing or not. In the first case, the operations centre sends a deactivation order to the level crossing. Otherwise the train is still approaching or just running on the level crossing and the rules for late arrival at the level crossing apply as described above.

3.5 Feared events

There are many feared events in the system, but we will interest only to the catastrophic one: the collision, it means the presence of a train and a road user in the danger zone at the same time.

4 Modelling

Petri nets have been used with success as a formal model for traffic signal control [11], urban traffic control [12], and level crossing control system [13] aiming security.

This section deals with the modeling of the level crossing control system by a t-time Petri net model (temporal intervals associated to transitions). Although the appropriate abstraction of certain dynamics of the system is a pt-arc-time Petri net (temporal intervals associated to arcs related places to transitions) or a P-time Petri net (temporal intervals associated to places) we have chosen the t-time Petri net model as the principal of the ESA-PetriNet tool is based on the priority of firing of conflictive transitions.

4.1 General view

In the general view given in Figure 3a, *msgi* represent radio messages. The message *msg1* is sent by the train to the *lccs* to switch on when the on-board system detects the approaching of a level crossing. The message *msg2* represents the receipt acknowledgement of the activation order. The message *msg3* corresponds to the status request of the level crossing and the message *msg4* represents the safe state of the level crossing reported to the train.

Note that, transmission times on the radio network may vary and messages may be lost as represented in Figure 3b. The radio message is represented by the place *msgi*. The time interval *[dmi, dMi]* associated to the out put transition of place *msgi* means that the transmission time may vary between the minimal value *dmi* and the maximum one *dMi*. According to the radio message and the crossing state, the train will pass with out braking, with braking, come to a stand still or stop.

The *dely1* corresponds to the maximum closure time of 240 seconds supervised by the level crossing control system starting from the red lights be switched on. Crossing the danger zone by the train and the road user are respectively represented by *dz1* and *dz2*. The message *msg7* corresponds to the deactivation order of the opening of the level crossing sent by the train when it detects that it can not arrive at the level crossing within the maximum supervised arrival time of 240 seconds.

In this paper, we will interest to the feared scenario corresponding to the presence of a train and a road user in the danger zone at the same time (collision). This is represented by the Petri net model of the Figure 3c, where the transition *E_fail* representing the feared event can be fired only when both places *dz1* (presence of a train in the danger zone) and *dz2* (presence of a road user in the danger zone) are marked. Place *S_fail* represents the feared state (collision).

Figure 4 represents a general view of different radio messages exchanged between the on-board system and the level crossing control system. To simplify the case study, we have not presented the radio messages exchanged with the operations centre like the failure and repair of different devices.

4.2 Petri net model of the level crossing control system

A detailed view of the *lccs* is given in Figure 5. Note that messages *msg1* and *msg2* are the same as in Figure 3. Places *lccs_off* and *lccs_on1* correspond respectively to the deactivation and activation mode of the level crossing control system. Transition *on1* will be fired after reception of the activation order *msg1*, to switch to the activated mode if the vehicle sensor (place *s3_ok*) and the red traffic light (place *red_off*) are not defective. The level crossing control system will be deactivated if the place *lccs_on2* or *lccs_on3* is marked. Place *lccs_on2* will be marked when the barriers are opened after closure. Place

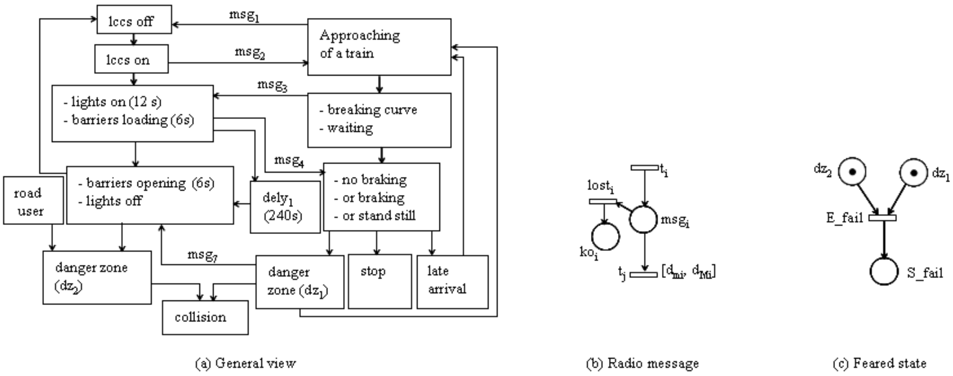


Figure 3: General view of the model

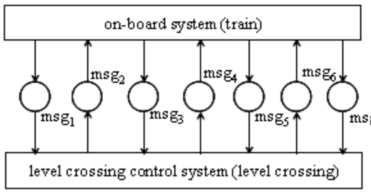


Figure 4: General view of radio messages exchanges

lccs_on3 corresponds to the cancelling of the closing procedure if the red traffic light fails after the activation of the level crossing control system. The green time passed since the last deactivation of the level crossing will be described in section 4.7

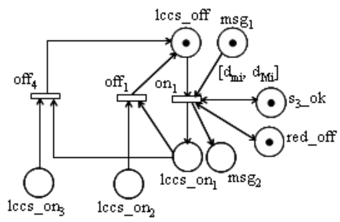


Figure 5: Petri net model of the level crossing control system

4.3 Petri net model of the yellow light

Place *yell_off1* in Figure 6a represents the *mode off* of the yellow light. It will be switched to the activated mode (place *yell_on*) when the level crossing is activated (place *lccs_on1* marked). After 3 seconds of the activation of the yellow light, it will be deactivated (marking of places *yell_off1* and *yell_off2*). The yellow light can fail in the deactivated mode (*yell_ko1*) or in the activated mode (*yell_ko2*). Figure 6b represents the Petri net model of failure and repair of the devices that may be faired in the system (traffic lights, vehicle sensor and barriers). Failure and repair are represented respectively by the stochastic transition *faili* and *repi*. While failure may occur at any time, repair will not take place when there is a train approaching or passing the level crossing. This is represented by the minimal value of reparation *dri*.

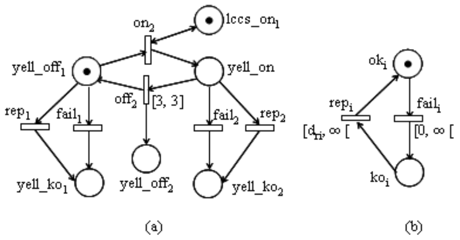


Figure 6: Petri net model of the yellow light

4.4 Petri net model of the red light

The model is similar to the yellow light. The red traffic light can be in *mode off* (place *red_off*), *mode on* (place *red_on*), fail before activation (place *red_ko1*) or after activation (place *red_ko2*). We note three cases of the activation mode of the red light represented in Figure 7 according to the time activation of the yellow light. In case (a), the yellow light was activated for 3 seconds before the lights traffic switch to the red. In this case the place *yell_off2* is marked and transition on3 can be fired to switch to the activated mode of the red traffic for 9 seconds. This delay is represented by the time interval *[9, 9]* related to the transition *cls1* that corresponds to the order of lowering barriers. The place *dely1* is the same as described in Figure 4. The red traffic light can be deactivated when the barrier will be completely opened represented by the place *br4*. Place *lccs_on2* is the same as described in Figure 5. In case of Figure 7b, the yellow traffic light becomes defective before the yellow light period (place *yell_ko1*). In this case the red traffic light period of 9 seconds is extended to 12 seconds to take into account the yellow light period. This is represented by the time interval *[12, 12]* attached to the transition *cls2* that corresponds to the order of lowering barriers. In case (c), the yellow traffic light becomes defective during the yellow light period (place *yell_ko2*). In this case, the red light period of 9 seconds is extended correspondingly to the missing time of the yellow light period. This is represented by the time interval *]9, 12[* associated to the transition *cls3*. Transitions and places concerning the barriers will be described in section 4.6.

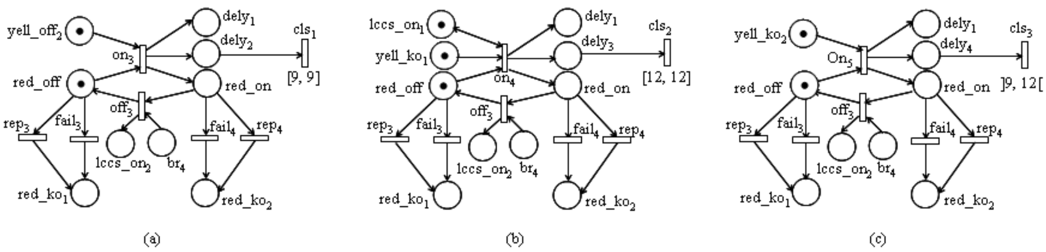
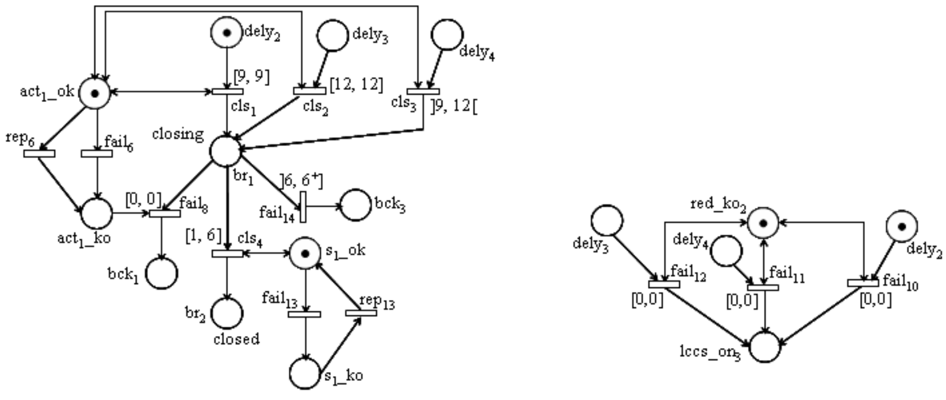


Figure 7: Petri net model of the red light

4.5 Petri net model of sensors

The system contains three sensors (*si*): a sensor for the barriers loading, a sensor for the barriers closing and a vehicle sensor. The Petri net model of a sensor *si* is similar to the model given in Figure 6b. As described in this figure, a sensor *si* can be defective and repaired by firing transition *repi*.



(a) Closing (b) Cancelling

Figure 8: Petri net model of barriers closing and cancelling of the closing

4.6 Petri net model of barriers (actuators)

Closing

To simplify the Petri net model, we assume that Figure 8a represents the closing of the two half barriers which are actuated by an actuator for opening (place *act1_ok*). Note that places *dely2*, *dely3* and *dely4* are the same as in Figure 7. The place *br1* represents the continuous dynamic of the closing barriers. Its temporal abstraction is represented by the temporal interval *[1, 6]* attached to the transition *cls4* as the maximum closure time is 6 seconds and we suppose that the minimum closure duration is 1 second. If the opening actuator fails before the barriers have completely closed (*act1_ko* marked), the immediate transition *fail8* will be fired and the dynamic of place *br1* will be interrupted. This corresponds to the blocking of the barriers in opening represented by the marking of the place *bck1*. If the sensor that detects that the door is closed is defective (marking of place *s1_ko*), the transition *cls4* can not be fired and the level crossing is considered in a failure state. This is represented by the firing of transition *fail14* in the temporal interval *]6, 6+]*.

Figure 8b represents the cancelling of the closing procedure if the red traffic light fails after the activation of the level crossing control system before the barriers begun to be lowered. This is represented by firing the immediate transitions *fail10*, *fail11* or *fail12* according to the activation mode of the red light represented in Figure 7. Place *lccs_on3* corresponding to the order of deactivation of the level crossing will be marked.

Opening

The Petri net model is similar to the Petri net model of closing. The dynamic of the barriers opening is determined by the position of the actuator for opening (place *act2_ok*). The dynamic of the opening is represented by the temporal interval *[1, 6]*. This dynamic can be interrupted if the actuator fails before the end of the opening procedure. In this case the immediate transition *fail9* will be fired and the place *bck2* corresponding to blocking on opening will be marked. If the sensor of opening is defected (place *s2_ko* marked) the transition *fail15* will be fired after 6 seconds. We note four cases for barriers opening represented in Figure 9. Case (a) corresponds to the nominal behaviour. In this case, the vehicle sensor is not defective (place *s3_ok*) and the train has completely passed the danger zone in time (marking of the place *trn12* as it will be detailed in section 4.7). The maximum closure time is represented by the temporal interval *[0, 240]* associated to the transition *opn1*. In case (c), the train detects that it can not arrive to the level crossing in time and it sends a deactivation order to open the level crossing. This is represented by the message *msg7*. In case (b) and (d) the vehicle sensor is defective and the level crossing

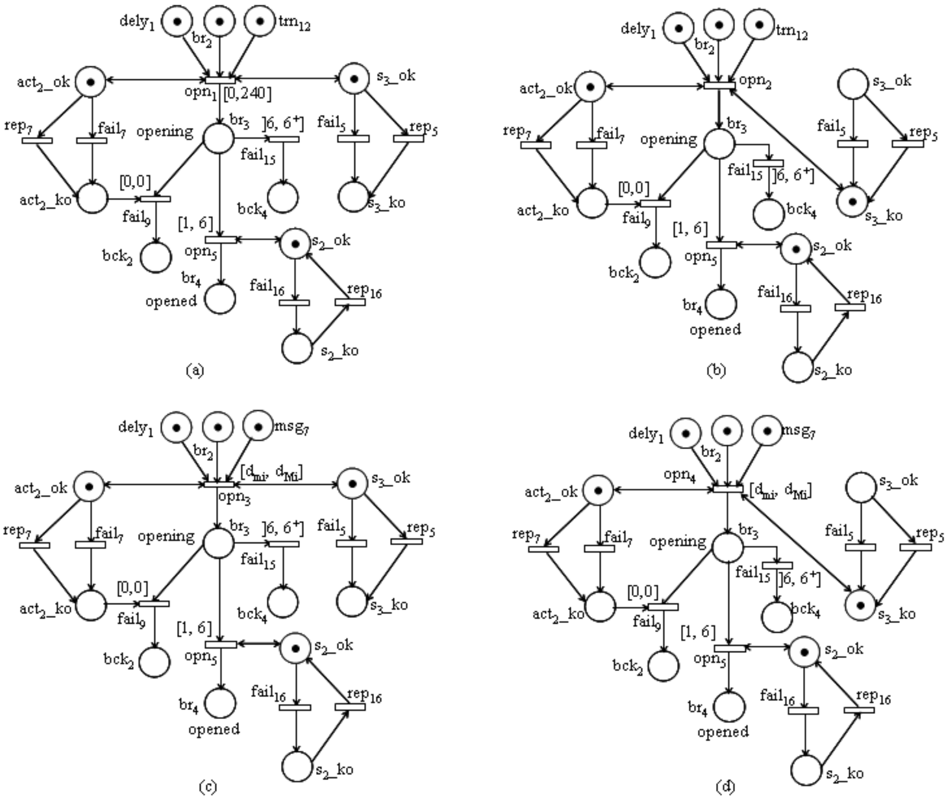


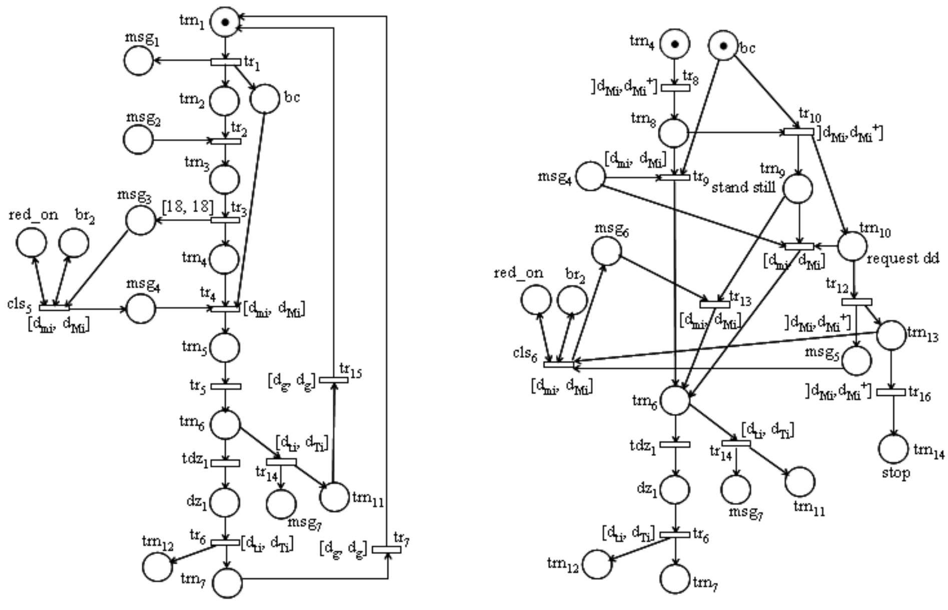
Figure 9: Petri net model of the barriers opening

can not be opened by passing of the train. In this case, the exceeding of the maximum closure time is reported to the operations centre that finds out wither the train has passed the level crossing or is still approaching. Accordingly the operations centre sends a deactivation order (b) in the first case and (d) in the second case.

4.7 Petri net model of the train

Nominal operating and late arrival

The detailed Petri net model of the train is given in Figure 10. Place *trn1* (Figure 10a) corresponds to the approaching of the train a level crossing. When the train on-board system detects this approaching, it sends a radio message *msg1* to the level crossing control system to switch on by firing the transition *tr1*. Place *bc* represents the setting of a breaking curve for speed supervision to make the train stop at the potential danger point in a failure situation. After receipt of the acknowledgement (place *msg2*), the on-board system waits an appropriate time (18 seconds) for the level crossing to be closed and sends the statute request (place *msg3*) to the level crossing control system. The level crossing is reported to the train to be in a safe state (place *msg4*) if the barriers are completely lowered (place *br2*) and the red traffic light is in the activated mode (place *red_on*). After reception of the safe state of the level crossing, the train cancels the breaking curve (place *bc*) and passes the level crossing with out braking. This is represented by firing transitions *tdz1* and *tr6*. The continuous dynamic of the train is represented by the temporal interval *[dti, dTi]* attached to transitions *tri* and *tdz1*. This means that the tokens has to remain in the input places of this transitions at least *dti* and at most *dTi*. Place *trn7* and *trn12* represent the train out of the danger zone. Transition *tr7* can be fired after a green time duration *dg* to specify a non-finite behaviour of the track. Transition *tr14* is fired if the train detects that it can not arrive at the



(a) Nominal and late arrival

(b) Braking, stand still and stop

Figure 10: Petri net model of the train

level crossing within the maximum supervised arrival time of 240 seconds (late arrival) and still is able to stop before the danger point. It sends a deactivation order to the level crossing (place *msg7*) and discards any information received so far from the level crossing and supervises a breaking curve (firing transition *tr15* after a green time duration *dg*).

Braking and stand still or stop

Figure 10b represents the case in which the train does not receive the status report with the safe state of the level crossing before entering its breaking curve. Note that places *trn4*, *bc*, *msg4*, *red_on*, *br2*, *trn6*, *trn12*, *dz1*, *msg7* and *trn11* are the same as in Figure 10a. The temporal interval *]dMi, dMi+]* represents the fact that the train does not receive the status report before entering its breaking curve. In this case the on-board system apply the breaks (place *trn8*) until the status report will be received. The transition *tr9* will be fired to release the breaks and continue the run if the status report is received before a stand still (place *trn9*). Place *trn10* represents the request prompted on the driver's display to make sure that the level crossing can be passed safely. Transition *tr11* is fired if meanwhile the status report has been received. Otherwise transition *tr12* will be fired to confirm the safe state by sending the message *msg5*. If the level crossing is in its safe state the transition (place *msg6*), the transition *tr13* will be fired otherwise the train will stop (place *trn14*).

4.8 Petri net model of the road user

Places *road_user* and *dz2* in Figure 11 represent respectively the road user in the entrance of the danger zone and crossing the danger zone. The road user may pass the level crossing only if the red traffic light is not in its activated mode (place *red_on* is not marked) or the level crossing is still open. It means that road users may pass when the red traffic light is off (place *red_off*) or in its defective mode (place *red_ko1* or *red_ko2*) even if the half barriers are lowered as they can pass in the opposite lane or when the half barriers are not yet lowered (place *dely2*, *dely3* or *dely4* marked). To simplify, note that we are focussing on the red traffic light as the yellow traffic light is included in this cases: the yellow traffic light can be activated when the red traffic light is in its deativated mode or defected before activation (*red_ko1*). the failure of the yellow light is also taken into account as in this case place *dely3* or *dely4* will be marked. The transition *usr* represents the non-finite behaviour of the road users.

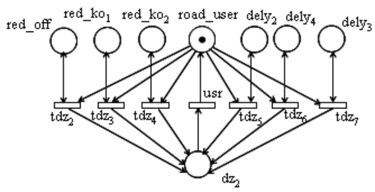


Figure 11: Petri net model of the road user

4.9 The whole Petri net model of the system

Places labelled with "*N*" in Figure 12, modelling the whole system, represent normal operating and transitions labelled with "*F*" will be added to forbidden transitions and can not be fired. This transitions concern repair and non-finite behaviour as repair of defective devices will not take place when there is a train approaching or passing the level crossing and we are interesting in this paper only to one round.

We will seek the feared scenarios corresponding to the presence of both train and road user in the danger zone, i.e. all the scenarios which lead to the marking of the place *S_fail*.

5 Extraction of feared scenarios

A general view of ESA_PetriNet and TINA tools is given in Figure 13. To use ESA_PetriNet, we first edit the Petri net model of the system on the graphic editor of TINA tool to generate two input files: a descriptive file of the Petri net model and a file containing the invariant of places. Generated scenarios can be illustrated in the form of a precedence graph. ESA_PetriNet generates a total of 196 scenarios (nominal and feared) in which 88 are feared. Note that the actual version of ESA_PetriNet generates non minimal scenarios, so most of the generated scenarios are redundant. This explains the important number of the scenarios generated. Note also that this version of ESA_PetriNet support continuous dynamics and temporal constraints and an important number of incoherent scenarios are yet eliminated. We have chosen these parameters: *dmi = 0, dMi = 4, dti = 1, dTi = dg = 10, dri= 250*

The 88 feared scenarios (collision) correspond to the following situations:

1) Crossing of both the road user (*tdz4*) and the train (*tdz1*) the danger zone when the red traffic light fails after activation (*fail4*). In this case, just after the train has received the safe state of the level crossing, the red traffic light fails and the road user passes at the same time the danger zone thinking that the train has already passed. We note three categories of scenarios according to the way of the train crossing.

- The train is crossing without braking: *sc10, sc13, sc19, sc22, sc16, sc25, sc30, sc33, sc36, sc41, sc46, sc53, sc61, sc65, sc69, sc76, sc80, sc84, sc91, sc95, sc102, sc108, sc112, sc116, sc123, sc127, sc131, sc138, sc142, sc149*. These scenarios are represented by *sc1a: {tr4, tr5, tdz1, fail4, tdz4, E_fail}*.
- The train is crossing with braking before stand still: *sc50, sc57, sc62, sc66, sc73, sc77, sc81, sc88, sc92, sc99, sc104, sc109, sc113, sc120, sc124, sc128, sc135, sc139, sc146, sc154, sc157, sc162, sc165, sc168, sc173, sc176, sc181*. These scenarios are represented by *sc1b: {tr8, tr9, tdz1, fail4, tdz4, E_fail}*.

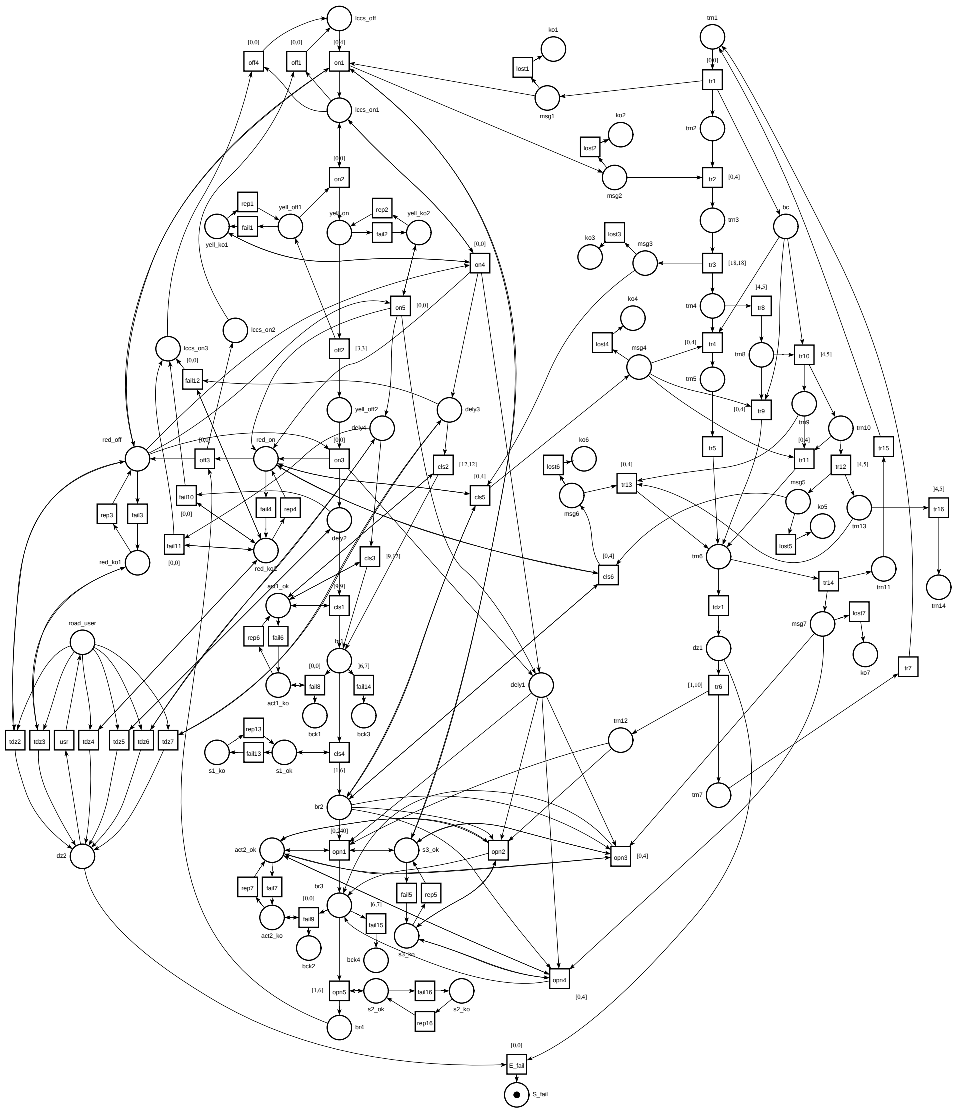


Figure 12: Whole Petri net model of the system

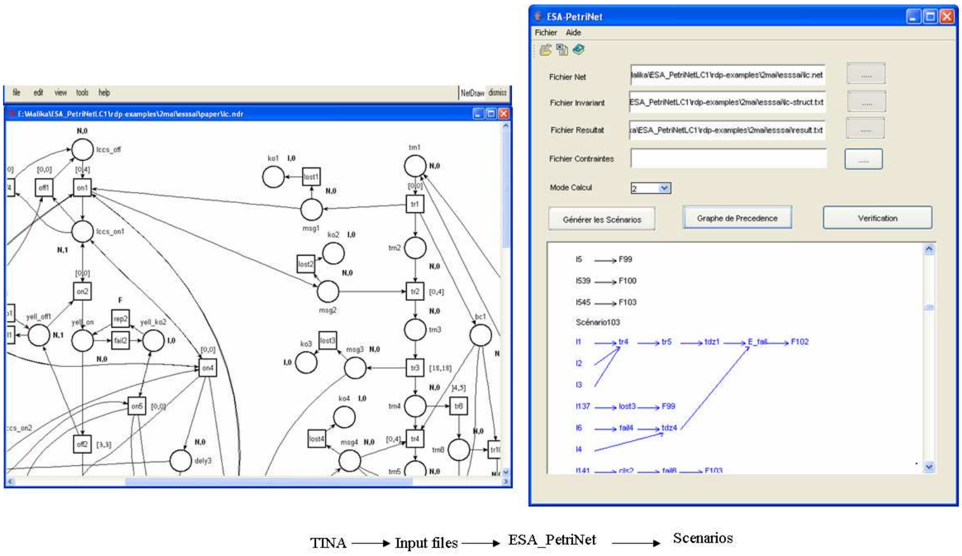


Figure 13: Screen shots of TINA and ESA_PetriNet tools

- The train is crossing after stand still: *sc54, sc71, sc86, sc172, sc180, sc161, sc97, sc118, sc133, sc144*. These scenarios are represented by *sc1c: {lost4, tr13, tdz1, fail4, tdz4, E_fail}*.

The precedence graph of these three scenarios is given in Figure 14. *Ii* and *Fi* represent respectively initial and final events.

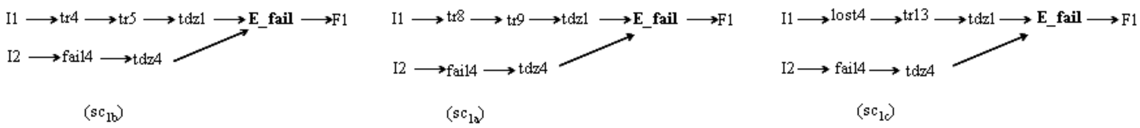


Figure 14: Precedence graph of the scenarios

2) Crossing of the road user the danger zone before the barriers to be lowered (*tdz5*, *tdz6* or *tdz7*) then, crossing of the train (*tdz1*). In this situation, the road user may be slow down stopped or break down on the danger zone. What often arrives on this zone, in general difficult to cross compared to the normal road as attested by the statistics of this field. We note three categories of scenarios according to the mode of activation of the red traffic light and each category contain deferent scenarios according to the way of train crossing.

- In the case of the activation of the red traffic light after the yellow light period (place dely2 marked), we find the scenario *sc21a: {tr4, tr5, tdz5, tdz1, E_fail}*, *sc21b: {tdz5, tr8, tr9, tdz1, E_fail}* and *sc21c: {lost4, tr13, tdz5, tdz1, E_fail}*. The scenario *sc21a* corresponding to the crossing of the train without braking regroups scenarios *sc3, sc5* and *sc11*. The scenario *sc21b* corresponding to the crossing of the train with braking before stand still regroups scenarios *sc23, sc28*, and *sc44*. The scenario *sc21c* representing to the crossing of the train after stand still corresponds to the scenario *sc37*.
- In the case of the activation of the red traffic light after the yellow traffic light become defective in its activated mode (place *dely4* marked), we find the scenario *sc22a: {tr4, tr5, tdz6, tdz1, E_fail}*, *sc22b: {tdz6, tr8, tr9, tdz1, E_fail}* and *sc22c: {lost4, tr13, tdz6, tdz1, E_fail}*. The scenario

sc22a corresponding to the crossing of the train without braking regroups the scenarios *sc1, sc2* and *sc7*. The scenario *sc22b* corresponding to the crossing of the train with braking before stand still regroups the scenario *sc17, sc20* and *sc34*.The scenarios *sc22c* representing the crossing of the train after stand still corresponds to the scenario *sc26*.

- In the case of the activation of the red traffic light when the traffic light become defective in its deactivated mode (place *dely3* marked), we find the scenario *sc23a: {tr4, tr5, tdz7, dz1, E_fail}*, *sc23b: {tdz7, tr8, tr9, tdz1, E_fail}* and *sc23c: {lost4, tr13, tdz7, tdz1, E_fail}*. The scenario *sc23a* corresponding to the crossing of the train without braking regroups the scenarios *sc6, sc9* and *sc14*. The scenario *sc23b* corresponding to the crossing of the train with braking before stand still regroups the scenario *sc31, sc39* and *sc51*.The scenarios *sc23c* representing the crossing of the train after stand still corresponds to the scenario *sc47*.

To facilitate the identification of the feared scenarios among the scenarios of normal operating, ESA_PetriNet tool illustrates them with a different colour.

6 Summary and Conclusions

Two objectives have been reached in this paper. The first is a whole modelling of the level crossing by a temporal Petri net model. The second is the extraction of the critical scenarios using ESA_PetriNet tool. The analysis of these scenarios permitted to propose a solution to improve the safety of the level crossing. This simplest solution consists on the importance of adding a sensor to allow the detection of road users by the train in the danger zone. Among the perspectives of this work: the quantification of these scenarios by a Monte Carlo simulation [1] that has been implemented in ESA_PetriNet, checking different temporal constraints and taking into account the minimality of the scenarios to eliminate the unnecessary events and the redundancies. These analyses can be extended to a level crossing used in the intersection area between a multiple track railway line and a road.

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Malika Medjoudj, Pascal Yim
LAGIS, Ecole Centrale de Lille
Cité Scientifique, BP 48
Villeneuve d'Ascq, 59651, France
E-mail: {malika.medjoudj, pascal.yim}@ec-lille.fr
Received: June 27, 2007
This work was supported by the pole ST2 and the region Nord-Pas de Calais

Malika Medjoudj was born in Tizi-ouzou (Algeria) on February 21, 1977. She received the Engineer Diploma degree in Electronics (Control) and the Diploma of Higher Education Applied in Technical English from Mouloud Mammeri University of Tizi-ouzou (Algeria) in 2001. She obtained the Master in Industrial Systems from UPS-LAAS-CNRS of Toulouse (France) in 2002 and the PhD in Industrial Systems from the same university and laboratory in March 2006. She is actually a Post Doctorate at the Ecole Centrale de Lille in collaboration with INRETS after a scientific stay of six months in the nuclear metrology service of the Université Libre de Bruxelles (FNRS-Belgium). Her research is related to the reliability of hybrid and dynamic systems (computer-controlled systems), checking of temporal constraints, extended Petri Nets for safety (transportation systems), feared scenarios and simulation.

Pascal Yim, Married, 3 children, was born in Papeete (French Polynesia) on November 3, 1963. He is Professor at the Ecole Centrale de Lille, a French Technical University. His research is based on the cross fertilization of concepts from discrete automatic control, and computer science. He has a particular interest in Petri Nets, Constraint Programming and Information Systems. His main application field is the design and optimisation of transportation systems (mainly railways). He published numerous papers in international journals and conferences. He has also supervised several industrial contracts for various customers: SNCF (the French Railway Company), the Fluvial Port of Lille, the "3 Suisses" (a large retail French Company) and other companies. Professor Pascal Yim is a member of scientific board of French "competitivity poles" on Intelligent Transportation Systems (I-Trans) and Distribution (PICOM). He is also correspondent for the North of France of the European Excellence Network on railways (EURNEX).

International Journal of Computers, Communications & Control
Vol. II (2007), No. 3, pp. 269-278

Efficient Variable Length Block Switching Mechanism

Jaidhar C.D, A.V. Reddy

Abstract: Most popular and widely used packet switch architecture is the crossbar. Its attractive characteristics are simplicity, non-blocking and support for simultaneous multiple packet transmission across the switch. The special version of crossbar switch is Combined Input Crossbar Queue (CICQ) switch. It overcomes the limitations of un-buffered crossbar by employing buffers at each crosspoint in addition to buffering at each input port. Adoption of Crosspoint Buffer (CB) simplifies the scheduling complexity and adapts the distributed nature of scheduling. As a result, matching operation is not needed. Moreover, it supports variable length packets transmission without segmentation. Native switching of variable length packet transmission results in unfairness. To overcome this unfairness, Fixed Length Block Transfer mechanism has been proposed. It has the following drawbacks: (a) Fragmented packets are reassembled at the Crosspoint Buffer (CB). Hence, minimum buffer requirement at each crosspoint is twice the maximum size of the block. When number of ports are more, existence of such a switch is infeasible, due to the restricted memory available in switch core. (b) Reassembly circuit at each crosspoint adds the cost of the switch. (c) Packet is eligible to transfer from CB to output only when the entire packet arrives at the CB, which increases the latency of the fragmented packet in the switch. To overcome these drawbacks, this paper presents Variable Length Block Transfer mechanism. It does not require internal speedup, segmentation and reassembly circuits. Using simulation it is shown that proposed mechanism is superior to Fixed Length Block Transfer mechanism in terms of delay and throughput.
Keywords: Crossbar switch, Un-buffered Crossbar switch, Buffered Crossbar switch, Combined Input Crossbar Queue switch.

1 Introduction

Packet switching technology has become the predominant technology for high speed data networks and has begun to be used for applications like voice communication which have traditionally relied on circuit switching. Recently, many large-scale fast routers have used Input Queued (IQ) switches. In an Input Queued switch, variable length packets arriving at the inputs are segmented into fixed size packets known as cells for transmission over the switch and reassembled into packets at the output before being transmitted. Cell transmission time is fixed and is called as cell time or time slot. When a packet size is not an integral multiple of cell size, padding bytes are needed for the last fragment and is called as segmentation overhead. Smaller cell size generates more number of cells per packet and leads to a large switch header overhead. In high-speed switches/routers, segmentation results in heavy load. Moreover, if an optical switching technology is introduced, it is even more difficult to segment optical domain packets.

In high speed optical networks, it is more reasonable that incoming IP packets pass through a switch fabric based on packet by packet switching scheme. Variable length packet switching considers the entire IP packet as a single switching unit, doing away with padding bytes and reassembly buffers. For high speed switches/routers, non-existence of reassembly buffers and circuits is an attractive feature. In IP networks, the speed at which a scheduler can switch cells is not really significant, as even if only one cell is remaining for switching in an input queue, it is impossible to reassemble a complete IP packet in the reassembly buffer. Hence, it is reasonable to compare the packet switching with cell switching, from the point of view of Quality of Service (QoS).

In general, latency problem in packet switching scheme is worse than in cell switching scheme because of a decrease in the statistical multiplexing effect. However, from the packet latency view point, packet switching scheme performs better than cell switching scheme. In addition, packet latency is much better than that of cell latency for QoS requirement, because each packet represents complete information.

Variable length packets dominate network traffic (e.g., IP packets in Ethernet frames). Thus, a study of high-speed switches that support variable length packet switching is needed. A high performance variable length packet switching mechanism is proposed, for efficiently switching variable length IP packets. Performance of the proposed mechanism is evaluated in terms of packet latency and throughput. Overall, performance of our mechanism is better than earlier one.

2 Previous work

Buffers in an Input Queued (IQ) switch can be a single queue or multiple queues. Simplest one is single First In First Out (FIFO) queue, in which cells are served according to their arrival order i.e., First Come First Served (FCFS) basis. Due to the Head of Line (HoL) blocking problem, FCFS service discipline limits the maximum throughput to 58.6% [1]. To overcome HOL blocking problem several techniques have been proposed. One of the techniques is Virtual Output Queue (VOQ) [2] in which each input maintains separate queue for each output. VOQ approach overcomes the HOL blocking problem. However, it creates an input contention. Output contention occurs when more than one input wishes to send a packet to the same output at the same time. To resolve both input and output contentions, schedulers are used, whose function is to find one to one conflict free match between inputs and outputs in every time slot. Recently many scheduling algorithms have been proposed for Input Queued switch [3–8].

To cope with the overheads and the scheduler inefficiencies, internal speedup is used as an alternative solution. The switch speedup S is defined as the ratio of the switch bandwidth to the bandwidth of the line rates. Internal speedup is a good solution but, it incurs significant cost. If the speedup is N for $N \times N$ switch, arriving cells at the inputs get immediately transferred to their corresponding outputs. Hence, buffers are used only at the output side and this kind of architecture is named as Output Queued (OQ) switch. An OQ switch can provide QoS guarantees to individual data flow or groups of data flow [9]. However, OQ switch is inherently less scalable when number of ports is more or link rate is higher. This makes an IQ switch an attractive candidate when line rate is higher or number of ports is more. But, IQ switch fails to provide guaranteed QoS. To satisfy both the requirements of high switching capacity and guaranteed QoS simultaneously, Buffered Crossbar switch was proposed as an alternative.

Buffered Crossbar (BC) switch overcomes the limitation of un-buffered crossbar switch by employing buffers at each crosspoint. Adoption of Crosspoint Buffer (CB) drastically improves the overall performance of the switch. The first BC switch was implemented as a large multi cabinet unit [10].

Pure Buffered Crossbar (PB) switch employs buffers only at each crosspoint and nowhere else. Incoming cells at the input, enter directly into the switch core to reside in their corresponding CB. PB switch consists of a FIFO CB, preceded by an address filter (AF) was proposed [11]. Yet another PB switch with a restricted CB of size 16 KB was introduced [12]. There is a possibility for packet loss due to the restricted CB size. To prevent packet loss completely, larger CB is needed, but CB size is inversely proportional to switch size. When port size increases, it forces larger memory requirement to switch core. The requirement of larger CB could be minimized by employing buffers at the input side, in addition to CBs. Such an architecture is known as Combined Input Crossbar Queue (CICQ) switch. It separates input and output contentions. Schedulers at each input and output port work independently and in parallel. CICQ switch to use FIFO input buffer was proposed [13, 14]. Using simulation it is shown that the throughput of the FIFO Input Buffered CICQ switch is limited to 91% due to the HoL blocking problem [13]. To overcome the HoL blocking problem, VOQ's have been used in most of the proposed

CICQ architectures. In the rest of the paper, Virtual Output Queued CICQ switch is referred as CICQ switch. The CICQ switch having VOQ was first proposed in [15]. To schedule the cells, Oldest Cell First (OCF) selection strategy is employed at all the contention points. CICQ switch in which CB size is one cell, has been proposed [16] in which the Longest Queue First (LQF) scheduling is used at the input side and Round Robin (RR) scheduling is used at the output side. Yet another CICQ switch architecture, where CB is restricted to a single cell, has been proposed [17] in which RR scheduling style used at all the contention points. All these scheduling algorithms were just simple mapping of earlier algorithms, proposed for un-buffered crossbar switch into the new CICQ switch architecture.

3 Combined Input Crossbar Queue Switch (CICQ) Architecture

Our $N \times N$ CICQ switch model is shown in Fig. 1 and has a structure as described below.

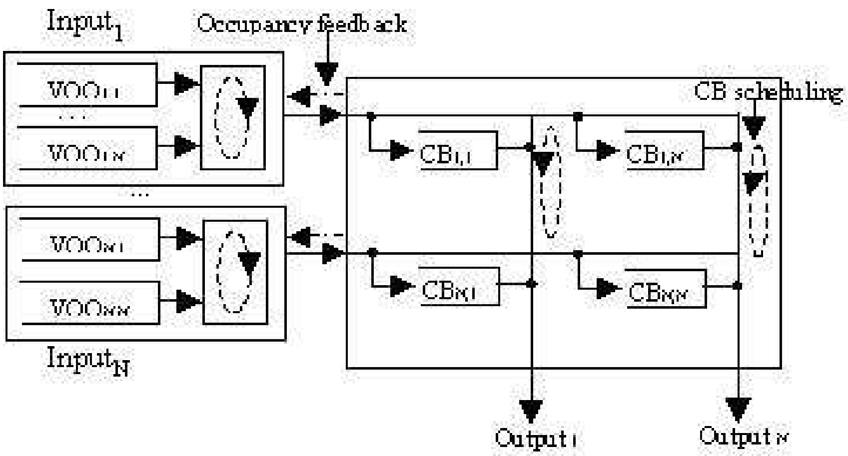


Figure 1: Combined Input Crossbar Queue switch with Round Robin Scheduling at all the contention points.

Input Queue: There are N VOQ's at each input, one for each output. Packets arriving at the input i destined for output j are stored in $VOQ_{i,j}$. Internal fabric consists of N^2 Crosspoint Buffers. The $CB_{i,j}$ stores the packets coming from input i destined to output j, where $i, j = 1, 2, \ldots, N$ and its size is set to 2250 bytes.

Scheduler: Each input and output port has its own scheduler and each of them work independently and in parallel. At all the contention points Round Robin (RR) scheduling is used. Input scheduler selects VOQ from among the active VOQs. A $VOQ_{i,j}$ is said to be active for being scheduled in the input scheduling process, if it is not empty and the corresponding $CB_{i,j}$ has enough space to accommodate the incoming block. i.e., the value of its credit counter is greater than or equal to the size of its head block. The output scheduler is responsible for: (a) selecting the next eligible flow (CB) in its column; (b) initializing the transmission of packets to the specific switch output and sending a credit back to the appropriate input credit scheduler. A flow is eligible when the corresponding CB is not empty. If there is more than one eligible flow, the output scheduler has to select one of them in a RR fashion.

Flow Control: A credit based flow control mechanism is used in order to provide lossless transmission between input port and CB [18]. Each input i maintain N credit counters, one for each VOQ. Initially, value of these counters is set to the CB size. Whenever an input scheduler forwards a block from a VOQ, it decrements its respective credit counter by the size of the forwarded block. When a block departs from $CB_{i,j}$, its corresponding output scheduler sends a credit back to the respective $VOQ_{i,j}$.

3.1 Variable Length Packet Switching

Significant advantage of the CICQ switch is their capacity to directly switch variable length packets without segmenting it. All the input and output schedulers operate independently and in parallel. Hence, there is no global "time-frame" that constrains the system to transmit fixed size packets. This does not hold good for unbuffered crossbar switch.

Native switching of variable length packets eliminates the internal speedup and reassembly circuit at all the outputs. However, native switching of variable length packets results in unfairness. Consider two VOQ's at a port i, where $VOQ_{i,1}$ is saturated with large packets and $VOQ_{i,2}$ is saturated with small packets. In this scenario, RR polling alternatively selects $VOQ_{i,1}$ and $VOQ_{i,2}$ regardless of packet size and $VOQ_{i,1}$ achieves high transfer rate than $VOQ_{i,2}$. Fig. 2 shows unfairness caused by RR selection strategy for a 2×2 switch. To overcome this unfairness, Fixed Length Block Transfer mechanism has

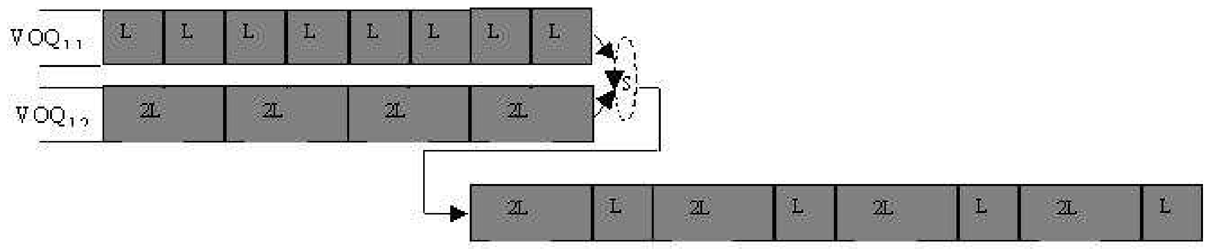


Figure 2: Native Switching of Variable Length Packets.

been proposed [19]. In this mechanism, VOQ is eligible to transfer predefined block bytes of data (i.e., 1500 B) to its CB, when it gets the chance. Each block consists of a set of entire packets and/or packet segments and packet reassembly is performed at the CB. Hence, minimum CB requirement at each crosspoint is twice the maximum size of the block. Due to restricted memory available to switch core, it does not work when port size is larger. Packet is eligible to transfer from CB to output port only when entire packet has arrived at the CB. As a result, latency of the fragmented packet is increased. Consider the worst case scenario where packet P_1 of size 40 B and P_2 of size 1500 B alternatively arrive at the input port. Each block contains a fragmented packet. Fragmented packet is delayed at the CB till the arrival of the complete packet, even when there is no output contention. Moreover, number of reassembly circuits is square of the switch size, which adds to the cost of the switch. To overcome these problems Variable Length Block Transfer mechanism is proposed in this paper.

Variable Length Block Transfer mechanism transfers up to a block of bytes, of a data packet from a selected VOQ to CB. Block size may vary from block to block and its maximum size is restricted to 2250 bytes. Block may contain set of entire packets or a single complete packet. Packets that share a common destination, are packed inside the block continuously one after other. When entire packet cannot be accommodated in a single block, it is packed into a new block instead of fragmenting it. Unlike cell switching, our mechanism does not use padding bytes to fill the block. Hence, speedup is eliminated. Fig. 3 shows Variable Length Block Transfer mechanism for the input port 1. The block 1 at the $VOQ_{1,1}$ consists of set of entire packets $P_{1,1}$ and $P_{1,2}$. Sum of the size of $P_{1,1}P_{1,2}$ and $P_{1,3}$ is greater than 2250 bytes. Hence, packet $P_{1,3}$ is packed into new block, block 2 without fragmenting it. Under heavy load, block size may be maximized. As a result, header overhead is reduced and crossbar operates very close to maximum efficiency. Table 1 compares the proposed mechanism and Fixed Length Block Transfer mechanism.

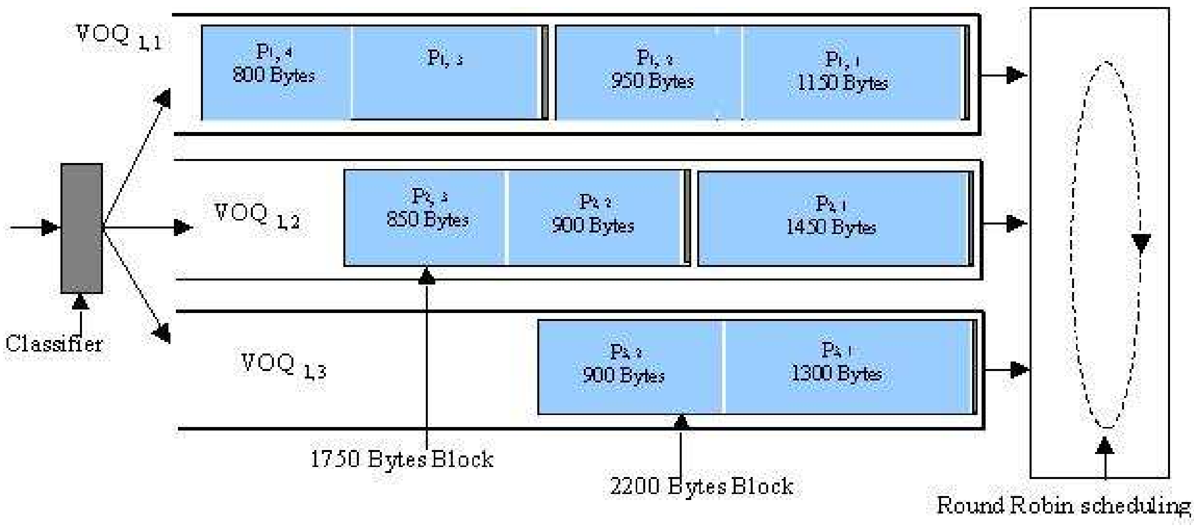


Figure 3: Variable Length Block Transfer Mechanism.

Table 1: Comparison of the proposed mechanism and Fixed Length Block Transfer mechanism.

Characteristics	Variable Length Block Transfer mechanism	Fixed Length Block Transfer mechanism
Cross-point Buffer Size	2250 Bytes	3000 Bytes
Segmentation and Reassembling Circuit	No	Yes
Scheduler	Round Robin	Round Robin
Packet Segmentation	No	Yes
Block Size	Variable Size	Fixed Size

4 Simulation Experiment

Three simulation experiments were designed in order to compare the performance of the proposed mechanism with earlier ones. For all experiments, a 32×32 switch, port speed of 10 Gbps, no internal speedup and single priority is assumed. Round Trip Time (RTT) between line cards and switch fabric has been set to 40 B times (corresponding to 32 ns at 10 Gbps line rate) which is the sum of the following delays (a) input arbitration (b) the transmission of a packet from an input port to the switch crossbar (c) the output arbitration and (d) the transmission of the flow control information back from the crossbar to the input port. Delay is measured as the time interval between the first byte of the packet arriving at the input port and its first byte departing from the output port. The reported delay is averaged over all packets.

Experiment #1: Poisson arrivals of variable length packets are assumed and each of the 32 input ports chooses an output port with a uniform distribution over the 32 output ports ($\lambda_{i,j} = \rho/N$ for all i and j). Every input port has identical offered load ranging from 80 to 98%.

Experiment #2: Each input i hosts two active flows, flow $i \rightarrow i$ and $i \rightarrow (i+1)$ mod N. The former flow consumes two thirds (2/3) of the incoming load and the latter consumes the remaining one third (1/3). Poisson arrival of variable length packets is assumed and the offered load ranges from 50 to 98% and 80 to 98% for small and large size packets respectively.

Experiment #3: Both Variable Length and Fixed Length Block Transfer mechanisms are modeled under non-uniform traffic such as unbalanced traffic as defined in [17]. It uses a probability w, as the fraction of the input load directed to a single predetermined output, while the rest of the input load is directed to all outputs with uniform distribution. Let us consider input port s, output port d, and the offered load for each input port $\rho_{s,d}$. The traffic load from input port s to output port d, $\rho_{s,d}$, is given by

$$\rho_{s,d} = \begin{cases} \rho\left(w + \frac{1-w}{N}\right), & \text{if } s = d \\ \rho\left(\frac{1-w}{N}\right), & \text{otherwise} \end{cases}$$

When $w = 0$, the offered traffic is uniform. On the other hand, when $w = 1$ the traffic is completely directional from input i to output j, i.e., $i = j$. Poisson arrivals of variable length packets are assumed and the throughput is measured as a fraction of the maximum possible one (320 Gbps in our simulation).

5 Experimental Results

Fig. 4(a) shows the results for experiment #1 under Bimodal packet size distribution in which packet size of 40 B and 1500 B alternatively arrived at the input ports. Average delay of the proposed mechanism is lower than Fixed Length Block Transfer mechanism. In a Fixed Length Block Transfer mechanism, each block contains a fragmented packet. When the block arrives at the CB, the fragmented packets' reassembly is delayed until the next packet arrives at the CB. Segmentation and reassembly delay increases the latency of the packet. These types of delay are non-existent in our mechanism. Hence, our mechanism exhibits shorter delay than the earlier mechanism. Block of data bytes are eligible for transfer from CB to output, when CB gets the chance to transfer. If there is no output contention in a column, block of data bytes can immediately be transferred without waiting for the next packet. Fig. 4(b) shows the results of experiment #1 in which packet size is uniform. Our mechanism shows lower average delay than Fixed Length Block Transfer mechanism due to the non existence of segmentation and reassembly delay.

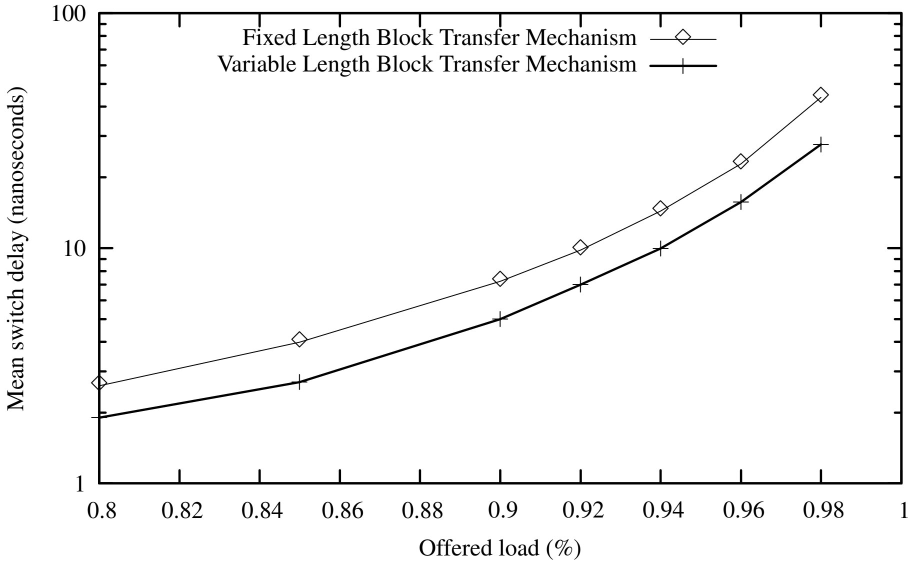
Figs. 5(a) and 5(b) show the results for the experiment #2 for small and large packets respectively. Mean delay of Block transfer mechanism is higher for larger packets than Output Queued switch. However, it shows smaller average delay for small packets.

Presence of two-stage buffering in a CICQ switch introduces priority, based on packet lengths. The transfer time required for packets from a VOQ to a CP is proportional to the size of the packet. Thus, a smaller packet requires less transfer time from a VOQ to a CP. Suppose the transfer of a small packet from port 1 to $CB_{1,1}$ and the transfer of a large packet from port 2 to $CB_{2,1}$ begin at the same time. The small packet arrives at a $CB_{1,1}$ before the large packet does at a $CB_{2,1}$. Thus, the small packet will be transmitted before the large packet, to an output link if the remaining $CB_{i,1}$ for all ports i are empty. The effect is demonstrated by the smaller mean delay than that of the OQ switch, for small packets, at a high offered load. The Block transfer mechanism further adds the packet size-based priority within each port. In the Block transfer mechanism, a multiple of small packets of a single block, are eligible for transfer from a single VOQ in the RR polling at an input port, giving higher priority to smaller packets over larger packets within the input port. This explains the lower small packet mean delay of the block transfer mechanism than the Output Queued switch for all offered loads considered.

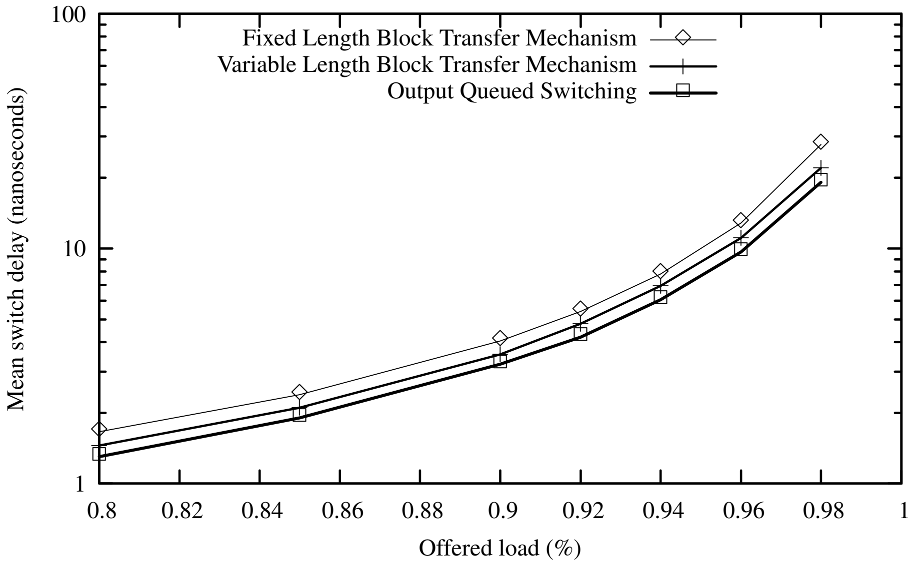
Fig. 6 shows the results for the experiment #3. It is observed that our mechanism shows higher throughput than earlier ones. Under heavy load, block size is maximized and as a result header overhead is reduced.

6 Conclusions and future work

In this paper, Variable Length Block Transfer mechanism is proposed to overcome the limitations of Fixed Length Block Transfer mechanism. Arriving packets at the inputs are not segmented as a result padding bytes and internal speedup is not required. In addition it eliminates reassembly circuit and

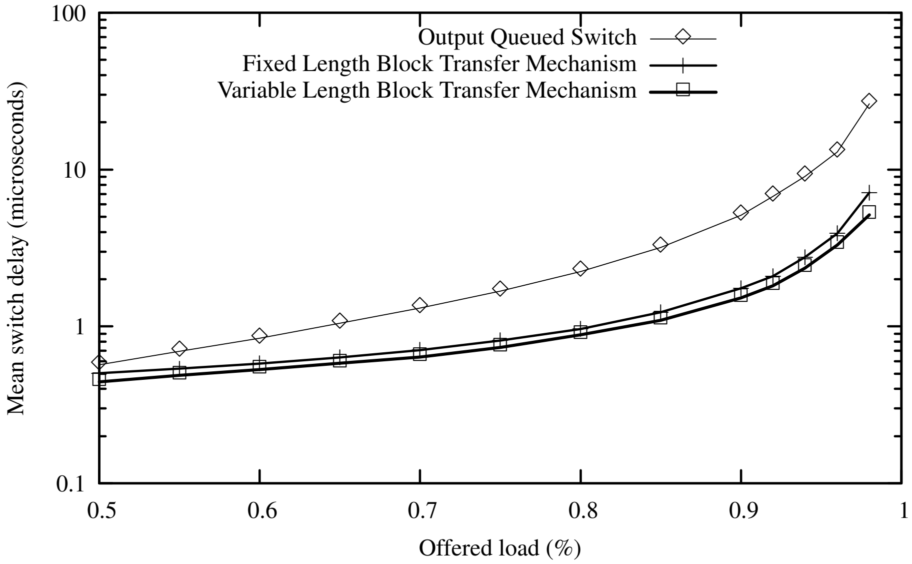


(a) Bimodel packet size

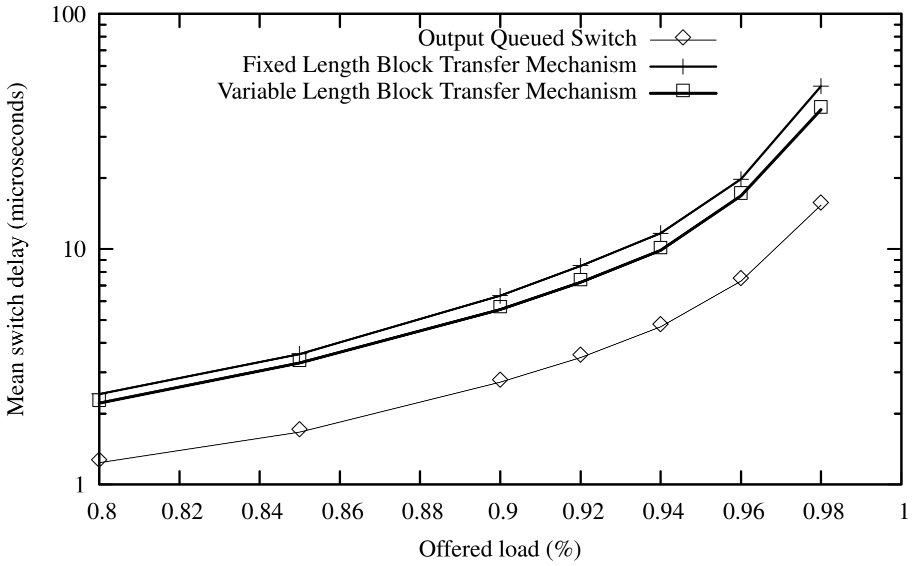


(b) Uniform packet

Figure 4: Delay performance of the proposed mechanism, Fixed Length Block Transfer under uniform traffic.



(a) Small packets



(b) Larger packets

Figure 5: Results for diagonal experiment.

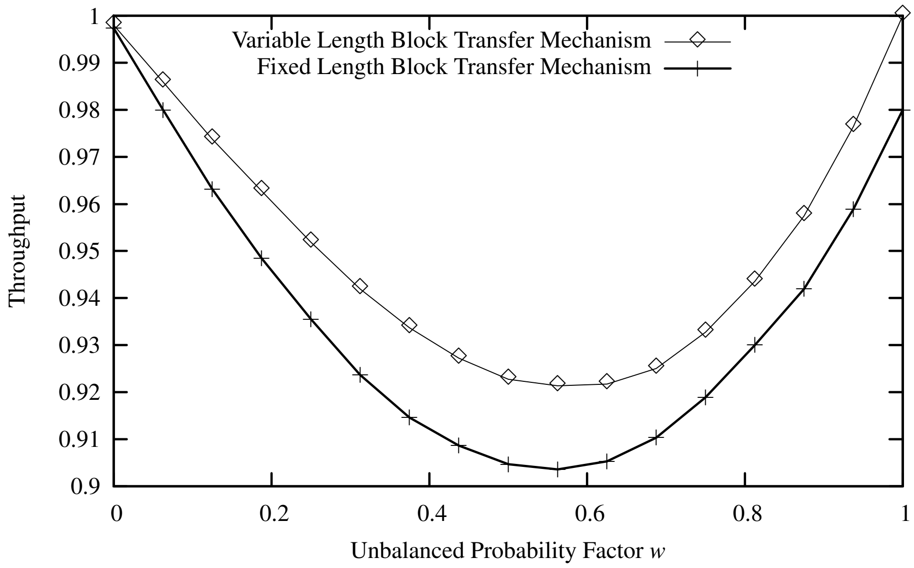


Figure 6: Throughput experiment under unbalanced traffic with load 100%.

buffers which reduces the cost of the switch. Block size is maximized under heavy load resulting in reduction of header overhead, scheduler rate and power consumption. Mean switch delay of the proposed mechanism is lower than earlier because of the not existence of the segmentation and reassembly. Memory requirement at the each crosspoint is 25% lesser than the earlier one and it is feasible to implement. Through simulation, proposed mechanism is compared with earlier one and found to be superior in terms of switch throughput and packet mean delay.

Our mechanism may produces the unfairness in terms of service rate when different VOQ's have different arrival rate which we are trying to rectify in our further work. Unfairness problem can be overcome by maintaining a counter called service counter for each VOQ and CB ($VSC_{i,j}$ and $CBSC_{i,j}$). Initial value of these counters is set to zero and the value may vary at the time of scheduling. During the time of scheduling, input port scheduler examines the content of the service counter $VSC_{i,j}$. If the value of $VSC_{i,j}$ is greater than or equal to threshold value, $VOQ_{i,j}$ is not eligible in the current round and its value is updated as $VCS_{i,j} = VCS_{i,j}$—Threshold value. Otherwise $VOQ_{i,j}$ is eligible in the current round and its service counter value is updated as $VCS_{i,j}$ =$VCS_{i,j}$+ $VOQ_{i,j}$ [Block size] − minimum block size.

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Jaidhar C.D.
Department of Computer Science and Engineering
National Institute of Technology
Tiruchirappalli – 620 015, India
E-mail: csk0305@nitt.edu

A.V Reddy
Department of Computer Applications
National Institute of Technology
Tiruchirappalli – 620 015, India
E-mail: reddy@nitt.edu

Received: March 30, 2007
Revised: May 19, 2007

International Journal of Computers, Communications & Control
Vol. II (2007), No. 3, pp. 279-287

Lorenz System Stabilization Using Fuzzy Controllers

Radu-Emil Precup, Marius L. Tomescu, Ştefan Preitl

Abstract: The paper suggests a Takagi Sugeno (TS) fuzzy logic controller (FLC) designed to stabilize the Lorentz chaotic systems. The stability analysis of the fuzzy control system is performed using Barbashin-Krasovskii theorem. This paper proves that if the derivative of Lyapunov function is negative semi-definite for each fuzzy rule then the controlled Lorentz system is asymptotically stable in the sense of Lyapunov. The stability theorem suggested here offers sufficient conditions for the stability of the Lorenz system controlled by TS FLCs. An illustrative example describes the application of the new stability analysis method.
Keywords: chaotic systems, fuzzy control, Lyapunov functions, nonlinear equations and systems.

1 Introduction

Chaotic systems exhibit exponential sensitivity to small perturbations and also have a large variety of distinct possible dynamical motions. These properties will be reviewed in this paper along with their consequences and implications to active control of chaotic systems using small control signals.

Chaos control refers to a process wherein a tiny perturbation is applied to a chaotic system in order to achieve a desirable (chaotic, periodic, or stationary) behavior [9]. The idea of chaos control was formulated in 1990 at the University of Maryland [5]. In [5] and a method for stabilizing an unstable periodic orbit was suggested. The basic idea is in the fact that a significant change in the behavior of a chaotic system can be made by a very small correction of its parameters.

There exist three historically earliest and most actively developing directions of research in chaos control: open-loop control based on periodic system excitation referred to also as nonfeedback control, the method of Poincaré map linearization called also the Ott, Grebogi and Yorke (OGY) method [5] and the method of time-delayed feedback (Pyragas method) [7, 8]. Lima and Pettini [3] proposed a disturbance-based technique of stabilizing the chaotic system towards a periodic state. In this case the periodicity is fixed by the frequency of a control signal disturbing the parameter space. Such a technique was called "suppression of chaos" or "nonfeedback control". Its implementation can be complicated by the fact that it needs a preliminary learning task of the system response to possible disturbances of variable amplitude.

The OGY method [5] stabilizes unstable periodic orbits (UPOs) found in the chaotic regime via small feedback disturbances to an accessible parameter. The control disturbance is offered when the orbit crosses a given Poincaré section such that the trajectory will be close to the stable manifold of the desired UPO. In this method in the limit of zero noise the orbit of the controlled system is identical to the UPO of uncontrolled system and the feedback disturbance vanishes. A drawback of the OGY method is that it becomes difficult to apply for very fast systems since it requires the detailed computer-aided analysis of the system at each crossing of the Poincaré section. Also, noise can result in occasional bursts where the trajectory moves far away from the controlled periodic orbit.

An alternative method of feedback stabilization of UPO's, introduced by Pyragas [7], consists of a continuous linear feedback applied at each computational time step. As in the OGY case, in this method the controlled orbit coincides with the UPO of the uncontrolled system and the feedback vanishes for zero noise when control is achieved. The feedback procedure can be applied without a priori knowledge on the location of the periodic orbit for a version in which the feedback term contains a delayed variable in which the delay corresponds to the period of the UPO. Moreover, it is expected that it can be used for fast systems, since no parameters are changed on a fast time-scale, and the method does not require a computer-aided analysis of the system. For some systems this method is robust even in the presence of considerable noise [7]. A disadvantage of Pyragas's method is that it achieves control only over a limited range of the parameter space i.e. a given orbit will become eventually unstable in the controlled system as the parameters are varied more deeply into the chaotic regime. The use of delayed feedback also increases the dimensionality of the system.

The paper is organized as follows. The accepted class of fuzzy logic control systems with Takagi-Sugeno (TS) fuzzy logic controllers (FLCs) is described in the next Section. Section 3 is focused on the design of stable fuzzy logic control systems based on the new stability analysis method expressed in terms of a theorem formulated on the basis of the Barbashin-Krasovskii theorem. Then, Section 4 performs an analysis of the Lorentz equation that exhibits chaotic behavior. Section 5 is dedicated to the stable design of a TS FLC to stabilize the Lorentz chaotic system, and Section 6 concludes the paper.

2 Accepted Class of Fuzzy Logic Control Systems

Fuzzy logic control has become an important methodology in control engineering because it can offer superior performance indices and better trade-off to system robustness and sensitivity, which results into handling nonlinear control better than traditional methods. Calvo and Cartwright [1] introduced the idea of fuzzy control in chaotic systems. Hua O. Wang and Kazuo Tanaka proposed a stability design approach to Lorenz system [10], based on TS fuzzy models using a linear matrix inequality (LMI) technique. In [11] Oscar Calvo proposed a Mamdani FLC for control of chaos in Chua's circuit. Ahmad M. Harb and Issam Al-Smadi presented in [11] a Mamdani FLC to control the Lorenz equation and Chua's circuit to be a stable constant or periodic solution, where a single tuning parameter is chosen in case of Lorenz system and the FLC adjusts this parameter.

In this paper the fuzzy logic control system is accepted to consist of a process and a TS FLC as shown in Figure 1. The FLC consists of r fuzzy rules. The process of extracting the knowledge from human operators in the form of fuzzy control rules is by no means trivial, nor is the process of deriving the rules based on heuristics and good understanding the process and control systems theory.

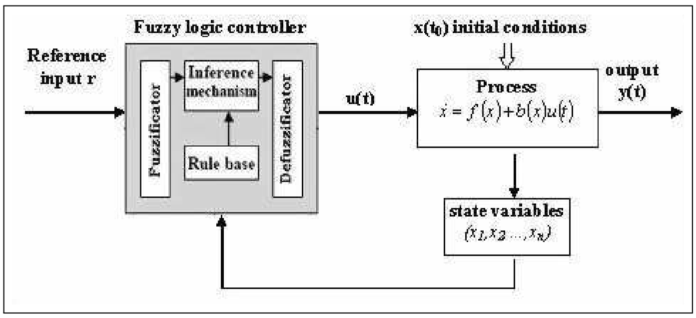

Figure 1: Fuzzy logic control system structure.

Let X be a universe of discourse. Consider the nonlinear autonomous system of the following form representing the state-space equations of the controlled process:

$$\dot{x} = f(x) + b(x)u, x(t_0) = x_0 \quad (1)$$

where:

- $x \in X$, $x = [x_1, x_2, ..., x_n]^T$ is the state vector,
- $f(x) = [f_1(x), f_2(x), ..., f_n(x)]^T$, $b(x) = [b_1(x), b_2(x), ..., b_n(x)]^T$ are functions describing the dynamics of the plant,

– u is the control signal applied to the process calculated by the weighted sum defuzzification method,

– the time variable, t, has been omitted to simplify the further formulation,

– $x(t_0)$ is the initial state vector at time t_0 .

The i-th fuzzy rule / fuzzy control rule in the fuzzy rule base of T-S FLC is of the form (2):

$$\textit{Rule } i: \text{IF } x_i \text{ is } X_{i,1} \text{ AND ... AND } x_n \text{ is } X_{i,n} \text{ THEN } u = u_i(x),\ i = \overline{1,r}, r \in IN^*, \tag{2}$$

where $X_{i,1}, X_{i,2}, .., X_{i,n}$ are fuzzy sets that describe the linguistics terms (LTs) of input variables, $u = u_i(x)$is the control output of rule i, and the function AND is a t-norm and can be a single value or a function of the state vector, x. Each fuzzy rule generates an activation degree:

$$\alpha_i(x(t)) = \text{AND}\left(\mu_{i,1}(x_1(t)), \mu_{i,2}(x_2(t)) \ldots \mu_{i,n}(x_n(t))\right), \alpha_i \in [0,1], i = \overline{1,r} \tag{3}$$

It is assumed that for any $x \in X$ in the input universe of discourse X there exists at least one $\alpha_i \in [0,1], i = \overline{1,r}$, among all rules that is nonzero. The control signal u, which must be applied to the process, is a function of α_i and u_i . Applying the weighted sum defuzzification method, the output of the FLC will be:

$$u = \frac{\sum_{i=1}^{r} \alpha_i u_i}{\sum_{i=1}^{r} \alpha_i} \tag{4}$$

where r is the total number of rules.

3 Stability Analysis of Fuzzy Logic Control Systems

The stability analysis presented in this Section is based on Barbashin-Krasovskii theorem presented in [2]. This section is concentrated on the formulation and proof of Theorem 3 that ensures sufficient conditions for the stability of nonlinear systems controlled by TS FLCs.

The function $V(x) = x^T P x$ is considered, where $P \in IR^{n \times n}$ is a positive definite matrix. From this it results that V is positive definite and has continuous partial derivatives. The derivatives of V in the conditions (1) are:

$$\dot{V}(x) = \dot{x}^T P x + x^T P \dot{x} = (f(x) + b(x)u(x))^T P x + x^T P (f(x) + b(x)u(x)) = F(x) + B(x)u(x) \tag{5}$$

where $F(x) = f(x)^T P x + x^T P f(x)$ and $B(x) = b(x)^T P x + x^T P b(x)$.

Definition 1. If $V(x) = x^T P x$ is defined on domain X containing the origin containing the origin, then for any fuzzy rule the derivative $\dot{V}_i = F + B u_i$ is defined.

Proposition 2. *For any input $x_0 \in X$ it results that $u_{min}(x_0) \le u(x_0) \le u_{max}(x_0)$, where $u_{min}(x_0) = min(u_1(x_0), ..., u_r(x_0))$ and $u_{max}(x_0) = max(u_1(x_0), ..., u_r(x_0))$.*

Proof. Let $x_0 \in X$, than among all rules two rules can be found, with indices p and q, such that $u_p(x_0) = u_{min}(x_0)$ and $u_q(x_0) = u_{max}(x_0)$. Hence the following result is valid:

$$u_{min}(x_0) = \frac{\sum\limits_{i=1}^{r} \alpha_i(x_0) u_{min}(x_0)}{\sum\limits_{i=1}^{r} \alpha_i(x_0)} \le \frac{\sum\limits_{i=1}^{r} \alpha_i(x_0) u_i(x_0)}{\sum\limits_{i=1}^{r} \alpha_i(x_0)} \le \frac{\sum\limits_{i=1}^{r} \alpha_i(x_0) u_{max}(x_0)}{\sum\limits_{i=1}^{r} \alpha_i(x_0)} = u_{max}(x_0)$$

$$\Rightarrow u_{min}(x) \le u(x) \le u_{max}(x), \forall x \in X \tag{6}$$

This property permits the formulation of Theorem 3 that outlines the stability analysis approach. □

Theorem 3. *Let $x=0$ be an equilibrium point for (1). Let $V(x)=x^T Px$ be a positive function on domain X containing the origin, such that $\dot{V}_i(x)\leq 0, i=\overline{1,r}, x\in X$. Let $S=\left\{x\in X \,\middle|\, \dot{V}(x)=0\right\}$ and suppose that no solution can stay identically in S excepting the trivial solution $x(t)\equiv 0$. Then, the origin is asymptotically stable.*

Proof. It should be proved that $\dot{V}$ is negative semidefinite in the conditions (1). From the conditions of Theorem 3 one may write:

$$\dot{V}(x)=F(x)+B(x)u_i<0, i=\overline{1,r}, x\in X \tag{7}$$

From Proposition 2 it is obtained that for $\forall x\in X$ there exist two rules, with indices p and q, such that $u_p(x_0)=u_{min}(x_0)$ and $u_q(x_0)=u_{max}(x_0)$.

Three possible cases should be considered as follows:

Case 1: If $B(x)$ is strictly positive, from Proposition 2 the result is:

$$u_p(x)\leq u(x)\leq u_q(x)\Rightarrow$$

$$\Rightarrow F(x)+B(x)u_p(x)\leq F(x)+B(x)u(x)\leq F(x)+B(x)u_q(x)\leq 0\Rightarrow$$

$$\Rightarrow \dot{V}_p(x)\leq \dot{V}(x)\leq \dot{V}_q(x)\leq 0, \tag{8}$$

therefore $\dot{V}(x)\leq 0$.

Case 2: If $B(x)$ is strictly negative, Proposition 2 yields:

$$u_p(x)\leq u(x)\leq u_q(x)\Rightarrow$$

$$\Rightarrow 0\geq F(x)+B(x)u_p(x)\geq F(x)+B(x)u(x)\geq F(x)+B(x)u_q(x)\Rightarrow$$

$$\Rightarrow 0\geq \dot{V}_p(x)\geq \dot{V}(x)\geq \dot{V}_q(x) \tag{9}$$

therefore once more $\dot{V}(x)\leq 0$.

Case 3: If $B(x)=0$ from (8) we have $\dot{V}(x)=F(x)<0$.

From the above cases it is justified to conclude that, whatever the value of is, the result will be $\dot{V}\leq 0$. Consequently, Theorem 3 satisfies all conditions of Barbashin-Krasovskii theorem [2], so the equilibrium point at the origin will be globally asymptotically stable. □

4 Properties of Lorenz Equations

This Section presents an overview on dynamic chaotic processes with focus on the Lorenz system referred to also as Lorenz equation or attractor [4]. Modern discussions of chaos are mainly based on the works about the Lorenz attractor. The Lorenz equation is commonly defined as three coupled ordinary differential equations expressed in (10) to model the convective motion of fluid cell, which is warmed from below and cooled to above:

$$\begin{aligned}\frac{dx}{dt}&=\sigma(y-x)\\ \frac{dy}{dt}&=x(\rho-z)-y\\ \frac{dz}{dt}&=xy-\beta z\end{aligned} \tag{10}$$

where the three parameters $\sigma,\rho,\beta>0$ are called the Prandtl number, the Rayleigh number and the physical proportion, respectively. These constant parameters determine the behavior of the system and the three equations exhibit chaotic behavior i.e. they are extremely sensitive to initial conditions. A small change in initial conditions leads quickly to large differences in corresponding solutions. The classic values used to demonstrate chaos are $\sigma = 10$ and $\beta = \frac{8}{3}$. It is important to note that x, y, z are not spatial coordinates. The variable x is proportional to the intensity of the convective motion while y is proportional to the temperature difference between the ascending and descending currents; similar signs of x and y denote that warm fluid is rising and cold fluid is descending. The variable z is proportional to the distortion of vertical temperature profile from linearity, a positive value indicating that the strongest gradients occur near the boundaries. The essential properties of Lorenz equation can be summarized as follows:

Nonlinearity. The two nonlinearities are xy and xz.

Symmetry. Equations are invariant under $(x,y) \to (-x,-y)$. In other words, if $(x(t),y(t),z(t))$ is a solution, $(-x(t), -y(t), z(t))$ will be also a solution.

Volume contraction. The Lorenz system is dissipative i.e. volumes in phase-space contract under the flow.

Fixed points. In order to solve (10) for the fixed points let $f(x) = \begin{pmatrix} \sigma(y-x) \\ x(\rho - z) - y \\ xy - \beta z \end{pmatrix}$ and it is necessary to solve $f(x) = 0$. It is clear that one of those fixed point is $s_0 = (0,0,0)$ and with some algebraic operations one may determine that $s_{1,2} = \left(\pm\sqrt{\beta(\rho-1)}, \pm\sqrt{\beta(\rho-1)}, (\rho-1)\right)$ are equilibrium points and real when $\rho > 1$.

Invariance. The z-axis is invariant, meaning that a solution that starts on the z-axis (i.e. $x = y = 0$) will remain on the z-axis. In addition, the solution will tend towards the origin if the initial conditions belong to the z-axis.

Solutions stay close to origin. If $\sigma, \rho, \beta > 0$ then all solutions of the Lorenz equation will enter an ellipsoid centered at $(0,0,2b)$ in finite time. In addition, the solution will remain inside the ellipsoid once it has entered. It follows by definition that the ellipsoid is an attracting set.

5 Design of Stable Fuzzy Logic Control System

The design of the fuzzy logic control system with TS FLC starts with rewriting the ordinary differential equation (10) as the following form representing the state-space equations of the controlled process:

$$\dot{x} = \begin{pmatrix} \sigma(x_2 - x_1) \\ x_1(\rho - x_3) - x_2 \\ x_1 x_2 - \beta x_3 \end{pmatrix} + \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} u, x(t_0) = x_0 \tag{11}$$

Next, the fuzzification module of TS FLC is set according to Figure 2 showing the membership functions that describe the linguistic terms (LTs) of the linguistic variables x_1 and x_2. The LTs representing "Positive", "Zero" and "Negative" values are noted by P, Z and N, respectively.

The inference engine employs the fuzzy logic operators AND and OR implemented by the *min* and *max* functions, respectively. The inference engine is assisted by the complete set of fuzzy control rules illustrated in Table 1, and the weighted sum defuzzification method is utilized. Summarizing, the only parameters to be calculated are the consequents u_i, $i = \overline{1,9}$, in the 9 fuzzy control rules.

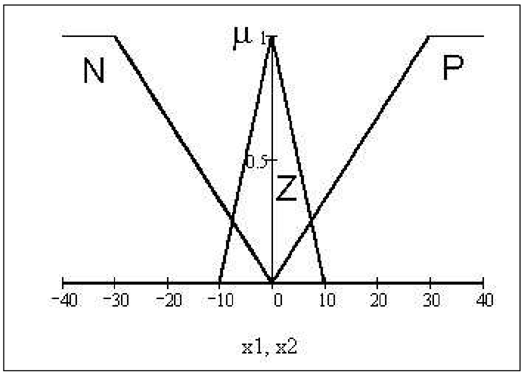

Figure 2: Membership functions of x_1 and x_2.

Table 1
Fuzzy Control Rule Base

Rule	Antecedent		Consequent
	x_1	x_2	u
1	P	P	u_1
2	N	N	u_2
3	P	N	u_3
4	N	P	u_4
5	P	Z	u_5
6	N	Z	u_6
7	Z	P	u_7
8	Z	N	u_8
9	Z	Z	u_9

Theorem 3 will be applied as follows to find the values of u_i for which the system (11) can be stabilized with the above described TS FLC. Let $X = [-40,40] \times [-40,40] \times [-40,40]$ that contain the origin. The Lyapunov function candidate $V(x) = \frac{1}{2}\left(x_1^2 + x_2^2 + x_3^2\right)$ is considered, which is a continuously differentiable positive function on domain X. The total derivative of V with respect to time using (11) is:

$$\dot{V}(x) = -\sigma x_1^2 - x_2^2 - \beta x_3^2 + x_1 x_2 (\sigma + \rho) + x_1 u \tag{12}$$

From (12) it is obvious that $\dot{V}(0) = 0 \Leftrightarrow x = 0$ and this implies $S = \{0\}$. Further on, each fuzzy control rule will be analyzed here:

- **For rule 1** it is obtained x_1 is P and x_2 is P. Then $\dot{V}_1(x) = -\sigma x_1^2 - x_2^2 - \beta x_3^2 + x_1 x_2 (\sigma + \rho) + x_1 u_1$. In these conditions to satisfy $\dot{V}(x) \leq 0$ it is chosen $u_1 = -40(\sigma + \rho)$.
- **For rule 2** it is obtained x_1 is N and x_2 is N. Then $\dot{V}_1(x) = -\sigma x_1^2 - x_2^2 - \beta x_3^2 + x_1 x_2 (\sigma + \rho) + x_1 u_2$. In these conditions to satisfy $\dot{V}(x) \leq 0$ it is chosen $u_2 = 40(\sigma + \rho)$.
- **For rule 3** it is obtained x_1 is P and x_2 is N. Then $\dot{V}_1(x) = -\sigma x_1^2 - x_2^2 - \beta x_3^2 + x_1 x_2 (\sigma + \rho) + x_1 u_3$. In these conditions to satisfy $\dot{V}(x) \leq 0$ it is chosen $u_3 = 0$.
- **For rule 4** it is obtained x_1 is N and x_2 is P. Then $\dot{V}_1(x) = -\sigma x_1^2 - x_2^2 - \beta x_3^2 + x_1 x_2 (\sigma + \rho) + x_1 u_4$. In these conditions to satisfy $\dot{V}(x) \leq 0$ it is chosen $u_4 = 0$.
- **For rule 5** it is obtained x_1 is P and x_2 is Z. Then $\dot{V}_1(x) = -\sigma x_1^2 - x_2^2 - \beta x_3^2 + x_1 x_2 (\sigma + \rho) + x_1 u_5$. In these conditions to satisfy $\dot{V}(x) \leq 0$ it is chosen $u_5 = -10(\sigma + \rho)$.

- **For rule 6** it is obtained x_1 is N and x_2 is Z. Then $\dot{V}_1(x) = -\sigma x_1^2 - x_2^2 - \beta x_3^2 + x_1 x_2 (\sigma+\rho) + x_1 u_6$. In these conditions to satisfy $\dot{V}(x) \leq 0$ it is chosen $u_6 = 10(\sigma+\rho)$.

- **For rule 7** it is obtained x_1 is Z and x_2 is P. Then $\dot{V}_1(x) = -\sigma x_1^2 - x_2^2 - \beta x_3^2 + x_1 x_2 (\sigma+\rho) + x_1 u_7$. In these conditions to satisfy $\dot{V}(x) \leq 0$ it is chosen $u_7 = -x_2(\sigma+\rho)$.

- **For rule 8** it is obtained x_1 is Z and x_2 is N. Then $\dot{V}_1(x) = -\sigma x_1^2 - x_2^2 - \beta x_3^2 + x_1 x_2 (\sigma+\rho) + x_1 u_8$. In these conditions to satisfy $\dot{V}(x) \leq 0$ it is chosen $u_8 = -x_2(\sigma+\rho)$.

- **For rule 9** it is obtained x_1 is Z and x_2 is Z. Then $\dot{V}_1(x) = -\sigma x_1^2 - x_2^2 - \beta x_3^2 + x_1 x_2 (\sigma+\rho) + x_1 u_9$. In these conditions to satisfy $\dot{V}(x) \leq 0$ it is chosen $u_9 = -x_2(\sigma+\rho)$.

Concluding, due to Theorem 3 it results that the system composes by this TS FLC and the Lorenz process described by (11) is globally asymptotically stable in the sense of Lyapunov at the origin. Considering the values of process parameters $\sigma = 10$, $\rho = 28$, $\beta = \frac{8}{3}$, the initial state $x_1(0) = 1$, $x_2(0) = -1$and $x_3(0) = 1$, the responses of x_1, x_2 and x_3 versus time in the closed-loop system are shown in Figures 3-7.

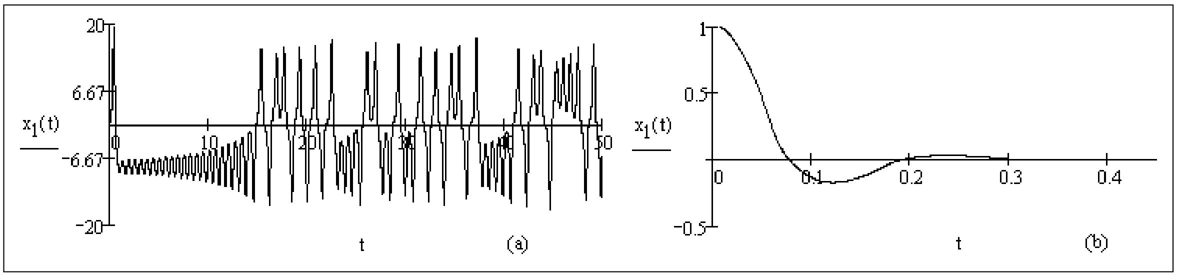

Figure 3: State variable x_1 versus time of Lorenz system without FLC (a) and with FLC (b).

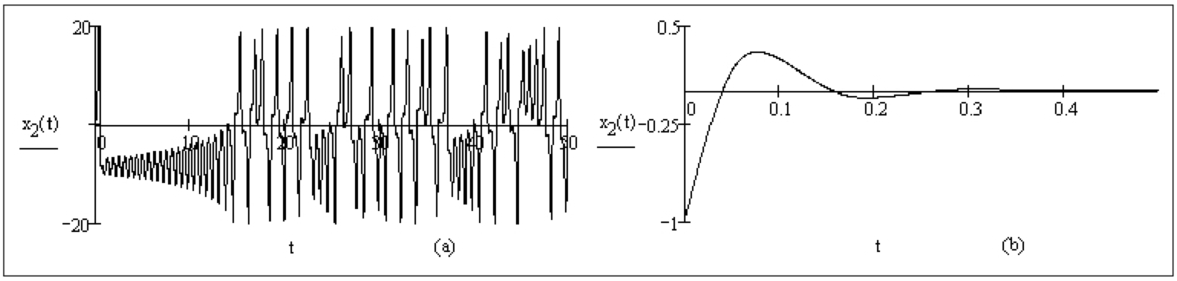

Figure 4: State variable x_2 versus time of Lorenz system without FLC (a) and with FLC (b).

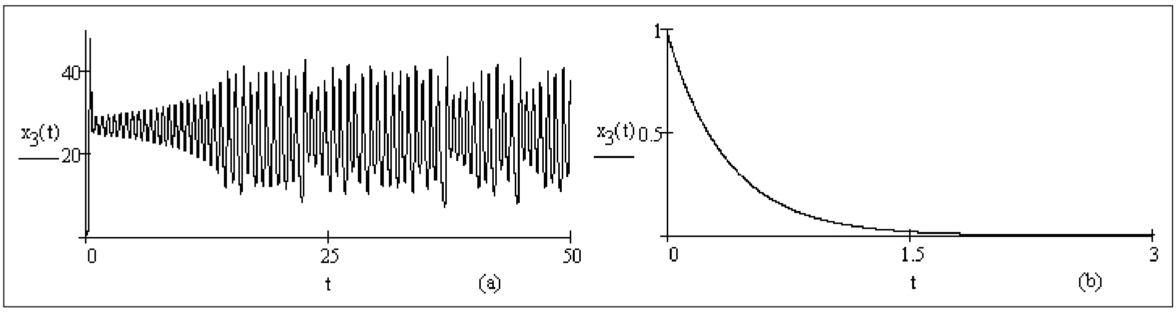

Figure 5: State variable x_3 versus time of Lorenz system without FLC (a) and with FLC (b).

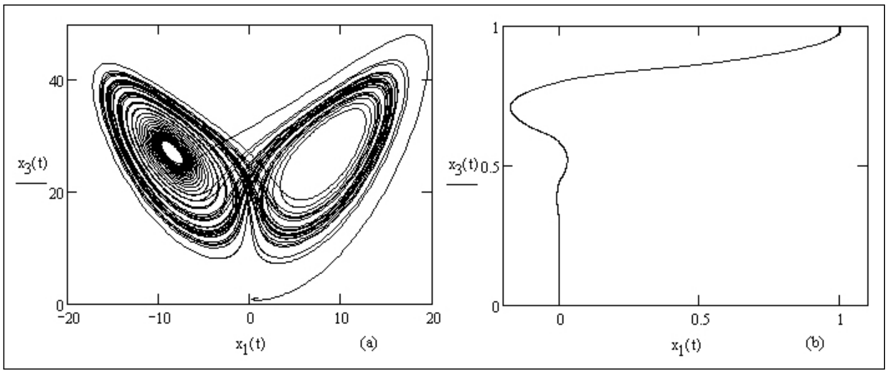

Figure 6: Phase portraits of Lorenz system without control (a) and with FLC (b).

6 Conclusions

The paper has proposed a simple and efficient fuzzy logic control solution employing a TS FLC meant for stabilizing the Lorenz system. The fuzzy logic controller design is assisted by the stability approach stated and proved in terms of Theorem 3. Theorem 3 has general character guaranteeing sufficient stability conditions for fuzzy logic control systems with TS FLCs. This approach decomposes the stability analysis to the analysis of each rule so the complexity is reduced drastically.

The new stability analysis approach is different to Lyapunov's theorem and allows more applications. In particular, it is well suited to controlling processes where the derivative of the Lyapunov function candidate is not negative definite, therefore applying Theorem 3 to nonlinear processes controlled by TS FLCs can be successful in case of a wide area of nonlinear dynamic systems.

Digital simulations illustrated in this paper prove that the proposed stability analysis method is simpler than the nonfeedback control method proposed by Lima and Pettini [3], than OGY method proposed by Ott, Grebogi and Yorke [5] and than Pyragas method [7]. Besides, the controller structure presented in Section 5 can be implemented as low cost automation solution [6]. Further research will be dedicated to offering other low cost fuzzy solutions for chaotic systems.

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Radu-Emil Precup
"Politehnica" University of Timisoara
Department of Automation and Applied Informatics
Bd. V. Parvan 2, RO-300223 Timisoara, Romania
E-mail: rprecup@aut.utt.ro

Marius L. Tomescu
"Aurel Vlaicu" University
Computer Science Faculty
Complex Universitar M, Str. Elena Dragoi 2, RO-310330 Arad, Romania
E-mail: tom_uav@yahoo.com

Ştefan Preitl
"Politehnica" University of Timisoara
Department of Automation and Applied Informatics
Bd. V. Parvan 2, RO-300223 Timisoara, Romania
E-mail: spreitl@aut.utt.ro
Received: December 24, 2006

International Journal of Computers, Communications & Control
Vol. II (2007), No. 3, pp. 288-298

Optimization of Queries with Conjunction of Predicates

Nicoleta Livia Tudor

Abstract:
A method to optimize the access at the objects of a relational database is through the optimization of the queries. This article presents an approach of the cost model used in optimization of Select-Project-Join (SPJ) queries with conjunction of predicates and proposes a join optimization algorithm named System RO-H (System Rank Ordering Heuristic). The System RO-H algorithm for optimizing SPJ queries with conjunction of predicates is a System R Dynamic Programming algorithm that extends optimal linear join subplans using a rank-ordering heuristic method as follows: choosing a predicate in ascending order according to the h-metric, where the h-metric depends on the selectivity and the cost per tuple of the predicate, using an expression with heuristic constants.
The System Rank-Ordering Heuristic algorithm finds an optimal plan in the space of linear left deep join trees. The System RO-H algorithm saves not a single plan, but multiple optimal plans for every subset, one for each distinct such order, termed interesting order. In order to build an optimal execution plan for a set S of i relations, the optimal plan for each subset of S, consisting of i-1 relations is extended, using the Lemma based on a h-metric for predicates. Optimal plans for subsets are stored and reused. The optimization algorithm chooses a plan of least cost from the execution space.
Keywords: optimal join subplans, cost function, query tree, join optimization algorithm, h-metric, heuristic method

1 Introduction

This article proposes a Select-Project-Join query optimization algorithm, based on a heuristic function and suggests an approach of the cost model used in optimization of queries with conjunction of predicates.

The paper is organized as follows:

- the section Prior work presents the improved alternatives of join optimization algorithms
- the section System Rank Ordering Heuristic Algorithm: Algorithm shows a different improved System R Dynamic Programming algorithm based on utilization of a heuristic function and the mathematical expression of the System Rank Ordering Heuristic algorithm
- the section Performance Evaluation presents the performance results and implementation details.

2 Prior Work

There are known many improved alternatives for optimizing queries with user defined predicates:

System R dynamic programming algorithm [1] illustrates the System R dynamic programming algorithm that finds an optimal plan in the space of linear (left-deep) join trees [2]. The algorithm proceeds by building optimal execution plans for increasingly larger subsets of the set of all relations in the join. In order to build an optimal plan for a set S of i+1 relations, the optimal plan for each subset of S, consisting of i relations is extended, and the cheapest of the extended plans is chosen. The System-R algorithm saves not a single plan, but multiple optimal plans for every subset S, one for each distinct such order, termed interesting order. The enumeration complexity of the algorithm is $O(n2^{n-1})$, where R_1, R_2,... , R_n - relations.

The optimization algorithm for the space of bushy join trees is similar to the System-R algorithm, except that the both inputs of a join operator can be an intermediate result. The number of optimal subplans that must be stored for a join with n tables is 2n times the number of interesting orders. The complexity is $O(3^n)$.

LDL algorithm was used in the LDL project at MCC [3] and subsequently at the Papyrus project at HP Laboratories [4]. The LDL algorithm treats expensive predicates and relations alike and may produce plans that are significantly worse than plans produced by the traditional optimization algorithm where all selections are evaluated as early as possible. LDL algorithm cannot consider all plans in the space of unconstrained linear execution trees. Hellerstein [5] shows that the LDL algorithm fails to consider plans that evaluate expensive predicates on operands of a join prior to taking the join. In order to optimize a query that consists of a join of n relations and k expensive predicates, the dynamic programming algorithm will need to construct 2^{n+k} optimal subplans.

The predicate migration algorithm improves on the LDL approach. Predicate migration approach, which given a linear join tree, chooses a way of interleaving the join and the user-defined predicates and is integrated with a System R style optimizer [5]. The algorithm places the user-defined predicates in their optimal position relative to the join nodes. This approach has serious drawbacks that limit its applicability [6]: it cannot guarantee an optimal plan because it uses a heuristic to estimate the rank of join predicates that influence the choice of the plan.

The naive optimization algorithm for the space of unconstrained linear join trees behaves exactly like the System R algorithm. The total number of stored plans per each distinct set of relations increases to 2^k, and the number of plans that need to be stored increases to 2^{k+n}, where k is the number of user-defined predicates. The complexity of this algorithm is exponential in the number of user-defined predicates and in the number of relations in the query.

Optimization algorithms with complete rank-ordering [7] use the ability to order the execution of predicates (called ranks or rank-order), that were applied prior to application of any other operators. When the join methods are regular, the algorithm restricts the sequence in which the user-defined predicates may be applied and reduces the complexity of enumeration from exponential to polynomial in the number of user-defined predicates.

Optimization algorithm with pruning [7] compares and prunes plans that have different tags. The "udp-pushdown" rule provides a sufficient condition for a predicate to be pushed down and it can be used to pin the selections as soon as they are evaluable and helps avoid constructing plans where the predicates are pulled up. The "udp-pullover" rule allows avoid generating alternative plans that push down user-defined predicates and are suboptimal.

The conservative local heuristic algorithm can choose among plans that result from application of a sequence of udp-pushdown and udp-pullover rules. The two plans picked by the conservative local heuristic complement each other, and the heuristic can guard against the choice of a plan resulting from greedily pushing down a predicate by the Pull-Rank algorithm. Thus, conservative local heuristic can find optimal plans that Pull-Rank and other global heuristics fail to find due to their greedy approach, but incurs only low computational overhead. As the following lemma states, the conservative local heuristic algorithm produces an optimal plan in several important special cases [7].

In the next section, we present a different improved System R Dynamic Programming algorithm for optimizing Select-Project-Join queries with conjunction of predicates, based on a heuristic method. We implement the optimization algorithm by extending a System R style optimizer.

3 System Rank Ordering Heuristic Algorithm

In this section, we discuss an approache proposed for optimizing Select-Project-Join (SPJ) queries with conjunction of predicates, using an algorithm System RO-H (System Rank Ordering Heuristic), based on a heuristic method.

This algorithm extends optimal linear join subplans by choosing one predicate in ascending order according to the h-metric (heuristic metric). H-metric determines minimum value between the rank of the predicate and the ratio between selectivity minus 1 and cost per tuple.

To define the heuristic method for extending optimal linear join subplans, the following shall be considered.

3.1 Regular Join Methods

Let us consider a class of SPJ queries on relations R_1, R_2, ..., R_n, n $\in$N* and an implementation of the JOIN operator with conjunction of k predicates p_1, ..., p_k, k$\in$N*.

Definition 1. A join method is called regular if the cost f(R_1, R_2) of joining two relations of sizes R_1 and R_2 depends on the sizes of the relations as follows: $f(R_1,R_2)$ = a + bR_1 + cR_2 + dR_1R_2 where the constants a, b, c, d are independent of the sizes of relations R_1 and R_2 [7].

If join operators follow the assumption of being regular joins, we can restrict enumeration to execution trees where all predicates are ordered by rank order heuristic.

3.2 Tags for Plan Representation

The following definition states formally how we associate a tag with a join tree [7]:

Definition 2. Let T be an unconstrained linear join tree that consists of a join among a set R of relations and evaluation of a set U $\subseteq$ S of user defined predicates where S is the set of all user defined predicates in the query that can be evaluated over the subexpression of the query that consists of the join among relations in R. Then, the tag associated with the tree T is the ordered set of predicates S$-$U, sorted by rank order.

Figure 1 illustrates the execution plans that need to be considered when there are three relations R_1, R_2, R_3 and two selection predicates p_1, p_2 on R_1. T and T' are possible plans for $R_1 \bowtie R_2 \bowtie R_3$ (each with differing tags). The tags for T and T' are $< >$ and $< p_1 >$ respectively.

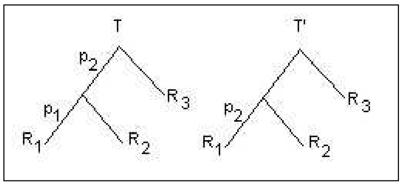

Figure 1: The execution plans

3.3 Predicate Order in Optimal Plans

Let us consider a class of SPJ queries on relations R_1, R_2, ... , R_n and an implementation of the JOIN operator with conjunction of k predicates p_1, ..., p_k. The problem of join ordering, addressed in [8], [9], [10] and [11] utilizes the notion of a rank. The rank of a predicate p_i, (i = 1, ..., n), rank(p_i) = costpertuple(p_i) / (1 $-$ selectivity(p_i)). Chaudhuri and Shim refer to such execution trees as rank ordered [7], as defined below:

Definition 3. The user-defined predicates in an unconstrained execution tree T are rank ordered if for any two user-defined predicates p and p' in T such that rank(p) < rank(p'), either p precedes p' in the tree T, or p is not evaluable in the tree T' obtained by exchanging the positions of p and p' in T.

Hellerstein et al. [12] consider expensive predicates, i.e., where the computation needed for evaluating whether the predicate is true or false dominates the overall cost [12]. In that context, it is shown that predicates should be ranked in ascending order according to the metric $(selectivity-1)/(costpertuple)$. Hellerstein et al. consider that the processor is perfect in its prediction, and it predicts the branch to the next iteration of the query will be taken when the selectivity ≤ 0.5, and will not be taken when selectivity > 0.5.

In System Rank Ordering Heuristic algorithm, we refer to such execution trees as rank ordered, according to the h-metric based on a heuristic method.

Definition 4. We call the h-metric (heuristic metric) of predicate p_i, i = 1, ... ,k having selectivity s_i, the pair

$$\left(s_i, \frac{c_1 * s_i + c_2 * (1-s_i)}{costpertuple(p_i)}\right),$$

where c_1 and c_2 are heuristic constants, defined as follows: c_1 = 0, c_2 = -1, if $0.5 < s_i \leq 1$ and c_2 = 0, c_1 = -1, if $0 \leq s_i \leq 0.5$.

Observations:

1. The utility of the h-metric is that we avoid generating a large number of intermediate-quality plans, that improve on the currently computed best cost, without being optimal.

2. The heuristic method is not guaranteed to find the optimal solution, but we will demonstrate that it finds good solutions.

Lemma 5. *Let T be an unconstrained linear join tree that consists of a join among a set of n relations and let s_i and s_j be the selectivities for p_i and p_j respectively. The plan of the execution tree T cannot be optimal if $s_i \geq s_j$ and*

$$\frac{c_1 * s_i + c_2 * (1-s_i)}{costpertuple(p_i)} > \frac{c_1 * s_j + c_2 * (1-s_j)}{costpertuple(p_j)},$$

where c_1 and c_2 are heuristic constants, defined as follows: c_1 = 0, c_2 = -1, if $0.5 < s_i \leq 1$ and c_2 = 0, c_1 = -1, if $0 \leq s_i \leq 0.5$.

Proof:

Let T be an unconstrained linear join tree that consists of a join among a set R of n relations, two predicates p_1, p_2 with $s_1 \geq s_2$ and let τ be a subexpression among execution tree T and let us refer to this subexpression by τ(R), where the parameter R refers to the input relation of τ. Then:

$$\tau(R) = \tau(\sigma_{p1}(R1))$$

We can relate the execution trees in Figure 2 and the following correspondence holds:

$$T = \sigma_{p_2}(\tau)$$

The following parameters shall be defined:

- cost(p_1) = cost of predicate τ per tuple
- $|R_1|$ = number of tuples in relation R_1

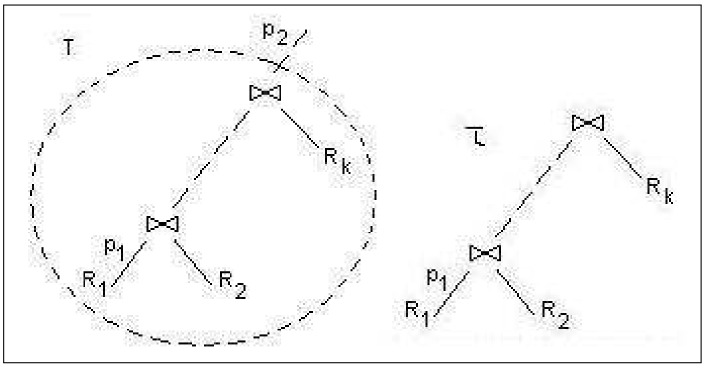

Figure 2: τ: subexpression of execution tree T

- cost(τ) = cost of execution tree τ
- size(τ) = size of the output of execution tree τ
- s_i = selectivity of the predicate p_i
- τ_0 = τ (R_1)

We now estimate the cost of the execution tree T as follows:

$$Cost(T) = cost(p_1)|R_1| + cost(\tau) + cost(p_2)size(\tau),$$

where size(τ) = size(τ_0) s_1, then Cost(T) = cost(p_1) $|R_1|$ + cost(τ) + cost(p_2) size(τ_0) s_1

We can represent that the cost of an expression τ (R_1) to be the sum of the following three components:

1. Cost of evaluating predicates in the expression τ (R_1): the sum of all such costs is

$$\sum_i cost_i size_i(R_1)$$

where cost$_i$ is the cost of applying the predicate per tuple and size$_i$ is the size of the relation preceding the i-th application of a predicate.

2. Cost of evaluating join nodes in the expression τ (R_1) that are ancestors of R_1: the sum of all such costs is

$$\sum_j cost(Join)_j(R_1)$$

3. Cost of evaluating all other operators that are not affected by the input relation R_1: We denote this cost by cost$_0$. Then the cost of an expression τ (R_1) can be computed as follows:

$$Cost(\tau(R_1)) = \sum_i cost_i size_i(R_1) + \sum_j cost(Join)_j(R_1) + cost_0$$

$$Cost(T) = cost(p_1)\,|R_1| + \sum_i cost_i size_i(R_1) + \sum_j cost(Join)_j(R_1) + cost_0 + cost(p_2)size(\tau_0)s_1$$

If s1 $\geq$ s2 and cost(p_1) = cost(p_2), then

$$\frac{c_1 * s_1 + c_2 * (1 - s_1)}{costpertuple(p_1)} > \frac{c_1 * s_2 + c_2 * (1 - s_2)}{costpertuple(p_2)}$$

If we change p_1 with p_2, let T' be a join tree that consists of a join among a set R of n relations, two predicates p_1, p_2 with $s_1 \geq s_2$, then

$$Cost(T') = cost(p_2)\,|R_1| + \sum_i cost_i size_i(R_1) + \sum_j cost(Join)_j(R_1) + cost_0 + cost(p_1)size(\tau_0)s_2$$

cost (T) > cost (T') $\Rightarrow$ the plan of the execution tree T cannot be optimal

A corollary of this lemma is that whenever two consecutive terms appear anywhere as conjunctions in an optimal plan, then the one with lower selectivity must appear first if it has the same h-metric.

We use Lemma 5. in the System Rank-Ordering Heuristic algorithm below.

3.4 System Rank-Ordering Heuristic Algorithm

The System Rank-Ordering Heuristic algorithm finds an optimal plan in the space of linear (left-deep) join trees. The cost function assigns a real number to any given plan in the execution space and satisfies the principle of optimality [13]. An optimal plan for a set of relations must be an extension of an optimal plan for some subset of the set. The optimization algorithm chooses a plan of least cost from the execution space.

Definition 6. The System Rank-Ordering Heuristic algorithm for optimizing SPJ queries with conjunction of predicates is a System R Dynamic Programming algorithm that extends optimal linear join subplans using a rank-ordering heuristic method as follows:

- choosing a predicate in ascending order according to the h-metric
- h-metric depends on the selectivity and the cost per tuple of the predicate, using an expression with heuristic constants.

The System Rank-Ordering Heuristic algorithm saves not a single plan, but multiple optimal plans for every subset, one for each distinct such order, termed interesting order [14]. In order to build an optimal execution plan for a set S of i relations, the optimal plan for each subset of S, consisting of i - 1 relations is extended, using the Lemma 1 based on a h-metric for k predicates. Optimal plans for subsets are stored in the OptPlan() array and are reused.

The System Rank-Ordering Heuristic algorithm is presented as follows:

```
Procedure System Rank-Ordering Heuristic
for i = 2 to n do
   for all  S  from  {R1, ..., Rn} with | S | = i
     BestPlan = a plan with infinite cost
     for all Rj, Sj, where S =
                 union ({Rj}, Sj),intersect({Rj},Sj) = null
     for all P from OptPlan(Sj, t) with all different tag t
              nr1 = |P|; nr2 = | Rj |
              r1 = array with evaluable predicates on P
              r2 = array with evaluable predicates on Rj
              EuristicOrder(r1); EuristicOrder(r2)
              // ascending ordering of predicates
              // in the P, Rj according to the h-metric
              for i = 0 to nr1
              for j = 0 to nr2
                   p' = ExtendJoinPlan( P, Rj, r1[i], r2[j])
                   if cost (p') < cost(BestPlan[tag(p')])
```

```
                          BestPlan[tag(p')] = p'
                    endif
               repeat
               repeat
      repeat
      repeat
      OptPlan(S) = BestPlan
    repeat
  repeat
  finalPlan = a plan with infinite cost
  for all plan P from OptPlan({R1, Ě, Rn})
      if complete_cost(P) < cost(finalPlan)
            finalPlan = completed plan of P
      endif
  repeat
  return(finalPlan)
  end

  Function ExtendJoinPlan( P, Rj, r1[i], r2[j])
    let r1[i] be a predicate applied to the plan P for Sj, t
    r2[j] = a predicate for the relation Rj
    p' = the join plan between Sj, t and Rj,
      for the subset of predicates (r1[i], r2[j])
    extend OptPlan(Sj, t) with the plan p'
  return

  Procedure EuristicOrder(r1)
    for i = 0 to nr1 - 1
    for j = i + 1 to nr1
      // si = selectivity for r1[i]
      // cost (pi) = cost of the predicate r1[i]
      if r1[i] > r1[j] and
       (c1*si + c2*(1-si)) / cost(pi) > (c1*sj + c2*(1-sj)) / cost(pj)
        change r1[i] with r1[j]
      endif
    repeat
    repeat
  return
```

Observation: Arrays r1 and r2 are useful for ascending ordering of the predicates according to the h-metric.

When the join methods are regular, the System Rank-Ordering Heuristic algorithm enables us to further restrict the sequence in which the predicates may be applied and reduces the complexity of enumeration in the number of predicates.

4 Performance Evaluation

In this section we present the results of performance evaluations on our implementation.

4.1 Experimental Framework

We used an experimental framework similar to that in [15] and [16] and [7]. We performed experiments using an AMD Athlon(tm)XP 1600+ machine with 256 MB of RAM and running Windows XP Professional version 2002.

The algorithms were run on queries consisting of equijoins. Relation cardinalities ranged from a hundred to a thousand tuples, and the numbers of unique values in join columns varied from $25^o/_o$ to $100^o/_o$ of the corresponding relation cardinality. The selectivities of predicates were randomly chosen from 10^{-4} to 1.0 and the cost per tuple of predicates was represented by the number of I/O accesses and selected randomly from 1 to 1000.

We considered nested-loop, merge-scan, and simple and hybrid hash joins as join methods [17]. In our experiments, only the cost for number of I/O accesses was accounted for. For our experiments, we generated 3 join (join among four relations) queries, 5 join queries, and 7 join queries.

We performed two sets of experiments. In the first set, we varied the number of selection predicates that apply on one relation. In the second set, we varied the distribution of the selection predicates among multiple relations in the query, i.e., we kept the number of selection predicates fixed, but varied how these predicates are distributed among the relations in a query.

4.2 Candidate Algorithms

For each query instance, we ran the following optimization algorithms:

- System R Dynamic Programming algorithm: The system R style optimization algorithm that evaluates all predicates as early as possible
- Optimization Algorithms With Complete Rank-Ordering: It compares plans that have the same tag over the same set of relations
- Opt-rank-conservative algorithm: This algorithm uses conservative local heuristic with complete rank-ordering
- System Rank-Ordering Heuristic algorithm that extends optimal linear join subplans using a rank-ordering heuristic method.

4.3 Effect of Number of Predicates

In this set of experiments, the number of predicates was varied from 1 to 5 and the number of join queries was varied from 3 to 7 (7 joins for 8 relations). The results presented for each data point represents an average over 100 queries. These queries were generated by randomly choosing one relation on which all the predicates apply and then randomly picking the cost and selectivities of the predicates as well.

Table 1 shows the average number of enumerated plans for the algorithms: System R Dynamic Programming, Optimization With Complete Rank-Ordering, Opt-rank-conservative and System Rank-Ordering Heuristic algorithm.

Figures 3, 4 and 5 show a comparison of the performances (average number of enumerated plans) for the 4 algorithms (System R Dynamic Programming, Optimization With Complete Rank-Ordering, Opt-rank-conservative and System Rank-Ordering Heuristic algorithm).

The results obtained for queries with 3, 5 or 7 joins show a similar trend:

- the enumerations necessary in the System R Dynamic Programming algorithm is independent of the number of predicates

Number of predicates / Number of enumerated plans	1	2	3	4	5
Complete Rank-Ordering	250.85	811.93	1148.57	1377.53	1603.26
System Rank-Ordering Heuristic	251.45	285.47	429.33	507.84	527.85
Opt-Rank-Conservative	117.66	139.69	169.37	194.30	225.40
System R Dynamic Programming	90.17	90.17	90.17	90.17	90.17

Table 1. Worst-Case Estimates for Enumerated Plans (3 Join Query)

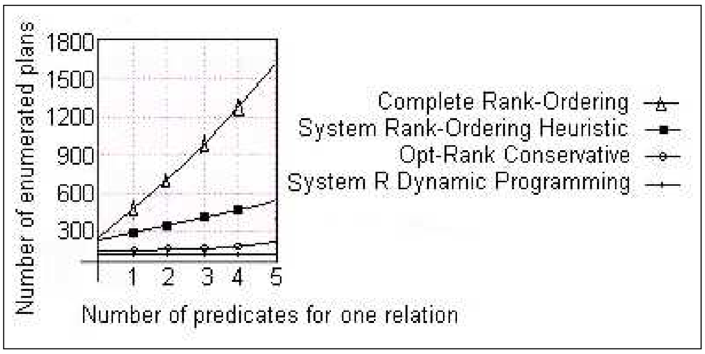

Figure 3: 3 Join Query

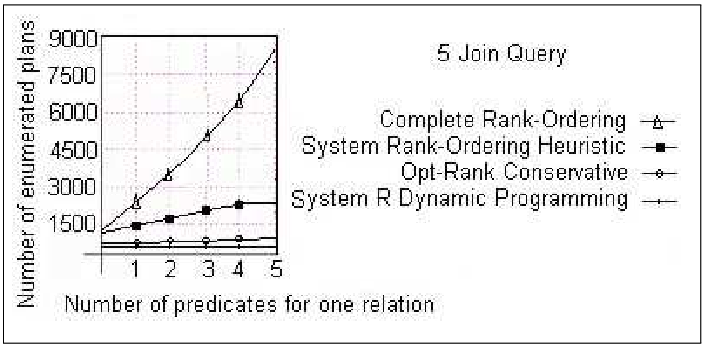

Figure 4: 5 Join Query

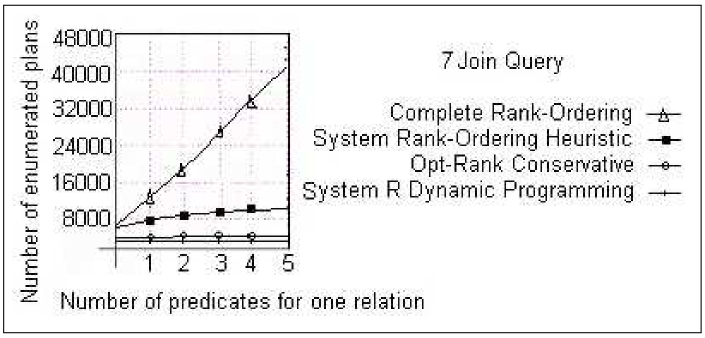

Figure 5: Performance on a varying number of predicates

- the Optimization Algorithms With Complete Rank-Ordering generated more plans than the Opt-rank-conservative algorithm and System Rank-Ordering Heuristic algorithm
- the average number of enumerated plans for the System Rank-Ordering Heuristic algorithm is approximately linear
- the gap in the number of enumerated plans between the Complete Rank-Ordering algorithm and System Rank-Ordering Heuristic algorithm increases significantly as the number of predicates grows

5 Conclusion

This article presents an approach of the cost model used in optimization of Select-Project-Join (SPJ) queries with conjunction of predicates and proposes a join optimization algorithm named System RO-H (System Rank Ordering Heuristic). The System RO-H algorithm is a System R Dynamic Programming algorithm that extends optimal linear join subplans using a rank ordering heuristic method. The comparison of the performances of algorithms shows that our proposed System Rank-Ordering Heuristic techniques are extremely effective and are guaranteed to generate optimal plans.

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Tudor Nicoleta Liviana
Petroleum-Gas University of Ploiesti
Department of Computer Science
39 Bucuresti Avenue, 100680, Ploiesti, Romania
E-mail: tudorl@upg-ploiesti.ro
Received: January 25, 2007
Revised: June 13, 2007

Nicoleta Liviana Tudor (born on July 15, 1968) graduated the Faculty of Mathematics of the Bucharest University in 1992. She has 15 years experience of teaching in the field of computer science both in Petroleum-Gas University of Ploiesti, and in other educational institutions of Romania. Since 2006 she is Lecturer in the Computer Science Department at Petroleum-Gas University of Ploiesti, Romania. She is a PhD student at the Petroleum-Gas University of Ploiesti, Control Engineering and Computers Department. Her main research fields are middle-tier business objects, XML web services, data processing, relational databases. She has authored 2 books and more than 14 research papers in the area of relational databases, data structure, and published in international journals, and in the proceedings of prestigious international conferences.

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The papers will be reviewed by two members of the program committee or other specialists.
The conference proceedings will be available at the conference. Some selected papers will be published in: International Journal of Computers, Communications & Control (IJCCC).

General topics of interest include, but are not limited to, the following:

1. Artificial Intelligence
2. Automata and Formal Languages
3. Computational Mathematics
4. Cryptography and Security
5. Control
6. Economic Informatics
7. E-Activities
8. Fuzzy Systems
9. Information Society - Knowledge Society
10. Natural Computing
11. Network Design & Internet Services
12. Multimedia & Communications
13. P2P Systems and Internet applications
14. Parallel and Distributed Computing

This event is dedicated to the Centenary of *John Bardeen* (1908-1991) the co-inventor of the transistor, a very important element in the development of the computers and the communications.
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