INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team coprin

Constraints solving, optimization and robust interval analysis

Sophia Antipolis - Méditerranée

Theme : Robotics

Activity Report

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1. Team

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2. Overall Objectives

2.1. Overall Objectives

The COPRIN project-team scientific objective is to develop and implement systems solving algorithms based on constraints propagation methods, interval analysis and symbolic computation, with interval arithmetic as the primary tool. The academic goals of these algorithms is to provide *certified solutions* to generic problems (e.g. to calculate all solutions of a system of equations within a search space) or to manage the *uncertainties* of the problems (e.g. to provide an enclosure of all solutions of a system of equations whose coefficients are intervals). These academic goals may also be declined in applicative goals. For example we may determine a domain that describes all possible dimensions of a mechanism that has to satisfy a set of performance requirements. Given this domain it will be possible to determine nominal dimensions for the mechanism so that even if there are bounded variations between the real dimensions and the nominal ones, then the real mechanism will still satisfy the requirements: hence we will be able to manage manufacturing uncertainties for the real process.

Our research aims to develop algorithms that can be used for any problem or are specific to a given class of problems, especially problems that are issued from application domains for which we have an internal expertise (such as mechanism theory and robotics).

A key point of these algorithms is that they rely heavily on symbolic pre-processing and formal calculation in order to improve the efficiency of the problem at hand. Our long term goal is to be able to synthesize automatically a specific solver according to the structure of the problem that has to be managed.

Implementation of the algorithms will be performed within the framework of general purpose software such as `Scilab`, `Maple`, `Mathematica` and will be based on the already existing library `ALIAS`, that are still being developed mostly for internal use.

Since a theoretical complexity analysis of interval analysis based solving algorithms is usually extremely difficult, the efficiency of the algorithm is systematically experimentally evaluated through `ALIAS` on various realistic test examples.

Dissemination is also an essential component of our activity because interval analysis based methods are not sufficiently known in the engineering and academic communities.

The study of robotics problems is a major focus point of the COPRIN project. In this field our objectives are:

- to develop methods for the analysis of existing robots, taking into account uncertainties in their modeling that are inherent to such mechatronic devices
- to propose innovative robotic systems
- to develop a design methodology for complex robotic systems that guarantees a required level of performance for the **real** robot. Our methodology aims at providing not a single design solution but a set of solutions offering various compromises among the performances. Furthermore the solutions will be robust with respect to errors in the realization of the real robot (e.g. due to manufacturing tolerances and control errors)

Experimental work and the development of our own prototypes (section 6.1.1) are strategic for the project as they allow us to validate our theoretical work and discover new problems that will feed in the long term the theoretical analysis developed by the team members.

We have started since three years a strategic move toward **assistance robots** (see section 6.1.5). Our long term goal will be to provide robotized devices for assistance, including smart objects, that may help disabled, elderly and handicapped people in their personal life. Our goals for these devices are that

- they can be adapted to the end-user and to its everyday environment
- they should be affordable and minimally intrusive
- they may be controlled through a large variety of simple interfaces, that may eventually be monitored to determine in advance possible pathologies

As this topic is very large and cannot be managed by a single project-team COPRIN has also proposed the creation of the "Action d'Envergure National" PAL (Personnal Assistant Living), that is leaded by D. Daney.

In summary COPRIN has two major research axes, interval analysis and robotics. The coherence of these axis is that interval analysis is a major tool to manage the uncertainties that are inherent to a robotized device while robotics provides realistic problems which allow us to develop, test and improve interval analysis algorithms.

3. Scientific Foundations

3.1. Scientific Foundations

3.1.1. Interval analysis

We are interested in real-valued system solving ($f(X)=0$, $f(X)\leq 0$), in optimization problems, and in the proof of the existence of properties (for example, it exists X such that $f(X)=0$ or it exist two values X_1, X_2 such that $f(X_1)>0$ and $f(X_2)<0$). There are few restrictions on the function f as we are able to manage explicit functions using classical mathematical operators (e.g. $\sin(x+y)+\log(\cos(e^x)+y^2)$ as well as implicit functions (e.g. determining if there are parameter values of a parametrized matrix such that the determinant of the matrix is negative, without calculating the analytical form of the determinant).

Solutions are searched within a finite domain (called a *box*) which may be either continuous or mixed (i.e. for which some variables must belong to a continuous range while other variables may only have values within a discrete set). An important point is that we aim at finding all the solutions within the domain whenever the computer arithmetic will allow it: in other words we are looking for *certified* solutions. For example, for 0-dimensional system solving, we will provide a box that contains one, and only one, solution together with a numerical approximation of this solution. This solution may further be refined at will using multi-precision.

The core of our methods is the use of *interval analysis* that allows one to manipulate mathematical expressions whose unknowns have interval values. A basic component of interval analysis is the *interval evaluation* of an expression. Given an analytical expression F in the unknowns $\{x_1, x_2, ..., x_n\}$ and ranges $\{X_1, X_2, ..., X_n\}$ for these unknowns we are able to compute a range $[A, B]$, called the interval evaluation, such that

$$\forall \{x_1, x_2, ..., x_n\} \in \{X_1, X_2, ..., X_n\} A \leq F(x_1, x_2, ..., x_n) \leq B \tag{1}$$

In other words the interval evaluation provides a lower bound of the minimum of F and an upper bound of its maximum over the box.

For example if $F = x\ sin(x + x^2)$ and $x \in [0.5, 1.6]$, then $F([0.5, 1.6]) = [-1.362037441, 1.6]$, meaning that for any x in [0.5,0.6] we guarantee that $-1.362037441 \leq f(x) \leq 1.6$.

The interval evaluation of an expression has interesting properties:

- it can be implemented in such a way that the results are guaranteed with respect to round-off errors i.e. property 1 is still valid in spite of numerical errors induced by the use of floating point numbers
- if $A > 0$ or $B < 0$, then no values of the unknowns in their respective ranges can cancel F
- if $A > 0$ ($B < 0$), then F is positive (negative) for any value of the unknowns in their respective ranges

A major drawback of the interval evaluation is that $A(B)$ may be overestimated i.e. values of $x_1, x_2, ..., x_n$ such that $F(x_1, x_2, ..., x_n) = A(B)$ may not exist. This overestimation occurs because in our calculation each occurrence of a variable is considered as an independent variable. If a variable has multiple occurrences, an overestimation may then occur. Such phenomena can be observed in the previous example where $B = 1.6$ while the real maximum of F is approximately 0.9144. The value of B is obtained because we are using in our calculation the formula $F = xsin(y + z^2)$ with y, z having the same interval value than x.

Fortunately there are methods that allow one to reduce the overestimation and the overestimation amount decreases with the width of the ranges. The latter remark leads to the use of a branch-and-bound strategy in which for a given box a variable range will be bisected, thereby creating two new boxes that are stored in a list and processed later on. The algorithm is complete if all boxes in the list have been processed, or if during the process a box generates an answer to the problem at hand (e.g. if we want to prove that $F(X) < 0$, then the algorithm stops as soon as $F(\mathcal{B}) \geq 0$ for a certain box $\mathcal{B}$).

A generic interval analysis algorithm involves the following steps on the current box [33]:

1. *exclusion operators*: these operators determine that there is no solution to the problem within a given box. An important issue here is the extensive and smart use of the monotonicity of the functions [13], [14], [23], [26], [8]
2. *filters*: these operators may reduce the size of the box i.e. decrease the width of the allowed ranges for the variables [12], [22], [24], [25]
3. *existence operators*: they allow one to determine the existence of a unique solution within a given box and are usually associated with a numerical scheme that allows for the computation of this solution in a safe way
4. *bisection*: choose one of the variable and bisect its range for creating two new boxes
5. *storage*: store the new boxes in the list

The scope of the COPRIN project is to address all these steps in order to find the most efficient procedures. Our efforts focus on mathematical developments (adapting classical theorems to interval analysis, proving interval analysis theorems), the use of symbolic computation and formal proofs (a symbolic pre-processing allows one to automatically adapt the solver to the structure of the problem), software implementation and experimental tests (for validation purposes).

3.1.2. Robotics

COPRIN has a long-standing tradition of robotics studies, especially for closed-loop robots [4]. We address theoretical issues with the purpose of obtaining analytical and theoretical solutions, but in many cases only numerical solutions can be obtained due to the complexity of the problem. This approach has motivated the use of interval analysis for two reasons:

1. the versatility of interval analysis allows us to address issues (e.g. singularity analysis) that cannot be tackled by any other method due to the size of the problem
2. uncertainties (which are inherent to a robotic device) have to be taken into account so that the *real* robot is guaranteed to have the same properties as the *theoretical* one, even in the worst case. This is a crucial issue for many applications in robotics (e.g. medical robot)

Our field of study in robotics focuses on *kinematic* issues such as workspace and singularity analysis, positioning accuracy, trajectory planning, reliability, modularity management [17] and, prominently, *appropriate design*, i.e. determining the dimensioning of a robot mechanical architecture that guarantees that the real robot satisfies a given set of requirements [19], [18]. The methods that we have developed can be used for other robotic problems, see for example the management of uncertainties in aircraft design [29], [27], [32].

Our theoretical work must be validated through experiments that are essential for the sake of credibility. A contrario, experiments will feed theoretical work. Hence COPRIN works with partners on the development of real robots, and also develops its own prototypes. We usually develop a new prototype every 6 years but since 2008 we have started the development of four new prototypes, mostly related to assistance robotics. We benefit here from the development of new miniature, low energy computers with an interface for analog and logical sensors such as the Arduino or the Phidgets. We intend to make a full use of such devices, especially for assistance purpose

In term of applications we have focused up to now on the development of special machines (machine-tool, ultra-high accuracy positioning device, spatial telescope). Although this activity will be pursued, we have started in 2008 a long-term move toward *service robotics*, i.e. robots that are closer to human activity. In service robotics we are interested in domotics, smart objects, rehabilitation and medical robots [10] and entertainment, that can be regrouped under the name of *assistance robotics*, section 6.1.5. Compared to special machines for which pricing is not an issue (up to a certain point), cost is an important element for assistance robotics. While we plan to develop simple robotic systems using only standard hardware, our work will focus on a different issue: the management of the robot *modularity*. The mechanical modularity of a robot is obtained by allowing one to change the arrangement of the robot's elements (whose cost may be quite low) so that it is most appropriate for the task. Many such mechanically modular robots are available (or can be designed at will) but finding the right arrangement of the hardware to fulfill the task requirements in spite of mechanical and control uncertainties is an open problem with no known algorithmic solution. The development of such algorithms is our long term goal.

4. Application Domains

4.1. Application Domains

While the methods developed in the project can be used for a very broad set of application domains (for example we have an activity in CO2 emission allowances, it is clear that the size of the project does not allow us to address all of them. Hence we have decided to focus our applicative activities on *mechanism theory*, where we focus on *optimal design* and geometrical modeling of mechanisms. Along the same line our focus is *robotics* and especially *service robotics* which includes rescue robotics, rehabilitation and assistive robots for elderly and handicapped people (sections 6.1.1,6.1.5). Although these topics are new for us, they will constitute the major research axis of the project on the long term. A direct consequence may be a reduction in our publication activity as these domains require to establish a strong collaboration with various experts (end-users, praticians, institutes) and a strong experimental involvement.

5. Software

5.1. Introduction

Software development is an essential part of the research done by COPRIN since a large part of our methods can only be validated experimentally. Software developments follow various directions:

1. interval arithmetic: although we do not plan to work in this very specialized area (we generally rely on existing packages) interval arithmetic is an important part of our interval analysis algorithms and we may have to modify the existing packages so as to deal, in particular, with multi-precision and arithmetic extensions
2. interval analysis libraries: we daily use two libraries that have been designed in the project and are still under development. A long term work is to develop a generic programming framework that allows for modularity and flexibility, with the objectives of testing new functionalities easily and building specific solvers by a simple juxtaposition of existing modules
3. interface to interval analysis: in our opinion interval analysis software must be available within general purpose scientific software (such as `Maple`, `Mathematica`, `Scilab`) and not only as a stand-alone tool. Indeed most end-users are reluctant to learn a new programming language just to solve problems that are only small elements of a more general problem. Furthermore interval analysis efficiency may benefit from the functionalities available in the general purpose scientific software.

5.2. Interval analysis libraries

5.2.1. ALIAS

Participants: David Daney, Jean-Pierre Merlet [correspondant], Odile Pourtallier.

The `ALIAS` library (*Algorithms Library of Interval Analysis for Systems*), whose development started in 1998, is a collection of procedures based on interval analysis for systems solving and optimization.

`ALIAS` is made of two parts:

- `ALIAS-C++`: the C++ library (87 000 code lines) which is the core of the algorithms
- `ALIAS-Maple`: the `Maple` interface for `ALIAS-C++` (55 000 code lines). This interface allows one to specify a solving problem within `Maple` and get the results within the same `Maple` session. The role of this interface is not only to generate the C++ code automatically, but also to perform an analysis of the problem in order to improve the efficiency of the solver. Furthermore, a distributed implementation of the algorithms is available directly within the interface.

These libraries can be freely downloaded.

5.2.2. Int4Sci : a Scilab interface for interval analysis

Participants: David Daney, Bertrand Neveu [correspondant].

In 2006, we have started the development of a Scilab interface to C++ Bias/Profil interval arithmetic package and to the library ALIAS.

The first version of Int4Sci has been released in 2008 – see http://www-sop.inria.fr/coprin/logiciels/Int4Sci/ for linux, MacOS and Windows. A second version, compatible with Scilab 5.3, is in preparation for 2011 [16].

This interface provides an interval arithmetic, basic interval manipulation tools as well as the solving of linear interval systems. All functions are documented and a tutorial is available. B. Neveu is in charge of maintaining this interface and of answering end-users requests.

5.2.3. Mathematica Interface to Interval Analysis

Participants: Yves Papegay [correspondant], Jean-Pierre Merlet.

Since 2006, we have been implementing in Mathematica a high-level modular interface to the ALIAS library. The initial aim of providing the Mathematica users community a transparent access to the functionalities of ALIAS, and of extending the dissemination of our library, has progressively turned into the aim of providing ALIAS advanced users and developers with a high-level modular interface for prototyping, easy testing and quick implementation of new interval analysis algorithms and procedures relying on symbolic computation skills. This includes symbolic preprocessing of expressions, and symbolic specializations of interval analysis algorithms.

This year, we have integrated part of the algorithms involved in the `polybox` filtering method (see section 6.2.1).

6. New Results

6.1. Robotics and mechanism theory

6.1.1. Prototypes of wire-driven robot

Participants: Guillaume Aubertin, Nicolas Chleq, David Daney, Jean-Pierre Merlet [correspondant].

Since 2006 we are strongly involved in the development of a family of wire-driven parallel robots, the `MARIONET` family [20]:

- `MARIONET-REHAB`: a 2m by 1.2m robot 6 d.o.f (degrees of freedom) robot using up to 7 wires. Its actuation differs completely from the classical approach (rotary motors and drums): it uses instead 40cm stroke linear actuators and a system of pulleys, allowing for improved accuracy and very high speed.
- `MARIONET-CRANE`: a very large 6 d.o.f. rescue crane using winches as actuators [17]. This system has been installed at the end of 2009 in an outdoor environment in a 20m by 20m by 12m space, leading to the largest 6 dof wire-crane that has ever been built. This project has partly benefited from INRIA support through an "Action de développement Technologique" (ADT),
- `MARIONET-VR`: a larger version of `MARIONET-REHAB`, using the same actuation scheme but with a stroke of 2m and powerful enough to lift a human being. This robot will be implemented in a virtual reality environment and will be used as a very large haptic device. This prototype will be installed in 2011.
- `MARIONET-ASSIST`: a 6 d.o.f wire crane, using a mixed actuation scheme (rotary drums but also elastic resistive pulley system) that will be implemented in our assistive flat, to be used as a lifting device, walking aid and manipulation system. This prototype will be tested in 2011

Pictures and videos of `MARIONET-REHAB` and `MARIONET-CRANE` can be seen at http://www-sop.inria.fr/coprin/developpements/main.html. `MARIONET-REHAB` has been fitted this year to be used for a biomechanics experiments (see section 6.1.5.1). Fundings for `MARIONET-CRANE`, `MARIONET-VR`, `MARIONET-ASSIST` and the assistive flat have been provided through an "Opération d'investissement programmé" of the "Contrat de plan État-Région", while `MARIONET-REHAB` has partly been funded by the Conseil Régional and the Conseil Général des Alpes-Maritimes.

6.1.2. Singularity of parallel robots

Participants: Julien Hubert, Jean-Pierre Merlet [correspondant].

The study of singularity is an old issue for parallel robots and the COPRIN project is a leading team on this subject. The project acts as a coordinator for the ANR project SIROPA, section 8.1.1, that is totally devoted to this topic.

We have defined the *static workspace* as the subset of the robot's workspace for which the joint forces/torques are lower in absolute value than a pre-defined threshold. Such a workspace constitutes a safe working zone with respect to singularities. We have developed an interval analysis software that calculate an approximation of the static workspace, up to an arbitrary accuracy [9]. Uncertainties in the robot geometry may be managed by assigning intervals to the parameters describing the geometry and considering that a pose is safe if and only if the joint constraints are satisfied whatever the real values of the geometrical parameters within their intervals.

6.1.3. Robot Calibration

6.1.3.1. Geometrical determination of optimal poses for robot calibration

Participants: David Daney, Odile Pourtallier.

The quality of the identification of robot kinematic parameters is sensitive to the location of robot measurement poses chosen during the calibration experimental planning. To determine these configurations, a numerical optimization algorithm has been proposed by Coprin, few years ago, and it is now considered as a reference method by the community. However, it suffers from difficulties of such algorithm: the local convergence can not guarantee the global optimality of the result. But one can remark that it is possible to have a geometrical interpretation of some index used to quantify the numerical quality of a set of measurement poses. This approach is explored to interprete the influence of the interaction of robot configurations and then to obtain a formal determination of optimal calibration poses.

6.1.3.2. Calibration of a space observation device

Participants: David Daney, Thibault Gayral, Jean-Pierre Merlet.

We have begun this year a collaborative work with Thales Alenia Space on the calibration of the mechanical structure of a space telescope. Its architecture is based on a parallel manipulator (type active wrist 6-PUS) used to correct the relative position of two mirrors. The aim is to identify the parameters of this robot, to improve its accuracy and then increase the quality of the images provided by the telescope. The difficulty is due to its components which have some particularities dedicated to space constraints such as flexible joints. Moreover, its small workspace, its high accuracy and the complexity of its model, require a particular calibration procedure.

6.1.3.3. Calibration of a cable-driven robot

Participants: David Daney, Julien Alexandre Dit Sandretto, Gilles Trombettoni.

To improve the accuracy of a cable manipulator, it is necessary to identify the uncertainties of its model. The robots, studied in Cogiro, an ANR National initiative, are redundantly actuated: the number of powered wires is larger than the number of degrees of freedom of the manipulator. Under some cable properties hypothesis, this over-contraint mechanism allows to perform a self-calibration - i.e. the identification of the parameters does not need additional external measurement. Based on this type of calibration, an interval based model is studied to determine the uncertainties on robot parameters but also to study the influence of the measurement noise. A state of the art has been made with the aim to propose an interval least-square. Well defined, this should be used to perform an adapted identification of the parameters.

6.1.4. Kinematics of wire parallel robots

Participants: Kazuyuki Hanahara, Jean-Pierre Merlet.

The kinematics of wire robot is a complex problem because a solution is possible only if the tension in the wire is positive. Hence the static equilibrium has to be taken into account. This problem is not well addressed in the literature. If we consider a 6-wires robot for which we assign a platform pose we may compute the lengths of the wire. Then the static equilibrium may be used to compute the tension in the wires and it is usually assumed that if these tensions are all positive, then when applying the wire lengths the platform will move to the assigned pose. However we have been able to show that

- the final pose may correspond to a configuration in which less than 6 wires are under tension, hence may be different from the assigned pose
- hence we have to consider all possible combinations of wire under tensions, which amounts to solve 63 different problems
- the final pose does not always correspond to the one with minimal potential energy
- for m wires under tension the geometrical and equilibrium equations represent a square system of $6+m$ equations, where the unknowns are the 6 pose parameters and the m tensions

Solving the system of $6+m$ equations for a m wire robot is a very complex task (remember that for a classical parallel robot the system has only 6 equations). However we have shown that two other approaches are possible:

- the system of static equilibrium equations may be considered as expressing a linear dependency between the lines associated to the wires and the line associated to gravity. This may occur only if specific geometrical conditions are satisfied and we end up with equations that do not involve the tension. This approach has allowed us to show that for a 2-wire robot the FK solutions may be obtained for solving a 12th order univariate polynomial
- similarly the static equilibrium equations imply a loss of rank of a $6 \times m+1$ matrix. By canceling the determinants of the minors we obtain a set of equations. For $m=3$ we have been able to reduce these equations to an univariate polynomial of order 156 [15]. But the large degree of the polynomial leads to a difficult solving process and we consider using interval analysis to deal with the canceling of the minors.

6.1.5. Assistance robotics

As mentioned earlier in the report we have started in 2008 a long term strategic move toward assistance robotics, with the objectives of providing low-cost, simple to control, robotized devices that may help disabled, elderly and handicapped people in their personal life, with the credo that they have to be adapted to the end-user and to its everyday environment (by contrast with the existing trend of focusing on a "universal" robot, to which the end-user and its environment have to adapt). To reach these objectives we have initiated a large number of contacts at various levels: institutions, end-users associations, nursing homes, praticians, nurses and individuals, with the purpose of identifying and organizing in a hierarchy real problems and their context. After these discussions we have decided to explore various full scale scenarii that cover a part of the daily life of an elderly, to develop specific assistance devices and to test them in a simulated flat currently being developed in our laboratory[1]. This flat and the scenarii involve a multitude of devices (mobile robots, interactive board, smart objects) but we will detail only the on-going experiments.

6.1.5.1. Rehabilitation and biomechanics

Participants: Guillaume Aubertin, Sami Bennour, David Daney, Mandar Harshe, Jean-Pierre Merlet [corre-spondant].

We are currently modifying the `MARIONET-REHAB` prototype (see section 6.1.1) in view of two major experiments:

- identification of knee motion during different training (biomechanics)
- at home monitoring of walking for elderly (assistance)

[1] pictures of this assistive flat are available at http://www-sop.inria.fr/coprin/developpements/main.html

For the biomechanics experiments the purpose is the identification of the knee motion during different exercises. A major problem when using non invasive methods for such purpose is that measurements are submitted to soft tissue artifacts (STA) i.e. skin motion are measured although one wants to identify bone motion, both motions being loosely coupled. Furthermore although several skin motion methods are available experiments in the biomechanics literature are based on a single type of measurements. To improve the accuracy of the measurements and to decrease the influence of the STA we have decided to develop a method involving various measurement methods. Our apparatus is constituted of:

- articulated collars attached to the thigh and calf. These collars are serial chains constituted of links connected by an hinge that may be locked. These collars will be fitted to the thigh and calf and then locked in place. A calibration process has been performed on each collar so that its geometry is completely determined as soon as the hinge angles are known. Furthermore each link of the collar is fitted with a force sensor that indicates the pressure between the collar and the skin
- several skin motion measurements:
  - a motion capture system with 10 cameras to determine the motion of markers fixed on the collar,
  - 5 high accuracy 3D accelerometers attached to the collars and several others fixed at various places on the limb and user body,
  - 14 high accuracy distance sensors using wires that are attached to the collars and IR distance sensors that measure the trunk motion
  - force pressure sensors that are fitted in the user shoes

Our purpose for this experiment is to use the large measurement redundancy for decreasing the influence of the STA. Furthermore the interval analysis approach is appropriate to manage several uncertainties we have in the parameters (e.g. the length of the femur and tibia). Preliminary experiments will start in 2011.

For the assistance version we will use a much simplified setup with only the collars and a reduced number of wire distance sensors. In that case the purpose is to obtain information on the gait pattern of an elderly training at home and to determine if these measurements allow doctors to detect well in advance possible emerging pathologies.

6.1.5.2. Transfer

Participants: Michael Burman, David Daney, Jean-Pierre Merlet [correspondant].

The assistance flat will be equipped with a `MARIONET-ASSIST` robot (see section 6.1.1) which will be devoted to transfer phases (e.g. sit-to-stand), act as a walking aid but also as a manipulation robot (bringing objects to the end-user). This robot will be installed in the ceiling of the flat and available on demand and in case of an emergency (e.g. a fall). The prototype is currently being installed and preliminary trials will be performed in 2011.

6.1.5.3. ANG Walker

Participant: Jean-Pierre Merlet.

We have instrumented a commercially available four-wheeled walker to build the robotized *Assistive Navigation Guide* (ANG) walker [21]. Two motors have been fitted to the rear wheels and may be connected to them through electromagnetic clutches. Hence `ANG` has two major modes: the free-mode in which the motors are unclutched and the motors-mode in which the motors are clutched. `ANG` is also equipped of encoders in the rear wheel, 2 3D accelerometers, a GPS, a light sensor, 4 infrared distance sensors (rear looking), 6 ultrasound sensor (in front and on the side), 2 webcams and 2 force sensors in the handles. The objectives of this walker are multiple and we will mention a few of them:

- fall prevention/detection: fall is a major problem for elderly (it is estimated that fall is the main cause of 10 000 elderly deaths per year in France). `ANG` may be used as a support for preventing a fall: if an abnormal motion is detected the clutches will connect the motors to the wheels thereby immobilizing the walker. If a fall cannot be prevented the walker will autonomously backtrack and come at close proximity of the elderly (whose pose is detected with the rear looking IR sensor and the webcams)

- mobility help: although the free-mode of the walker must be favored in general the walker may provide a mobility help on demand. A simple action on the force sensors in the handles will connect the motors to the wheels for that purpose
- gait pattern monitoring: in free-mode the trajectory of the walker may still be calculated through the encoders measurements. We have performed preliminary experiments of gait monitoring in which we have asked subject to perform a 10m straight line with the walker. Analysis of the walker trajectory has allowed us to detect that one of the subjects was having a motricity problem in the left limb. In view of this result the local hospital (Nice CHU) has agreed to be part of a large scale study on this topic. Such study will involve about 100 patients but is submitted to a lengthy administrative procedure and we hope to be able to perform it in 2011

Energy autonomy is a major problem for motorized walkers. To improve this autonomy we have used as on-board computer and sensors new miniature and low energy devices: preliminary test have shown that the on-board batteries allows for an autonomy of 7 days in the free-mode. Furthermore a solar panel is fitted to the rear of the walker in order to provide additional energy (on a sunny day the power output of the panel is larger than the walker energy consumption in the free-mode). Finally note that this walker will also be used by the AROBAS project-team as a mobile platform for testing autonomous maneuverings.

6.1.5.4. Rehabilitation robots for the immersive space

In 2011 we will integrate the `MARIONET-VR` robot (see 6.1.1) in the virtual reality environment of the CRISAM. This robot will be able to lift a subject in a large workspace or used as an haptic device. Furthermore the subject, in front of a large 3D screen, may stand on a 6 DOF motion base. We plan to use this robots combination for various heavy rehabilitation, simulation and training tasks.

6.2. Interval Constraint Programming

6.2.1. PolyBox: A Box-Consistency Contractor Based on Extremal Functions

Participants: Gilles Trombettoni [correspondant], Yves Papegay, Gilles Chabert, Odile Pourtallier.

Interval-based methods can approximate all the real solutions of a system of equations and inequalities. The `Box` interval constraint propagation algorithm enforces *Box consistency*. Its main procedure `BoxNarrow` handles one function f corresponding to the revised constraint, and one variable x, replacing the other variables of f by their current intervals.

We propose an improved `BoxNarrow` procedure for narrowing the domain of x when f respects certain conditions. In particular, these conditions are fulfilled when f is polynomial. f is first symbolically rewritten into a new form g. A narrowing step is then run on the non-interval *extremal functions* that enclose the interval function g. The corresponding algorithm is described and validated on several numerical constraint systems [22].

6.2.2. Exploiting Monotonicity in Interval Constraint Propagation

Participants: Ignacio Araya, Bertrand Neveu, Gilles Trombettoni [correspondant].

We propose a new interval constraint propagation algorithm, called *MOnotonic Hull Consistency* (`Mohc`), that exploits monotonicity of functions [13], [23], [8]. The propagation is standard, but the `Mohc-Revise` procedure, used to filter/contract the variable domains w.r.t. an individual constraint, uses monotonic versions of the classical `HC4-Revise` and `BoxNarrow` procedures. `Mohc-Revise` appears to be the first adaptive revise procedure ever proposed in (interval) constraint programming. Also, when a function is monotonic w.r.t. every variable, `Mohc-Revise` is proven to compute the optimal/sharpest box enclosing all the solutions of the corresponding constraint (hull consistency). Very promising experimental results suggest that `Mohc` has the potential to become an alternative to the state-of-the-art `HC4` and `Box` algorithms.

We have also reported in [26], [14] a rigorous empirical study resulting in a variant of `Mohc` that avoids a manual tuning of the parameters. In particular, we propose a policy to adjust in an auto-adaptive way, during the search, the parameter sensitive to the monotonicity of the revised function.

6.2.3. An Interval Extension Based on Occurrence Grouping

Participants: Ignacio Araya, Bertrand Neveu, Gilles Trombettoni [correspondant].

In interval arithmetics, special care has been brought to the definition of interval extension functions that compute narrow interval images. We propose here a so-called “occurrence grouping” interval extension $[f]_{og}$ of a function f. When f is *not* monotonic w.r.t. a variable x in a given domain, we try to transform f into a new function f^{og} that is monotonic w.r.t. two subsets x_a and x_b of the occurrences of x: f^{og} is increasing w.r.t. x_a and decreasing w.r.t. x_b. $[f]_{og}$ is the interval extension by monotonicity of f^{og} and produces a sharper interval image than the natural extension does. For finding a good occurrence grouping, we propose a linear program and an algorithm that minimize a Taylor-based over-estimate of the image diameter of $[f]_{og}$. Experiments show the benefits of this new interval extension for solving systems of equations [25], [24], [8].

6.3. Miscellaneous results

6.3.1. Symbolic tools for modeling and simulation

Participant: Yves Papegay.

This activity is the main part of a long-term ongoing collaboration with Airbus whose goal is to directly translate the conceptual work of aeronautics engineers into digital simulators to accelerate aircraft design.

An extensive modeling and simulation platform has been designed which includes a dedicated modeling language for the description of aircraft dynamics models in term of formulae and algorithms, and a symbolic compiler producing as target an efficient numerical simulation code ready to be plugged into a flight simulator, as well as a formatted documentation compliant with industrial requirements of corporate memory.

Implementation of this platform is a modeling and simulation environment based on symbolic computation tools. It contains several components :

- a model editor, that makes it possible and easy to enter the whole set of equations describing large and complex industrial models,
- an highly interactive and modular evaluation workbench allowing to simulate the models and to visualize the results inside the modeling environment with the benefits for the designer of being able to directly use all its computational functionnalities.
- a C code generator which, using these models, automatically generates the numerical real-time simulation engines
- a technical documentation generator

In 2010, preparing the transfer of the technology demonstrated by our prototype to our industrial partner, we have focused on the robustness and on the efficiency of our implementation, enhancing the internal representation and the algorithms used for the symbolic analysis of the models, and extensively testing and documenting the source code of the environment.

6.3.2. Multi-agent aircraft design

Participants: François Courty, Yves Papegay.

The modeling environment described in the previous section has been used, in collaboration with other teams at Airbus, to develop simple complete models of aircraft to be use for multi-agent optimization during the preliminary design process. This work is part of the ID4CS project founded by ANR. Ongoing improvements consist in automatic generation of model-based agents.

6.3.3. Equilibrium strategies for linked Electricity and CO2 markets

In collaboration with M. Bossy (INRIA -TOSCA Team) and N. Maïzi (CMA - Mines Paristech) O. Pourtallier studied an equilibrium model where electricity producers behave both on electricity market and Carbon emission allowance exchange market (see also Section 7.2). A static equilibrium model has been developed, where each of the producer has to propose both on the electricity market (short term day ahead market) quantity and price of electricity to sell, and a bid/ask policy on the carbon emission allowance exchange market. Nash equilibrium strategies have been determined. At this stage, the main criticism on the model developed is the fact that it is static and that we assume perfect information. We are currently working on a multi-period formulation and to the relaxation of the perfect information assumption. Interval analysis approach will be one of the tools to handle the imperfect information approach.

Together with Laurent Violeau (INRIA -TOSCA Team) we have also pursued an indifference pricing methodology which is presented in more details in INRIA -TOSCA Team section.

7. Contracts and Grants with Industry

7.1. Thales Alenia Space

Participants: David Daney [correspondant], Jean-Pierre Merlet, Thibault Gayral.

Thales Alenia Space, in partnership with the Coprin team, is studying a new concept of active space telescope. Based on a parallel architecture, its structure allows not only the telescope deployment in space but also the accurate positioning of the secondary mirror relative to the primary one in order to improve the provided images quality. The deployment and re-positioning concepts were validated thanks to a first prototype, and the telescope performances improvement is currently under study. A first study brought to light the front-seat role of mechanical joints on the structure accuracy. However, in order to deal with the required optical accuracy and space constraints, those mechanical joints had to be replaced by flexible ones. A new prototype was then designed and built in order to validate its ability to ameliorate its images quality using flexible joints. The goal of this project is to self-calibrate the mechanical structure of the telescope: using only proprioceptive information, parameters of the robot model will be identified. Thus, a space telescope based on this concept will be able to reach its final orbit, and then to improve its image accuracy thanks to an autonomous procedure.

7.2. Collaboration with ADEME: carbon value and carbon tax in the context of renewable energies deployment

Participants: Mireille Bossy, Odile Pourtallier.

Started in January 2009, this collaboration financed by the French Environment and Energy Management Agency (ADEME), involves the Centre for Applied Mathematics (CMA), at Mines ParisTech, COPRIN and TOSCA teams at INRIA. It focuses on a short term carbon value derived from the so-called financial *carbon market*, the European Union Emission Trading Scheme (EU ETS), which is a framework for GHG emissions reduction in European industry.

The objective of this project is to study the compatibility and complementarity of a carbon tax and a target for renewable energy deployment. (see also INRIA -TOSCA Team report).

7.3. Airbus France

Participant: Yves Papegay.

To improve the production of numerical (flight) simulators from models of aerodynamics, Airbus France is interested in methods and tools like those described in 6.3.1.

Following the contracts signed in 2003, 2005 and 2007 with the aircraft maker, and a consulting contract in 2008 to study the possible development of an industrial tool, we have initiated in 2009 a 2-years collaboration to enhance the functionnalities and performances of the existing pieces of software belonging to Airbus and to turn them into a prototype that integrates our results and can be used as a showcase.

Some libraries, components of this prototype, have been licensed to Airbus in a transfer agreement signed in 2010.

7.4. Wolfram Research Inc.

Participant: Yves Papegay.

One necessary step of C code generation is the internal representation of the semantics entities of the C language expressions. As a side-effect of our work on modeling and simulation 6.3.1 we developed a Mathematica package SymbolicC implementing such a symbolic representation. Wolfram Research Inc., makers of Mathematica, has been interested in this library which has been licensed in a transfer agreement. SymbolicC is distributed with the version 8 of Mathematica.

8. Other Grants and Activities

8.1. National Initiatives

8.1.1. ANR SIROPA project

Participants: David Daney, Julien Hubert, Jean-Pierre Merlet [correspondant], Yves Papegay.

We have started in 2006 the ANR funded SIROPA project[2] whose objectives is a better understanding of the singularities of parallel robots. The partners of this project are:

- IRCCYN Nantes
- University Rennes 1
- Nantes University (LINA)
- project teams SALSA (INRIA Rocquencourt) and COPRIN

8.1.2. ANR CoGiRo project

Participants: David Daney [correspondant], Jean-Pierre Merlet, Julien Alexandre Dit Sandretto.

The project CoGiRo, "Control of Giant Robots", deals with parallel cable-driven robots with very large workspaces and possibly heavy to very heavy payloads. This project, which began in February 2010, is funded by the French National Research Agency (ANR - Agence Nationale de la Recherche).

Despite a great application potential, very large parallel cable robots have rarely been studied and even more rarely build. The main goal of the project CoGiRo is to propose and validate innovative methodologies and means to control, calibrate and design parallel cable-driven robots with very large workspaces. A prototype of a large parallel cable robot will be built. This prototype will serve as a demonstrator and will enable the experimental validation of the results obtained during the project.

The partners of the project are:

- LIRMM - DEXTER project team
- INRIA Sophia Antipolis - Méditerranée - COPRIN project team
- LASMEA - ROSACE
- FATRONIK France SAS

[2] https://twiki-sop.inria.fr/twiki/bin/view/Projets/Coprin/SIROPA

8.1.3. ANR ID4CS project

The ID4CS project, supported by French National Research Agency (ANR) through COSINUS program has the ambition to propose a modeling and simulation environment for designing complex systems such as aircrafts, based on a self-adaptive, distributed and open multi-agent architecture distributing the optimization process inside the agents.

As a partner of the project we are mainly involved, in collaboration with Airbus, in the definition of the use case on preliminary aircraft design in development of uncertainty analysis algorithms, and in automatic generation of agents based on models.

8.2. Participation to National and International Conferences

8.2.1. International Conferences

- D. Daney was invited as plenary speaker in SCAN 2010, 14th GAMM-IMACS International Symposium on Scientific Computing, Computer Arithmetic and Validated Numerics, ENS de Lyon, France, September 27-30, 2010.
- J-P. Merlet has presented papers at the ICRA conference (Anchorage), at the ARK conference (Portoz) and at the EUCOMES conference (Cluj-Napoca). He gave invited talks at the SIAM annual meeting (Pittsburgh) and the WAFR conference (Singapor)
- Bertrand Neveu has presented a paper at the CP 2010 conference on constraint programming (St Andrews, UK).
- Y. Papegay gave a talk at the International Mathematica Symposium 2010 in Beijing, at the 16th International Conference on Principles and Practice of Constraint Programming in Scotland, and at the Wolfram Technology Conference at Urbana Champaign, Illinois, USA.
- Gilles Trombettoni has presented papers at the AAAI 2010 conference in artificial intelligence (Atlanta, US), at the SCAN 2010 conference on scientific computing and validated numerics (Lyon, France) and at the SWIM 2010 workshop on intervals (Nantes, France).

8.2.2. National Conferences

- D. Daney attended to the 9th International French-Speaking Congress of Gerontology and Geriatric, Nice, France, October 19-21, 2010.
- Thibault Gayral attended to a GDR Robotics meeting in Paris the 5th October in Paris, the subject presented was "Requirements and Design Optimization of a New Haptic Device for Medical Applications".
- Bertrand Neveu has presented a paper at the JFPC 2010 French-speaking conference on constraint programming (Caen).
- Julien Alexandre Dit Sandretto attended a GDR Robotics meeting in Paris the 4th October, the main subject was the singularities in the parallel robot models.
- Gilles Trombettoni has presented a paper at the JFPC 2010 French-speaking conference on constraint programming (Caen).
- G. Trombettoni has given one of the eleven invited talks in the bi-annual *Journées nationales du GDR informatique Mathématique* [33].
- the project has organized the first PAL workshop at Sophia-Antipolis.

9. Dissemination

9.1. Animation of the scientific community

- D. Daney is in charge of the MARIONET-CRANE ADT and of the Large Scale Initiative Action Personal Assistant Living (PAL).
- J-P. Merlet is a member of the scientific committee of the European Conference on Mechanism Science (EUCOMES). He is also a board member of the european robotics network EURON. He is an associate editor of the journals Mechanism and Machine Theory and ASME Journal of Mechanisms and Robotics and board member of the Journal of Behavorial Robotics. He is a member of the IFToMM Technical Committees on History and on Computational Kinematics. He is chairman of the scientific Committee of the Computational Kinematics workshop and a member of the steering Committee of IROS.
- B. Neveu was member of JFPC program committee and LSCS programm committee (CP workshop on local search techniques in constraint satisfaction) and was an expert for ANR and CONICYT proposals.
- Y. Papegay is a permanent member of the International Steering Committee of the International Mathematica Symposium conferences serie. He was also a member of the Program Committee of the Computer Algebra Systems and Their Applications, CASA'2010 conference.
- O. Pourtallier is a member of the International Society of Dynamic Games.
- G. Trombettoni was expert for a CEFRIPA proposal and has reviewed papers in the CP (constraint programming), JFPC (constraint programming), Synasc (symbolic and numeric computation) conferences; in the Constraints journal.

9.2. Teaching

- D. Daney gave a lecture on medical robotics, Master of Bio-Medical, Univ. Nice Sophia Antipolis (22h ETP).
- D. Daney gave a lecture on industrial control systems, ITII, Polytech'Nice (48h ETP).
- O. Pourtallier lectured 6 hours on game theory to Master OSE, at École des Mines de Paris, Sophia Antipolis and 24 hours on mathematical tools for engineer for undergraduate students at university of Nice.
- G. Trombettoni is associate professor in computer science at IUT R&T (networks and telecoms) of Sophia Antipolis.

9.2.1. PhD thesis

- B. Neveu was referee of two PhD theses.
- G. Trombettoni was referee of one PhD thesis.

Current PhD theses:

1. I. Araya, Filtering techniques for interval solvers, 2007-2010, supervisors: B. Neveu, G. Trombettoni, submitted in March 2010
2. S. Bennour, Modeling of human joints for rehabilitation purposes, 2008-2011, supervisor: J-P. Merlet, L. Rhomdane
3. J. Borràs, Classification of singular robots, 2008-2011, supervisor: , J-P. Merlet, F. Thomas
4. T. Gayral, Calibration of parallel telescope, 2010-2013, supervisors: D. Daney, J-P. Merlet
5. M. Harshe, Active rehabilitation, 2009-2012, supervisors: D. Daney, J-P. Merlet
6. J. Hubert, Classification of the singularity of parallel robots, 2007-2010, supervisor: J-P. Merlet, submitted in September 2010
7. H. Qu, Optimization of parallel robots, 2009-2012, supervisor: J-P. Merlet
8. J. Alexandre Dit Sandretto, Calibration of large parallel robots, 2010-2013, supervisors: D. Daney, G. Trombettoni

9.3. Other Activities

9.3.1. National Activities

- J-P. Merlet is president of IFToMM France and member of the scientific committee of the CNRS Robotics GDR.

9.3.2. INRIA activities

- J-P. Merlet is a member of the "Bureau du Comité des Projets" of the Sophia-Antipolis INRIA center, of the Scientific Communication Commission, of the local durable development committee, and of INRIA Evaluation Board (CE). As a CE member he is involved in the evaluation of INRIA ADT.
- O. Pourtallier is a member of the CSD (doctoral students monitoring) and NICE (long term invited scientists selection).

10. Bibliography

Major publications by the team in recent years

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[2] D. DANEY, Y. PAPEGAY, B. MADELINE. *Choosing measurement poses for robot calibration with the local convergence method and Tabu search*, in "Int. J. of Robotics Research", June 2005, vol. 24, n^{o} 6, p. 501-518.

[3] C. JERMANN, G. TROMBETTONI, B. NEVEU, M. RUEHER. *A Constraint Programming Approach for Solving Rigid Geometric Systems*, in "Proceedings of CP'2000,Sixth International Conference on Principles and Practice of Constraint Programming", LIM, 2000, vol. 1894, p. 233-248.

[4] J.-P. MERLET. *Parallel robots, 2nd Edition*, Springer, 2005.

[5] J.-P. MERLET. *Interval Analysis and Reliability in Robotics*, in "International Journal of Reliability and Safety", 2009, vol. 3, p. 104-130, http://hal.archives-ouvertes.fr/inria-00001152/en/.

[6] Y. PAPEGAY. *From Modeling to Simulation with Symbolic Computation: An Application to Design and Performance Analysis of Complex Optical Devices*, in "Proceedings of the Second Workshop on Computer Algebra in Scientific Computing", Munich, Springer Verlag, June 1999.

[7] G. TROMBETTONI. *A Polynomial Time Local Propagation Algorithm for General Dataflow Constraint Problems*, in "Proc. Constraint Programming CP'98, LNCS 1520 (Springer Verlag)", 1998, p. 432–446.

Publications of the year

Doctoral Dissertations and Habilitation Theses

[8] I. ARAYA. *Exploiting Common Subexpressions and Monotonicity of Functions for Filtering Algorithms over Intervals*, University of Nice–Sophia, 2010.

[9] J. HUBERT. *Singularités et manipulateurs parallèles*, Ecole des Mines de Paris, 2010.

Articles in International Peer-Reviewed Journal

[10] K. HARADA, D. OETOMO, E. SUSILO, A. MENCIASSI, D. DANEY, J.-P. MERLET, P. DARIO. *A reconfigurable modular robotic endoluminal surgical system: Vision and preliminary results*, in "Robotica", 2010, vol. 28, n^o 2, p. 171–183, http://dx.doi.org/10.1017/S0263574709990610.

[11] M. HLADÍK, D. DANEY, E. TSIGARIDAS, P. ELIS. *Bounds on real eigenvalues and singular values of interval matrices*, in "SIAM Journal of Matrix Analysis and Applications", 2010, vol. 31, n^o 4, p. 2116-2129.

[12] B. NEVEU, G. TROMBETTONI, G. CHABERT. *Improving Inter-Block Backtracking with Interval Newton*, in "Constraints", 2010, vol. 15, n^o 1, p. 93-116, http://hal.inria.fr/hal-00481324.

International Peer-Reviewed Conference/Proceedings

[13] I. ARAYA, G. TROMBETTONI, B. NEVEU. *Exploiting Monotonicity in Interval Constraint Propagation*, in "Proc. AAAI", Atlanta, AAAI Press, 2010, p. 9–14.

[14] I. ARAYA, G. TROMBETTONI, B. NEVEU. *Making Adaptive an Interval Constraint Propagation Algorithm Exploiting Monotonicity*, in "Proc. CP, Constraint Programming", St Andrews, LNCS, Springer, 2010, n^o 6308, p. 61–68.

[15] M. CARRICATO, J.-P. MERLET. *Geometrico-static Analysis of Under-constrained Cable-driven Parallel Robots*, in "ARK", Piran, 28 June-1 July 2010.

[16] D. DANEY. *Int4Sci: Scilab Interface for Interval Analyis*, in "Proceedings of the 14th GAMM-IMACS International Symposium on Scientific Computing, Computer Arithmetic and Validated Numerics (SCAN'2010)", Lyon, France, September 2010, Invited Talk.

[17] J.-P. MERLET, D. DANEY. *A portable, modular parallel wire crane for rescue operations*, in "IEEE Int. Conf. on Robotics and Automation", Anchorage, 3-8 May 2010, p. 2834-2839.

[18] J.-P. MERLET. *Managing Uncertainties in Kinematics*, in "SIAM 2010 Annual Meeting", Pittsburgh, 12-16 July 2010, Invited talk.

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[20] J.-P. MERLET. *MARIONET, a family of modular wire-driven parallel robots*, in "ARK", Piran, 28 June-1 July 2010, p. 53-62.

[21] J.-P. MERLET. *Preliminary design of ANG, a low-cost automated walker for elderly*, in "3rd European Conf. on Mechanism Science (Eucomes)", Cluj-Napoca, 14-17 September 2010, p. 529-536.

[22] G. TROMBETTONI, Y. PAPEGAY, G. CHABERT, O. POURTALLIER. *A Box-Consistency Contractor Based on Extremal Functions*, in "Proc. CP, Constraint Programming, LNCS 6308", St Andrews, Springer, 2010, p. 491–498.

National Peer-Reviewed Conference/Proceedings

[23] I. ARAYA, B. NEVEU, G. TROMBETTONI. *Exploitation de la monotonie des fonctions dans la propagation de contraintes sur intervalles*, in "JFPC 2010 - Sixièmes Journées Francophones de Programmation par Contraintes", Caen, France, Jun 2010, p. 23-31, http://hal.inria.fr/inria-00520371.

[24] I. ARAYA, B. NEVEU, G. TROMBETTONI. *Une nouvelle extension de fonctions aux intervalles basée sur le groupement d'occurrences*, in "JFPC 2010 - Sixièmes Journées Francophones de Programmation par Contraintes", Caen, France, Jun 2010, p. 13-22, http://hal.inria.fr/inria-00520373.

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[25] I. ARAYA, B. NEVEU, G. TROMBETTONI. *An Interval Extension Based on Occurrence Grouping*, in "Abstract at SCAN, Int. Symposium on Scientific Computing, Computer Arithmetic and Validated Numerics", Lyon, France, 2010.

[26] I. ARAYA, G. TROMBETTONI, B. NEVEU. *Making Adaptive an Interval Constraint Propagation Algorithm Exploiting Monotonicity*, in "Abstract at SWIM, WS on Interval Methods", Nantes, 2010.

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[29] Y. PAPEGAY. *Garantir le calcul numérique malgré les incertitudes*, in "Conférence Mathematica Paris 2010", Juin 2010.

[30] Y. PAPEGAY. *Modeling and Simulation of French Elections*, in "Wolfram Technology Conference", Champaign, Illinois, USA, 2010.

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[31] M.-C. RIFF, E. MONTERO, B. NEVEU. *C-Strategy: A Dynamic Adaptive Strategy for the CLONALG Algorithm*, in "Transactions on Computational Science VIII", M. L. GAVRILOVA, C. TAN (editors), Lecture Notes in Computer Science, Springer, 2010, vol. 6260, p. 41-55.

Research Reports

[32] Y. PAPEGAY. *The Mosela Modeling and Simulation Environment: Efficient Compilation*, INRIA/Airbus France, December 2010.

Other Publications

[33] G. TROMBETTONI. *Introduction aux méthodes à intervalles pour la résolution de systèmes d'équations non linéaires*, janvier 2010, Journées Nationales du GDR Informatique Mathématique.