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Project-Team Coprin

Constraints solving, OPtimization, Robust INterval analysis

Sophia Antipolis - Méditerranée

Theme : Robotics

Activity Report

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1. Team

Research Scientist

Jean-Pierre Merlet [Team Leader,DR1, HdR]
David Daney [CR1]
Bertrand Neveu [Certis Staff members, “Ingénieur en chef des Ponts et Chaussées”, HdR]
Yves Papegay [CR1]
Odile Pourtallier [CR1]
Nacim Ramdani [On leave from Paris XII until September 2009]

Faculty Member

Gilles Trombettoni [Assistant Professor UNSA, HdR]

Technical Staff

Guillaume Aubertin ["Ingénieur Associé", since September 2009]
Nicolas Chleq ["DREAM Engineer"]
Bogdan Rosca ["Ingénieur Associé", until May 2009]

PhD Student

Ignacio Araya [funded by Conicyt]
Sami Bennour [joint supervision with Monastir Engineer School]
Júlia Borràs [joint supervision with University of Barcelona]
Mandar Harshe [funded by INRIA]
Julien Hubert [funded by ANR]

Visiting Scientist

Marco Carricato [University Bologna]

Administrative Assistant

Christine Claux [part-time in the project]

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. Being given this domain it will be possible to determine nominal dimensions for the mechanism so that even if there are bounded variation between the real dimensions and the nominal one, 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 problem, 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 are 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 guarantee 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 6.1.4) are strategic for the project as they allow us to validate our theoretical work and discover new problems that will feed on the long term the theoretical analysis developed by the team members.

We have started since two years a strategic move toward **assistance robots** (section 6.1.6). 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
- they may be controlled through a large variety of simple interfaces

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.

2.2. Highlight of the year

As highlight of this year we will mention the experimental test of our robotized rescue crane. This crane, with a workspace of roughly 2000 cubic meters, making it the largest that has ever been deployed, has been installed outdoor and we have performed various rescue experiments and demonstrations (see section 6.1.4 for further details).

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 exists two values X_1, X_2 such that $f(X_1) > 0$ and $f(X_2) < 0$). There are few restrictions on the f we can deal with as we are able to manage explicit functions using classical mathematical operators (e.g. $\sin(x+y) + \log(\cos(e^x) + y^2)$ or 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 will be 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 to find all the solutions within the domain as soon as 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 includes one, and only one, solution together with a numerical approximation of this solution, that may further be refined at will using multi-precision.

The kernel of our methods is the use of *interval analysis* that allows one to manipulate expression 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

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

In other words the interval evaluation provide a lower bound for 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 way that the results are guaranteed with respect to round-off errors i.e. in spite of numerical errors induced by the use of floating point numbers property 1 is still valid
- if $A > 0$ or $B < 0$, then there are now values of the unknowns in their respective ranges that may cancel F
- if $A > 0$ ($B < 0$), then F is positive (negative) for any value of the unknowns in their range

But there is a major drawback of the interval evaluation: there may be an overestimation of $A(B)$ i.e. there may be no value of $x_1, x_2, ..., x_n$ such that $F(x_1, x_2, ..., x_n) = A(B)$. This overestimation occurs because in our calculation each occurrence of a variable is considered as an independent variable and consequently if a variable have multiple occurrences, then an overestimation may 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 this 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 will be stored in a list and processed later on. The algorithm will be completed 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 it is shown that for a box $\mathcal{B}$ we have $F(\mathcal{B}) \geq 0$).

A generic interval analysis algorithm involves the following steps in sequence on the current box [14]:

1. *exclusion operators*: these operators determine that there is no solution to the problem within a given box. An important step here is an extensive and smart use of the monotonicity of the functions [28], [43], [27], [42]
2. *filters*: these operators may reduce the size of the box i.e. decrease the width of the allowed ranges for the variables [29], [39], [9]
3. *existence operators*: they allow one to determine that there is a unique solution within a given box and are usually associated to a numerical scheme that enable to compute 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 focuses on mathematical developments (adapting classical theorems to interval analysis, proving interval analysis theorems), on the use of symbolic computation and formal proof (a symbolic pre-processing allows one to automatically adapt the solver to the structure of the problem), on software implementation and on experimental tests (for validation purposes).

3.1.2. Robotics

COPRIN has a long-standing tradition of robotics studies, especially for closed-loop robots [12], [13], [14]. We address first theoretical issues with the purpose of obtaining analytical and theoretical solutions, but in many cases only numerical solutions can be considered because of 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 because of the size of the problem
2. we want to take uncertainties (which are inherent to a robotic device) into account so that we can guarantee that the performance level of the *real* robot will satisfy 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 [13], modularity management [36] and prominently *appropriate design*, i.e. finding the dimensioning of a robot mechanical architecture that guarantees that the real robot will satisfy a given list of requirements [17], [18]. But the methods that we have developed can be used for other robotic problems, see for example the management of uncertainties in posture estimation and rehabilitation [19], [40], [41] or motion planning for humanoid robot [32], [33].

Our theoretical work must be validated through experiments that are essential for the sake of credibility. A contrario, experiments will feed the theoretical work (quite often COPRIN has been the first robotic group to address some theoretical issues that were pointed out by experiments). Hence COPRIN works with partners for the development of real robots but also develops its own prototypes (approximately one every 6 years and since 2008 we are in the development phase for several prototypes).

In term of applications we have focused 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 [11] and entertainment, that can be regrouped under the name of *assistance robotics*, section 6.1.6. 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 and developing 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 [10], [46]), 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 (section 6.1.4). Although these topics are new for us, they will constitute the major research axis of the project for a 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 is an essential part of the research within COPRIN since a large part of this research can only be validated experimentally. Software developments are addressed along various axes:

1. interval arithmetic: although our purpose is not 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 extend 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 of 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 will be reluctant to learn a new programming language just to solve problems that are only small elements of a more general problem context. 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 has started in 1998, is a collection of procedures based on interval analysis for systems solving and optimization.

`ALIAS` is constituted 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 to get the results within the same `Maple` session. The role of this interface is not only to generate automatically the C++ code, 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. This interface provides an interval arithmetic, basic interval manipulation tools as well as 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 the request of end-users.

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 namely symbolic preprocessing of expressions, and symbolic specializations of interval analysis algorithms.

This year, we have extended the functionalities of symbolic preprocessing of expressions, and symbolic specializations of interval analysis algorithms, with evaluation and visualization procedures for intervals and boxes. We have also integrated an implementation of our previous work on computations of reachable sets for continuous nonlinear dynamical systems based on comparison theorems for differential inequalities and on hybridization.

6. New Results

6.1. Robotics and mechanism theory

6.1.1. Modeling human sensori-motor control of postural coordination dynamics

Participant: Nacim Ramdani.

As part of a collaboration with LIRMM and the EDM group (Univ. Montpellier 1), we have addressed the issue of modeling human sensori-motor control of postural coordination dynamics. We proposed a closed-loop controller which captures the complex postural behaviors observed in humans and can be used to implement efficient and simple balance control principles in humanoids [30], [31], [44]. We also proposed a closed-loop model with actuator dynamics and sensory feedback to capture the complex postural behaviors observed in a human head tracking task. In motor-control literature, it is usually conjectured that spindle feedback gains are scaled by the central nervous system to adapt muscle stiffness according to postural task. We propose to identify these feedback gains for several target's frequency values. Comparison with experimental results on human shows the relevance of our modeling [45]. We are also addressing this modeling issue with stroke patients [38].

6.1.2. Planning and Fast Re-Planning of Safe Motions for Humanoid Robots

Participant: Nacim Ramdani.

These works deal with the computation of optimal motions for humanoid robots. Most motion planning methods rely on optimization algorithms which need motion parametrization and a time-discretization of the constraints which define robot physical limits. We show that time-grid discretization is hazardous for robot safety and integrity. Hence, we propose a new method for safe discretization which computes constraints extrema over time-interval [33] and we implement our approach within a hybrid method which ensures constraint validity while requiring the same CPU time load as state-of-the-art point methods. Using our method, we created a database of elementary motion sequences, which were then used to follow a moving target. However, there is no method fast enough to re-plan a new motion when the environment changes. Thus, we proposed a new re-planning method which uses a sub-set of feasible motions computed off-line in the vicinity of an optimal motion. Then, the re-planning process consists in picking up, within this sub-set, a new motion which fits the new environment. We tested our re-planning method for a kicking motion where ball location changes and we were able to re-plan motion in less than 1.5s CPU-time [32].

6.1.3. 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 8.1.2, that is totally devoted to this topic.

Our first study was to define a meaningful index to quantify the proximity to singularities. As singularity should be avoided in general because the joint forces of the robot may go to infinity in the vicinity of such a pose, 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. We have shown that it was possible to calculate the border of the static workspace for planar robots having a fixed load and a constant orientation by using an algebraic approach [12]. However generalizing this method for spatial robots having uncertainties in their geometrical model and being submitted to a possible set of loads is not possible. Hence we are currently developing an interval analysis software that will allow to calculate an approximation of the static workspace. Our objective is to present a *safe* subset of the static workspace as a set of 6-dimensional boxes that define poses for which the joint forces/torques satisfy the threshold constraint. The uncertainties in the robot geometry is 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 are the real values of the geometrical parameters within their intervals. For that purpose we define a minimal width for the boxes and if a box has a width lower than this minimum while interval analysis does not allow to determine if it is safe or can be rejected as unsafe, then it is neglected. Our algorithm is incremental as the neglected boxes at a given run will still be stored; for the next run with a lower minimal width for the box we will consider only the neglected boxes obtained at the previous run.

6.1.4. 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:

- MARIONET-REHAB: a 2m by 1.2m robot 6 d.o.f robot using up to 7 wires. Its actuation scheme differs completely from the classical approach (rotary motors and drum): it uses instead 40cm stroke linear actuators and a pulleys system, allowing for improved accuracy and very high speed. This robot exhibits also a high mechanical modularity (the location of the wire system may be changed at will and various maximal length changes will be possible)
- MARIONET-CRANE: a very large 6 d.o.f. rescue crane using winches as actuators. This system has been installed this year in an outdoor environment in a 20m by 20m by 12m space, leading to the largest 6 dof wire-crane that has been ever built. This project has partly benefited from INRIA help 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 as well as motion provider. This prototype will be build in 2010.
- 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 implemented in 2010

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 used as a rehabilitation tool for patient suffering arm coordination problem after a heart stroke. The patient is put in front of a computer screen on which a red dot is moving and he/she has to extend the arm, pointing a finger along the line joining to successive dots. We have first used MARIONET-REHAB in a passive mode: 3 to 6 wires are attached to the patient's wrist and are following the arm motion. Using the forward kinematic of the robot we are able to monitor the finger motion, hence asserting its deviation from the perfect linear trajectory. The robot has also been used in a semi-active mode in which the wires are used to exert a vertical force to relieve the patient by almost suppressing the gravity. This allows for longer rehabilitation session, Then we have experimented the use of the robot in an active mode in which the wires are exerting a correcting force as soon as the finger deviates from the right trajectory. We intend to use now the robot to monitor and correct human joint motion [40], [41]. We have also tested MARIONET-REHAB as a fast motion device for planar motion, up to a speed of 8 m/s. Although the robot is potentially able to reach a much higher speed (probably up to 400m/s in some part of its workspace), our current experimental setup does not allow us to fully investigate such motion.

The second part of the year has been devoted to the deployment of MARIONET-CRANE in an outdoor environment. Six winches located on top of tripods have been installed on the roof of two buildings and on a parking lot. MARIONET-CRANE is a powerful tool that may lift up to 1 ton in a workspace of roughly 2000 cubic meters. We have experimented various lifting motion combining translation (going up to an height of 8 meters) and rotation (with a tilting angle of up to 50 degrees) with 2 mannequins. We have also lifted a 750 kg trailer and have made it roll along a pre-defined path. We have also experimented getting a mannequin out of an intermixed set of pallets in a very unstable equilibrium. Such system involves a set of difficult problems that have never been addressed. For example the forward kinematics (FK) is much more complex than the already difficult equivalent problem for parallel robot having rigid legs. Indeed a crane configuration implies that we have to take also into account the mechanical equilibrium of the system, with the additional constraint that the tension in the wire should be positive (as a wire cannot exert a pushing force). Consequently to determine the current pose of the robot we need to solve a system of equations that is larger than for classical parallel robots because of the equilibrium equations and, furthermore, we have to solve this system by considering all possible combinations of wires under tension, as some of them may become slack and hence do not contribute to the mechanical equilibrium. Note also that the inverse kinematics (i.e. finding the values of the control variables to reach a given pose), that is trivial for parallel robots having rigid legs, becomes also more complex for wire robots, as the wire tensions of the rigid solution, that are required to satisfy the mechanical equilibrium, may not satisfy the positive tension condition. Hence the desired pose may not be reachable exactly and we have identify the possible motion variety and/or to determine the reachable pose that is the closest to the desired pose.

We have started to address these problems for 4 wires [34] and then have developed a generic certified Newton schemes, both for the inverse and direct kinematics, that works whatever is the number of wires of the robot. These schemes also examine all possible wire combinations as a n wires robot may be locally in an equilibrium with only $m < n$ wires in tension.

The deployment of MARIONET-CRANE has been also the opportunity to test the use of "smart objects", i.e. small communicating devices. For example we have installed on the stretcher that was used to move victims the following devices:

- a small mobile robot with a webcam and wifi connection
- a "Sunspot": a 74g device with a radio link, on board accelerometers and temperature sensor and the possibility of adding other sensors
- a multi-purpose internet connected Nabaztag

Our purpose was to allow the medical support team to gain access to physiological measurements on the victim while he/she was still in a transfer phase. During the transfer it was possible to move the mobile robot around the victim through a simple i-phone interface and to get body temperature measurements, allowing the medical team to gain time for its diagnosis and prepare its intervention in advance. The Nabaztag was used as a phone call center: receiving the physiological measurements it is able to call a rescue center for asking additional rescue equipments. Such devices will also play an important role for our projects in assistance robotics (see section 6.1.6). We have organized a demonstration for the "Groupement de reconnaissance et d'intervention en milieu périlleux" (GRIMP), a special rescue service that specializes in difficult and dangerous operations and it is also planned that we attend a training session of this group. These rescuers were impressed by the quality and diversity of the proposed motion, but have asked us to improve the final phase of the transfer in which the surface team recovers the victim. A full scale public demonstration of `MARIONET-CRANE` has been organized for INRIA personnel, with over 100 attendees. A reduced version of this demonstration has been exhibited during "La fête de la Science" and during the visit of local authorities.

6.1.5. Calibration of cable robot using distance matrices

Participant: David Daney.

The particular geometry of the location of the anchor points of a cable robot may be described through a distance matrix. Its coefficients are given by the distance of the cable's anchor points between them. The Cayley-Menger determinant of this matrix provides some interesting information that can help in the self-calibration of redundant robots. The main interest of this approach is that it reduces the number of parameters which have to be considered in the calibration equation and improves the numerical conditioning of the systems. This original approach, which has been implemented, needs to be further studied.

6.1.6. Assistance robotics

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

As mentioned in the presentation 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 (at the opposite of the existing trend of focusing on some "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 and nurses and individuals, with the purpose of identifying and organize in a hierarchy the real problems and their context. According to the first results of these discussions we have decided to explore various full scale scenarii that cover a part of the daily life of an elderly. In each scenario there will be some phases that may require assistance and we will examine how such assistance may be given. This involves an heavy experimental activity and consequently we have decided to build a full scale furnished flat with a sleeping area, a kitchen, a meal area, toilets, a fully instrumented rehabilitation zone (that includes the `MARIONET-REHAB` prototype, walking mill, magnetic bike, rowing machine) and various mobility aids (electric wheelchair and scooter, walking frame). Smart objects (Nabaztag, Sunspots, Phidgets) are also present and several mobile robots (Rovio, PekeeII, Spykee, PoBot, 4WD rovers) are available as well. Pictures of this assistive flat are available at http://www-sop.inria.fr/coprin/developpements/main.html. In 2010 we will equip this flat with a `MARIONET-ASSIST` robot which will be devoted to transfer phases and we will work on fall prevention, detection and assistance whenever it is needed.

A complement of the assistive flat will be the use of `MARIONET-VR` in a virtual reality environment as a rehabilitation and training tool and also as an haptic device with a very large workspace. We plan to conduct the first experiment of `MARIONET-VR` at the end of 2010.

Fundings for `MARIONET-CRANE`, `MARIONET-VR`, `MARIONET-ASSIST` and the assistive flat has 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 .

COPRIN has also proposed the creation of the "Action d'Envergure National" PAL (Personnal Assistant Living), that is leaded by D. Daney, and is strongly involved in PAL.

6.2. Equation systems and linear algebra

6.2.1. Eigenvalues and singular values of interval matrices

Participant: David Daney.

This year was devoted to publish and to finalize our contributions on the approximation of eigenvalues (or singular values) of interval matrices, started in 2006 – see previous activity reports. All details are available in two new Research reports [49], [50] These works have been submitted to journals and are currently in review.

6.2.2. Zeros of interval polynomials

Participant: Odile Pourtallier.

Interval polynomials are polynomials where the coefficients are not real values, but instead interval values. For an uni-variate interval polynomials, the real zeros of some extremal (non interval) polynomials determine the boundaries of the set of real zeros of the interval polynomial. Some Edge theorem give a similar property for complex zeros of an interval polynomial, and allows to decrease the complexity (only the zeros of polynomials with only one interval coefficient (the edge polynomials) has to be determined). Nevertheless, as soon as the degree of the polynomial increases, the number of edges is so large, that the theorem is of no help for practical determination.

We have explored the possibility to determine the set of complex zeros of an interval polynomial by using the above extremal polynomials result and by considering the polynomial system formed by the real part and the imaginary part of the interval polynomial. It amounts to determine the real zeros of a bi-variate polynomial system. We have used projection techniques. This allows to construct a set of the imaginary plan that contains all the complex solutions of the interval polynomial. Nevertheless, due to redundancy problem, this set is not tight enough and the approach should be improved.

6.3. Interval Constraint Programming

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

6.3.1. A New Monotonicity-Based Interval Extension Using Occurrence Grouping

When a function f is monotonic w.r.t. a variable in a given domain, it is well-known that the monotonicity-based interval extension of f computes a sharper image than the natural interval extension does.

We have developed a so-called "occurrence grouping" interval extension $[f]_{og}$ of a function f [27], [42]. When f is *not* monotonic w.r.t. a variable x in the given domain $[B]$, we try to transform f into a new function f^{og} of two new variables x_a and x_b, having the same range than x, so that f^{og} is monotonic, increasing w.r.t. x_a and monotonic, decreasing w.r.t. x_b. Usually the interval extension by monotonicity $[f]_{og}$ of f^{og} produces a sharper interval image than the natural extension does.

For finding a good occurrence grouping, we have proposed an algorithm that minimizes a Taylor-based overestimation of the image diameter of $[f]_{og}$. Experiments have shown the benefits of this new interval extension for solving systems of equations.

6.3.2. An Interval Constraint Propagation Algorithm Exploiting Monotonicity

We may also exploit monotonicity in interval filtering/contraction algorithms for solving systems of nonlinear constraints over the reals.

We have proposed in the paper [28], [43] a new interval constraint propagation algorithm, called MOnotonic Hull Consistency (`Mohc`), that exploits monotonicity of functions. The propagation is standard, but the `Mohc-Revise` procedure, used to filter/contract the variable domains involved in an individual constraint, is novel. This revised procedure uses two main bricks for narrowing intervals of the variables involved in f. One procedure is a monotonic version of the well-known `HC4-Revise`. A second procedure performs a dichotomic process calling interval Newton iterations, close to (while less costly than) the procedure `BoxNarrow` used in the `Box` contraction algorithm.

When f is monotonic w.r.t. every variable with multiple occurrences, `Mohc` is proved to compute the optimal/sharpest box enclosing all the solutions of the constraint (hull consistency). Experiments show that `Mohc` is a relevant approach to handle constraints having *several* variables with multiple occurrences, contrarily to `HC4` and `Box`.

6.3.3. Filtering Numerical CSPs Using Well-Constrained Subsystems

When interval methods handle systems of equations over the reals, two main types of filtering/contraction algorithms are used to reduce the search space. When the system is well-constrained, interval Newton algorithms behave like a global constraint over the whole $n \times n$ system. Also, filtering algorithms issued from constraint programming perform an AC3-like propagation loop, where the constraints are iteratively handled one by one by a *revise* procedure. Applying a revise procedure amounts in contracting a 1×1 subsystem.

We have investigated the possibility of defining contracting well-constrained subsystems of size k $(1 \leq k \leq n)$ [29], [39]. We theoretically define the *Box-k-consistency* as a generalization of the state-of-the-art Box-consistency. Well-constrained subsystems act as *global constraints* that can bring further filtering compared to interval Newton and 1×1 standard subsystems. Also, the filtering performed on a subsystem allows to discover interesting multi-dimensional branching points, i.e., to bisect several variable domains simultaneously. Experiments have highlighted gains in CPU time w.r.t. state-of-the-art algorithms on decomposed and structured systems.

6.4. Miscellaneous results

6.4.1. Continuous and hybrid reachability analysis in presence of uncertainty

Participants: Nacim Ramdani, Yves Papegay.

To address dynamical issues for parallel closed loop robots in a reliable way, even in presence of uncertainty, we are developing tools to compute reachable sets for continuous and hybrid systems, i.e. complex systems where discrete and continuous dynamics interact.

We have first addressed nonlinear continuous reachability computation. When the size of the uncertainty domains are large, the state-of-the-art validated numerical integration methods based on interval Taylor series can produce effective results only for very particular cases. Hence, we have developed alternatives techniques. They rely on comparison theorems for differential inequalities, more precisely the Muller's theorem, in order to bracket the uncertain dynamical between two coupled dynamical systems where there is no uncertainty. In general, the derived bracketing systems are piecewise differentiable functions, hence they cannot be directly integrated using interval Taylor series. Our contribution then resides in the use of hybrid automata to model them [20]. When the system is a monotone dynamical systems, the bracketing hybrid systems are decoupled [21].

These new reachability computation tools are also at the core of new solving techniques for set-membership state estimation with uncertain nonlinear continuous-time systems [15], [22], [24], [35].

In a collaboration with N.S. Nedialkov, we are investigating numerical solving of initial-value problem for differential-algebraic equation (DAE) [51]. We are also investigating solution techniques for numerical constraint satisfaction problems and validated numerical set integration methods for computing reachable sets of nonlinear hybrid dynamical systems in presence of uncertainty [37].

6.4.2. 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 work of aeronautics engineers into digital simulators to accelerate aircraft design. This project already has applications in the aircraft maker development departments.

Modeling and simulation processes usually begin with using scientific theories which describe physical features in terms of formulae and computation algorithms. Based on these models, numerical codes are then implemented for the simulation and visualization of these features. In an industrial context, the large number of parameters and equations involved in the models make the whole process very long, complex and expensive, all the more so that reliable and safe codes are required.

Since the beginning of our collaboration, in 2002, we have successively developed:

- a model edition environment, based on symbolic computation tools, that makes it possible to enter the formulae and the algorithms of the models and to validate them numerically on a reduced set of data [52],
- a C code generator which, using these models, automatically generates the numerical real-time simulation engines to be plugged in the flight simulator, as well as the technical documentation associated with such simulations, which is indispensable for corporate memory [25].
- an highly interactive and modular evaluation code 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 functionalities.

In 2009, we have extended the capabilities of the environment to take into account generic models and instantiation, tree-like hierarchies of models and submodels. We also have extended the nature of the components of the models, taking namely in account the physical dimension of the variables. A new set of model analysis and verification procedures have been provided to help the design of large models.

7. Contracts and Grants with Industry

7.1. 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 6.4.2.

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 enhanced the functionalities and performances of the existing pieces of software belonging to Airbus and to turn them into a prototype that integrate and showcase our results.

7.2. Fatronik Tecnalia

Participant: Nacim Ramdani.

The HumanPost project, conducted also in collaboration with LIRMM, is a study on postural coordination in the elderly, during the Sit-To-Stand movement (STS). The movement has been shown to have different characteristics in the young and in the elderly, but the causes of the discrepancies are still under investigation. The goal of this study is to show if these differences are a consequence of a change in the optimality criteria adopted for the synthesis of the movement.

8. Other Grants and Activities

8.1. International and National initiatives

8.1.1. 3+3 Med RorasII project

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

In 2008 we have obtained an INRIA grant for a collaborative work with Cassino University, Monastir engineer school and University of Oran for a preliminary work on the development of a wire-driven parallel robot for rehabilitation[1], as a follow-up from a the RORAS project. A state of the art on rehabilitation and on rehabilitation protocol has been produced in the RORAS project. In RORASII we plan to use these documents as main inputs to develop an appropriate design software that will allow us to calculate the best robot geometry given a pathology, the patient morphology and the rehabilitation protocol and to use the `MARIONET-REHAB` prototype as main rehabilitation tool.

The RORASII has officially started in June 2009, but has suffered from administrative difficulties.

8.1.2. ANR SIROPA project

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

One of major result we have obtained this year is the video of our `MARIONET-CRANE` prototype going through an assembly mode change (i.e. the robot is moving from a solution of the forward kinematics to another solution with locked actuators) without singularity crossing. The existence of such change have been theoretically proved but they have never been observed in practice, except in trivial cases. A careful experiment planning has allowed us to observe this interesting phenomena (a video is available in the SIROPA web site).

8.2. Participation to National and International Conferences

8.2.1. International Conferences

- I. Araya, B. Neveu and G. Trombettoni participated to: SWIM'09 workshop in Lausanne, Switzerland, IntCP'09 workshop and CP'09 in Lisbon, Portugal,
- D. Daney participated in the IEEE International Conference on Robotics and Automation (ICRA) at Kobe, Japon; in the International Conference On Smart Homes and Health Telematics (ICOST) at Tours, France; and in Journées Nationales de la Recherche en Robotique (JNRR) at Neuvy sur Barangeon , France, as a session organizer. He had been invited by the University of Athens for one week in January, to work on a rehabilitation device.
- J-P. Merlet participated in the IEEE International Conference on Robotics and Automation (ICRA) at Kobe, Japon, in the Computational Kinematics workshop in Duisburg, Germany and in Journées Nationales de la Recherche en Robotique (JNRR) at Neuvy sur Barangeon , France
- Yves Papegay gave a course on Interval Methods at the JDMACS conference in Lausanne, attended and he gave an invited talk at the International Mathematica Users Conference 2009 at Urbana Champaign, Illinois, USA
- N. Ramdani presented papers at: Progress in Motor Control 2009, Marseille, France; International Conference on Perception and Action 2009, Mineapolis, USA; IEEE International Conference on Robotics and Automation, ICRA 2009, Kobe, Japan; IFAC ADHS'09 Analysis and Design of Hybrid Systems 2009, Zaragoza, Spain; 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, St Louis, MO, USA; IEEE Conference on Decision and Control 2009, Shanghai, China.

8.3. Other Activities

8.3.1. National Activities

[1] see https://twiki-sop.inria.fr/twiki/bin/view/Projets/Coprin/RORAS2
[2] https://twiki-sop.inria.fr/twiki/bin/view/Projets/Coprin/SIROPA

- I. Araya, B. Neveu and G. Trombettoni participated to national conference JFPC 2009 in Orléans, France, where 1 paper was presented.
- J-P. Merlet is president of IFToMM France and member of the scientific committee of the CNRS Robotics GDR
- N. Ramdani is co-responsible for the working group ”Méthodes Ensemblistes pour l'Automatique” - GDR MACS[3]. He has co-organised the second edition of the Special Workshop on Interval Methods, SWIM 2009 (http://www.ensieta.fr/e3i2/Jaulin/swim08.html), at Lausanne, Switzerland.

8.3.2. INRIA activities

- D. Daney was president of the CUMIR (Comité des Utilisateurs des Moyens Informatiques, Recherche) until June 2009.
- J-P. Merlet is a member of the "Bureau du Comité des Projets" of Sophia, 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 (invitation of long term scientist visitors).

8.3.3. European Activities

- J-P. Merlet is a member of the scientific committee of the European Conference on Mechanism Science (EUCOMES). He is also board member of the european robotics network EURON.

9. Dissemination

9.1. Leadership within scientific community

- I. Araya was reviewer for IJCAI 2009 and JFPC 2009.
- D. Daney is responsible of the `MARIONET-CRANE` ADT and of the possible AEN Personal Assistant Living (PAL)
- J-P. Merlet is 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 member of the steering Committee of IROS.
- B. Neveu was reviewer for international conferences (CPAIOR 2009, CP 2009, IJCAI 2009), the national conference JFPC 2009. and for Journal of Advanced Research in Evolutionary Algorithms. B. Neveu was member of the program committee of Local Search Techniques in Constraint Satisfaction (LSCS 2009) workshop and of Workshop on Emergent Computing (WEC 2009). B. Neveu was also an expert for an ANR project. He visited the research team of Maria-Cristina Riff Rojas at Federico Santa Maria University in Valparaiso, as invited guest during 10 days in November 2009, while E. Montero, a PhD student from Federico Santa Maria University in Valparaiso, Chile visited the COPRIN team during a month in September 2009.
- 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'2009 conference.
- O. Pourtallier is a member of the executive board of the International Society of Dynamic Games.

[3]http://www.lirmm.fr/ensemble

- N. Ramdani is a member of the IFAC Technical Committee 1.3 on Discrete Event and Hybrid Systems, for the 2008-2011 triennium. He is a member of the editorial advisory board of The Open Mechanical Engineering Journal. He was a member of the program committee of the 13th International Conference on Hybrid Systems: Computation and Control (HSCC'10).
- G. Trombettoni has been reviewer for JAIR journal, and for the Constraints journal. He was a member of IJCAI 2009 and JFPC 2009 program committees and co-organizer of the IntCP'09 workshop. He participated to RAIM'2009, in Lyon, where he gave an invited talk and give a talk to the SAMOS seminar in Paris 1 University.

9.2. Teaching

- D. Daney gave a course on medical robotics, Master of Bio-Medical, Univ. Nice Sophia Antipolis (15h).
- J-P. Merlet have taught 18h during the Int. Summer School on "Mathematical methods for kinematics" at University Innsbruck
- O. Pourtallier has taught 6 hours on game theory to master OSE, at École des Mines de Paris, Sophia Antipolis and 6 hours on optimization, to DESS IMAFA at UNSA.
- G. Trombettoni is an assistant professor in computer science at IUT R&T (networks and telecoms) of Sophia Antipolis.
- B. Neveu has given lectures on constraint programming in the Computer Science Master at University of Nice Sophia (2 h)

9.2.1. PhD thesis

- J-P. Merlet has been a reviewer of 3 PhD theses and jury member of 1 HDR
- B. Neveu has been a reviewer of 2 PhD theses and a jury member of 3 PhD theses.
- N. Ramdani was a jury member for 5 PhD defense.

9.3. PhD thesis

Current PhD theses:

1. I. Araya, Filtering techniques for interval solvers
2. S. Bennour, Modeling of human joints for rehabilitation purposes
3. J. Borràs, Classification of singular robots
4. M. Harshe, Active rehabilitation
5. J. Hubert, Classification of the singularity of parallel robots

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