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Project-Team COPRIN

Constraints solving, optimization and robust interval analysis

IN COLLABORATION WITH: Laboratoire Centre Enseignement Recherche Traitement Information Systèmes (CERTIS)

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THEME
Robotics

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Project-Team COPRIN

Keywords: Interval Analysis, Numerical Methods, Robotics, Human Assistance

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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 (see sections 6.1.4,6.1.5.1,6.1.5.2) 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 four 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 has been accepted this year and that is coordinated 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.

2.2. Highlights

- experimental analysis of gait pattern with the instrumented walker `ANG-light`: 24 subjects from INRIA (age: from 25 to 61) were submitted to a one hour walking protocol. This experiment was a preliminary for the one that will take place at CHU with elderly people, for which the CPP has been finally granted
- 275 visitors have attended a demonstration of the project this year during 14 visits (among which an open lab day organized for the European Robotics Week)
- simultaneous development of several innovative prototypes: two instrumented walkers, two wire-driven parallel robot, assistive devices

3. Scientific Foundations

3.1. 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

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

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. Hence if a variable has 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 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 [1], [7], [3], [5]:

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
2. *filters*: these operators may reduce the size of the box i.e. decrease the width of the allowed ranges for the variables [8], [29], [25], [28], [22]
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).

3.2. 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 [17] such as workspace and singularity analysis [24], positioning accuracy, trajectory planning, reliability, modularity management 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 [10]. The methods that we develop can be used for other robotic problems, see for example the management of uncertainties in aircraft design [32], [31].

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 [9], [16], [23], [19], [20] and entertainment, that can be regrouped under the name of *assistance robotics* (see 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 6.1.5). 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, Gilles Trombettoni, Bertrand Neveu.

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 . 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.

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.

6. New Results

6.1. Robotics

6.1.1. Calibration and identification

6.1.1.1. Calibration of a cable-driven robot

Participants: David Daney, Julien Alexandre dit Sandretto, Jean-Pierre Merlet, 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-constraint mechanism allows to perform a self-calibration - i.e. the identification of the parameters does not need additional external measurement. A first experimentation, done in Montpellier, validated a novel approach which consists in a simultaneous identification of parameters and robot position (unknown in self-calibration process).

6.1.1.2. Cable properties

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

The majority of researches done on cable-driven robot modeling need to take into account that the mass and the elasticity of wires are neglectable. However, they can not prove that these hypotheses are acceptable regarding these objectives. We have proposed an algorithm based on interval analysis to judge the validity of these assumptions for a cable-robot in a specific workspace. This method have been tested on the Tecnalia/LIRMM's prototype and used for the construction of the Cogiro robot.

6.1.1.3. Optimal calibration poses of a 3-RPR planar parallel robot

Participant: David Daney.

The choice of the measurement configuration is crucial to improve the robustness of the calibration for measurement uncertainties. This year, a geometrical approach has been used to determine formally the set of the optimal poses for the identification of the kinematic parameter of a 3-RPR planar parallel robot. This result is important because it explains the influence of the location of some particular robot poses in their workspaces during the model identification process. A generalization is explored to construct automatically an optimal set for robot calibration and moreover, to improve experimental design algorithms. The aim is now to obtain similar results for cable driven robots calibration.

6.1.1.4. Geometric calibration of a space telescope

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

In October 2010 begun 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. Thus, a geometric calibration procedure was considered and a campaign of photogrammetry was performed on the telescope. Using a kinematic description, a final accuracy of at worst 10 μm was reached on the position of the platform of the telescope. The aim of these measures were also to valid or not the model of comportment of the flexible parts of the device. This campaign brought to light the necessity to consider forces and torques acting on the structure in the deformation of the flexible parts in order to reach a submicrometric accuracy.

6.1.1.5. Modelization of flexible articulations of the telescope

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

In order to improve the final accuracy of the above-mentioned space telescope, a novel model including the statics equations in order to calculate deformations of the flexible articulations is currently under study. The main difficulty is to identify parameters (stiffness matrix and geometric parameters) that have different units and are not of the same order of magnitude. To solve this issue, we are focusing our effort to write the problem in a better robust form.

6.1.1.6. Interval Identification

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

There are many approaches to identify the parameters of a model. In most cases, it consists in providing a particular solution of an over-constraint set of equations which must be robust to measurement to errors: in least square sense, with some statistical properties.... However, the interpretation and the validity of the result can be difficult and prone error. We propose to investigate some interval approaches in order to associate to the result some information and a certification of solutions.

6.1.2. Rehabilitation and biomechanics

Participants: Sami Bennour, David Daney, Mandar Harshe, Jean-Pierre Merlet [correspondant].

The focus of the work is on analyzing knee joint motion during a walking activity. The measurement system is based on the wire actuated parallel robot architecture. To increase the reliability of our analysis, and decrease the influence of Skin Tissue Artifacts (STA), we also incorporate a passive wire measurement system, IR camera based motion capture system, accelerometers, and force sensors to measure human motions.

The main principle of the system is to observe relative motions of the collars attached to tibia and femur. These are connected to the base by wires and also hold the other sensors. Measurements in the global frame and collar specific local frames give precise data to reconstruct collar (and thus, knee joint) motion.

Over the past year we have finalized the experimental setup, by calibrating the collars and the sensor systems, and adapting the existing wire robot system (MARIONET-REHAB) to work along with the other sensors. The software developed uses a single unified input file to specify all sensor configurations, streamlining experiments. We performed our preliminary experimental trials for walking motion on three subjects using the wire sensors, accelerometers and optical motion capture system.

We began work on processing the data obtained from these trials. Post-processing functions have also been developed to calculate additional collar properties, perform sensor data processing (filtering, noise removal and estimation) and access files in the C3D file format, which is used a binary file format used by the motion capture system.

The main challenge we are working on is to perform sensor data fusion and increase reliability of results. For this we must identify parameters that correlate the different sensor measurements and perform error analysis. Possible solutions include using interval analysis methods to address the uncertainties.

6.1.3. Kinematics of wire parallel robots

Participant: 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. Curiously the forward kinematics of robot (i.e. finding the possible poses of the platform for given wire lengths) with at least 6 wires is straightforward: the distance equations allows to determine all poses and then we use the static equations to calculate the wire tensions and discard the one having at least one negative tension. For robot having less than 6 wires we have to consider simultaneously the distance equations and the static equations in order to get a square system (of $n + 6$ equations for a n-wires robot). We have investigated the case of a 3-wires robot with all wires attached at different points on the platform and have shown that all solutions can be computed provided the solving of an univariate polynomial of degree 158 [17]. Although we are not able to guarantee that the degree of this polynomial cannot be decreased, we believe that nevertheless the order will be too high for robust determination of the solutions and can only be used to determine an upper bound for the maximal number of solutions. We have also investigated theoretically and experimentally the kinematics of a n-wires ($n \geq 4$) robot with all wires attached at the same point (i.e. only the position of the center of the platform can be controlled). Although this robot is apparently redundant, we have shown that in any pose at most 3 wires will be simultaneously under tension and therefore that the redundant wires cannot be used to control the wire tensions.

As the wire length measurements are not sufficient to determine the current pose of the platform (which is necessary for control purposes) we are investigating the use of additional sensors. Our prototypes `MARIONET-ASSIST` and `MARIONET-VR` are instrumented to measure wire directions, but with a large uncertainties. We have started a theoretical investigation to determine under which conditions these uncertainties may lead to a non-unique solution and we will validate the results on the two prototypes.

6.1.4. Rehabilitation robots for the immersive space

Participants: Michael Burman, Jean-Pierre Merlet.

The on-site immersive room provides 3D visualization but is lacking of haptic feedback and motion capabilities. We plan to implement in this room a movable system, constituted of:

- a *6 degrees-of-freedom motion base*: the motion system 710-6-500-220 by Servos Simulation Inc. has been selected and is now operational and fully calibrated. If necessary the user may stand on this motion base
- the `MARIONET-VR` wire-driven parallel robot: this robot uses the same actuation principle than the `MARIONET-REHAB` robot (linear actuator with a pulley system for coiling and uncoiling of the wires), but is able to lift a person. The prototype is basically functionnal but its installation in the immersive room has been delayed because of lack of appropriate fixing elements

The full system will be installed in the immersive room at the beginning of 2012.

6.1.5. Assistance robotics

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

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 communicant 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) [18], [14], [21]. We have started last year the development of a simulated flat in order 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. We describe in the following sections several devices that have been developed/improved during this year[1]. Note that our demonstration in assistance are highlighted during the visit of Sophia (275 visitors have attended our demonstration during 14 visits) and have received serious press coverage (5 papers, 2 TV interviews).

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

6.1.5.1. *Walking aids*

Wheeled walking aids are usually the first tools that are used when motricity problems occur. We are developing the family of robotized *Assistive Navigation Guide* (ANG), which are based on commercially available Rollators, with several objectives (we mention only 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).
- mobility help: provide an on-demand mobility help
- gait pattern monitoring: we believe that being able to monitor the trajectory of the walking aid will provide useful information on the gait pattern of the user

For reaching these objectives we have developed two walking aids:

- `ANG-light`: a walking aid with encoders in the wheels, 3D accelerometer, gyrometer. These sensors allow to measure the trajectory of the walking aid and several features of the user's gait (step pattern, gait assymetry,...). `ANG-light` has been tested by the CHU of Nice-Cimiez that was willing to perform an in-depth investigation of its use. For that purpose we have asked in September 2009 for the necessary formal authorization to the local CPP, which has been granted only in December 2011. To prepare this study we have organized a large scale experiment at INRIA, where 24 users were asked to perform the trajectories of the protocol twice, with and without the aid. When not using the aid the users were equipped with 3D accelerometer on the wrists and knees and were using specific shoes with force sensors in the sole. Initial analysis of the records shows that indeed we are able to obtain significant information on the gait pattern, that are not available using the existing tools, and detect differences in the gait pattern for user having even a light pathology in the lower limb. The experiment with elderly patients at CHU will take place in January 2012.
- `ANG-II`: this aid is an evolution of the motorized walker `ANG`, with a lower weight and better integration

6.1.5.2. *MARIONET-ASSIST*

This wire-driven parallel robot is installed in the ceiling of the flat. It has been used this year in the 4-1 configuration (4 wires attached at the same point), which allows for controlling the position of the platform, but not its orientation. Several platforms have been developed, all of them incorporating a webcam and allowing for a free rotation around the vertical axis, while an accelerometer measure the tilt angle of the platform (which is used to determine in which direction the end-user is willing to move). One of the platform incorporate a 4 d.o.f. robot that may grasp light object (one of our objective is to use also the robot as a manipulator for bringing object back to the user in a more or less autonomous way, which is the subject of the PhD thesis of R. Ramadour).

We have shown that the the robot can be used for sit-to-stand transfer and for lifting handicapped people. A specific attention has been devoted to propose very simple control interface: joystick, remote TV set, control box whose tilt determine the motion axis.

6.1.5.3. *Other flat equipments*

Our scenario includes the management of emergency situations such as the fall. Fall detection can be performed by the `ANG` walkers but we have also started investigating the inclusion of fall detection system in the clothes of the end-user either through a GEO-300 devices or by incorporating an Arduino Lilypad processor. When a fall is detected indoor an alert is transmitted to a coordinator (a Nabaztag) which will order the walker and the `MARIONET-ASSIST` robot to move close to the user to provide a support. At the same time two mobile robots will converge to the same location: a remote-controlled, webcam equipped ROVIO (which can provide images of the end-user to a rescue center) and a Pekee II, that we will equip to provide first aid.

An important point in assistance is to be able to have at all time a rough idea of the localization of the patient. Although we plan to use a Kinect for that purpose, we will also investigate the use of non-vision sensors (which are much less intrusive and therefore can be more easily accepted) such as RFID tag (`ANG-II` has a RIFID tag reader), directive distance sensors and light barriers.

Another axis for assistance is to reduce the risks of fall by using the principle that the objects has to come to the hand of the user (or of the robot), not the opposite. This implies instrumenting the environment with drawer openers and doors manipulation and we have started implementing them on drawers and on the fridge of the flat.

6.2. Interval analysis

6.2.1. Inner Regions and Interval Linearizations for Global Optimization

Participants: Gilles Trombettoni [correspondant], Bertrand Neveu.

Researchers from interval analysis and constraint (logic) programming communities have studied intervals for their ability to manage infinite solution sets of numerical constraint systems. In particular, *inner* regions represent subsets of the search space in which *all* points are solutions. Our main contribution is the use of recent and new inner region extraction algorithms in the *upper bounding* phase of constrained global optimization.

Convexification is a major key for efficiently *lower bounding* the objective function. We have adapted the convex interval taylorization proposed by Lin & Stadtherr for producing a reliable outer and inner polyhedral approximation of the solution set and a linearization of the objective function. Other original ingredients are part of our optimizer, including an efficient interval constraint propagation algorithm exploiting monotonicity of functions.

We end up with a new framework for reliable continuous constrained global optimization. This interval Branch & Bound significantly outperforms the best reliable global optimizers [22], [25], [28].

6.2.2. An Interval Extension Based on Occurrence Grouping

Participants: Bertrand Neveu [correspondant], Gilles Trombettoni.

We proposed last year a new "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} which 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.

This year we have improved the linear program and algorithm that minimize a Taylor-based over-estimate of the image diameter of $[f]_{og}$. We have detailed the proofs of correctness and reliability of this occurrence grouping algorithm [8], [29].

6.3. Miscellaneous results

6.3.1. Equilibrium strategies for linked Electricity and CO2 markets

Participant: Odile Pourtallier.

In collaboration with M. Bossy (INRIA -TOSCA Team) and N. Maïzi (CMA - Mines Paristech) O. Pourtallier the study of equilibrium model for coupled electricity and CO2 allowance exchange markets has been pursued. (see also Section 7.1). A static equilibrium model has been studied under various assumptions on the CO2 market design. All the CO2 market designs do not lead equilibrium, which interfers on the (short term day ahead) electricity market, which in turn interfers on the electricity mixe and consequently on the total emission.

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

6.3.2. 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 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

During the year 2011 the technology demonstrated by our prototype has been transferred to our industrial partner. A lot of work has been done on our modeling and simulation environment to improve its robustness and its development level of quality toward industrial standards. Final version of our prototype is to be delivered to Airbus at the end of the year.

6.3.3. Multi-agent aircraft design

Participant: Yves Papegay.

The modeling environment described in the previous section is used, in collaboration with other teams at Airbus, in the framework of the ID4CS project founded by ANR and dedicated to multi-agent optimization of large scale system. Several models of aircraft engines and of aircrafts have been developed as user cases for the project. Automatic generation of extended models namely computing first order derivatives of the original models has been implemented.

7. Contracts and Grants with Industry

7.1. 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).

7.2. 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 6.3.2.

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

Following a first transfer agreement signed in 2010, another contract licensing to Airbus a final and complete version of this prototype has been signed in 2011.

7.3. Thales Alenia Space

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

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.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR CoGiRo project

Participants: David Daney, 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
- Tecnalia France

8.1.2. ID4CS project

Participant: Yves Papegay.

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 the definition of the use case on preliminary aircraft design, in collaboration with Airbus (6.3.2), in development of uncertainty analysis algorithms, and in automatic generation of agents based on models.

8.1.3. ANR SIROPA project

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

The ANR funded SIROPA project[2] whose objectives was a better understanding of the singularities of parallel robots has been concluded this year [24]. The partners of this project were:

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

Several interesting results regarding singularities of less than 6 degree-of-freedom and wire-drive parallel robots were obtained and were validated experimentally. This project has been concluded by an October school attended by 15 european students.

8.1.4. Large scale initiative PAL

COPRIN has played an important role for the creation of the INRIA large scale initiative Personnal Assistant Living (PAL), devoted to the assistance to elderly and handicaped people. Our work in this field is described in the sections 6.1.5, 6.1.4, 6.1.2.

8.2. European Initiatives

Participants: David Daney, Jean-Pierre Merlet, Yves Papegay.

Program: FP7-2011-NMP-ICT-FoF, Factory of the Future

Project acronym: CableBot

Project title:Parallel Cable Robotics for Improving Maintenance and Logistics of Large-Scale Products

Duration: December 2011- December 2014

Coordinator: Tecnalia

Other partners: LIRMM (France), FRAUNHOFER-IPA (Germany), Duisburg-Essen University (Germany), EADS (France), ACCIONA (Spain), VICINAY (Spain)

Abstract: The CableBOT project deals with a novel methodology for designing, developing and evaluating cable robots customized for the automation in large-scale auxiliary processes. Parallel cable robots extend the payloads and workspace of conventional industrial robots by more than two orders of magnitude. The main objective is to develop a new generation of modular and reconfigurable robots able to perform many different steps in the post-production of large-scale structures.

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

9. Dissemination

9.1. Animation of the scientific community

9.1.1. International activities

We will not detail the reviewing process done in the project but it can estimated that over 20 journal papers and 40 conference papers were reviewed by the team this year.

- 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, while chairing IFToMM France. He has been elected to be one of the 10 members of IFToMM Executive Council, effective on January 1st, 2012 (which implies that he has to step down from chairing IFToMM France). He is chairman of the scientific Committee of the Computational Kinematics workshop and a member of the steering Committee of IROS.
- 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'2011 conference.
- O. Pourtallier is a member of the International Society of Dynamic Games
- Gilles Trombettoni has been member of the program committee of the conference CPAIOR 2011 (constraint programming, operational research)

9.1.2. National activities

- D. Daney is a member of the scientific committee of the CNR SDA (Centre National de Référence Santé à Domicile et Autonomie) and of the evaluation committee of the ANR TecSan.

9.1.3. INRIA activities

- Julien Alexandre dit Sandretto has begun the construction of two small cable-driven robots in order to propose demonstration and lecture for students
- D. Daney is coordinator of the Large Scale Initiative Personally Assisting Living (PAL)
- J-P. Merlet is a member of the "Bureau du Comité des Projets" of the Sophia-Antipolis INRIA center. As a former member of INRIA Evaluation Board he is part of a national working group on scientific indicators.
- O. Pourtallier is a member of the CSD (doctoral students monitoring), and is responsible of the NICE committee (long term invited scientists and post-doctoral student selection).

9.2. Teaching

D. Daney gave a lecture on industrial control systems (L3), ITII, Polytech Nice (48h ETP).

T. Gayral gave practicals on mechanics of continuous media, elasticity and beam theory, Polytech'Nice (64h ETP).

O. Pourtallier lectured 24 hours on mathematical tools for engineer for undergraduate students (L1) at university of Nice.

D. Daney gave a lecture on medical robotics, Master of Bio-Medical (M2), Univ. Nice Sophia Antipolis (22h ETP).

O. Pourtallier lectured 6 hours on game theory to Master OSE (M2), at École des Mines de Paris, Sophia Antipolis

G. Trombettoni gave courses (5h) about constraint programming and intervals in the Sophipolitan master including Normal Sup Lyon students.

G. Trombettoni is associate professor in computer science at IUT R&T (networks and telecoms) of Sophia Antipolis.

J. Alexandre dit Sandretto, Calibration of large parallel robots, 2010-2013, supervisors: D. Daney, G. Trombettoni

S. Bennour, Modeling of human joints for rehabilitation purposes, 2008-2012, supervisor: J-P. Merlet, L. Rhomdane

J. Borràs, Classification of singular robots, 2008-2012, supervisor: , J-P. Merlet, F. Thomas

T. Gayral, Calibration of parallel telescope, 2010-2013, supervisors: D. Daney, J-P. Merlet

M. Harshe, Active rehabilitation, 2009-2012, supervisors: D. Daney, J-P. Merlet

H. Qu, Optimization of parallel robots, 2009-2012, supervisor: J-P. Merle

R. Ramadour, Manipulation for assistance, 2011-2014, supervisors: F. Chaumette, J-P. Merlet

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Publications of the year

Articles in International Peer-Reviewed Journal

[8] I. ARAYA, B. NEVEU, G. TROMBETTONI. *An Interval Extension based on Occurrence Grouping*, in "Computing", 2012, to appear.

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