Activity Report 2012

Project-Team COPRIN

Constraints solving, optimization and robust interval analysis

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Robotics

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Project-Team COPRIN

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

Creation of the Project-Team: February 01, 2002 .

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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 section 6.2.1.4) are strategic for the project as they allow us to validate our theoretical work and to discover new problems that will feed in the long term the theoretical analysis developed by the team members.

We have started since five years a strategic move toward **assistance robots** (see section 6.2.1.3). 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
- they may eventually be used to monitor the health status of the end-user in order to detect emerging pathologies

As this topic is very large and cannot be managed by a single project-team COPRIN has been one of the main proponant for the creation of the "Action d'Envergure National" PAL (Personnal Assistant Living), that has been accepted in 2011 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.

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

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

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], [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 [11], [19]
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 or assistance robot)

Our field of study in robotics focuses on *kinematic* issues [13], [21] such as workspace and singularity analysis, positioning accuracy [24], trajectory planning, reliability, calibration [33], 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 [28]. The methods that we develop can be used for other robotic problems, see for example the management of uncertainties in aircraft design [34], [10].

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 but also develops its own prototypes. We usually develop a new robot prototype every 6 years but since 2008 we have started the development of seven new robot prototypes, mostly related to assistance robotics. Furthermore we have extended our development to devices that are not strictly robots but are part of an overall environment for assistance. 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 [8], [9], [26] and entertainment, that can be regrouped under the name of *assistance robotics* (see section 6.2.1.3). 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: *adaptability*. We aim at providing assistance devices that are adapted to the end-user, its trajectory of life and its environment, are easy to install (because installation uncertainties are taken into account at the design stage), have a low intrusivity and are guaranteed to fulfill a set of requirements.

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 [32]), 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 6.2.1.3). Although these topics were new for us in 2008 we have spent two years determining priorities and guidelines by conducting about 200 interviews with field experts (end-users, praticians, family and caregivers, institutes), establishing strong collaboration with them (e.g. with the CHU of Nice-Cimiez) and putting together an appropriate experimental setup for testing our solutions (see 6.2.1.4). A direct consequence of setting up this research framework is a reduction in our publication and contract activities. But this may be considered as an investment as assistance robotics will constitute the major research axis of the project on the long term (COPRIN will reach its twelve years of existence in 2014 but we intend to propose in 2013 a new project on this topic, code-named HEPHAISTOS).

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 (both for our numerical experiments and in robotics). 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 the ALIAS library that has been designed in the project and is 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.

Although these libraries are intended to be used within the project-team they can be freely downloaded as a library file (but the user may introduce its own code in several part of the package) and has been used for example at LIRMM and IRCCyN.

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. Int4Sci is used in several universities for teaching the basis of interval analysis in place of using Rump's INTLAB for Matlab. We however lack the manpower to further enhance this software.

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. Lack of manpower has slowed down this development.

6. New Results

6.1. Interval analysis

6.1.1. A Contractor Based on Convex Interval Taylor

Participants: Gilles Trombettoni [correspondant], Bertrand Neveu.

Interval Taylor has been proposed in the sixties by the interval analysis community for relaxing continuous non-convex constraint systems. However, it generally produces a non-convex relaxation of the solution set. A simple way to build a convex polyhedral relaxation is to select a *corner* of the studied domain/box as expansion point of the interval Taylor form, instead of the usual midpoint. The idea has been proposed by Neumaier to produce a sharp range of a single function and by Lin and Stadtherr to handle $n \times n$ (square) systems of equations.

This paper presents an interval Newton-like operator, called `X-Newton`, that iteratively calls this interval convexification based on an endpoint interval Taylor. This general-purpose contractor uses no preconditioning and can handle any system of equality and inequality constraints. It uses Hansen's variant to compute the interval Taylor form and uses two opposite corners of the domain for every constraint.

The `X-Newton` operator can be rapidly encoded, and produces good speedups in constrained global optimization and constraint satisfaction. First experiments compare `X-Newton` with affine arithmetic[31], [19], [20]

6.2. Robotics

6.2.1. Robotics

6.2.1.1. Kinematics of wire-driven parallel robots

Participants: Laurent Blanchet, Jean-Pierre Merlet [correspondant].

The kinematics of wire robot is a complex problem because it involves both the geometrical constraints and the static equilibrium constraints as only positive tensions in the wire are possible. A major issue, that has not been addressed in the literature [16], [15], is that for a robot having n wires the forward kinematic problem (FK) (determining the possible pose(s) of the robot knowing the wire lengths, a problem that is crucial to solve for controlling the robot) cannot be solved by assuming that all n wires are under tension as the current pose of the robot may be such that only a subset of the wires may be under tension. Hence the FK problem has to be solved for **all** robots that may be derived from the initial one by removing 1 one to $n-1$ wires, each solving leading to a set of possible poses for the platform. Solving the FK for 1 wire is trivial, while for 6 wires the FK solving may be based on the already complex FK of parallel robot with rigid legs. For 2 wires it can be shown that the FK solutions can be found by solving a 12th order univariate polynomial, while for 3 wires we have shown last year by using an elimination procedure that the solutions are obtained by solving a 158th order polynomial. A very recent result of this year is that for 4 wires the order of this polynomial is 216, while no known result has been established for 5 wires (note that for 3 to 5 wires the size of the system of equations that has to be solved for the FK is larger than the one for the FK of 6-dof robot with rigid legs, a problem that has required 20 years to be solved).

Drawbacks of the elimination approach is that it does not take into account 1) that the solution should be mechanically stable, 2) that the wire tensions at the solution(s) must be positive. Hence, assuming that all solutions may be computed by the elimination approach, an a-posteriori analysis has to be performed to sort out the solutions that verify 1) and 2). We have proposed this year an efficient method to determine if a solution was mechanically stable [13]. But another major issue with the elimination method is that it leads to high order polynomial that cannot be safely numerically solved. To address this problem and 2) we are considering a numerical algorithm based on interval analysis, that consider also the tension as unknowns, hence allowing to search only for solution(s) with positive tensions [21].

Another issue for wire-driven parallel robots is the concept of redundancy. Having more wires than dof to be controlled is interesting for increasing the workspace of the robot. But it is believed that redundant wires may also be used to better distribute the load among the wires. Unfortunately we have shown for the $N-1$ robot (all N wires connected at the same point on the platform) with non elastic wires that whatever N there will be at most 3 wires under tension simultaneously [25] and consequently that tension management is not possible (with 3 wires the tensions is uniquely determined). If the wires are elastic, then tension management is possible but the positioning error is very sensitive to errors in the stiffness model [24]. Hence new method for tension management should be devised and we have explored some possibilities [23]. Still there is some magic in wire-driven parallel robots: in spite of all the uncertainties prototypes work quite well, a phenomenon which has been explained through a sensitivity analysis [24], [22].

Finally we address the management of modular robots, whose geometry can be adapted to various tasks and different objects to be manipulated, especially for very large scale robot [28], that may be used in industry for maintenance and logistics (see the Cablebot project in section 8.2.1).

6.2.1.2. Robot Calibration

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

6.2.1.2.1. Experimental calibration of a high-accuracy space telescope

A collaborative work began in October 2010 with Thales Alenia Space on the calibration of the mechanical structure of a space telescope. Its architecture is based on a parallel manipulator (of the active wrist 6-PUS type, which has been patented by COPRIN) and is used to correct the relative position of two mirrors. The aim is to reach a micrometer accuracy in order to obtain a suitable quality of the images provided by the telescope. Thus, a complete model of the space telescope needs to be developed and validated through calibration. Since high velocity is not required in such an application, the dynamic effects can be neglected and only geometric and/or static calibration has to be considered. Moreover, measurements for calibration were performed in a clean room under controlled pressure, temperature and humidity conditions to minimize the influence of the non-geometric errors. Thus, two possible static inaccuracy sources were identified and modeled: one from the deformation of the mobile platform and the other resulting from the behavior of the flexure joints. Three incremental models of the flexure joints were developed and compared: a spherical joint model, a model issued from the beam theory and a stiffness model. Results of calibration using an accurate measurement system of photogrammetry showed that the flexure joints can be modeled by perfect spherical joints due to the small workspace of the telescope. Concerning the mobile platform deformation, two models were developed. Good accuracy results were obtained for both models. The developed models allowed us to explain how the model errors are directly accounted in the parameter identification during calibration. This resulted in different sets of identified parameters which all enable a good positioning accuracy. Those differences were explained and results of calibration allow a proper choice of the model of the mobile platform deformation. Considering this model, a positioning accuracy of some micrometers was finally reached after calibration with only position and orientation measurements of the mobile platform, which should allow the calibration of the telescope in space [33]. This is currently under study using interferometric measurements on the prototype of the space telescope.

6.2.1.2.2. Calibration of a cable-driven robot

To improve the accuracy of a cable manipulator, it is necessary to identify the uncertainties of its model. The cable robots, studied in the ANR funded project Cogiro (see section 8.1.1.2), are theoretically redundantly actuated: the number of powered wires is larger than the number of degrees of freedom of the manipulator (however see section 6.2.1.1 about the reality of this redundancy).

In 2011 an over-constrained prototype was self-calibrated (the identification of the parameters does not need additional external measurement), under some assumptions on the cable properties [17], [29]. We will apply our recent calibration methods on the large scale robot prototype developed for the Cogiro project at the very end of this year.

6.2.1.2.3. Cable properties

Quite often cable-driven robot analysis assume mass-less and non-elastic wires. We proposed a method based on interval analysis to judge the validity of this assumption for a particular robot in a specific workspace. Our aim is to use this method in order to determine a a region within the robot workspace for which the hypothesis is valid and consequently for which self calibration of the robot is possible. Indeed, the assumption on the cable properties is not acceptable over the full workspace of the large scale robot developed in the Cogiro project. Still a self-calibration is possible if calibration poses are chosen within a specific subpart of the workspace. A more efficient calibration approach is in progress with additional measures and a more complex model (static and elasticity). The results has been published in [18], [30].

6.2.1.3. Assistance robotics

Participants: David Daney, Claire Dune, Jean-Pierre Merlet [correspondant], Yves Papegay, Odile Pourtallier.

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 smart devices that may help disabled, elderly and handicapped people in their personal life, provide also assistance to family and caregivers while allowing doctors to get better and objective information on the health state of the end-user. Our credo is that these devices 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). As for cost reasons we intend to use only standard hardware adaptation has to be taken into account at the very early stage of the system design and uncertainties in the physical instances of our systems are also to be considered.

For validation purposes we have developed a 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 [1]. Our activity in this field is concentrated on transfer, manipulation, walking monitoring, rehabilitation and the use of virtual reality. We are also investigating how such complex environments with multiples smart agents, quite heterogeneous from a computing viewpoint, but that have to cooperate, may be programmed. All these topics are in accordance with the one of the large scale initiative PAL [2] of which we are an active member.

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

6.2.1.3.1. Transfer and manipulation

Participants: François Chaumette [Lagadic], Jean-Pierre Merlet, Rémy Ramadour.

For transfer operation we are using the MARIONET-ASSIST robot (see section 6.2.1.4) that is installed in our flat. Currently we use 4 winches with the wires connected at the same point on the platform, hence providing 3 translational degrees of freedom. This low-cost, low-intrusivity robot has proved to be very effective for transfer operation. Apart of transfer operation robot may be used for manipulation. Adding one or several low-cost cameras (the cost being here a fundamental constraint), visual-servoing control is used to provide a whole new set of useful services such as grasping objects in order to bring them to the end-user (if they are too heavy, too far, high or low), or cleaning the table after lunch. Using a parallel crane robot, we are able to cover a large workspace, the vision-control allowing us to obtain the precision required by the manipulation of daily-life objects. The collaborative implementation of the vision and the kinematic control of the robot gives us a way to make best use of the advantages of both parts, while overcoming their respective drawbacks.

Given a region where the object of interest belongs, the first step is to detect it in an evolutive environment. A segmentation is made, robust to luminance variations and perspective projections. The vision is then used to move the platform toward a desired position relatively to the target. In order to execute this task, some carefully chosen features are measured, allowing to estimate the incremental displacement required to move the end-effector to the desired place. We use the library ViSP for both the detection and the visual-control part.

Experimental results were obtained using a platform with 3 degrees of freedom and a single camera, grasping a single object and moving it from a place to another. We used for that basic image data such as 2D moments, allowing a fast computing and yet robustness in measurements. We currently address to generalize this manipulation to other configurations and to evaluate its robustness to calibration errors and other uncertainty sources. We also are looking for a global paradigm merging both the vision-based kinematic model and the mechanical one, which could significantly improve the efficiency of the experiment, while reducing the mathematical complexity behind each kinematic model considered on its own.

6.2.1.3.2. Walking monitoring

Participants: Claire Dune [Handibio], Jean-Pierre Merlet.

We use the walking aids ANG-light and ANG-II (see section 6.2.1.4) to monitor the trajectory of the walking aid. The on-board sensors of these aids allow to evaluate the step pattern, gait asymmetry,...during daily walking, hence providing an health monitoring system that is always available. ANG-light has been tested last year with 24 subjects that were themselves instrumented (accelerometers in the wrists and knees, pressure sensors in the shoes) and were asked to perform two different trajectories twice with/without the walking aid. The purposes were:

- to determine pertinent walking indicators
- to obtain a “gold” standard of these indicators for non pathological walking, taking into account the normal variability of the walking pattern
- to determine if indicators obtained with the walking aid may led to an accurate estimation of the indicators when the walking aid is not used

Several indicators have been determined after the analysis of these data. In a second phase the inclusion test of elderly people (30 subjects) is taking place at the CHU of Nice-Cimiez and will last until the first trimester of 2013. An analysis of the collected data, in close collaboration with the doctors, will allow to determine if the proposed walking indicators are pertinent.

Another interest of the walking aids ANG is that they allow to collect significant information for mobility during their daily use: slope and surface quality of the sidewalks and automatic detection of lowered kerbs with a ranking of their convenience. It will be interesting for a community to share such information that is collected by the community members. For that purpose we propose to use collective maps, such as OpenStreeMap, which allow for map annotation. To validate this concept we have used ANG-light to automatically annotate the map of the Inria Sophia site with pertinent information for walking aid and wheelchair users [3].

[3] see http://www-sop.inria.fr/coprin/prototypes/main.html#ang

6.2.1.3.3. Rehabilitation

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

The focus of our work is on analyzing knee joint motion during a walking activity. The main principle of the system is to observe relative motions of the collars attached to tibia and femur. The measurement of the motion of these collars is based on the wire actuated parallel robot architecture (using the MARIONET-REHAB robot, see section 6.2.1.4). 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.

Measurements in the global frame and collar specific local frames give precise data to reconstruct collar (and thus, knee joint) motion. The system developed already incorporates the optical motion capture, inertial measurement units and the wire sensors for comprehensive coordinated measurements of the motion of the knee.We have performed preliminary trials on three subjects for walking motion.

In the past year, we worked on processing the data to obtain pose and orientation information of knee joint. Data obtained from the trials was analyzed and post-processing steps were implemented to reduce noise and errors. In order to perform sensor fusion, we implemented a probabilistic estimation based method to estimate the pose.

The results from these analysis have allowed us to identify the merits of our approach and also helped us identify improvements that are needed. We have also identified the possible changes to our mathematical model that could allow use of interval analysis tools along with probabilistic estimation methods. We have identified the changes needed to the hardware setup that will help reduce the sensor noise and error. These changes once implemented will allow us to improve the usability of the system and also point us towards newer areas for further investigation, including, for example, effect of sensor placement, collar design, and interval based extended Kalman Filters for pose estimation[8], [9].

6.2.1.3.4. Virtual reality

Virtual reality has proved to be an effective mean for dealing with rehabilitation, provided that motion is added to the 3D visual feedback. The MARIONET-VR robot, together with our motion base (see section 6.2.1.4) may provide very realistic motion in an immersive room and we will start in 2013 a collaboration with the VR4I and REVES project-teams on this issue. A first task will be to install a moving walking treadmill in the immersive room at Sophia and to combine motion of the treadmill with 3D viewing.

6.2.1.3.5. Programming

In our opinion there will not be a single assistance device that will be able to offer all the required help that may be needed but rather numerous redundant smart agents that are able to perform very efficiently (at low cost and with a small energy consumption) a set of specific tasks. Such agents must be able to communicate and possibly will have to cooperate in some cases (e.g. after a fall). They will be heterogeneous from a computer view point as the used agents will change according to technological advances and to the trajectory of life of the end-users. If the manual programming of a single agent is possible (although quite complex for some of them) the overall system cannot be managed in that way: we need an unifying framework for this development. For that purpose we are currently investigating the use of HOP, a multi-tier programming language for the diffuse Web developed in the INDES project-team. Already one of our wire-driven parallel robot MARIONET-SCHOOL has been programmed in HOP and can be seen as a web resource.

6.2.1.4. Prototypes

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

Experimental works are a key point in the field of service robotics: it allows for validating concepts, getting feedback from the end-users and discovering new problems. We have extensively developed prototypes this year [4]

[4] pictures and videos of our prototypes are available at http://www-sop.inria.fr/coprin/prototypes/main.html or on our YouTube channel http://www.youtube.com/user/CoprinTeam/videos?flow=grid&view=0

6.2.1.4.1. Wire-driven parallel robots

The `MARIONET` family is now constituted of

- `MARIONET-REHAB` (2004-): using up to 7 linear actuators it is mainly used for rehabilitation and health monitoring although it is also a very fast pick-and place robot
- `MARIONET-CRANE` (2008-): a very large 6-dof rescue crane, portable and autonomous that can be deployed in 10 minutes and has a lifting capability of 2 tons
- `MARIONET-ASSIST` (2011-): a robot deployed in our flat with up to 6 winches, that is used for transfer operation and health monitoring, with a lifting ability of about 2000 kg
- `MARIONET-VR` (2011-): using up to 6 linear actuators it will be used in the Sophia immersive room for simulation and rehabilitation. It allows to fully lift a person and has been physically installed in the immersive room this year although it is not fully operational
- `MARIONET-SCHOOL` (2012-): a set of very low-cost robots that are intended to be used for dissemination. They fit in a small suitcase and can be deployed on a table or over a full classroom. We believe that such robots may be used by roboticists but also by researchers from other domains that may use the motion of the robot(s) to illustrate scientific concepts. Currently we have 3 such robots (one using Lego components, one with step motors and one with servos)

6.2.1.4.2. Walking aids

The *Assistive Navigation Guide* (ANG) family is 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
- 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 and GPS. These sensors allow to measure the trajectory of the walking aid and several features of the user's gait. This walking aid is currently being used at CHU Nice, see section 6.2.1.3.2. A replica of `ANG-light` is currently under development at the Handibio laboratory of Toulon and will include force sensors in the handles to get measurement of muscular activities while walking.
- `ANG-II`: this aid is an evolution of the motorized walker `ANG`, with a lower weight and better integration

6.2.1.4.3. Other devices

As seen in the previous sections we have focused our work on mobility as it has been identified as a major priority during our two years interview period. Another priority is fall management: it is adressed with the `ANG`'s) but requires that the patient uses a walking aid. To obtain a better coverage we have developed an instrumented vest that includes an Arduino Lilypad microcontroller to monitor a 3D accelerometer and verticality sensors in order to detect a fall. This system may communicate an alarm through wifi, zigbee or even infrared signals. Apart of its low cost the system is washable and has a very low power consumption (we are considering energy harvesting to further increase its energy autonomy).

Two other important issues for assistance robotics is activities monitoring and patient localization. In cooperation with the STARS project-team an activity monitoring system within the Dem@care project. Its purpose is to log specif events such as taking a pen, setting on a kettle, ...using only simple sensors such as proximity and distance sensors, switches, that are more reliable and less complex than using a vision system. We have provided to the CHU a system that allows to monitor up to 208 different events. In the same manner we are working on a localization system of elderly in a room based only on distance sensors, that will be less intrusive and/or may complement the measurements of a vision system.

Rehabilitation is also part of our activities. Apart of the MARIONET-REHAB system we plan to investigate the use of Sophia immersive room for that purpose. To complement the motion that will be provided by the MARIONET-VR robot we have bought a 6-dof motion base from Servos with a nominal load of 150kg, that we have modified to accommodate our needs. We will use also two lifting columns with a load of 100 kg each, that will allow to manage motion for rehabilitation apparatus such as treadmill.

6.3. Miscellaneous results

6.3.1. Symbolic tools for modeling and simulation

Participant: Yves Papegay.

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

An extensive modeling and simulation platform has been designed which includes a dedicated modeling language for the description of aircraft dynamics models in term of formulae and algorithms, and a symbolic compiler producing as target an efficient numerical simulation code ready to be plugged into a flight simulator, as well as a formatted documentation compliant with industrial requirements of corporate memory [10].

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

To finalize the transfer of the technology demonstrated by our prototype to our industrial partner, an extensive collection of testing and corresponding improvements have been done in 2012. This step has delayed the delivery of the final version of our modeling and simulation environment to Airbus until November 2012.

6.3.2. 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 aircraft have been developed as user cases for the project.

In 2012 we focused on automatic generation of agent code based on models that is ready for integration in the ID4CS platform prototype.

6.3.2.1. 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 has pursued the study of equilibrium model for coupled electricity and CO2 allowance exchange markets (see also Section 7.3). We have mainly focused on the determination of Nash equilibrium for the coupled electricity and carbon markets with the assumption that the producers maximize their market shares. Nash equilibrium have been obtained by using as an intermediary step a decreasing auction mechanism.

We have also pursued an indifference pricing methodology which is presented in more details in Inria -TOSCA Team section.

7. Bilateral 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 6.3.1.

Following the contracts signed in 2003, 2005 and 2007 with the aircraft maker, and a consulting contract in 2008 to study the possible development of an industrial tool, we have initiated in 2009 a 2-years collaboration (extended in 2012) 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, and another contract licensing to Airbus a second version of this prototype in 2011, a last agreement to be signed in November 2012 will license the final and tested version [34].

7.2. Thales Alenia Space

Participants: David Daney [correspondant], 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 with respect to the primary one in order to improve the provided images quality. The deployment and re-positioning concepts were validated thanks to a first prototype, and the telescope performances improvement is currently under study. A first study brought to light the front-seat role of mechanical joints on the structure accuracy. However, in order to deal with the required optical accuracy and space constraints, those mechanical joints had to be replaced by flexible ones. A new prototype was then designed and built in order to validate its ability to ameliorate its images quality using flexible joints. The goal of this project is to self-calibrate the mechanical structure of the telescope: using only proprioceptive information, parameters of the robot model will be identified. Thus, a space telescope based on this concept will be able to reach its final orbit, and then to improve its image accuracy thanks to an autonomous procedure.

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

Participants: Odile Pourtallier, Mireille Bossy.

Started in January 2009 and finished in October 2012, 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 [32], see also Inria -TOSCA Team report.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

8.1.1.1. 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 (6.3.1), in development of uncertainty analysis algorithms, and in automatic generation of agents based on models.

8.1.1.2. COGIRO project

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

We are collaborating with LIRMM, LASMEA and TECNALIA for the development of large scale wire-driven parallel robots [5]. We are especially involved in the calibration of a prototype developed by LIRMM and TECNALIA, see section 6.2.1.2.

8.2. European Initiatives

8.2.1. FP7 Projects

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

9. Dissemination

9.1. Scientific Animation

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 50 conference papers were reviewed by the team this year.

- Julien Alexandre dit Sandretto was invited in the Department of Mechanical Engineering in the University of Melbourne where he mainly worked on the muscle parameter identification using the analogy between muscles and cables with a novel workspace satisfaction method.

[5] http://www2.lirmm.fr/cogiro/

- D. Daney has organized and has been a member program committee of IROS 2012 workshop on Assistance and Service Robotics in a Human Environment and an associate editor of ICRA 2013. He has presented the activity of the large scale initiative action PAL to the university of Athens, Athens, Greece, and to the National Taiwan University, Taipei, Taiwan.
- J-P. Merlet is a member of the scientific committee of the European Conference on Mechanism Science (EUCOMES), chairman of the scientific Committee of the Computational Kinematics workshop, a member of the steering Committee of IROS and board member of the Journal of Behavorial Robotics. He is also a board member of the european robotics network EURON which has joined with the industrial robotics network EUROP to constitute the PPP Eurobotics aisbl, of which he is a board member. He is a member of the IFToMM (International Federation for the Promotion of Mechanism and Machine Science) Technical Committees on History and on Computational Kinematics and is one of the 10 members of IFToMM Executive Council, the board of this federation.
- Y. Papegay is a permanent member of the International Steering Committee of the International Mathematica Symposium conferences serie.

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. He has presented the large scale initiative action PAL to the "Centre National de Référence, Santé à Domicile + Autonomie", Paris, the "Pôle service à la personne" PACA, Marseille, the Centre Expertise National Habitat et Logement, Troyes.
- J-P. Merlet is a member of the scientific committee of the CNRS GDR robotique

9.1.2.1. Inria activities

- 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.
- 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 - Supervision - Juries

9.2.1. Teaching

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

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

T. Gayral gave practicals on mechanics (kinematics, dynamics and energy), Polytech'Nice (64h ETP).

J-P. Merlet gave a 8h lecture during the Summer School on Models and Methods in Kinematics and Robotics 2012 (01 July – 08 July 2012) at the Technical University of Cluj-Napoca, Romania.

J-P. Merlet gave a 3h lecture at the Collége de France during the colloque Robotique et Santé on May 2.

O. Pourtallier lectured 30 hours on mathematical tools for engineer for undergraduate students (L1) at university of Nice.

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

9.2.2. Supervision

HdR: Y. Papegay, De la modélisation littérale à la simulation certifiée, Université de Nice Sophia-Antipolis, June 2012

PhD: S. Bennour, Contribution au Développement d'une Plateforme Robotisée pour la Rééducation Fonctionnelle, Ecole Nationale d'Ingénieurs de Monastir, February 2012

Phd: M. Harshe, Analyse et conception d'un système de rééducation de membres inférieurs reposant sur un robot parallèle à câbles, Université de Nice, December 2012

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

PhD in progress :K. Bakal, Indices biomécaniques globaux de capacité de génération de forces, supervisor: P. Gorce (Handibio), J-P. Merlet

PhD in progress :L. Blanchet, Design of large scale wire-driven parallel robots, 2012-2016, supervisor: J-P. Merlet supervisors: D. Daney, J-P. Merlet

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

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

9.2.3. Juries

- J-P. Merlet has been the member of the jury of 2 PhD defense and of one HdR

9.3. Popularization

- Julien Alexandre dit Sandretto has completed the construction of two small cable-driven robots in order to propose demonstration and lecture for students. The largest robot was presented during the french event "Fête de la science", during October, to four classes (second grade and first grade of high school). The subject of this speech was the High school Mathematics in the robotics. He gave a lecture on fundamental robotics in the Pobot club, and achieved the construction of a Delta parallel manipulator
- J-P. Merlet has completed the construction of one pedagogic wire-driven parallel robot. This robot, together with the robots developed by Julien Alexandre dit Sandretto, are tools that are intended to demonstrate basic concepts of several scientific domains (mathematics, networks, robotics, mechanics, ...) by researchers (not only roboticists) for a large variety of audience
- 180 visitors have attended this year a demonstration by the project team. This has led, for example, to articles in the newspapers Le Monde, Le Figaro, Les Echos, Le Quotidien du Médecin and interviews on RFI, France Culture and France Inter.

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