Activity Report 2016

Project-Team HEPHAISTOS

HExapode, PHysiology, AssISTance and RobOtics

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Robotics and Smart environments

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Project-Team HEPHAISTOS

Creation of the Team: 2014 January 01, updated into Project-Team: 2015 July 01

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1. Members

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Odile Pourtallier [Inria,Researcher]

Engineers

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Post-Doctoral Fellow

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Juan Antonio Carretero [New Brunswick University, Professor, from January 2016 until July 2016]

Martin Pfurner [Innsbruck University, from Jun 2016 until Jul 2016]

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Joshua Pickard [Inria, PhD, until June 2016]

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2. Overall Objectives

2.1. Overall Objectives

HEPHAISTOS has been created as a team on January 1st, 2013 and as a project team in 2015.

The goal of the project is to set up a generic methodology for the design and evaluation of an adaptable and interactive assistive ecosystem for the elderly and the vulnerable persons that provides furthermore assistance to the helpers, on-demand medical data and may manage emergency situations. More precisely our goals are to develop devices with the following properties:

- they can be adapted to the end-user and to its everyday environment [19]
- 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 pathology

Assistance will be provided through a network of communicating devices that may be either specifically designed for this task or be just adaptation/instrumentation of daily life objects.

The targeted population is limited to frail people [1] and the assistive devices will have to support the individual autonomy (at home and outdoor) by providing complementary resources in relation with the existing capacities of the person. Personalization and adaptability are key factor of success and acceptance. 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.

Assistance is a very large field and a single project-team cannot address all the related issues. Hence HEPHAISTOS will focus on the following main **societal challenges**:

- **mobility**: previous interviews and observations in the HEPHAISTOS team have shown that this was a major concern for all the players in the ecosystem. Mobility is a key factor to improve personal autonomy and reinforce privacy, perceived autonomy and self-esteem
- **managing emergency situations**: emergency situations (e.g. fall) may have dramatic consequences for elderly. Assistive devices should ideally be able to prevent such situation and at least should detect them with the purposes of sending an alarm and to minimize the effects on the health of the elderly
- **medical monitoring**: elderly may have a fast changing trajectory of life and the medical community is lacking timely synthetic information on this evolution, while available technologies enable to get raw information in a non intrusive and low cost manner. We intend to provide synthetic health indicators, that take measurement uncertainties into account, obtained through a network of assistive devices. However respect of the privacy of life, protection of the elderly and ethical considerations impose to ensure the confidentiality of the data and a strict control of such a service by the medical community.

[1] for the sake of simplicity this population will be denoted by *elderly* in the remaining of this document although our work deal also with a variety of people (e.g. handicapped or injured people, ...)

- **rehabilitation and biomechanics**: our goals in rehabilitation are 1) to provide more objective and robust indicators, that take measurement uncertainties into account to assess the progress of a rehabilitation process 2) to provide processes and devices (including the use of virtual reality) that facilitate a rehabilitation process and are more flexible and easier to use both for users and doctors. Biomechanics is an essential tool to evaluate the pertinence of these indicators, to gain access to physiological parameters that are difficult to measure directly and to prepare efficiently real-life experiments

Addressing these societal focus induces the following **scientific objectives**:

- **design and control of a network of connected assistive devices**: existing assistance devices suffer from a lack of essential functions (communication, monitoring, localization,...) and their acceptance and efficiency may largely be improved. Furthermore essential functions (such as fall detection, knowledge sharing, learning, adaptation to the user and helpers) are missing. We intend to develop new devices, either by adapting existing systems or developing brand-new one to cover these gaps. Their performances, robustness and adaptability will be obtained through an original design process, called *appropriate design*, that takes uncertainties into account to determine almost all the nominal values of the design parameters that guarantee to obtain the required performances. The development of these devices covers our robotics works (therefore including robot analysis, kinematics, control, ...) but is not limited to them. These devices will be present in the three elements of the ecosystem (user, technological helps and environment) and will be integrated in a common network. The study of this robotic network and of its element is therefore a major focus point of the HEPHAISTOS 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
- **evaluation, modeling and programming of assistive ecosystem**: design of such an ecosystem is an iterative process which relies on different types of evaluation. A large difference with other robotized environments is that effectiveness is not only based on technological performances but also on subjectively perceived dimensions such as acceptance or improvement of self-esteem. We will develop methodologies that cover both evaluation dimensions. Technological performances are still important and modeling (especially with symbolic computation) of the ecosystem will play a major role for the design process, the safety and the efficiency, which will be improved by a programming/communication framework than encompass all the assistance devices. Evaluation will be realized with the help of clinical partners in real-life or by using our experimental platforms
- **uncertainty management**: uncertainties are especially present in all of our activities (sensor, control, physiological parameters, user behavior, ...). We intend to systematically take them into account especially using interval analysis, statistics, game theory or a mix of these tools
- **economy of assistance**: interviews by the HEPHAISTOS team and market analysis have shown that cost is a major issue for the elderly and their family. At the opposite of other industrial sectors manufacturing costs play a very minor role when fixing the price of assistance devices: indeed prices result more from the relations between the players and from regulations. We intend to model these relations in order to analyze the influence of regulations on the final cost

The societal challenges and the scientific objectives will be supported by experimentation and simulation using our development platforms or external resources.

In terms of methodologies the project will focus on the use and mathematical developments of **symbolic tools**(for modeling, design, interval analysis), on **interval analysis**, for design, uncertainties management, evaluation), on **game theory**, for control, localization, economy of assistance) and on **control theory**. Implementation of the algorithms will be performed within the framework of general purpose software such as `Scilab`, `Maple`, `Mathematica` and the interval analysis part will be based on the existing library `ALIAS`, that is still being developed mostly for internal use.

Experimental work and the development of our own prototypes 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.

Dissemination is also an essential goal of our activity as its background both on the assistance side and on the theoretical activities as our approaches are not sufficiently known in the medical, engineering and academic communities.

In summary HEPHAISTOS has as major research axes assistance robotics, modeling (see section 7.3.2), game theory, interval analysis and robotics (see section 7.1). 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 assistance robotics provides realistic problems which allow us to develop, test and improve our algorithms. Our overall objectives are presented in http://www-sop.inria.fr/hephaistos/texte_fondateur_hephaistos.pdf and in a specific page on assistance http://www-sop.inria.fr/hephaistos/applications/assistance_eng.html.

3. Research Program

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], [8], [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
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 HEPHAISTOS 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).

Important note: We have insisted on interval analysis because this is a **major componant** or our robotics activity. Our theoretical work in robotics is an analysis of the robotic environment in order to exhibit proofs on the behavior of the system that may be qualitative (e.g. the proof that a cable-driven parallel robot with more than 6 non-deformable cables will have at most 6 cables under tension simultaneously) or quantitative. In the quantitative case as we are dealing with realistic and not toy examples (including our own prototypes that are developed whenever no equivalent hardware is available or to very our assumptions) we have to manage problems that are so complex that analytical solutions are probably out of reach (e.g. the direct kinematics of parallel robots) and we have to resort to algorithms and numerical analysis. We are aware of different approaches in numerical analysis (e.g. some team members were previously involved in teams devoted to computational geometry and algebraic geometry) but interval analysis provides us another approach with high flexibility, the possibility of managing non algebraic problems (e.g. the kinematics of cable-driven parallel robots with sagging cables, that involves inverse hyperbolic functions) and to address various types of issues (system solving, optimization, proof of existence ...).

3.2. Robotics

HEPHAISTOS, as a follow-up of COPRIN, has a long-standing tradition of robotics studies, especially for closed-loop robots [4], especially cable-driven parallel robots. 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 [15]. 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 such as workspace and singularity analysis, positioning accuracy, trajectory planning, reliability, calibration, 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. The methods that we develop can be used for other robotic problems, see for example the management of uncertainties in aircraft design [6].

Our theoretical work must be validated through experiments that are essential for the sake of credibility. A contrario, experiments will feed theoretical work. Hence HEPHAISTOS works with partners on the development of real robots but also develops its own prototypes. In the last years we have developed a large number of prototypes and 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. The web pages http://www-sop.inria.fr/hephaistos/mediatheque/index.html presents all of our prototypes and experimental work.

4. Application Domains

4.1. Domain 1

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 *modeling*, *optimal design* and *analysis* 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. Although these topics were new for us when initiating the project 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. 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 is a long term goal. It must be reminded that we are able to manage a large variety of problems in totally different domains only because interval analysis, game theory and symbolic tools provides us the methodological tools that allow us to address completely a given problem from the formulation and analysis up to the very final step of providing numerical solutions.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Science

- strong advances on the analysis of cable-driven parallel robots (section 7.1.1)
- collaboration with lawyers on the ethical and legal aspects of robotics
- strong collaboration with the medical community on walking analysis, rehabilitation (section 7.2.3) and activities detection (section 7.2.1)

5.1.2. Experimentation

- extensive test period for our walkers in clinical environment (section 7.2.3)
- start of the daily activities monitoring in a retirement house (section 7.2.1)

5.1.3. Transfer

- contract with Ellcie-Healthy for the evaluation of connected objects

5.1.3.1. Awards

- J-P. Merlet has been a finalist for the best paper award of the Eucomes conference and of the IROS conference

BEST PAPERS AWARDS:

[14]
J.-P. MERLET. *Preliminaries of a new approach for the direct kinematics of suspended cable-driven parallel robot with deformable cables*, in "Eucomes", Nantes, France, 2016, https://hal.archives-ouvertes.fr/hal-01419700

[10]
J.-P. MERLET. *A generic numerical continuation scheme for solving the direct kinematics of cable-driven parallel robot with deformable cables*, in "IEEE Int. Conf. on Intelligent Robots and Systems (IROS)", Daejeon, South Korea, 2016, https://hal.archives-ouvertes.fr/hal-01419699

6. New Software and Platforms

6.1. ALIAS

Algorithms Library of Interval Analysis for Systems
FUNCTIONAL DESCRIPTION

The ALIAS library 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.

- Participants: Odile Pourtallier and Jean-Pierre Merlet
- Contact: Jean-Pierre Merlet
- URL: http://www-sop.inria.fr/hephaistos/developpements/main.html

6.2. Platforms

We describe here only the new platforms that have been developed in 2016 while we maintain a very large number of platforms (e.g. the cable-driven parallel robots of the MARIONET family, the ANG family of walking aids or our experimental flat).

6.2.1. GMSIVE ADT: virtual reality and rehabilitation

Inria has agreed to fund us for developing the platform GMSIVE whose purpose is to introduce end-user motion and their analysis in a virtual reality environment in order to make rehabilitation exercises more attractive and more appropriate for the rehabilitation process. For example we have developed an active treadmill whose slope will change according to the user place in the virtual world while the lateral inclination may be changed in order to regulate the load between the left and right leg. Such a system may be used in rehabilitation to simulate a walk in the mountain while increasing on-demand the load on an injured leg (that is usually avoided by the user) for a shorter rehabilitation time. At the same time the walking pattern is analyzed in order to assess the efficiency of the rehabilitation exercise.

The motion system is composed of two vertical columns whose height may be adjusted (they are used for actuating the treadmill), a 6 d.o.f motion base and a cable-driven parallel robot which may lift the user (in the walking experiment this robot may be used to support partly the user while he is walking allowing frail people to start the rehabilitation earlier). We intend to develop sailing and ski simulators as additional rehabilitation environment. Currently the columns and motion base are effective while the robot has been installed but not tested yet and we have started to study the coupling between the motion generators and the 3D visualization.

6.2.2. Activities detection platform

For non intrusive activities detection we use low cost distance and motion sensors that are incorporated in a 3D printed box (figure 1) and constitute a detection station. Several such station are implemented at appropriate place in the location that has to be monitored (e.g. the Valrose EHPAD where 15 such stations has been deployed at the end of 2016 while 17 stations will be deployed at Institut Claude Pompidou at the very beginning of 2017). Although the information provided by each station is relatively poor an appropriate network of such station allow us to provide the information requested by the medical community.

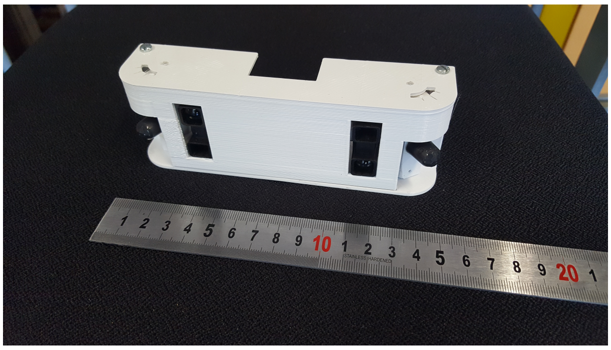

Figure 1. A station for activities detection. The 4 sensors allow to determine the presence of the subject in a given zone, his/her direction of motion and speed even at night

7. New Results

7.1. Robotics

7.1.1. Analysis of Cable-driven parallel robots

Participants: Alain Coulbois, Artem Melnyk, Jean-Pierre Merlet [correspondant], Yves Papegay.

We have continued the analysis of suspended CDPRs for control and design purposes[12]. For control it is essential to determine the current pose of the robot for given cable lengths (forward kinematics, FK) and to be able to calculate the cable lengths for a given pose of the platform (inverse kinematics, IK). If the cables are supposed to be non-deformable the IK problem is trivial and has a single solution but the FK is complex, admits several solutions and raises several issues. We have shown in the past that to get all FK solutions for a CDPR with m cables we have to consider not only the case where all cables are under tension but also have to solve the FK for all combinations of cables under tension with 1 to m cables. Surprisingly the FK is more difficult if the CDPR has less than 6 cables under tension. Our team, in collaboration with M. Carricato of Bologna University, is the first to have designed a solving algorithm that allow to compute in a guaranteed manner all FK solutions while a theoretical approach has allowed us to provide a bound for the maximal number of solutions according to the number of cables under tension (respectively 24, 156, 216, 140 and 40 for 2, 3, 4, 5, 6 cables).

Even more complex kinematic problems are involved if we assume that the cable are catenary-like, which is valid for large dimension robot, and involves inverse hyperbolic functions and square root, prohibiting to use algebraic geometry tools for estimating the maximal number of solutions and for the solving. In that case both the IK and FK may have multiple solutions and we have exhibited last year interval analysis-based solving algorithms for the IK and FK based on our interval analysis library `ALIAS`, that is the only existing algorithm for managing such complex cables. However such algorithm has the drawback, beside being computer intensive, to provide only solution(s) within a given search space for the unknowns. In our IK and FK problems two unknowns for each cable are the horizontal and vertical components F_x, F_z of the force exerted by the cables on the platform. In our case we have only the constraint $F_x > 0$ and F_z lower than half the mass of the cable but have no upper bound for F_x and lower bound for F_z. We may choose arbitrary large values for these bounds at the expense of an exponentially increasing computation time. As for the IK, beside F_x, F_z, the length of the cable at rest L_0 is an unknown with $L_0 > 0$ but no known upper bound. This year we have both improved the interval analysis algorithms but have also explored an original continuation scheme that be used both for the IK and FK whatever is the cable model. The idea is to assume that the cable model includes a set of physical parameters $\mathcal{P}$ which describe the elastic and deformation behavior of the cable material. We assume that their are limit values $\mathcal{P}_r$ for these parameters such that the cable behave like a non-deformable, non-elastic cable while the real cable parameter is $\mathcal{P}_d$. For example for catenary cables elasticity is defined by the Young modulus E of the cable material while the cable deformations is conditioned by its linear density μ. If E goes to infinity and μ to 0, then the cable is non-deformable, non-elastic. Now let us assume that we have a robot state for which the IK or FK are satisfied with the parameters $\mathcal{P}$. Assume that we modify $\mathcal{P}_d$ by a sufficient small amount ϵ toward $\mathcal{P}_r$ so that the Newton scheme allow us to determine the new robot state for $\mathcal{P} = \mathcal{P}_d + \epsilon$. Proceeding iteratively along this way will lead us to a robot state that must be very close to one obtained for non deformable, non elastic cables. Now we may revert the process: starting from all the IK or FK solutions obtained for non deformable cables (corresponding to $\mathcal{P} = \mathcal{P}_r$) we use Newton to compute a new robot state with $\mathcal{P}$ closer to $\mathcal{P}_d$ and doing that iteratively will lead to the solution(s) for $\mathcal{P} = \mathcal{P}_d$). We have also shown that a safe value of ϵ (ie. one that guarantee to obtain continuous solution without jump) may be calculated at each step by using the Kantorovitch theorem. We have implemented this principle for both the IK and FK problems (for 6 cables for the IK) and have found new IK and FK solutions which not been found previously because they were outside the search space of the interval analysis algorithms. A side benefit of this principle is that it has allowed us to be the first to provide an upper bound on the maximal number of solutions (63 for the IK of a robot with 6 cables, 33383 for the FK of a robot with 8 cables) whatever is the cable model. These new algorithms are much faster than the previous one (around one minute for the IK and 10 mn for the FK instead of several hours). However they raise a theoretical issue as the continuation scheme may lead to a solution that is close to be singular in which case the scheme cannot work. Understanding the singularity of the kinematics of CDPR is therefore a major problem. For the time being we mix the continuation scheme with the interval one that is basically used to solve the kinematic problem when the continuation scheme detect a singularity. As a test example we have considered a difficult CDPR with 8 cables and have shown a case with up to 41 solutions for the FK [10],[14],[11]. Figure 2 shows two of these solutions.

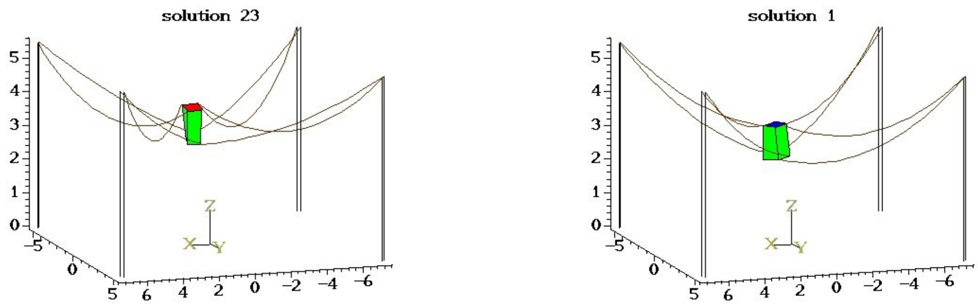

Figure 2. Two poses that are solutions of the forward kinematics, the left one being unstable while the right one is stable.

We have also investigated the calculation of cross-section of the workspace of CDPR [13]. We have shown that the border of this workspace for non deformable of purely elastic cables may be calculated rigorously by using an algorithm mixing a theoretical approach and numerical calculation. For catenary cables we have proposed a method that calculates a set of boxes that are guaranteed to lie in the workspace, getting smaller and smaller as soon as they are close to the border. Unfortunately this algorithm is highly computer intensive.

7.1.2. Cable-Driven Parallel Robots for additive manufacturing in architecture

Participant: Yves Papegay.

Easy to deploy and to reconfigure, dynamically efficient in large workspaces even with payloads, cable-driven parallel robots are very attractive for solving displacement and positioning problems in architectural building at scale 1 and seems to be a good alternative to crane and industrial manipulators in the area of additive manufacturing.

Based on the proof of concept developed during the previous collaboration with CNAM and Ecole Nationale Supérieure d'Architecture Paris-Malaquais, the design of a new large scale CDPR for additive manufacturing of building based on ultra-high performance concrete has started under our supervision.

A new partnership with the the XtreeE start-up company aiming at developing a real size industrial 3D-printer of concrete has been established.

7.2. Assistance

7.2.1. Smart Environment for Human Behaviour Recognition

Participants: Mohamed Hedi Amri, Alain Coulbois, Artem Melnyk, Aurélien Massein, Yves Papegay, Odile Pourtallier [correspondante].

The general aim of this research activity focuses on long term indoor monitoring of frail persons. In particular we are interested in early detection of daily routine and activity modifications. These modifications may indicate health condition alteration of the person and may require further medical or family care. Note that our work does not aim at detecting brutal modifications such as faintness or fall.

In our research we envisage both individual and collective housing such as rehabilitation center or retirement home.

Our work relies on the following leading ideas :

- We do not base our monitoring system on wearable devices since it appears that they may not be well accepted and worn regularly,
- Privacy advocates adequacy between the monitoring level needed by a person and the detail level of the data collected. We therefore strive to design a system fitted to the need of monitoring of the person.
- In addition to privacy concern, intrusive feature of video led us not to use it.

This year we have concentrated our effort on the first step of this research that consists in being able to locate the person in his/her indoor environment.

A natural way of being able to adapt the accuracy of localization (and consequently accuracy of monitoring), is to use a partition of the monitoring area in a finite number of elementary zones ; the number of zones together with their geometry being closely related with the pursued level of monitoring. In practice these zones will be materialized by sensors barriers that detect the passage of a person from one zone to the other. Henceforth each zone are polygonal.

Several directions have been followed this year.

- monitoring system design,
- material development,
- data gathering and analysis,
- experimentation.

7.2.1.1. Monitoring system design

We aim at designing the partition of the monitoring space. Given the geometry of the monitoring area, the admissible position of the sensors barriers and a set of points of interest, the objective is to determine the positions of a minimal number of barriers such that each zone therefore defined includes at most one point of interest. The crossing of a given secession of barriers therefore allows to determine the trajectory of a person from one point of interest to another. An algorithm for solving this problem has been developed.

7.2.1.2. Material development

We initially used commercialized Infra Red barriers to detect the crossing time from one zone to an other. Nevertheless although the collected data is sufficient for the monitoring of a single person it prove not to be sufficient in a environment where there may be several persons, which is typically the case when considering retirement home for example.

Hence we have developed a multi-sensor barrier, a box containing two infra red distance sensors and two motion sensors (passive infrared type). It has been designed and created by 3D fast prototyping printer. The box is light, cheap and discreet. In addition to detecting the crossing time, it also gives the direction of crossing together with information about the speed and the size of the crossing person or object. This last information is helpful to differentiate for example a person using a wheelchair, a valid person (e.g medical staff), or an elderly.

We use phidget interface kits connected to a fit-pc for data acquisition and recording.

7.2.1.3. Data gathering and analysis

The aim of this data processing is to transform the raw data provided by the sensor barriers in a higher level data composed by the time and direction of crossing and rough estimation of the speed and size of the object or person crossing the barrier. This information can be deduced using only the data given by the distance sensors after processing. Nevertheless in real situations the barrier may be hidden by an object (food or cleaning trolley for example), and the redundant information from PIR sensors of an other closed barrier may be useful to recover the missing information.

The data are intended to be collected on large period of time (typically months). Inline filtering and averaging techniques were used to transform large and noisy raw data to get reasonable dataset size. Figure 3 shows in blue or red the general direction of the measurement of the stations (that create detection zones) and in each zone the current estimation of the number of people in each zone (a cross indicates 0, a black circle represents one person). For example the lower left zone has between 1 and 2 people.

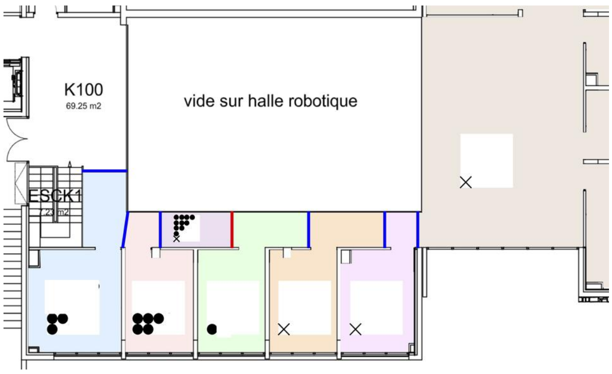

Figure 3. Occupancy of zone in a complex environment as measured by several stations

7.2.1.4. Experimentation

A monitoring system has been installed in the first floor of EHPAD Valrose in Nice. The area of monitoring was restricted to the hallway that leads to the individual rooms of six residents. Residents are proposed several activities (social or cultural activities, physical activities, meals) and have to use the hallway when participating to those activities. In addition to residents medical and service staff also use this hallway. The aim of this experiment is to determine an activity measure for each resident and to study its evolution with time. In that case the sensor placement is designed in such way that individual information may be obtained (e.g. by having stations on both side of the door of the individual room).

The installed system is composed of 10 multi sensor barriers installed on the wall of the hallway and 7 additional PIR sensors installed on the ceiling of the hallway. The data are transmitted by phidget interface kits and are processed by a fit-PC that store the daily data sets. A similar setup will be installed at the very beginning of 2017 in the Institut Claude Pompidou to monitor the activity in the corridors and in the waiting room. Here the medical community is more interested in statistical analysis than in individual analysis.

7.2.2. Sensors placement

Both economic motivations due to demographic evolution and willingness of people to live independently at home when aging, facing physical impairment or recovering from injuries has raised the need for activity monitoring at home, in rehabilitation center or in retirement home. Monitoring systems provide informations that can range from a broad measure of the daily activity to a precise analysis of the ability of a person performing a task (cooking, dressing, ...) and its evolution.

The broad range of needs and contexts, together with the large variety of available sensors implies the necessity to carefully think the design of the monitoring system. An appropriate system should be inexpensive and forgettable for the monitored person, should respect privacy but collect necessary data, and should easily adapt to stick to new needs. We aim to provide an assisting tool for designing appropriate monitoring systems.

As a second year of a PhD work, metrics have been defined to evaluate quality of sensors solutions and placement to infer people behaviors inside a smart environments. Based on these metrics, a methodology for optimal design of smart environments has been developed.

7.2.3. Rehabilitation

Participants: Alain Coulbois, Artem Melnyk, Jean-Pierre Merlet [correspondant].

We have developed the specific walking aid `ANG-med` to be used to monitor rehabilitation exercises beside performing analysis of walking pattern as any walker of the `ANG` family. The main addition for this walker are two rear looking distance sensors and two of such sensor mounted on a pan-tilt head (figure 4). These sensors have been placed under the guidance of the medical community in order to monitor and assess rehabilitation exercise such as leg flexion/extension/abduction and plantar flexion.

Figure 4. Rear view of the `ANG-med` walker with the 4 distance sensors that are used to monitor and assess rehabilitation exercises

The walker is since on year in test in the MATIA fundation in Spain. The software that is used to for this walker has been developed with the European RAPP project (see section 9.3.1.1) so that new exercise may easily be programmed and downloaded through a message passing system [9].

7.3. Miscellaneous results

7.3.1. Analysis of multi unit uniform price auction

Participant: Odile Pourtallier [correspondante].

From previous works on CO2 and electricity market we have identified relevant auction mechanism. This mechanism is strongly related with multi unit uniform price auction. In collaboration with M. Tidball (Lameta INRA) we study this mechanism using game theory models such as optimal stopping time game. The first results have been presented to the 17th ISDG conference (Urbino, Italy July 12-15 2016).

7.3.2. 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 - MOSELA - 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.

Technology demonstrated by our prototype has been transferred : final version of our modeling and simulation environment has been delivered to Airbus in November 2012 and developer level know-how has been transferred in 2013 to a software company in charge of its industrialization and maintenance.

Since 2014, we are working on several enhancements and extension of functionalities, namely to enhance the performances and the numerical quality of the generated C simulation code, and ease the integration of our environment into the airbus toolbox.

In 2016, we have studied how to map modeling concepts used by other Airbus tools into our modeling concepts to allow import in MOSELA of existing models, and perform corresponding C generation [17].

8. Bilateral Contracts and Grants with Industry

8.1. Airbus

8.1.1. Airbus

Participant: Yves Papegay.

Research activities on MOSELA environment, section 7.3.2, have been covered by a contract with Airbus company.

8.1.2. GénérationRobot

Participant: Jean-Pierre Merlet.

- we have got a grant from the company GénérationRobot to develop a pedagogical cable-driven parallel robot as a direct consequence from our research work, see section 7.1.1.

8.1.3. Ellcie-Healthy

Participants: Alain Coulbois, Jean-Pierre Merlet.

- we have got a grant from the company Ellcie-Healthy to evaluate connect objects that are developed by this company.

9. Partnerships and Cooperations

9.1. Regional Initiatives

- CPER project MADORSON for the assistance to elderly people (with the STARS project)
- we have submitted several projects to the local IDEX without success but we are preparing several projects for the next year

9.2. National Initiatives

9.2.1. FHU

- the team has been involved for the FHU *INOVPAIN : Innovative Solutions in Refractory Chronic Pain* that has been labeled in December

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. RAPP

Type: COOPERATION

Instrument: Specific Targeted Research Project

Objective: Robotic Applications for Delivering Smart User Empowering Applications

Duration: December 2013-December 2016

Coordinator: CERTH/ITI

Partner: CERTH/ITI(Greece), Inria, WUT (Poland), ORTELIO (UK), ORMYLIA (Greece), INGEMA (Spain)

Inria contact: David Daney, Jean-Pierre Merlet, Manuel Serrano

Abstract: our societies are affected by a dramatic demographic change, in the near future elderly and people requiring support in their daily life will increase and caregivers will not be enough to assist and support them. Socially interactive robots can help to confront this situation not only by physically assisting people but also functioning as a companion. The increasing sales figures of robots are pointing that we are in front of a trend break for robotics. To lower the cost for developers and to increase their interest on developing robotic applications, the RAPP introduces the idea of robots as platforms. RAPP (Robotic Applications for Delivering Smart User Empowering Applications) will provide a software platform in order to support the creation and delivery of robotics applications (RAPPs) targeted to people at risk of exclusion, especially older people. The open-source software platform will provide an API that contains the functionalities for implementing RAPPs and accessing the robot's sensors and actuators using higher level commands, by adding a middleware stack with added functionalities suitable for different kinds of robots. RAPP will expand the computational and storage capabilities of robots and enable machine learning operations, distributed data collection and processing, and knowledge sharing among robots in order to provide personalized applications based on adaptation to individuals. The use of a common API will assist developers is creating improved applications for different types of robots that target to people with different needs, capabilities and expectations, while at the same time respect their privacy and autonomy, thus the proposed RAPP Store will have a profound effect in the robotic application market. The results of RAPP will be evaluated through the development and benchmarking of social assistive RAPPs, which exploit the innovative features (RAPP API, RAPP Store, knowledge reuse, etc.) introduced by the proposed paradigm.

9.4. International Initiatives

9.4.1. Informal International Partners

We have numerous international collaborations but we mention here only the one with activities that go beyond joint theoretical or experimental works:

- University of Bologna: 2 joint PhD student, publications
- University Innsbruck: joint conference organization
- Fraunhofer IPA, Stuttgart: joint conference organization
- Duisburg-Essen University: joint conference organization
- University of New-Brunswick: 1 joint PhD student
- University Laval, Québec: joint book
- University of Tokyo: joint conference organization
- Tianjin University, China: joint book

9.5. International Research Visitors

9.5.1. Visits of International Scientists

We have received for an extended stay our joint PhD student J. Pickard from University of New Brunswick together with his canadian supervisor J.A Carretero. We have received the Associate Professor Martin Pfurner from Innsbruck University for an extended stay and and Cuong Trinh Duc, PhD student from University Genova while several other scientists from other domains have visited our robotics flat.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

- J-P. Merlet was General Chair of ARK 2016, organized by the team in Grasse (70 attendees), [16]

10.1.1.2. Member of the Organizing Committees

- 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
- Y. Papegay is a permanent member of the International Steering Committee of the International Mathematica Symposium conferences series.

10.1.2. Scientific Events Selection

10.1.2.1. Reviewer

- J-P. Merlet has been reviewing Editor for IROS 2016.
- The members of the team reviewed numerous papers for numerous international conferences.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- J-P. Merlet is board member of the Journal of Behavorial Robotics

10.1.4. Invited Talks

- J-P. Merlet has given a talk during the Scientific days of Inria and the Human Robot Interaction workshop

10.1.5. Leadership within the Scientific Community

- J-P. Merlet is Inria representative to the PPP Eurobotics aisbl. 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 has be re-elected as one of the 10 members of IFToMM Executive Council, the board of this federation. He is a member of the scientific committee of the CNRS GDR robotique.

10.1.6. Scientific Expertise

- J-P. Merlet was involved in project evaluations for several foreign funding agencies (Israel, Austria, Finland). He was also appointed as *Nominator* for the Japan's Prize. He was a member of the jury of the PhD Award of GDR robotique.

10.1.7. Research Administration

- J-P. Merlet is an elected member of Inria Scientific Council. and member of the CAC of UCA COMUE.
- O. Pourtallier is a board member of SeaTech, an Engineering School of University of Toulon. She is a member of the Inria CSD (doctoral students monitoring), and is responsible of the Inria NICE committee (long term invited scientists and post-doctoral student selection).
- Y. Papegay is a member of the Inria CUMIR and of the ADT committee

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master: J-P. Merlet lectured 8 hours on robotics and connected objects to Master NeuroMoteur (M2) at University Paris Est. He has participated to the Parallel Kinematic Machine summer school organized by LIRMM (6h)

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

E-learning

Mooc ICN : J-P. Merlet and Y. Papegay have contributed to this MOOC which is intended top introduce the numerical world to teacher. ‘

10.2.2. Supervision

- PhD in Progress : A. Massein, Design of Smart Environment for Human Behaviour Recognition, 2013-2016, supervisors: D.Daney, Y. Papegay

10.2.3. Juries

- J-P. Merlet has been a member of 5 PhD and 3 HDR juries, and for 6 of them has been the president of the jury.

10.3. Popularization

- J-P. Merlet has participated to a meeting “Future of robotics” organized by the Académie of Sciences. As a member of Executive Council of IFToMM he has contributed to the organization of the third Students International Olympiad on Mechanism and Machine Science held in Madrid. He is also a regular reviewer for Interstices and a contributor [18]
- Y.Papegay is actively participating to the Math.en.Jeans initiative for Mathematics teaching for undergraduate students. He has organized and animated summer schools in experimental mathematics and computer sciences. A three weeks session has been held at the University of Western Australia in Perth in July and three other one week sessions have been held in Oxford in June and August gathering around 50 high-school students - most of them were awardees in Mathematics Olympiads.

11. Bibliography

Major publications by the team in recent years

[1] C. Bliek, B. Neveu, G. Trombettoni. *Using Graph Decomposition for Solving Continuous CSPs*, in "Principles and Practice of Constraint Programming, CP’98", LNCS, Springer, 1998, vol. 1520, pp. 102-116

[2] D. Daney, N. Andreff, G. Chabert, Y. Papegay. *Interval method for calibration of parallel robots: a vision-based experimentation*, in "Mechanism and Machine Theory", August 2006, vol. 41, n^{o} 8, pp. 929-944

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

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

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

[6] Y. PAPEGAY. *De la modélisation littérale à la simulation certifiée*, Université de Nice Sophia-Antipolis, Nice, France, June 2012, Habilitation à Diriger des Recherches, http://tel.archives-ouvertes.fr/tel-00787230

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

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

Publications of the year

Articles in International Peer-Reviewed Journals

[9] S. E. REPPOU, E. G. TSARDOULIAS, A. M. KINTSAKIS, A. L. SYMEONIDIS, P. A. MITKAS, F. E. PSOMOPOULOS, G. T. KARAGIANNIS, C. ZELIENSKI, V. PRUNET, J.-P. MERLET, M. ITURBURU, A. GKIOKAS. *RAPP: A Robotic-Oriented Ecosystem for Delivering Smart User Empowering Applications for Older People*, in "International Journal of Social Robotics", June 2016 [*DOI :* 10.1007/S12369-016-0361-Z], https://hal.inria.fr/hal-01336250

International Conferences with Proceedings

[10] *Best Paper*
J.-P. MERLET. *A generic numerical continuation scheme for solving the direct kinematics of cable-driven parallel robot with deformable cables*, in "IEEE Int. Conf. on Intelligent Robots and Systems (IROS)", Daejeon, South Korea, 2016, https://hal.archives-ouvertes.fr/hal-01419699.

[11] J.-P. MERLET. *A new generic approach for the inverse kinematics of cable-driven parallel robot with 6 deformable cables*, in "ARK", Grasse, France, 2016, https://hal.archives-ouvertes.fr/hal-01419701

[12] J.-P. MERLET. *Cable-driven parallel robots and their extension to other domains*, in "IEEE Int. Conf. on Robotics and Automation", Stockholm, Sweden, 2016, https://hal.archives-ouvertes.fr/hal-01419702

[13] J.-P. MERLET. *On the workspace of suspended cable-driven parallel robots*, in "IEEE Int. Conf. on Robotics and Automation", Stockholm, Unknown or Invalid Region, 2016, https://hal.archives-ouvertes.fr/hal-01419703

[14] *Best Paper*
J.-P. MERLET. *Preliminaries of a new approach for the direct kinematics of suspended cable-driven parallel robot with deformable cables*, in "Eucomes", Nantes, France, 2016, https://hal.archives-ouvertes.fr/hal-01419700.

Conferences without Proceedings

[15] A. MASSEIN, D. DANEY, Y. PAPEGAY. *Robust Design of Parameter Identification*, in "ARK 2016 - Advances in Robotics Kinematics", Grasse, France, June 2016, https://hal.archives-ouvertes.fr/hal-01405825

Books or Proceedings Editing

[16] J. LENARČIČ, J.-P. MERLET (editors). *Advances in Robot Kinematics : Proceedings of the 15th international conference on Advances in Robot Kinematics*, June 2016, https://hal.archives-ouvertes.fr/hal-01339423

Research Reports

[17] Y. A. PAPEGAY. *Import de projets MODELIA : MOSELA - Modelling and Simulation Environment*, Inria, November 2016, https://hal.archives-ouvertes.fr/hal-01405834

Scientific Popularization

[18] J.-P. MERLET. *Au service des personnes fragiles*, in "Interstices", February 2016, https://hal.inria.fr/hal-01350468

[19] B. SENACH. *Prendre en compte l'utilisateur*, in "Interstices", April 2016, https://hal.inria.fr/hal-01350447