Activity Report 2014

Team HEPHAISTOS

HExapode, PHysiologie, AssISTance et Objets de Service

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Robotics and Smart environments

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Team HEPHAISTOS

Keywords: Robotics, Modeling, Interval Analysis, Game Theory, Assistance, Medical Monitoring, Uncertainties Management

Creation of the Team: 2014 January 01.

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2. Overall Objectives

2.1. Overall Objectives

HEPHAISTOS has been created as a team on January 1st, 2013 and will probably become 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
- 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 people with mobility impairments [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.
- **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 robotics problems is a major focus point of the HEPAHAISTOS 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

[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, ...)

- **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, game theory, 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 assistance robotics provides realistic problems which allow us to develop, test and improve our algorithms.

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).

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. 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.

4. Application Domains

4.1. Application Domains

While the methods developed in the project can be used for a very broad set of application domains (for example we have an activity in CO2 emission allowances), it is clear that the size of the project does not allow us to address all of them. Hence we have decided to focus our applicative activities on *mechanism theory*, where we focus on *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.

5. New Software and Platforms

5.1. Introduction

Software development is an essential part of the research done by HEPHAISTOS 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`) 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: 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.

5.3. Platforms

A large number of teams at Inria are developing hardware platforms whose development is quite different from pure software. In our case we have several of such platforms:

- *instrumented flat*: HEPHAISTOS benefits from its own experimental workplace with a simulated flat that includes all the basic home elements (kitchen, bedroom, toilets, relaxation and rehabilitation area) [2]
- *walking aids family* `ANG`: `ANG-light` (for walking analysis), `ANG-II` (a fully motorized rollator) and `ANG-med` (with adjustable friction brakes in the rear wheels).

[2] see http://www-sop.inria.fr/hephaistos/prototypes/main.html

- *cable-driven parallel robots family* MARIONET: MARIONET-ASSIST for transfer and manipulation, MARIONET-REHAB for rehabilitation purposes, MARIONET-VR for rehabilitation and training in an immersive room, MARIONET-SCHOOL for dissemination
- *miscellaneous robots and sensors*: mobile robots (Roomba, Wanny, PoBots), a motion base supporting up to 250 kg, a motion capture system with 12 cameras, force plates ...

6. New Results

6.1. Highlights of the Year

Yves Papegay received a "Wolfram Innovator Award" in December 2014

6.2. Robotics

6.2.1. Cable-driven parallel robots (CDPR)

6.2.1.1. Analysis of Cable-driven parallel robots

Participants: Alessandro Berti, Laurent Blanchet, Houssein Lamine, Jean-Pierre Merlet [correspondant], Yves Papegay, Rémy Ramadour.

We have continued the analysis of suspended CDPRs for control and design purposes. For control it is essential to determine the current pose of the robot for given leg lengths. This forward kinematic problem (FK) is usually very complex and admits several solutions. For parallel robot with rigid legs we have established the important property (P) that the FK may be solved in real-time i.e. being given the leg lengths ρ and platform pose $\mathbf{X}$ it is possible to determine the single pose $\mathbf{X_1}$ that can be reached from $\mathbf{X}$ if the leg lengths has been changed to $\rho + \Delta\rho$ provided that $\Delta\rho$ satisfies some properties. For CDPR with sagging cables determining all the FK solutions is more complex but we have proposed the first algorithm to solve it the for a full scale model of sagging cables [24]. For CDPR with non sagging cables the problem is also very complex because we cannot make any assumption on the number of cables under tension i.e for a CDPR with m cables we have to solve all the FK problems for all possible set of cables under tension from 1 to m and as soon as this number is lower than 6 the system of equations is much larger than for classical robots. We have however been able to propose an interval analysis based algorithm that allow one to get all the solutions [18]. But we have also shown that for non sagging cables the property (P) does not hold. Indeed it requires that the system of equations that governs the FK remains the same at all time. But for CDPR this system depend on the set of cables under tension (which is called the *cable configuration CC*) and it may change when the cable lengths change from 'ρ to $\rho + \Delta\rho$, even for redundant CDPR [23]. If the CC changes at some point the pose solution of the FK together with the cable tensions will differ from the one that is obtained when assuming no change in the CC. This has a drastic effect on control as we have now a system whose state equations may change over time but also on design as in the new CC the cable tensions may be quite different from the expected one. Hence property (P) will hold if and only if we are able to show that there will not be any change in the CC during the change of the cable lengths and therefore it is crucial to detect CC changes. But this require to fully simulate the discrete-time control laws together with the behavior of the coiling system. We have been able to implement a simulation tool that tracks a trajectory for the robot for arbitrary control laws and coiling system model [22], [25]. The principle of the algorithm is to determine if on a time interval $[t, t + \delta t]$ the solution of the FK with the current CC satisfies (P) by using Kantorovitch theorem. If this is not the case Δt is divided by 2 and the process is repeated. We then check if there is a time t_1 in $[t, t + \delta t]$ for which the tension of a cable in the CC may become 0 If there is no such t_1 for any cable in the current CC, then it will be the CC at time $t + \delta t$ and we may compute the pose and cable tensions at any time in $[t, t + \delta t]$. If there is a least one such t_1 (and there may be several $t_1^i, t_1^j, \ldots$ as we consider each cable in the CC) we order these times by increasing values and check sequentially if a cable tension become negative with the current CC at time $(t_1^i + t_1^{i+1})/2$. If yes we determine what can the CC at this time by looking at all possible CC. As soon as the new CC at time t_1^i has been determinated the simulation can go on. Implementing this algorithm has been difficult mainly for numerical reasons: the accuracy of the calculation may sometime exceed the floating point accuracy and we have to resort to symbolic computation and extended arithmetics. Our tests have shown that indeed CC changes may occur on trajectories: on a typical trajectory up to 10 different CC will appear with 5 or 6 cables under tension. These results have been confirmed experimentally on a prototype at LIRMM.

6.2.1.2. Tool for Agencement Analysis and Synthesis of CDPRs

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

HEPHAISTOS has been working on tools to design the layout and geometry of CDPRs, while accounting for numerical errors as well as practical errors – actual position of the winches, of the attachments on the platform, errors of the controllers, of the cables, etc. Within this work, collision analysis plays an important role. Indeed the concept of cable robot aims to increase the workspace that is restricted for robots having rigid legs but interferences may reduce this workspace. Two types of interference analysis approaches exist: intersection of numerically-mapped boundaries (InB) and distance between features (DbF). The two sets of interference types that can be analysed using these approaches are distinct but overlapping. The first approach greatly benefits from Inria's computational geometry research and particularly from the AABB tree algorithms implemented in CGAL. Algorithms and implementation based on those were developed, along with several new algorithm and implementation to extend the scope of intersection types, and thus, of interference types. Algorithms to improve efficiency of given intersection types were also developed. We have already used the second approach, DbF, to develop algorithms for leg interference of parallel robots that are very efficient for non deformable cables but now well adapted for sagging cables. An interference detection algorithm has been developed and implemented for a restricted scope of applications [10], and research is on-going for a more generic case.

6.2.1.3. Visual-servoing of a parallel cable-driven robot

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

The last two years, we studied how visual servoing could improve accuracy, controllability and performance of cable-driven parallel robots [13]. Previous works on this domain showed very interesting results but some issues remained to be investigated , such as :

- ratio accuracy/workspace : cable-driven parallel robots are known to allow a large reachable workspace, but also to have complex geometric and dynamic models which affect the accuracy. Using visual-servoing in a closed-loop scheme, we were able to enhance the accuracy by a factor of ten, allowing to manipulate daily-life objects in a whole living room.
- image-based joint-space control : in order to reach a desired pose, the usual method involves several computing and evaluations of both the Jacobian matrix of the manipulator and the interaction matrix linking visual features to the displacements of the end-effector. We designed a control scheme, based on an iterative updating using the Broyden update law, in order to link the visual features directly to the joint coordinates. This scheme is less sensitive to model uncertainties and require much less computing.
- stability of the command law : classical control laws ignore cable configuration effects that change the pose of the platform. We have proposed a counter-intuitive strategy: the robot `MARIONET-ASSIST` we are using has a specific geometry that allow to predict which cables set may be under tension for a given trajectory i.e. we are able to split the trajectory in parts for which we know all possible cables configurations. Among them we select the one that optimize an accuracy criteria and we enforce it by forcing the cables not part of the configuration to be slack by adding a sufficient amount of length to their nominal values. It allowed to enhance both the stability and the accuracy of a vision-based control scheme [26].

We also used interval analysis in order to guaranty every step of the process, in order to provide safety and reliability of our methods, as the robots that we use were initially deployed in the context of assistive technologies.

Finally, simulations and experiments on prototypes were conducted and presented in order to validate the mentioned results. However, the prototype that we used presents a very particular configuration (all wires are connected to the same point on the end-effector, allowing only translational movements), further works may be required in order to test our methods for a wider variety of cable-driven parallel robots.

6.2.1.4. 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 deplacement and positioning problems in architectural building at scale 1 and seems to be a good alternative to crane and industrial manipulators in this area.

In a collaboration with CNAM and Ecole Nationale Supérieure d'Architecture Paris-Malaquais, we aim to design and realize a CDPR of large size as a proof of concept in additive manufacturing of building based on ultra-high performance concrete.

Challenges are modeling and control to get enough accuracy.

6.2.2. Assistance robotics

This is now the core of our activity and our work on CDPR is deeply connected to this field as they are an efficient solution for mobility assistance, a high priority for the elderly, helpers and medical community. We have presented our vision of assistance robotics in several occasions [20], [21], [19].

6.2.2.1. Assessment of elderly frailty

Participants: Karim Bakal, Jean-Pierre Merlet.

The assessment of elderly frailty is a difficult concept because it involves the physical capacities of a person and its environment (health-care services, families, funds...). We consider the assessment of upper limb capabilities by looking at the joint torques τ of the arm and the maximal force F that can be exerted by the hand, which are related by the equation

$$\tau = \mathbf{J}^{\mathbf{T}} F \tag{2}$$

where $\mathbf{J}$ is a matrix which depends only upon the configuration of the arm. This equations constitutes an underconstrained linear system. In biomechanics the torque τ is measured together with the configuration of the arm and the force F is evaluated by using the method of Chiacchio, that involves the pseudo-inverse of $\mathbf{J}^{\mathbf{T}}$ to calculate F. But there are several uncertainties that are neglected when using this method: the measurement errors on τ and on the configuration of the arm together with uncertainties on the physical parameters of the arm (such as the length of the bones). The method of Chiacchio provides one of the possible solutions of equation (2) and not necessary the one corresponding to the force at the hand. We use another approach based on interval analysis. We assume that all uncertainties may be bounded (τ is an interval vector τ_m, $\mathbf{J}^{\mathbf{T}}$ is an interval matrix) so that equation (2) become an interval linear system. Interval analysis then allows one to determine an approximation as accurate as wanted of the set F_s of all forces F that satisfy the equation and therefore this set includes the real force at the hand. Now assume that with the same arm configuration we measure the force at the hand, here again with some bounded uncertainties (i.e. F is an interval vector F_m). Here again we may use interval analysis applied on equation (2) in order to determine an interval vector τ_v for the τ that is guaranteed to include the real τ. Furthermore τ must be included in the intersection τ_i of τ_v and τ_m while F must be included in the intersection F_i of F_m and F_s. If τ_i is strictly included in τ_m, then we may compute a better approximation of F_s. Reciprocally if F_i is strictly included in F_m we will get a better τ_v. If one of these situation occurs we repeat the process until no significant improvement of F_s or τ_v is obtained. In a second step we consider that the uncertainties that lead to uncertainties in the matrix $\mathbf{J}^{\mathbf{T}}$ are constrained as we have to satisfy $\tau_v = \mathbf{J}^{\mathbf{T}} F_s$. Here again we use interval analysis to determine if this constraint does not allow to reduce the size of the interval on the physical parameters in which case we may obtain a new $\mathbf{J}^{\mathbf{T}}$ that is included in the initial one. In turn this may allow to obtain better τ_v and F_s. The process stops when no improvement has been obtained for F_s, τ_v and the physical parameters.

To test this approach the right upper limb joint torque of 10 males and the force capacity at the right hand was measured by a dynamometer (Biodex III, Biodex Medical Systems) and respectively by a 6-axis load sensor during an experiment performed at HandiBio laboratory. The configuration of the upper limb was measured with a motion capture system (Qualisys, Sweden). The approach is currently being evaluated.

6.2.2.2. Walking analysis

Participants: Claire Maillard, Ting Wang, Jean-Pierre Merlet [correspondant].

The walkers of the ANG family allow one to determine accurately the trajectory of the walker and therefore to analyse the walking of the user. We have used this property for performing until mid 2013 a large scale experiment: 23 young adults and 25 elderly people (> 69 years) were asked to walk along with two reference trajectories with the help of the walker. The objective of this research is to develop walking quality index and examine if the walker may be used to monitor the health state of elderly people at home. We compared and statistically analyzed the walking patterns of the two groups of people. The results show that it is possible to obtain new indicators by using the walker measurements [9],[14]. Next step will be to perform a similar analysis for a sit-to-stand (STS) exercice and to test our approach in two rehabilitation centers, MATIA in Spain (in the framework of the RAPP project) and Centre Héliomarin de Vallauris.

A start-up plan was proposed in November 2014 to transfer the walking analysis technology of Hephaistos with the ANG walker. In order to study the feasibility of our plan, we have interviewed Patrick Nenert (Kiné, Centre Hélio-Marin), Françoise Dubourgeois (DR, EPHAD) and Sophie Morgenstern (Métropole NCA, Living Lab Paillon 2020) about their impression of the walker and the possibility of the future collaboration with them. Several contact with local actors of the silver economy sector have already been established : Livinglab Paillon2020 (Nice), CIU-santé, as well as with research lab for collaboration on future projects (Lapcos, I3M, Gredeg).

6.2.2.3. Design and evaluation of assistive devices, ethics

Participants: Marc Beninati, Bernard Senach [correspondant], Jean-Pierre Merlet.

Providing appropriate support, services and information to the elderly, to their caregivers and to the medical profession, through a fleet of communicating devices must rely on a structured processes. A generic design and evaluation framework is being elaborated and will be validated through field experiments.

Assistance robotics raises many ethical questions. We started reflection about conducting experiments with frail and old people. A listing of questions to be addressed at each step of an experiment has been written (internal document). We have also hired a joint PhD student with University Bologna about the legal aspects of assistance robotics and we plan to organize a national forum on this topic with Nathalie Nevejans from University of Douai.

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.

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

In 2014, we have worked again 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.

7. Partnerships and Cooperations

7.1. Regional Initiatives

7.1.1. SyRreMuse project: recommender for museum and exhibit visitors

Participant: Bernard Senach [correspondant].

The goal of the SyReMuse Project is to design and implement a recommender system for Museum and exhibits visitors. The project brings together a cluster of research labs from Inria and from University of Avignon mixing computer scientists and Human Science researchers (Laboratoire d'informatique d'Avignon, -Centre Norbert Elias, Wimmics, Hephaistos, ICT usage labs) . The project has been submitted to an ANR Call and, though not successful is still going on with a restricted objective focusing on modeling visitor's expectations and experience (individual and group).

7.1.2. Gnothi Seauton project : Evaluation of communicating objects

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

In collaboration with a rehabilitation center, we are setting up an experiment of self-quantification devices based on actimetrics (measurement and analysis of motor activities of a subject). The goal of the study is to assess utility and usability of these devices in the context of mobility rehabilitation. The study will take place at Vallauris' Centre Heliomarin with physical therapists and patients with mobility impairments.

7.2. European Initiatives

7.2.1. FP7 & H2020 Projects

7.2.1.1. CABLEBOT

- Type: COOPERATION
- Instrument: Specific Targeted Research Project
- Objective: to develop a new generation of modular and reconfigurable robots able to perform many different steps in the post-production of large-scale structures.
- Duration: November 2011 - October 2014
- Coordinator: Ms. Mariola Rodríguez (TECNALIA, Spain)
- Partner: TECNALIA (Spain), CNRS-LIRMM, FRAUNHOFFER-IPA, UDE, Inria, EADS, ACCIONA, VICINAY
- Inria contact: Jean-Pierre Merlet
- Abstract: The CABLEBOT project [3] 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. Three key technologies will be developed: a) Design of Cable Robot: Software tools to design the layout and geometry of cable robots, b) Industrial Process Planning: Simulation of cable robots to verify the operation of cable robots in environments with large-scale structures c) Control Algorithms and Systems: Distributed control and kinematic transformation to operate modular cable robots. Two application examples are targeted in close cooperation to industry: aeronautical applications of maintenance and the handling of construction beams. In both cases existing automation can hardly be used due to maneuverability of heavy and big parts and the risk associated. The results are feasible for many other fields including large-workspace movements of products, with impact in logistics, transport, and warehousing. The exploitation and commercialization of CABLEBOT are

[3] http://www.cablebot.eu/

driven by VICINAY CEMVISA, the application of industrial scenarios, two end-users of different sectors - EADS and ACCIONA - will automate their currently manual post-production. TECNALIA provides the technology for simulation in terms of productivity, cost, safety and robustness, whereas the design of the robots is in charge of LIRMM and Inria. IPA and UDE are in charge of the control algorithms, on distributed and force control of redundant systems. Benefits include an increase of production efficiency, a wider range of products, light and reconfigurable structure mechanisms and adaptable and more flexible operator assistance systems.

7.2.1.2. 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: s 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.

7.2.2. Collaborations with Major European Organizations

Our collaboration are described in the figure 1.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific events organisation

8.1.1.1. General chair, scientific chair

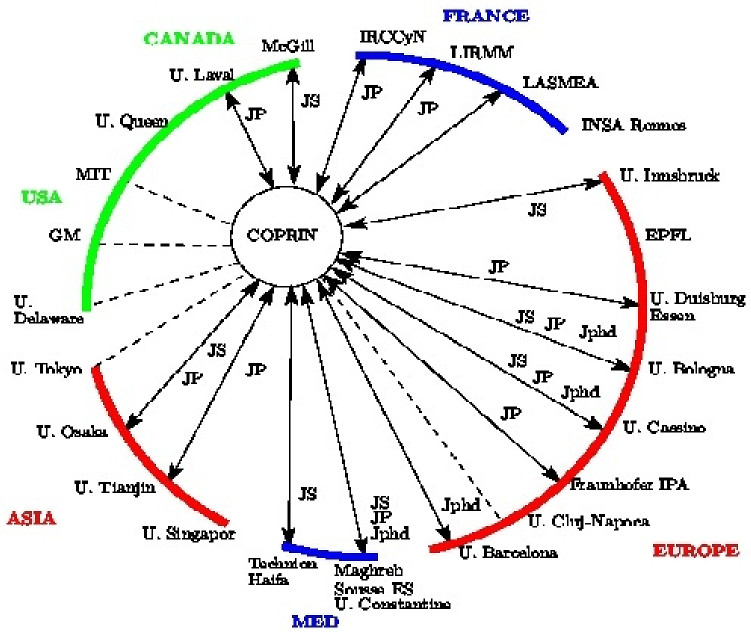

Figure 1. COPRIN collaboration. JP:joint project, JS: joint stay, Jphd: joint PhD students

- 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 also Inria representative to 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 is 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

8.1.2. Scientific events selection

8.1.2.1. Member of the conference program committee

- J-P. Merlet has been reviewing Editor for IROS 2014
- Y. Papegay is a permanent member of the International Steering Committee of the International Mathematica Symposium conferences series, and member of the Program Committee of the 2015 edition

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

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

8.2.2. Supervision

PhD in Progress : K. Bakal, Biomechanics of the upper limb, 2013, supervisors: D. Daney, J-P. Merlet, P. Gorce

PhD in Progress :M. Beninati, Legal aspect of assistance robotics, 2015, supervisor: J-P. Merlet

PhD in Progress : A. Berti, Forward kinematics of cable driven parallel robots, 2012, supervisors: M. Carricato, J-P. Merlet

PhD in Progress : L. Blanchet, Interference and modularity management in cable-driven parallel robots, 2011, supervisor: J-P. Merlet

PhD in Progress, H. Lamine, Cable-driven parallel robot for rehabilitation, 2013, supervisors: J-P. Merlet, L. Romdhane

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

PhD in Progress : R. Ramadour, Visual servoing for cable-driven parallel robot, 2011, supervisors: F. Chaumette, J-P. Merlet

8.2.3. Juries

- J-P. Merlet has been the member of the jury of 5 PhD defense and of one HdR

8.3. Popularization

- M. Gautier has participated to the Fête de la science CIV, to the Carrefour des métiers Nice and has proposed a programming initiation to a 6ème class in view of the participation to the Junior Robotics Pobot Cup.
- Y.Papegay is actively participating to the Math.en.Jeans initiative for Mathematics teaching for undergraduate students.
- we extensively us the `MARIONET-SCHOOL` robots for pedagogy and teaching at all level.
- J-P. Merlet has given several national newspapers and TV interviews

9. Bibliography

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Publications of the year

Articles in International Peer-Reviewed Journals

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International Conferences with Proceedings

[10] L. BLANCHET, J.-P. MERLET. *Interference detection for cable-driven parallel robots (CDPRs)*, in "IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)", Besancon, France, July 2014, pp. 1413 - 1418 [*DOI :* 10.1109/AIM.2014.6878280], https://hal.archives-ouvertes.fr/hal-01095093

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Other Publications

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