Activity Report 2018

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. Team, Visitors, External Collaborators

Research Scientists

Jean-Pierre Merlet [Team leader, Inria, Senior Researcher, HDR]
Yves Papegay [Inria, Researcher, HDR]
Odile Pourtallier [Inria, Researcher]
Eric Wajnberg [INRA, Senior Researcher]

Technical staff

Alain Coulbois [Inria, until Oct 2018]
Artem Melnyk [Inria, until Nov 2018]

Interns

Gregoire Mortureux [Inria, from May 2018 until Oct 2018]
Pierre Mortureux [ESIEE, from Jul 2018 until Aug 2018]

Christopher Raymond [Inria, from Apr 2018 until Sep 2018]

Administrative Assistant

Laurie Vermeersch [Inria]

Visiting Scientists

Hiparco Lins Vieira [University Sao Paulo, from Nov 2018]

Maysa Tome [Escola Superior de Agricultura "Luiz de Queiroz", Piracicaba, from Dec 2018]

External Collaborator

Ting Wang [ESIEE, from May 2018]

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
- 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 [16].

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 8.1.1), 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

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

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 [8], [4]:

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 component** 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 ...). However whenever needed we will rely as well on continuation, algebraic geometry, geometry or learning.

3.2. Robotics

HEPHAISTOS, as a follow-up of COPRIN, has a long-standing tradition of robotics studies, especially for closed-loop robots [3], 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 [18]. 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. Domains: a transversal approach

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 assistance robotics
- strong collaboration with the medical community on walking analysis, rehabilitation (section 7.2.1) and activities detection (section 7.3)

5.1.2. Experimentation

- completion of the first version of our immersive environment for rehabilitation (section 7.2.1)
- continuation of the daily activities monitoring in a day hospital (section 7.3)

5.1.3. Awards

J-P. Merlet has received the best paper award at the Eucomes conference .

BEST PAPER AWARD:

[15]
J.-P. MERLET. *Some properties of the Irvine cable model and their use for the kinematic analysis of cable-driven parallel robots*, in "EUCOMES", Aachen, Germany, 2018, https://hal.archives-ouvertes.fr/hal-01965230

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: Jean-Pierre Merlet and Odile Pourtallier
- Contact: Jean-Pierre Merlet

6.2. PALGate

KEYWORDS: Health - Home care - Handicap

- Contact: David Daney

6.3. Platforms

6.3.1. ALIAS, Algorithms Library of Interval Analysis for Systems

Participants: Hiparco Lins Vieira, Jean-Pierre Merlet [correspondant], Yves Papegay.

URL: http://www-sop.inria.fr/hephaistos/developpements/main.html

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6.3.2. Hardware platforms

We describe here only the new platforms that have been developed or improved in 2018 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).

6.3.2.1. REVMED: virtual reality and rehabilitation

Inria and Université Côte d'Azur have agreed to fund us for developing the platform REVMED 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 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 by using lidar, kinect and distance sensor 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 instrumented treadmill are effective and we have completed at the end of this year the coupling between the subject motion and the 2D visualization of a walk in a nice-looking environment, including basic sound (figure 1). Walking analysis is performed using a lidar, a kinect and a distance sensor at the head of the treadmill.

6.3.2.2. Activities detection platform

For non intrusive activities detection we use low cost distance and motion sensors that are incorporated in a 3D printed box and constitute a detection station. Several such station are implemented at appropriate place in the location that has to be monitored. Currently we have 15 such stations deployed at Valrose EHPAD since end of 2016 and 17 (which amount to 77 different sensors) deployed at Institut Claude Pompidou since the end of 2017.

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.

Figure 1. Our rehabilitation station in a configuration with a treadmill, 2 columns for changing its slope and inclination and lidar and kinect for motion analysis

We have continued the analysis of suspended CDPRs for control and design purposes. This analysis is heavily dependent on the behavior of the cable. Three main models can be used: *ideal* (no deformation of the cable due to the tension, the cable shape is a straight line between the attachments points), *elastic* (cable length changes according to the tension to which it is submitted, straight line cable shape) and *sagging* (cable shape is not a line as the cable is submitted to its own mass). The different models leads to very different analysis with a complexity increasing from ideal to sagging. All cables exhibit sagging but the sagging effect is often neglected if the CDPR is relatively small while it definitively cannot be neglected for large CDPRs. The most used sagging model is the Irvine model [19]. This is a non algebraic planar model with the upper attachment point of the cable is supposed to be grounded: it provides the coordinates of the lowest attachment point B of the cable if the cable length L_0 at rest and the force applied at this point are known. It takes into account both the elasticity and deformation of the cable due to its own mass. A drawback of this model is that we will be more interested in a closed-form of the L_0 for a given pose of B (for the inverse kinematics of CDPR) and in alternate form of the model that will provide constraint on the force components (for the direct kinematics). We have proposed new original formulations of the Irvine model in [15] (best paper award of the Eucomes conference) and have shown that their use drastically improve the solving time for both the inverse and direct kinematics (i.e finding all possible solutions for both problems) that are required for CDPRs control. Still the solving time of the direct kinematics is too large for the real-time direct kinematics and in that case only the current pose of the platform is of interest. For that purpose it is of interest to add sensors on the robot beside the measurement of cable lengths in order to improve the solving time by using additional constraints and possibly ending up with a single solution. But these measurements are uncertain although we may assume that the measurement errors are bounded. It is necessary to determine these error bounds for a practical use of these measurement and we have conducted an experimental investigation of various additional measurements [12]: a mechanical system for measuring the angle of the cable plane with respect to a reference axis, cable angulation with accelerometers glued on the cable, a "poor man lidar" on the platform for optically determining several cables angulation, accelerometers on the platform and cable tensions with strain gauges while the pose of the platform was estimated accurately by using a metrology arm and laser range-meters. This investigation has shown that:

- the friction in the mechanical system leads to large errors for the cable plane angle (up to 30 degrees). For later measure we have bypassed this system
- even for small and medium-sized CDPRs the sagging effect cannot be neglected for estimating cable angulation
- accelerometers on the cable and the lidar system have a good accuracy (between 1 and 5 degrees)
- cable tension measurement is very approximate even with high accuracy strain gauges and cannot be used for control purposes.

We have also continued to investigate calculation of planar cross-sections of the workspace for CDPR with sagging cables, i.e. when 4 of the 6 platform pose parameters are fixed leaving only 2 free parameters. Brand new algorithms have been developed, based on a continuation approach [12],[13]. The main idea is that almost everywhere the workspace border is a one-dimensional variety so that if one of the free parameters is fixed, then a pose on the border should satisfy a square equation system constituted of the kinematic equations and the constraints equations (e.g. that a cable length is equal to a given maximum limit). Pose on the border are obtained by choosing an arbitrary pose that has an inverse kinematic solution that satisfy the constraints in the workspace and then moves incrementally along one of the free axis using a certified Newton scheme for finding the inverse kinematics solution until the constraint equations are almost satisfied in which case the certified Newton scheme is used to determine exactly (i.e with an arbitrary accuracy) a pose that lies on the border. Then a continuation scheme is used to find new poses on the border until we reach a pose at which a new set of constraints is satisfied i.e. a starting point for a new border arc. The border is then composed of several polygonal arcs that approximate the real border. The scheme is devised so that we completely master the difference between the real workspace area and the region defined by the polygonal approximation of the border. If necessary we may reduce this difference by adding new vertices on the border polygon. An important point is that the constraints define border arcs but also singularity curves (i.e. pose at which the direct kinematics equations are singular) and a specific continuation scheme has been developed to determine those arcs. Indeed the cancellation of the determinant of the jacobian of the direct kinematic equations is part of the equations that are satisfied on this type of border arc but this determinant cannot be obtained in closed-form. Consequently we have devised a certified Newton scheme that just require to evaluate the determinant and its derivatives at a given pose. A consequence of the existences of such arcs is that the workspace may have several *aspects* i.e. workspace region that can be reached only for a given inverse kinematics solution and is unreachable for the other one(s).

7.1.2. Cable-Driven Parallel Robots for large scale additive manufacturing

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

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 large scale seems to be a good alternative to crane and industrial manipulators in the area of additive manufacturing. We have co-founded in 2015 years ago the XtreeE (www.xtreee.eu) start-up company that is currently one of the leading international actors in large-scale 3D concrete printing.

We have been contacted this year by artists interested in mimicking the 3D additive manufacturing process on a large scale with glass micro-beads for a live art performance to be held in 2019 (www.lestanneries.fr/exposition/monuments-larmes-prince). We have been working on the design of the robotics system, namely a cables parallel robots with autonomous refilling capabilities.

7.1.3. Robotized ultrasound probe

Participant: Jean-Pierre Merlet.

In collaboration with the EPIONE project we have started investigation the development of a portable robotized cardiac ultrasound probe that may be used while performing an effort test. A first step, somewhat surprising was the necessity to instrument an existing probe in order to determine what are the forces that the doctor exert on the probe during an investigation and the maximal angulation of the probe (apparently this data has not been measured beforehand). We add an accelerometer (for measuring the angle) and a force sensor in a 3D-printed covering of the probe and recorded the data during several experiments. We were then planing to develop a small, portable 3 d.o.f. rotational parallel robot whose range of motion was within the maximum angles that has been determined experimentally and was able to sustain the force exerted by the doctor. Unfortunately there was not a general consensus between the doctors and the company manufacturing the probe on the number of d.o.f. that was requested for the robot (which clearly have a drastic influence on the mechanical design and on the dimensional synthesis of the robot) so that the project is on stand-by.

7.1.4. *Parallel robot performances and uncertainties*

Participants: Jean-Pierre Merlet, Hiparco Lins Vieira [correspondant].

The purpose of this study, which is the PhD subject of H. Lins Vieira, is to develop interval analysis-based algorithm for determining if some performance requirements for parallel robots (e.g. on workspace, accuracy, load lifting ability) can be guaranteed in spite of the unavoidable manufacturing and control uncertainties of the system.

7.2. Assistance

We are still going on in building a framework for customizable and modular assistive robotics including hardware, software and communication and medical monitoring. The development of our platforms shows that we are now able to identify problematic issues for end-users, helpers and the medical community and to propose appropriate hardware/software solutions. But the most time consuming part of our work is related to evaluation and therefore experimentation: this involves legal/ethical issues (for which we have contributed [5]), participation of the medical community (for evaluation and recruitment) and heavy administrative management. Clearly we are lacking of permanent staff as we have long term objectives that cannot be fulfilled only with PhD or post-doc students. We need also engineers during specific periods (for hardware development and experimentation) but over a longer time than the one or two years currently proposed by Inria.

7.2.1. *Rehabilitation in an immersive environment*

Participants: Artem Melnyk, Jean-Pierre Merlet, Yves Papegay [correspondant], Ting Wang.

Rehabilitation is a tedious and painful process and it is difficult to assess its trend. Using an immersive environment has shown to increase the patient motivation but is not sufficient regarding rehabilitation efficiency. First the visual feedback (event 3D) is not sufficient to provide a full immersive feeling as body motion is not involved. Controlling body motion is also very important for therapists that currently must continuously correct the patient pose so that the rehabilitation exercise is the most efficient. We propose to add motion generators in the environment to reinforce realism (thereby increasing patient motivation) but also to allow therapists to use these generators to control the body pose so that they will be able to repeat rehabilitation exercises in a controlled context. Furthermore these generators are instrumented to provide information on the body pose and additional external sensors complete these measurements for rehabilitation assessment. We have developed 3 types of motions generators: one 6 d.o.f. motion base, a CDPR that is able to lift a patient and 2 multipurpose lifting columns.

When starting this project we were planning to use Inria-Sophia immersive room , hence allowing us to focus on the rehabilitation station. Unfortunately this room is no more available. This year we have developed a 2D renderer that has been connected to a flexible software platform allowing the various agents to exchange messages. We have been able to build a first version of our rehabilitation platform using a treadmill as exercise tool and columns to animate the treadmill (figure 1). For measuring the gait pattern we are using a planar lidar for detecting the leg motions, a kinect for detecting the motion of a skeleton and a distance sensor that measure the body motion with respect to the head of the treadmill. Figures 2 and 3 show an extract of the measurements obtained during a typical walk. It may be seen that the lidar data are very clean and allows one to estimate the mean position of the leg as a function of time (from which we will be able to deduce the number of steps, velocities of the leg, ...). Kinect data are much more noisy although that a fusion with the lidar data and the distance data will allows us to detect significant trunk motion. A typical walk of 3mn provides approximately 20 Mo of data.

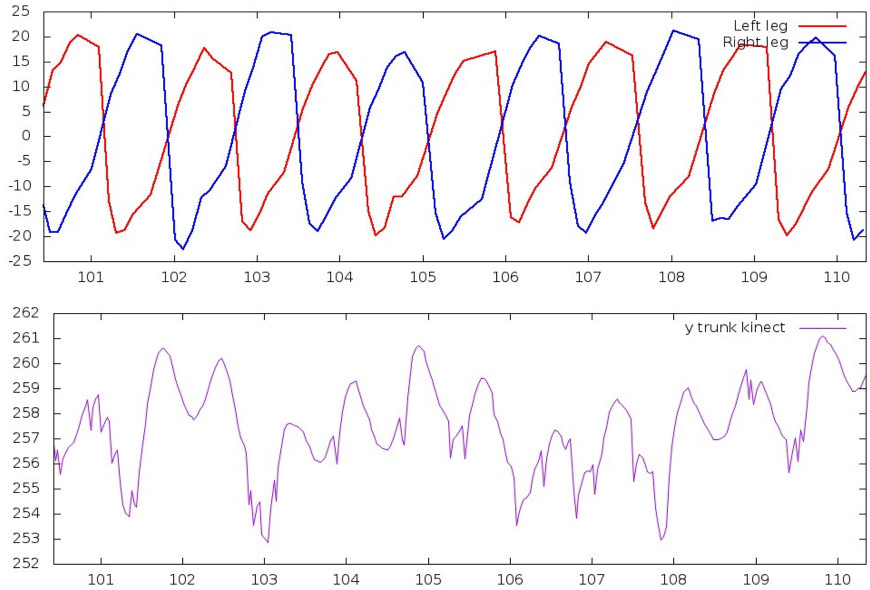

Figure 2. An extract of the legs motions in the walking direction as measured by the lidar and the trunk forward/backward motion estimated by the kinect

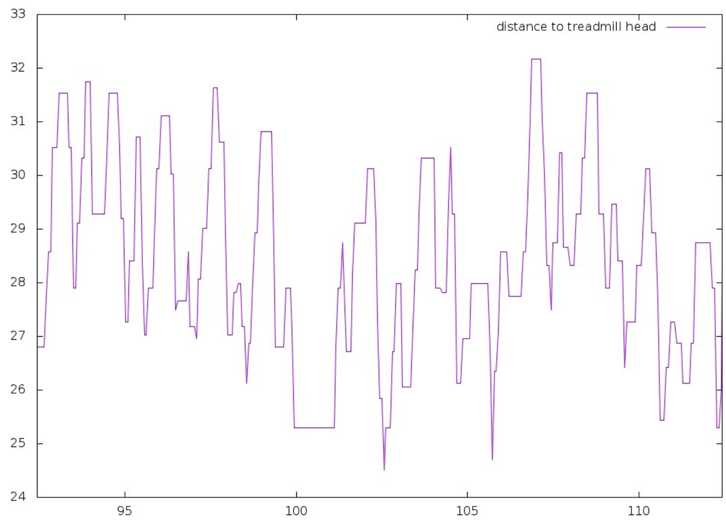

Figure 3. An extract of the trunk forward/backward motions as measured by the distance sensor in the head of the treadmill

Note that we are not using wearable sensors (although they are available: accelerometers for the arms and legs, shoes with pressure sensor and accelerometers): this is voluntary as our contacts with the medical community have indicated that many patients will not be comfortable with wearable sensors. In the same manner we have experimented having a headset instead of the screen but it appears that visualization is very disturbing and uncomfortable. Subject safety is ensured: during the exercise the subject must keep a push button pressed and when released the treadmill stop immediately. An emergency stop button is also available for the operator. Furthermore the system has been designed to provide various supports for avoiding fall and is surrounded by soft carpets.

The rehabilitation station for walking analysis on a treadmill in various walking condition is now almost fully functional and reliable. The next step will start of the beginning of 2019 with an experiment involving a cohort of voluntary subjects of Inria in order to obtain a significant amount of data. A statistical analysis of these data will then be performed in order to examine if synthetic and medically pertinent indicators (besides classical indicators such a number of steps, velocity, ...) may be obtained. The next step will involve repeating this experiment with pathological patients from Centre Héliomarin de Vallauris, most probably at the end of 2019. Meanwhile we will integrate our motion base as another element of the rehabilitation station with the purpose of equilibrium analysis, using a sea landscape as virtual environment with fans providing a realistic simulation of winds.

7.3. Smart Environment for Human Behaviour Recognition

Participants: Alain Coulbois, Aurélien Massein, Yves Papegay, Odile Pourtallier [correspondant], Eric Wajnberg.

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.

The main aspect that grounds this work is the ability to locate a person or a group in their indoor environment. We focus our attention to the case where several persons are present in the environment. As a matter of fact the single person case is less difficult.

This year we have focused our attention in several aspects : improvement of the hardware of the experimental monitoring system and tools for handling and analyzing the data gathered.

The PhD work about optimal location of sensors in a smart environments has been defended in november, defining new metrics on set of sensors and new methods [2].

7.3.1. Hardware

Two monitoring systems have been installed. The first one in the first floor of EHPAD Valrose in Nice, and a second one in Institut Claude Pompidou in Nice. Both systems are composed of multi sensors barriers that provide raw data from which we deduce the time and direction of its crossing by a person.

[2] Design of Instrumented Environment for Human Monitoring, defended on 12/26/2018

For the second experimental system the analysis of the first data have shown that the system was not reliable enough while the data themselves were not satisfactory because of the specificity of the building (large corridors, large waiting room, picture windows and the number of sensors installed (77). We have worked on the hardware of the system (redundant power supply, better orientation of barriers, better communication system) to improve the gathered data.

7.3.2. Tools for handling data and data analysis

We have developed a simulation program, written in C and using the GTK library, that generates barrier-events (i.e. crossing time, direction of crossing, speed of crossing). This program is based on Monte Carlo procedures simulating the displacement of both elderly and caregivers in the EHPAD environment equipped with movement detectors. The code can simulate up to 20 persons and randomly draws room-to-room movements according to the walking speed of each individual (caregivers walk at a faster pace than elderly), and counts the locations and time coordinates of each movement event identified by the detectors. The figure 4 gives a view of the graphic interface. Such a simulation program, and the results produced, will provide basic training data to reconstruct patient movements from the information collected by the activity detectors.

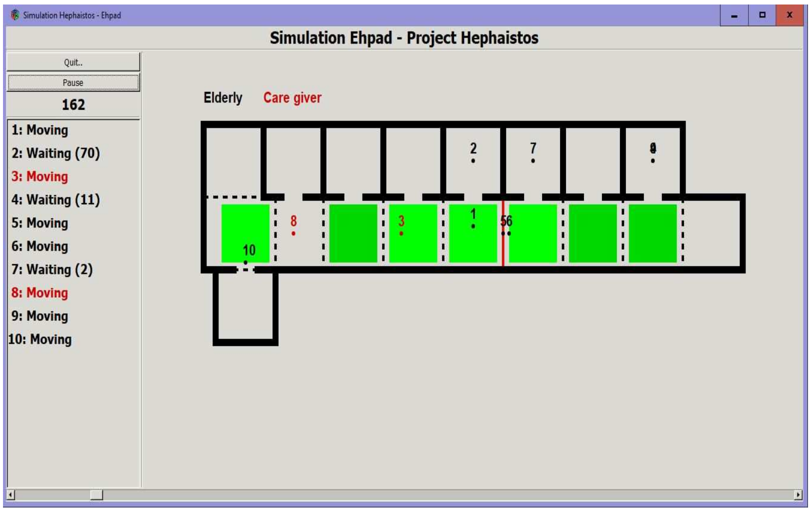

Figure 4. Simulation tool for event detection analysis

Another scientific activities were based on the development of diagnostic tools (also written in C) to visualize (and thus to check and to interpret) events identified by each detector in such equipped environment. Finally, another activity – that is still under development – is to analyze statistically gait data obtained through the event detection. In this case, the goal is to build a series of relevant statistical descriptive parameters that will be used to describe, identify and compare gait features and pathology in medically assisted environments. This last part is developed used the R software.

In the two installed system data are collected continuously during the all day and a large number of barrier crossing is observed. We are currently comparing raw and simulated data before moving on with a statistical analysis.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. 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 - 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, ease the integration of our environment into the airbus toolbox, help improving the robustness of the environment and the documentation.

9. Partnerships and Cooperations

9.1. Regional Initiatives

- the HEPHAISTOS and CHORALE teams together with I3S have organized the 2-days workshop *Robopaca* supported by Inria and UCA. The purpose was to organize a meeting between academics, industry and end-users to examine together the possibility of structuring the robotic activities in PACA

9.2. National Initiatives

- the project **Craft** on collaborative cable-driven parallel robot has been funded by ANR. It involves LS2N (Nantes) and the Cetim. This project will start in 2019

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 2016

9.3. International Initiatives

9.3.1. Inria International Partners

9.3.1.1. 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

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation, Steering committees

- J-P. Merlet is a permanent member of the International Steering Committee of the IROS conference, of the CableCon conference and chairman of the scientific Committee of the Computational Kinematics workshop,
- Y. Papegay is a permanent member of the International Steering Committee of the International Mathematica Symposium conferences series.

10.1.2. Reviewing

- The members of the team reviewed numerous papers for numerous international conferences and journals

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
- E. Wajnberg is Editor-in-Chief of the journal BioControl, a board member of the journals Entomologia Experimentalis et Applicata, Neotropical Entomology, Applied Entomology and Zoology and Journal of Economical Entomology

10.1.4. Invited Talks

- J-P. Merlet has given a talk on parallel robots at the workshop "Rigidity theory for multi-agent systems meet parallel robototics", Nantes, a talk on interval analysis at SCAN, Tokyo and a talk on bibliometric indicators at the SIF workshop
- E. Wajnberg has been invited for talks by the University of Palermo (Italy, February), the University of Haifa (Israel, March), the conference "l'Ere du Temps" (Nice, June), the European Congress of Entomology, Naples (Italy, July), and the University dell'Insubria (Varese, Italy, November).

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 is one of the 10 elected members of IFToMM Executive Council, the board of this federation. He is a member of the scientific committee of the CNRS GDR robotique. J-P. Merlet is an IEEE Fellow, doctor honoris causa of Innsbruck University and IFToMM Awards of Merits
- Y. Papegay is a member of the OpenMath Society, building an extensible standard for representing the semantics of mathematical objects.

10.1.6. Scientific Expertise

- J-P. Merlet was involved in project evaluations for several foreign funding agencies (Israel, Austria, ERC). He was also appointed as *Nominator* for the Japan's Prize.
- E Wajnberg is involved in project evaluation for several foreign funding agencies (Belgium, Italy).
- E. Wajnberg was invited to be a committee number for recruiting an Institute Director by the CNR (Rome, Italy).

10.1.7. Research Administration

- J-P. Merlet is an elected member of the Academic Council of UCA COMUE, a corresponding member of Inria ethical committee (COERLE) and member of the Research, Ethical Committees of UCA. He is an elected member of Inria Scientific Committee and of the “Commission Administrative Paritaire” of Inria
- Y. Papegay is a member of the CUMIR (the committee managing the interaction between researchers and the computer support staff)
- O. Pourtallier is a board member of SeaTech, an Engineering School of University of Toulon. She is responsible of the NICE committee (long term invited scientists and post-doctoral student selection) and a member of the CGL AGOS

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

In February, Y. Papegay has been visiting lecturer of University of French Polynesia, where he gave an object oriented programming course.

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

E. Wajnberg has taught one week course (about 30 h) about the use of the R program and statistics for PhD students and senior scientists in Rehovot (Israel, March), and another week with the same teaching program in Piracicaba (Brazil, July).

10.2.2. Supervision

PhD : A. Massein, Design of Instrumented Environment for Human Monitoring, defended in november 2018, supervisor: Y.Papegay.

PhD in progress: W. Plouvier. Improving pest control efficiency: a modelling approach (2015-2019). Supervisor: E. Wajnberg.

10.2.3. Juries

- J-P. Merlet has been a member of four PhD juries. He was also president of the jury for the Best PhD thesis award of the robotics GDR. He is a member of the “Comité de Suivi Doctoraux” (preliminary evaluation committee of PhD students) of Dayan Hassan (project team Chorale) and of Matheuse Laranjeira (Toulon University).
- E. Wajnberg has been a member of one PhD jury.

10.3. Popularization

10.3.1. Articles and contents

- J-P. Merlet has given two interviews at Nice-Matin and is a member of the scientific committee for the preparation of a permanent robotics exhibition at Cité des Sciences et de l’Industrie, Paris

10.3.2. Education

- Y.Papegay is actively participating to the Math.en.Jeans initiative for Mathematics teaching for undergraduate students. He is developing several pedagogical resources based on small robotics devices at high-school level. He has organized and animated summer schools in experimental mathematics and computer sciences. Several one week sessions have been held in Oxford in June, July, August and November gathering more than 70 high-school students - most of them were awardees in Mathematics Olympiads.
- O. Pourtallier is corresponding researcher for two MATh.en.JEANS workshops, an initiative for Mathematics teaching for undergraduate students.

10.3.3. Interventions

- J-P. Merlet and Y. Papegay have meet several schoolchildren (3ème)
- J-P. Merlet has given a talk during the Art'DI (a meeting between handicapped people and artists) day at Cannes
- J-P. Merlet and E. Wajnberg have given two talks in the framework of "Science pour tous"

10.3.4. Internal action

- J-P. Merlet has given a talk at Café Techno and at Café ADSTIC (for local PhD students), has invited Nathalie Rochet, a member of south-east CPP to give a talk at a Café-In

10.3.5. Creation of media or tools for science outreach

- the Hephaistos team proposes simple cable-driven parallel robots that are used to illustrate scientific concepts such as showing what is a sinus, instantiating the geometrical definition of an ellipse

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