Activity Report 2019

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

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External Collaborator
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2. Overall Objectives

2.1. Overall Objectives

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

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

- they can be adapted to the end-user and to its everyday environment
- 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.

[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, ...)

- **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 this robotic network and of its element is therefore a major focus point of the HEPHAISTOS project. In this field our objectives are:
  - to develop methods for the analysis of existing robots, taking into account uncertainties in their modeling that are inherent to such mechatronic devices
  - to propose innovative robotic systems
- **evaluation, modeling and programming of assistive ecosystem**: design of such an ecosystem is an iterative process which relies on different types of evaluation. A large difference with other robotized environments is that effectiveness is not only based on technological performances but also on subjectively perceived dimensions such as acceptance or improvement of self-esteem. We will develop methodologies that cover both evaluation dimensions. Technological performances are still important and modeling (especially with symbolic computation) of the ecosystem will play a major role for the design process, the safety and the efficiency, which will be improved by a programming/communication framework than encompass all the assistance devices. Evaluation will be realized with the help of clinical partners in real-life or by using our experimental platforms.
- **uncertainty management**: uncertainties are especially present in all of our activities (sensor, control, physiological parameters, user behavior, ...). We intend to systematically take them into account especially using interval analysis, statistics, game theory or a mix of these tools.
- **economy of assistance**: interviews by the HEPHAISTOS team and market analysis have shown that cost is a major issue for the elderly and their family. At the opposite of other industrial sectors manufacturing costs play a very minor role when fixing the price of assistance devices: indeed prices result more from the relations between the players and from regulations. We intend to model these relations in order to analyze the influence of regulations on the final cost.

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

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

Experimental work and the development of our own prototypes are strategic for the project as they allow us to validate our theoretical work and to discover new problems that will feed in the long term the theoretical analysis developed by the team members.

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

In summary HEPHAISTOS has as major research axes assistance robotics, modeling (see section 7.1.1), game theory, interval analysis and robotics (see section 6.1). 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 [0.5,1.6] 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 as 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. 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. Highlights of the Year

4.1. Highlights of the Year

4.1.1. Science

- strong advances on the analysis of cable-driven parallel robots (section 6.1.1)
- first results the daily activities monitoring in a day hospital (section 6.2)

4.1.2. Experimentation

- Two months experimentation of a very large cable-driven parallel robot for an artistic exhibition (section 6.1.2)
- Completion of the second version of our immersive environment for rehabilitation (section 5.3.2.1)

5. New Software and Platforms

5.1. 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

5.2. PALGate

KEYWORDS: Health - Home care - Handicap

- Contact: David Daney

5.3. Platforms

5.3.1. 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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ALIAS is a core element for solving the usually complex equations we have to manage our robotics problems. We may mention as example our work on cable-driven parallel robot (see section 6.1.1) involves non-algebraic models whose exact solving is required while the unknowns of our system are physical entities that may usually be bounded (meaning that we are not interested in all solutions of the system but only in the one that make physical sense) and therefore interval analysis is appropriate (and quite often the only one that may manage to get exactly all solutions). This year we have also used ALIAS to provide certified solutions of the kinematics of a flexible parallel robots [17]. We have confirmed the solutions that has been provided by a computer intensive iterative methods and have shown that the interval analysis method was able to manage a more complex case for which the iterative method cannot be reasonably used. In a third example we combine interval analysis and Monte-Carlo method for developing a reliable motion planning for parallel manipulators [15] while interval analysis has been used for the design of parallel robot [14].

5.3.2. Hardware platforms

We describe here only the new platforms that have been developed or improved in 2019 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,r our experimental flat and the activities detection platform implemented in the day hospital Institut Claude Pompidou and EHPAD Valrose, Nice). Among the MARIONET family we have reactivated and adapted the MARIONET-CRANE prototype for the experiment described in section 6.1.2. We have also updated our parallel $6-\underline{P}US$ prototype for the medical application mentioned in section 6.3.

5.3.2.1. 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. The main idea is to have a modular rehabilitation station allowing to manage various exercise devices with a very low set-up time (typically 10 mn), that will be actuated in order to allow ergotherapists to favor the work of various muscles groups and the difficulty of the exercise, while monitoring the rehabilitation process with various external sensors, providing an objectification of the evaluation. Version 2 has been completed this year and we will proceed in 2020 to the first trials. These trials will consist in establishing walking patterns for non-pathological people in various conditions that will be created by a walk in a mountainous environment.

6. New Results

6.1. Robotics

6.1.1. Analysis of Cable-driven parallel robots

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

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 [24]. 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 [13] 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.

The direct kinematics relies on an accurate estimation of the cable lengths that is usually based on the measurement of the winch drum rotation. We have evaluated the influence of uncertainties in the cable length measurement on the result of the FK [19] and have shown that for a poor robot geometry (which was for example the case for the prototype described in section 6.1.2 for which the geometry was imposed) this influence may be quite large . An usual strategy to decrease this uncertainty for small to medium-sized CDPR is to use a drum with a cable spiral guide for the coiling which impose a coiling path for the cable. However this strategy is unfeasible for large and very large CDPR (that we called *Ultrabot*) for which the large length of the cables impose to have several layers on the drum and therefore leads to a more erratic coiling process that leads to possibly large errors of the cable lengths estimation. To get a better estimation of the cable lengths we have proposed an original method, based on the Vernier principle [21]. The idea is to have several small colored marks on the cable at known distances from the end-point of the cable and to have several color sensors in the mast of the CDPR. We have first shown that if 3 colors (e.g. RGB) were used, then an appropriate disposition of the marks on the cable allows to have up to 29 marks on the cable so that the sequence of 3 successive colors is always unique. Hence by coiling the cable and detecting the 3 successive color detected by a sensor allows to determine exactly the distance between the sensor and the cable end-point, i.e. to *calibrate* the cable length. Calibration is always an issue for CDPR which uses usually incremental encoders for measuring the drum rotation (which explain why we have also proposed another approach [18]. Then we have considered the sequence of color detection when coiling the cable, starting from its largest length. We have looked at the distribution of cable length changes $\Delta\rho$ between two successive detection and have proposed a strategy that provide the distance between the marks so that this distribution is quasi-uniform with a mean value that is minimal. For example we have shown that for a 60 meters length cable having 29 marks we were able to have an almost constant $\Delta\rho$ of 40 cm, meaning that when the cable length changes by this value, then we get an exact evaluation of the cable length at each detection. In between such detection we rely on the drum rotation measurement to estimate the cable length. Furthermore we have shown that the difference between the expected detection time and the real one allows one to update the estimate of the drum radius, thus enabling to manage an erratic coiling process. We have initially installed this system on the prototype presented in section 6.1.2. The few initial tests were really promising but on-site we have had problems for ensuring a constant positioning of the marks on the synthetic cables. Being given the very short deployment time we have not been able to fix this problem. Consequently we have decided to use another approach based on direct measurement of the load pose with lidars, this approach being described in section 6.1.2.

We have also continued to investigate the calculation of planar cross-sections of the workspace for CDPR with sagging cables. We have shown in a previous paper that the border of this workspace was either determined by cable length limits but also by the singularity of the kinematics equations. Hence these singularities play an important role for the design of a CDPR. We have started a preliminary investigation on this topic [20]. We have shown that these singularities may be classified in two categories:

- *classical singularity* which corresponds to the singularity of parallel robots with rigid legs which basically implies that the mechanical equilibrium of the system cannot be obtained, leading to a motion of the platform even if the actuators are locked
- *full singularity* which are singularity of the kinematics equations but are not classical singularity. In this case mechanical equilibrium is obtained but the CDPR is unable to move in a given direction

We have also developed an algorithm that check if a full singularity exists in the neighborhood of a given pose and to locate it with an arbitrary accuracy.

6.1.2. 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 in 2018 by the artist Anne-Valérie Gasc that is interested in mimicking the 3D additive manufacturing process on large scale for a live art performance. She was interested in a mean for widespreading glass micro-beads on a given trajectory over a 21 $\times$ 9m large platform located at the contemporary art center *Les Tanneries* (figure 1), located close to Montargis. She was especially interested in using a CDPR for that purpose because of the low visual intrusivity of the cables and its ability to move large load. After a few month of discussions we agree to recycle our old MARIONET-CRANE prototype (2009) for this exhibition although the place was not the most appropriate for the CDPR as the height of the location was only 3 meters. We design as load a 80 liters drum of weight 55 kg with 40 kg of powder that was sufficient for printing one trajectory (figure 1). An on-board computer connected through wifi to a master computer was managing the lidar measurement and the opening/closing of the servo-valve controlling the powder flow. The drum was supported by 4 Dyneema cables of diameter 3mm whose output points were located at the corners of the platform and whose lengths were varying between 3 and 26 meters. The master computer was controlling the CDPR and the parameters of the system were recorded every second in log files. The development was very fast and we were not able to test a full scale installation in our laboratory for lack of the appropriate space. The on-site deployment was difficult because it has to be done in a record time, far away from our home base. The lack of height has especially a strong influence on the positioning errors of the drum that drastically increase if the cables are close to the horizontal. We solve on-site this problem by adding 3 low-cost lidars that were providing partial measurement on the drum pose. The system was fully operational a few days after the official opening of the exhibition and was at the heart of the artistic exhibition "Les Larmes du Prince - Vitrifications" (http://www.lestanneries.fr/exposition/larmes-prince-vitrifications), that was run during July and August under the control of a local student. The exhibition was scheduled to run 5 days per week until the end of August. During this period the CDPR has worked 174 hours (4h15mn/day), has traveled 4757 meters and has dispersed about 1.5 tons of powder. We get two failures: one of the cables has broken but without any consequence because of the redundancy of the robot and a failure of the reduction gear of one of the winch on the exhibition closing day, which has been immediately repaired. From a scientific viewpoint we have been able to test, in this quasi-industrial context, the efficiency of a control law using external measurements of the pose and the logs, still being processed has allowed us to identify possible improvements and scientific issues regarding the modeling of the system. An unexpected benefit of using the lidars was to allow to record a profile of the powder wall at each trajectory, showing its life over time as it was always evolving because of the powder particle motion after a printing.

Figure 1. The exhibition place and the drum. Photos copyrighted Anne-Valérie Gasc, "Vitrifications", Photograph: Aurélien Mole

6.1.3. *Killing robots*

Participant: Jean-Pierre Merlet [correspondant].

The director, Linda Blanchet, of a theater company has contacted us for helping organizing a theater event, *Killing Robots*, centered on the story of *Hitchbot*, a passive 70cm high mannequin designed by Canadian colleagues, that was put on the side-way of roads in Canada so that people may transport it, the purpose being to study the human interaction with people during a travel from the east to the west cost of Canada. The mannequin was located through a GPS and has taken a picture of its surrounding every 20 minutes while it was active. This mannequin indeed performs this travel in 15 days and a similar experiment was then scheduled in the US, the purpose being to go from Boston to San Francisco. Unfortunately after 5 days of travel the mannequin was discovered completely dismantled in Philadelphia. The idea of Linda Blanchet's performance was to propose a thriller based on the robot data for discovering who has dismantled the robot and in parallel to have the robot interacts with the actors to describe its feeling. For that purpose it was necessary that the robot becomes actuated while keeping its appearance identical to the original model. We have therefore retrieved a clone of the original Hitchbot and we have actuated the arms and head, so that the robot was able to move them, adding a lidar on top of the head so that it was able to locate the actors on stage (figure 2).

Figure 2. The transformed Hitchbot robot

The Canadian colleague have also provided a conversational agent so that the robot was able to speak with a learning process. The opening of the performance was done on November 6 at the National theater of Nice and it is now performing in various places in France. We have been present at several of them to interact with the public at the end of the performance. From a scientific viewpoint our interest in this exhibition was to better understand why adding motion to a mannequin modify drastically the perception of the robot by the public. These understanding will help to work on the factors that increase the acceptance of a technological object by the public, which is clearly a major factor for the efficiency of our assistance devices.

6.2. Smart Environment for Human Behaviour Recognition

Participants: Jean-Pierre Merlet, 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 t 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.

6.2.1. Tools and data analysis for experimental systems

Two experimental systems are installed in two areas (a consultation center (Institut Claude Pompidou, ICP, Nice), and a retirement home (EHPAD Valrose, Nice)) were several types of persons (residents, visitors, staff) evolve. They are made up of virtual barriers (constituted of distance and motion sensors) displayed in the environment and connected to a PC that collects and stores the measurements of the barriers. Each crossing of a barriers hence corresponds to a specific signal of a set of sensors. We develop a set of codes that aim to analyze the data collected to construct information on the moves of the persons in the experiment areas [23].

This year we have improved the code that yields the barrier events (time and direction of crossing of barriers) from the raw data. This allowed us to use this first step to reconstruct the individual trajectories of the users.

Although the filtering technics do not use external information (such as specific use of a zone bounded by barriers, habit of users according to time....) we can determine most of the individual trajectories of the users, even when several users evolve simultaneously in the area. Although some uncertainties remain (and could probably be improved using external knowledge), we can use the results obtained to perform a statistical analysis.

The aim on the main scientific efforts this year was to develop a detailed statistical treatment chain to extract and to visualize the events information coming from the set of movement activity detectors installed at ICP. All the (statistical and graphical) development were performed in the R software environment. Globally, two sets of information were collected, for the recorded data. The first provides a kinematic view of the presence of individuals on the mass plan of ICP during a chosen time interval. The following graph gives a static example of the kinematic graph obtained. Such a dynamic information points, for example, to specific movement activities in the medical center, at given time intervals. Figure 3 shows the presence of individuals in the corridors and consultation rooms at ICP at different times.

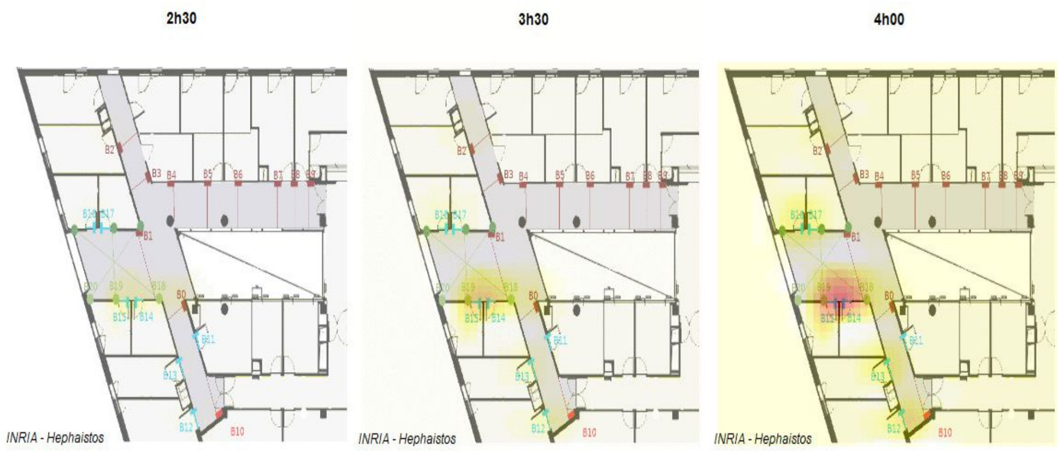

Figure 3. Three photograms on a kinematic view of the presence of individuals on the mass plan of ICP

Such a graph is only descriptive. Hence, it does not provide a functional analysis of the displacements of individuals in the medical center. In order to understand this better, the chronological movement patterns were functionally described by building, for every time interval, the transition matrix between all zones present in the analyzed medical center. After proper algebraic manipulation, the obtained transition matrices were analyzed using a factorial correspondence analysis, a multivariate method that - in this case and among other features – built graphs describing the functional movement patterns between zones. The graph presented in figure 4 gives an example of the obtained results.

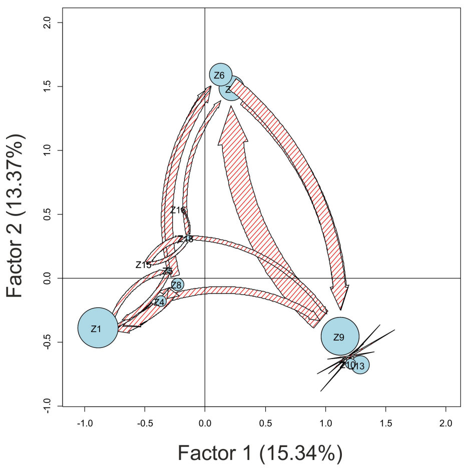

Figure 4. Example of the best factorial plan (explaining almost 30% of all the information contained in the data) obtained from a factorial correspondence analysis used to describe the functional movement patterns of individual between zones in the followed medical center during a full day of activity. Each blue circle represents a zone, with a radius proportional of its frequentation frequency. Arrows between zones (in red) are proportional to the observed flux of individual movements between zones. Only the most important arrows are presented.

The next step will be to statistically compare such results, e.g., between morning or afternoon activity, between days with or without medical consultation, etc. Results obtained might lead to a better organization of the medical activities at ICP.

6.3. Other medical activities

Participants: Jean-Pierre Merlet [correspondant], Sylvain Guénon.

Eric Sejor, a surgeon at Nice hospital, has contacted us about developing a robotized system for realizing sutures in an autonomous way. Suturing is a lengthy process while in many cases this is not a complex operation. Eric Sejor mentions that developing an autonomous system allowing to manage standard wounds may be extremely interesting, especially for emergency service that are under-staffed. Instead of developing a new robot dedicated to this purpose we have proposed to Eric Sejor to build a system based on the existing manual tools that require to put the instrument in place and then simply squeezing a trigger. The placement will be realized by one of our small parallel robot, with the help of vision system to locate the edge of the wound, while the trigger squeezing will be performed by an actuator. We have obtained an Idex funding (one year for an engineer) to develop a proof-of-concept prototype that will perform the operation on silicone mockups that are used for the surgeon training.

We have had also a contact with the ergotherapist Nicolas Ciai from Nice hospital for the evaluation of patient motricity before an operation. For this evaluation the ergotherapist performs muscular testing before the operation, right after the operation and 6 months later. The exercise consists in opposing the ergotherapist palm against the musculo group that has to be tested until a force equilibrium is reached. Then the ergotherapist ranks the tonicity of the muscles on a discrete scale between 0 and 6 according to his muscular feeling. As numerous muscles have to be tested, the process is quite lengthy. Clearly this process is quite subjective and we have proposed an objectification of the process by developing a glove prototype that includes pression sensors for measuring accurately the pressure exerted by the patient. These sensors are used by a micro-computer the size of a large watch located on the wrist of the ergotherapist. This computer determines when the pressure becomes stable, in which case this pressure is displayed and recorded. A companion software will then exploit the recorded data to provide an evaluation report. Beside the objectification of the ranking, the purpose is also to speed-up the tests. Although this project is quite advanced, we are lacking of manpower to complete it so that we have presented a project to Nice hospital for funding an engineer that may complete the second version of the glove.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Grants with Industry

7.1.1. 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.

8. Partnerships and Cooperations

8.1. 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

8.1.1. FHU

- the team has been involved for the FHU *INOVPAIN : Innovative Solutions in Refractory Chronic Pain* that has been labeled in December 2016

8.2. International Initiatives

8.2.1. Inria International Partners

8.2.1.1. 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, Italy: 2 joint PhD student, publications

- University Innsbruck, Austria: joint conference organization
- Fraunhofer IPA, Stuttgar, Germany: joint conference organization
- Duisburg-Essen University, Germany: joint conference organization
- University of New-Brunswick, Canada: 1 joint PhD student
- University Laval, Québeç Canada: joint book
- University of Tokyo, Japan: joint conference organization
- Tianjin University, China: joint book

8.3. International Research Visitors

8.3.1. Visits of International Scientists

- W. Godoy, Pr. Univ Sao Paolo, from Dec 2019
- M. Tome, PhD student, Univ Sao Paolo, from Dec 2019
- I.D. Weber, Master student, Univ Sao Paolo, from Dec 2019
- M. Tuda, PhD student, Univ Sao Paolo, from Jun 2019 until July 2019
- H. Lins Vieira, PhD student, Univ Sao Paolo, from January until Aug 2019

8.4. Transfert

- J-P. Merlet is scientific advisor of the startup *Farmboy Labs* that is currently being created by our former PhD student L. Blanchet. The purpose of this startup is to propose cable-driven parallel robots for agriculture (monitoring, maintenance, weeding, ...). .

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events: Organisation

- 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. He is also an advisor for ICRA 2020,
- Y. Papegay is a permanent member of the International Steering Committee of the International Mathematica Symposium conferences series. He is a member of the OpenMath Society, building an extensible standard for representing the semantics of mathematical objects.

9.1.1.1. Reviewer - Reviewing Activities

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

9.1.2. Journal

9.1.2.1. Member of the Editorial Boards

- E. Wajnberg is Editor-in-Chief of the journal BioControl (published by Springer).
- E. Wajnberg is a board member of the journals Entomologia Experimentalis et Applicata (published by Wiley), Neotropical Entomology (published by Springer), Applied Entomology and Zoology (published by Springer), and Journal of Economical Entomology (Publish by Oxford University Press).

9.1.3. Invited Talks

- E. Wajnberg has been invited for talks by the University of Beer Shava at Sde Boqer (Israel, March), the University of La Plata (Argentina, April), the University of Buenos Aires (Argentina, April), the University of São Paulo at Piracicaba (Brazil, October)

9.1.4. 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 and a chair of 3IA Côte d'Azur.

9.1.5. 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)

9.1.6. Research Administration

- J-P. Merlet was an elected member of the Academic Council of UCA COMUE (until July 2019), is 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 CUMI (the committee managing the interaction between researchers and the computer support staff)
- O. Pourtallier is responsible of the NICE committee (long term invited scientists and post-doctoral student selection).
- O. Pourtallier is a board member of the Scientific and Pedagogical Council of DS4H graduate school of UCA.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

J-P. Merlet has taught 6 hours on parallel robots to Master ISC (M2) at University of Toulon. He has also been invited at ESIEE Paris for a talk about assistance robotics

J-P. Merlet, P. Martinet (CHORALE) and G. Allibert (I3S) have organized the first GDR robotics winter school, *Foundation of robotics*. During 5 days 35 students, mostly 1st year PhD students, have followed courses taught by international experts. Slides and additional materials have been regrouped in a HAL collection, *Robotics principia*, that has been organized in such a way that the next occurrences of this school will also be able to deposit additional documents. The idea of this collection is to be able to address all topics in robotics with various viewpoints.

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

Y. Papegay has taught 3 hours on parallel robots to Master ISC (M2) at University of Toulon

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

E. Wajnberg lectured One week course (about 30 h) about the use of the R program and statistics for PhD students and senior scientists in Rehovot (Israel, February)

9.2.2. Supervision

J. Moussaid. Analyse de robots parallèles à câbles (2019-), Supervisor: J-P. Merlet

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

E. Thomine. Agencement cultural pour promouvoir le transfert des services écosystémiques de biocontrôle au sein des paysages agricoles (2016 à 2019). Supervisors : N. Desneux & E. Wajnberg.

9.2.3. Juries

- J-P. Merlet was a jury member for the Best PhD Awards of the robotics GDR and has been president of 2 PhD juries.

9.3. Popularization

- J-P. Merlet gives 3 talks in the Alpes-Maritimes in the framework of the *Science pour Tous* association. He has also participated in a seminar on *robotics and media* involving 6 robotics experts and 6 journalists for a reflexion on the bias of the presentation of robotics to a general audience. He was also a member of the scientific committee for the permanent exhibition *Robot* at the Cité des Sciences, Paris
- Y. Papegay is actively participating to the Math.en.Jeans initiative for Mathematics teaching for undergraduate students.
- Y. Papegay is developing several pedagogical resources based on small robotics devices at high-school level.
- Y. Papegay 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.
- E. Wajnberg gives 5 talks in the Alpes-Maritimes in the framework of the *Science pour Tous* association

9.3.1. Interventions

- the HEPHAISTOS project has on average about 100 visitors per year, either young students or teachers, to which we present our robotics and assistance activities

9.3.2. Internal action

- the HEPHAISTOS project has developed a set of cable-driven parallel robots, the MARIONET-SCHOOL series, that is used to illustrate visually scientific concepts in various domains

10. Bibliography

Major publications by the team in recent years

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

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

[3] J.-P. Merlet. *Parallel robots, 2nd Edition*, Springer, 2005

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

[5] N. NEVEJANS, O. POURTALLIER, S. ICART, J.-P. MERLET. *Les avancées en robotique d'assistance à la personne sous le prisme du droit et de l'éthique*, in "Revue générale de droit médicale", December 2017, https://hal.inria.fr/hal-01665077

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

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

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

Publications of the year

Articles in International Peer-Reviewed Journals

[9] M. C. FOTI, E. PERI, E. WAJNBERG, S. COLAZZA, M. ROSTÁS. *Contrasting olfactory responses of two egg parasitoids to buckwheat floral scent are reflected in field parasitism rates*, in "Journal of Pest Science", March 2019, vol. 92, n° 2, pp. 747-756 [*DOI :* 10.1007/S10340-018-1045-2], https://hal.archives-ouvertes.fr/hal-02076202

[10] T. KEASAR, E. WAJNBERG. *Evolutionary constraints on polyembryony in parasitic wasps: a simulation model*, in "Oikos", March 2019, vol. 128, n° 3, pp. 347-359 [*DOI :* 10.1111/OIK.05479], https://hal.archives-ouvertes.fr/hal-02061872

[11] S. LE HESRAN, E. RAS, E. WAJNBERG, L. BEUKEBOOM. *Next generation biological control – an introduction*, in "Entomologia Experimentalis et Applicata", July 2019, vol. 167, n° 7 [*DOI :* 10.1111/EEA.12805], https://hal.archives-ouvertes.fr/hal-02238902

[12] A. MELNYK, P. HENAFF. *Physical Analysis of Handshaking Between Humans: Mutual Synchronisation and Social Context*, in "International Journal of Social Robotics", 2019, forthcoming [*DOI :* 10.1007/S12369-019-00525-Y], https://hal.archives-ouvertes.fr/hal-01988627

[13] J.-P. MERLET. *Some properties of the Irvine cable model and their use for the kinematic analysis of cable-driven parallel robots*, in "Mechanism and Machine Theory", 2019, vol. 135, pp. 271 - 280 [*DOI :* 10.1016/J.MECHMACHTHEORY.2019.02.009], https://hal.inria.fr/hal-02426393

[14] J. K. PICKARD, J. A. CARRETERO, J.-P. MERLET. *Appropriate analysis of the four-bar linkage*, in "Mechanism and Machine Theory", September 2019, vol. 139, pp. 237-250 [*DOI :* 10.1016/J.MECHMACHTHEORY.2019.04.013], https://hal.archives-ouvertes.fr/hal-02127752

[15] H. L. VIEIRA, E. WAJNBERG, A. T. BECK, M. MARTINS DA SILVA. *Reliable motion planning for parallel manipulators*, in "Mechanism and Machine Theory", October 2019, vol. 140, pp. 553-566 [*DOI :* 10.1016/J.MECHMACHTHEORY.2019.06.022], https://hal.archives-ouvertes.fr/hal-02166684

[16] E. WAJNBERG, N. TEL-ZUR, I. SHAPIRA, Y. LEBBER, S. S. LEV-YADUN, U. ZURGIL, O. REISMAN-BERMAN, T. KEASAR. *Pollinator Behavior Drives Sexual Specializations in the Hermaphrodite Flowers of a Heterodichogamous Tree*, in "Frontiers in Plant Science", October 2019, vol. 10 [*DOI :* 10.3389/FPLS.2019.01315], https://hal.inria.fr/hal-02321408

International Conferences with Proceedings

[17] O. ALTUZARRA, J.-P. MERLET. *Certified Kinematics Solution of 2-DOF Planar Parallel Continuum Mechanisms*, in "IFToMM WC 2019 - 15th IFToMM World Congress", Cracow, Poland, June 2019, https://hal.inria.fr/hal-02426407

[18] E. IDÁ, J.-P. MERLET, M. CARRICATO. *Automatic Self-Calibration of Suspended Under-Actuated Cable-Driven Parallel Robot using Incremental Measurements*, in "CableCon 2019 - 4th International Conference on Cable-Driven Parallel Robots", Cracow, Poland, June 2019, https://hal.inria.fr/hal-02430605

[19] J.-P. MERLET. *Influence of uncertainties on the positioning of cable-driven parallel robots*, in "IROS 2019 - IEEE/RSJ International Conference on Intelligent Robots and Systems", Macau, China, November 2019, https://hal.inria.fr/hal-02426402

[20] J.-P. MERLET. *Singularity of cable-driven parallel robot with sagging cables: preliminary investigation*, in "ICRA 2019 - IEEE International Conference on Robotics and Automation", Montreal, Canada, May 2019, https://hal.inria.fr/hal-02426398

[21] J.-P. MERLET, J.-P. MERLET. *Improving cable length measurements for large CDPR using the Vernier principle*, in "CableCon 2019 - 4th International Conference on Cable-Driven Parallel Robots", Cracow, Poland, June 2019, https://hal.inria.fr/hal-02426400

Other Publications

[22] M.-H. AMRI, T. JIMÉNEZ, Y. PAPEGAY, O. POURTALLIER, V. ROY. *Minimal information sensor system for indoor tracking of several persons*, October 2019, working paper or preprint, https://hal.inria.fr/hal-02315252

[23] O. POURTALLIER, Y. PAPEGAY, A. MELNYK, A. COULBOIS, T. JIMÉNEZ, E. WAJNBERG, J.-P. MERLET. *Non-Intrusive Sensors for Activity Analysis of Elderly People*, October 2019, working paper or preprint, https://hal.inria.fr/hal-02315248

References in notes

[24] H. M. IRVINE. *Cable Structures*, MIT Press, 1981