RESEARCH CENTRE

Inria Centre
at Université Côte d'Azur

2023
ACTIVITY REPORT

Project-Team

HEPHAISTOS

HExapode, PHysiology, AssISTance and RobOtics

DOMAIN

Perception, Cognition and Interaction

THEME

Robotics and Smart environments

Inria

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Creation of the Project-Team: 2015 July 01

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1 Team members, visitors, external collaborators

Research Scientists

- Yves Papegay [Team leader, INRIA, Researcher, from Dec 2023, HDR]
- Jean-Pierre Merlet [INRIA, Emeritus, from Dec 2023, HDR]
- Yves Papegay [INRIA, Researcher, until Nov 2023, HDR]
- Odile Pourtallier [INRIA, Researcher]
- Eric Wajnberg [INRAE, Senior Researcher, HDR]

Post-Doctoral Fellow

- Adriano Gomes Garcia [Université de São Paulo, from Feb 2023 until Mar 2023]

PhD Students

- Clara Thomas [INRIA, from Oct 2023]
- Romain Tissot [INRIA]

Interns and Apprentices

- Julien Bondyfalat [Inria, Intern, from Jul 2023 until Sep 2023]
- Axel Refalo [Inria, Intern, until Feb 2023]

Administrative Assistant

- Jane Desplanques [INRIA, from Jun 2023]

Visiting Scientist

- Pierre Berthet-Rayne [CARANX MEDICAL]

External Collaborator

- Eric Sejor [CHU Nice]

2 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 [7] 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 focuses 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

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

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

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

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

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

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

In summary HEPHAISTOS has as major research axes assistance robotics, modeling, game theory, interval analysis, robotics and AI (see section 8.1). The coherence of these axes 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 this document and in a specific page on assistance.

3 Research program

As seen in the overall objectives managing uncertainties is a key point of our research. In the health domain uncertainties is managed with statistics (which explain partly presence of E. Wajnberg in our team) but statistics just give trends while in some cases we will be more interested in the worst case scenario. Interval analysis is an approach that can be used in that case and we constantly improve the foundations of this method.

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 $\{x_1, x_2, \ldots, x_n\}$ and ranges $\{X_1, X_2, \ldots, X_n\}$ for these unknowns we are able to compute a range $[A, B]$, called the interval evaluation, such that

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

In other words the interval evaluation provides a lower bound of the minimum of F and an upper bound of its maximum over the box.

For example if $F = x\ sin(x + x^2)$ and $x \in [0.5, 1.6]$, then $F([0.5, 1.6]) = [-1.362037441, 1.6]$, meaning that for any x in [0.5,1.6] 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 $x_1, x_2, \ldots, x_n$ such that $F(x_1, x_2, \ldots, x_n) = A(B)$ 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 [10, 1]:

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 verify 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 statistics, continuation, algebraic geometry, geometry while AI is currently being investigated (see section 8.1.1).

3.2 Robotics

HEPHAISTOS, as a follow-up of COPRIN, has a long-standing tradition of robotics studies, especially for closed-loop robots [6], 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 [8].

Our theoretical work must be validated through experiments that are essential for the sake of credibility and, a contrario, experiments will feed our 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 page presents all of our prototypes and experimental work. Note that this familiarity with hardware is also used from time to time to develop devices for others INRIA projects and during the Covid crisis our building was instrumented for accurately monitoring CO and CO2 level well before it becomes the norm.

4 Application domains

While the methods developed in the project can be used for a very broad set of application domains (for example we have an activity in CO2 emission allowances and biology), 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, doctors, 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.

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. Hence although we mainly focus on medical and assistance robotics we address also a large number of applications: agriculture, biology, arts, system design to name a few.

5 Social and environmental responsibility

5.1 Footprint of research activities

Clearly our activities have a negative impact on the environment (travels, hardware orders, ...). Although Sophia-Antipolis is not the best place regarding national travels we have decreased our national and international travel activities while having reduced our global impact at work in different manners (lighting, work mobility, ...). Still we must emphasize that all aspects of our impact have to be taken into account before coercive measures are taken. For example when we travel to a retirement house to install assistive devices, the footprint impact has to be balanced with our social impact and finding the right compromise is not an easy task and the choice is not the responsibility of the team alone. Furthermore human relationships are essential for initiating new research areas and for the time being virtual collaborations and conferences are not very effective for that purpose.

5.2 Impact of research results

Our works on assistance clearly may have a social impact and we are deeply aware of our ethical responsibilities as illustrated by the activity of the team in ethical committees, our collaboration with the academic law community and our large dissemination effort toward the general audience.

Regarding environmental responsibility energy has been since the very beginning of our project an important topic in our research. Indeed our assistance/health monitoring devices require additional energy source and elderly people may have some difficulties to deal with battery charging. Consequently since the beginning of the project we have focused on low consumption electronic components and most our devices use mechanical energy converter or solar panel to produce most of the energy they need. However the intended benefits of these devices on health, self-esteem and dignity (all issues that are difficult to measure/compare in pure financial terms or with respect to environmental impacts in all their dimensions) have to be taken into account.

6 Highlights of the year

Highlights of this year are mainly:

- changes in the team members and management,
- extensive research activities in the field of solving robotic kinematics problems with AI.

6.1 Team life

After spending one year at Inria Start-up Studio to explore the market opportunity and the economic feasibility to create a start-up dealing with human activities recognition using non-intrusive measurements, a former team member (Yves Papegay) joined the team back in June.

Starting December, Yves Papegay is succeeding as leader of the team, to Jean-Pierre Merlet, who got retired and will continue his activities as an emeritus Research Director.

6.2 Scientific highlights

Hybrid methods using symbolic computation, numerical analysis and AI (neural networks) have been developped to solve robotics models. Given the good results obtained on several examples, an important work has been done to extend their genericity to resolution of systems of parametric equations. (see section 6.1)

Other important points includes:

- a new PhD candidate (Clara Thomas) joined the team to work theoretically and experiment on cable-driven parallel robots with extended non-convex workspaces,
- a team member (Eric Wajnberg) moved to University of Sao-Polo for an 8-monthes invited stay
- we start new activities in the field of Human Activity Recognition, namely weak signals exploitation for early detection of pathologies,
- we start investigating design and conception problems of frugal robots for industrial recurrent but adaptative tasks.

7 New software, platforms, open data

7.1 New software

7.1.1 ALIAS

Name: Algorithms Library of Interval Analysis for Systems

Keyword: Interval analysis

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.

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

Contact: Jean-Pierre Merlet

Participants: Jean-Pierre Merlet, Odile Pourtallier

7.1.2 CAVATOI

Name: Smart digital contact-book

Keywords: Web Application, Home care, Data analysis, Machine learning, Anomaly detection, Data visualization

Functional Description: This piece of software is a web application designed for collection, analysis and visualisation of activities data of an elderly people based on the testimonies of helpers/visitors. It includes functionalities for detecting and analysing slight changes, and based on AI algorithms deciding wether or not alerting authorised family or helpers.

Release Contributions: Fully functional proof of concept

News of the Year: Initially developed at Inria Start-up Studio as the technological part of a transfer process, this software will be used and enhanced in our scientific activities.

Authors: Pierre Pigeon, Yves Papegay

Contact: Yves Papegay

7.2 New platforms

Participants: Jean-Pierre Merlet, Yves Papegay, Clara Thomas, Romain Tissot.

Cable-driven parallel robot A completely new version of our old modular MARIONET-CRANE cable-driven parallel robot prototype is now installed in the robotic hall, for experiments in the field of walking assistance and health monitoring for frail people.

This installation takes benefit and improves the two previous ones, installed for art performances in exhibition center in Amilly (45) and in Mouans-Sartoux (06) - see below 7.3.

Software environment for solving parametric equations with IA Our work in robotics has led us to investigate the use of IA for finding the real root(s) of parametric non linear square system of equations i.e. systems which have as many unknowns as equations but with equation coefficients that are functions of parameters that are assumed to be bounded. Such a system has usually several solutions and their number depends on the parameters values and cannot be determined in advance. An example of such a system is presented in section 8.1.1 together with the principle of the method. Just as an outline the method requires to have determined the solutions (not necessarily all of them) for a small set $\mathscr{S}$ of specific systems. We are then able to create from $\mathscr{S}$ different learning sets i.e. a set of samples that are described by a pair (P_i, S_i) where P_i is a valued parameters vector and S_i is a solution of the system for the given P_i. These learning sets are obtained by using a structure rule based on the concept of *linear aspect*: two samples (P_1, S_1), (P_2, S_2) belong to the same aspect if when following a linear path between P_1 and P_2 we don't cross a singular system and the solution path leads from S_1 to S_2. These learning sets are used to create neural networks using a specific training process based not only on the decrease of a loss function but also on an index that quantifies how many exact solutions can be obtained over all samples of the training set. Creating these networks is relatively computer intensive but then getting the *exact* solutions from the networks predictions for a specific system is very fast. Consequently using this approach is appropriate when a sufficient number of system instances have to be solved, this number depending upon the computation time of alternate methods. Furthermore the process have numerous steps that can benefit from a distributed implementation both for creating the networks but also when solving a given system and we are currently investigating the use of low power consumption AI processors to speed up the calculation.

We cannot guarantee to obtain all solutions (although our extensive tests have shown that in general we will miss very few solutions) but we have developed a self-learning process that may allow to reduce the number of missed solution(s) as soon as new system instances are solved . The method is generic and we are currently developing a software framework that takes as input $\mathscr{S}$ and produces an AI-based solver with minimal manual intervention.

7.3 Open data

In 2019 during 2 months and in 2022 for 4 months, we have installed two large-scale cable-driven parallel robots as robotics parts of art performances created by A-V. Gasc. These robots were acting like an huge 3D-printer, achieving during the whole exhibitions their assigned task: to continuously deposit several layers of glass micro-beads on a given trajectory at a given velocity. An huge amount of data on the operation of the robots has been collected during these period (about 2 To of data only for the 2022 exhibition) We are currently structuring and curating these data, to make (parts of) them widely available to the robotics community.

8 New results

8.1 Robotics

Participants: Jean-Pierre Merlet *(correspondant)*, Yves Papegay, Clara Thomas, Romain Tissot.

8.1.1 Kinematics and AI

As mentioned last year we have started to work on the direct kinematics (DK) of cable-driven parallel robot (CDPR) having sagging cables (i.e. being elastic and having their own mass). The direct kinematics consists in determining the pose(s) of the platform for given cable length L_0. Sagging cable may be modeled by the Irvine textbook planar model where the upper attachment point A of the cable is supposed to be grounded and be the origin of a planar frame with horizontal and vertical axis. The model provides the coordinates of the lowest attachment point B of the cable as functions of the cable length L_0 at rest and of the horizontal and vertical components F_x, F_z of the force applied at B:

$$x_b = F_x\left(\frac{L_0}{EA_0} + \frac{sinh^{-1}(\frac{F_z}{F_x}) - sinh^{-1}(\frac{F_z-\mu g L_0}{F_x})}{\mu g}\right) \quad z_b = \frac{F_z L_0}{EA_0} - \frac{\mu g L_0^2}{2EA_0} + \frac{\sqrt{F_x^2+F_z^2} - \sqrt{F_x^2+(F_z-\mu g L_0)^2}}{\mu g}$$

where E is the Young modulus of the cable material (which characterizes its elasticity), μ its linear density and A_0 the area of a cross-section of the cable that are all supposed to be known. Note that if x_b, z_b and L_0 are known the 2 unknowns F_x, F_z of these equations may be found using neural networks [18].

We have proposed last year a preliminary version of a DK solver using AI and we have finalized this year a very efficient DK solver [17].

The pose of a CDPR is defined by a vector $\mathbf{X}$ which has 6 components: three coordinates of the center of mass of the platform and 3 angles which describes the platform orientation. For a CDPR with n cables we have $2n+6$ unknowns (the $2n$ F_x, F_z and the components of $\mathbf{X}$). As the x_b, z_b of each cable can be expressed as functions of $\mathbf{X}$ we have $2n$ Irvine equations. In a static case we must ensure the mechanical equilibrium of the platform, which provide 6 equations in $\mathbf{X}$ and in the F_x, F_z. Hence solving the DK consists in solving a square system $\mathscr{F}$ of $2n+6$ equations, that has usually several solutions whose number cannot be determined in advance. For solving the DK we assume that we have been able to determine solutions of $\mathscr{F}$ (not necessarily all of them) for a few set of nL_0. Hence we have a set of $(L_0^j, S_1^j, S_2^j, \ldots S_m^j)$ where S_k^j are solutions of $\mathscr{F}$ for the set of lengths L_0^j. These data can be represented graphically: an horizontal line, called *level*, represents a set of lengths L_0^j and points, called *nodes*, on this line represents the S_k^j. A node is there represented by a pair (L_0^j, S_k^j). Consider two nodes at different levels (L_0^j, S_k^j), (L_0^u, S_l^u). We define a linear path in the L_0 space as $L_0 = L_0^j + \lambda(L_0^u - L_0^j)$ and we use a continuation scheme with S_k^j as starting point and λ as continuation parameter for determining a solution of $\mathscr{F}$ for $L_0 = L_0^u$. Starting from $\lambda = 0, S = S_k^j$ we incrementally increase λ and use Newton with S as guess to determine a solution S of $\mathscr{F}$. This scheme stops if either $\lambda = 1$ or if Newton encounters a singularity. Note that if $\lambda = 1$, then S may be a solution that was unknown for L_0^u.

If two nodes (L_0^j, S_k^j), (L_0^u, S_l^u) are connected with this scheme we establish an *edge* between them, allowing to establish a directed graph called the *solution graph*. In this graph we may identify the *non* *redundant circuits* i.e. a list of successively connected nodes that contains at most one node at a given level. In robotics terms these circuits define a path in the L_0 space and an associated singularity-free path for the platform that allow to connect the pose of the first node of the circuit to the pose of the last one and all poses of the nodes of the circuit belong to the same variety called an *aspect*. Poses belonging to the same aspect have the property that any two poses in the same aspect can be joined by following a singularity-free path in the L_0 space. The non redundant circuits will be used to obtain learning sets for the neural networks that we will create: when creating the edges with the continuation scheme we may store sets of samples (L_0, S) using storage rules such that

- the maximal change between the current L_0 and the previously stored sample is larger than a given threshold
- the distance between the current location of G and the previously stored one is larger than a given threshold

If not enough samples have been obtained for a given circuit we may add samples just by selecting a stored sample (L_0^u, S^u), choosing an arbitrary unit vector $\mathbf{v}$ in the L_0 space and applying a continuation scheme $L_0 = L_0^u + \lambda\mathbf{v}$ starting at $\lambda = 0$, solution S^u while storing samples along this path by using the same storage rules.

Regarding the neural networks we use multi-layer perceptron (MLP) with a specific training procedure. It is partly based on a decrease of the MSE loss but when a new MLP is obtained we run a verification procedure to obtain the *success rate* of the MLP. For calculating this rate the verification procedure runs the MLP on each sample of the training set and use the solution prediction of the MLP as guess for a Newton scheme. The success rate is then calculated as the percentage of samples such that the verification procedure leads to the expected solution of $\mathscr{F}$ (e.g if the success rate is 100, then the verification procedure obtains the expected solution for all samples in the training set). Clearly if during the training we find a MLP that has a 100% success rate, then it is not necessary to continue the training and furthermore given the size of our problem the training time is low (a few minutes). Consequently as we have no a-priori knowledge on the number of layers, number of neurons in the layers and activation function that may lead to a MLP that has a 100% success rate we may perform a systematic approach by testing all combinations of MLP that have from 2 to 10 layers, between 10 to 200 neurons with a step size of 20 and activation function among a set of 3 classical one (ReLU, LeakyReLU, CELU). We also use an adaptive learning rate usually starting at 10^{-3} and decreasing by 2 the learning rate if after 15 optimizer step the loss has not decreased and stopping the learning if the learning rate is lower than 10^{-6}. For a given training set we stop the systematic MLP exploration as soon as a MLP with 100% success rate is obtained. If a 100% success rate is not reached we retain the MLP having the highest success rate and we consider in sequence the sample(s) whose solution has not been found and use them as starting point for creating a new learning set using random unit vectors in the L_0 space and a continuation process to obtain new samples. This set is used to train a new MLP that will allow to find the missed solution and possibly other missed solution(s). New MLPs are then added until all solutions of the training set are found. After having processed all the training sets we obtain a set of MLPs such that the the MLP prediction used as a guess for Newton (a procedure called *local solver*) will provide the solution for all the samples of the training sets.

For example for a CDPR having 8 cables (and consequently the DK has 22 equations) we have used 11 initial sets of L_0 with between 8 and 24 DK solutions to establish 1133 MLPs that cover all solutions of the training sets. However some of these MLPs are redundant (they provide solutions that will also be discovered by other MLPs) and it is interesting to reduce the number of necessary MLPs while still getting all solutions. For that purpose let $\mathscr{U}$ be the set of all samples over all training sets. We run in sequence all MLPs on $\mathscr{U}$ and determine the MLP that provides the largest number of solutions $\mathscr{V}_1$ over $\mathscr{U}$ and store it in a list. We repeat this procedure for the remaining MLPs over the set of samples in $\mathscr{U} - \mathscr{V}_1$ until this list of samples is empty. In our example the final number of MLPs is 138 and we are able to establish a DK solver by using the local solver for each MLP.

We may then assess the quality of this DK solver on verification sets that provide all DK solutions for a given set of L_0. These sets are established as the training sets by selecting random unit vectors in the L_0 space but at the opposite of the training set the continuation scheme follows all solutions from the starting point, which implies that the number of DK solutions for each sample is the same than the number of solution of the starting point. We also ensure that the L_0 of the samples in the verification set are all different from the one used in the training sets. The result are very good with about 99.9% of the samples for which all solutions are found. But two cases may occur:

- the DK solver find solution(s) for some samples that were not present in the verification set: we just update the verification set. Note that this update may also be used to update the solution graph by discovering new nodes and possibly new non redundant circuits which will provide new MLPs
- the DK solver miss solution(s) for some samples: we just use the missed solution to create new learning sets and their corresponding MLPs

After this update all solutions are found for all samples of the verification set. We may then repeat the procedure with a new verification set. However we cannot guarantee that the current DK solver will find all solutions in all case. For example we have found examples where we have assessed 10 verification sets with 100% success rate but for the 11-th one solution has been missed, imposing the creation of a new MLP.

The computation time for this DK solver may be decomposed into the time for establishing the necessary MLPs and the exploitation time for solving one instance of the DK. In a sequential process about 100 hours are necessary to establish the solver while solving one instance of the DK takes about 1 second (to be compared to the 20+ hours that are required when using interval analysis or continuation). However these times may be improved as there are numerous steps for establishing the MLPs that may benefit from a parallel implementation while the local solvers of DK solver may be run in parallel. This year we have investigated the use of the IA processor JETSON Nano but the result was somewhat disappointing because of the limited floating point power of the GPU. Anyhow this AI solver is intended to be used when numerous DK instances have to be solved and here as soon as at least 5 DK instances have to be solved the AI solver is faster than the alternate methods.

Finally as mentioned in section 7.2 the principle of the DK solver is generic and may be used for any parametric square equations system.

8.1.2 Preventive maintenance and AI

The kinematics equations governing the behavior of CDPR with sagging cables have been presented presented in section 8.1.1. They are used for control purpose as they establish the relationship between the actuated variables (the cable lengths L_0) and the pose of the CDPR platform under the assumptions that the L_0 can be measured accurately. Special winches with cable guide have been designed for that purpose but have the drawback of restricting the CDPR workspace and of not being completely reliable as the guide is working only under the assumption that there is a sufficient tension in the cable, a condition that cannot always be enforced. At the opposite simple multi-layered winch offers a compact solution while providing a very large workspace but with the drawback that the cable length deduced from the drum rotation is more approximate. We have proposed to have *redundant sensing* i.e. to complement the cable length measurements with additional sensors:

- having planar lidars that allow to estimate the location of the platform in the 3D space
- having angular sensors on the cables, located at a known distance from the attachment point of the cables on the platform, that measure the slope of the cable at the sensor location. It can be shown that the cable slope at this point is a function of F_x, F_z, L_0, μ, A_0 and E.

These two sensing methods have been implemented on one of our prototype and have shown to be very effective. Here we investigate if this sensing redundancy may also allow to assess the wear of the cables which will decrease the E of the cables with the objective of improving the accuracy of the CDPR by using more accurate E and of preventive maintenance e.g. changing cables before their breakdown.

When controlling the cable lengths to reach a given pose $\mathbf{X_i}$ we assume that the E of all cables are identical and equal to E_i. If this assumption is wrong the CDPR will reach a pose $\mathbf{X_r} \neq \mathbf{X_i}$ and the lidars will allow to calculate the distance Q_d between $\mathbf{X_r}, \mathbf{X_i}$ while the angular sensors will measure a change Q_a compared to the inclination of the cable at $\mathbf{X_i}$. These measurements have an error margin and therefore can be exploited if the changes are larger than given thresholds $\Delta Q_d, \Delta Q_a$.

First we have to perform a *sensitivity* analysis i.e to determine how much change in the E is required to obtain $Q_d \geq \Delta Q_d$ and/or $Q_a \geq \Delta Q_a$. Indeed if measurable changes in the Q are obtained only when the E becomes very low our objectives cannot be reached. Clearly the changes in Q_a, Q_d are dependent upon the pose and upon the way the E of the cables are changing. We have therefore selected a set of representative cable lengths L_0 and solved the DK for these lengths which provides the different possible poses of the platform. We have then defined a variation law for the E which uses a unit vector $\mathbf{v}$ in the E space (with only negative of null components) such that the vector of the E is equal to $\mathbf{E} = \mathbf{E_i} + \lambda\mathbf{v}$. Consequently Q_d and the Q_a of the cables are functions of λ and a continuation scheme may be used to follow the curves $Q_d(\lambda), Q_a(\lambda)$ for determining the first λ_d such that $Q_d(\lambda_d) \geq \Delta Q_d$ and λ_a such $Q_a(\lambda_a) \geq \Delta Q_a$. Clearly the λ_a, λ_d are functions of the vector $\mathbf{v}$: we have decided to test the wear of a single cable (one component of $\mathbf{v}$ equal to -1, the others to 0) and random $\mathbf{v}$. We have also discarded cases where the λ_d, λ_a correspond to less than 30% of the E_i. The analysis is not yet complete but we have found cases where we have measurable changes in Q for moderate changes in the E so that it appears that changes in the E are observable.

After considering the sensitivity we will have to solve the inverse problem, i.e. determining the current value of all the E of the cables. We will have to determine how many Q are required to safely determine these values. Fortunately change in the E is a slow process so that this estimation may be based on records of the Q obtained during trajectories. Still the inverse problem implies solving a set of non-linear equations and our approach will be based on AI. Indeed we may obtain training set in simulation and we believe that, as for the DK, we will have to structure the data and to train several networks for obtaining reliable estimations.

8.1.3 Green robotics

A large number of industrial robots are used mostly only for simple pick-and-place operation, taking an object at a given position and moving it to another one. In most cases this task is performed by serial robot which are not energy efficient (beside the load the robot actuation has to move part of the robot own weight) while using a computer and various electronic boards that are largely under exploited which constitutes a waste of energy and resources. We intend to investigate the use for this task of cable-driven parallel robot, which are 25% more energy efficient, and to design an electro-mechanical mechanism for executing pick-and place trajectories while getting rid of the computer and of most electronic resources.

8.2 Medical activities

By lack of manpower, we have reduced our medical activities to human activity recognition. Work on the modular rehabilitation station (described in previous activity reports) has been stopped during one year and will continue in the coming future.

8.2.1 Human activity recognition

Participants: Jean-Pierre Merlet, Yves Papegay, Odile Pourtallier, Eric Wajnberg.

Human activity recognition (HAR) is a major topic in the team. We are focusing on monitoring mobility and displacements (we are not yet interested in recognizing the individual action of our subject) using a sensor-based approach, excluding vision which is intrusive and even prohibited in some places for legal reasons. For that purpose we have in the previous years developed a *smart barrier* combining redundant passive infrared motion detectors and infrared distance sensors. Smart barriers have been implemented in Ehpad Valrose, a new retirement house in which a specific infrastructure has been put in place to accommodate research works and in Institut Claude Pompidou, an Alzheimer day care hospital from 2019 to 2020. These two long term experiments have allowed us to determine that essential points in HAR are to determine what is possible to measure, the sensor types, how to retrieve and process sensor data, how effective are the quality of measurements on a long term basis and the level of monitoring that is acceptable for frail peoples and their helpers while providing significant and reliable data for the medical community in spite of the uncertainties both in the measurements and in the system modeling. These samples of questions will become central in our work.

We are interested in and currently investigating the use of another type of barriers, based on Lidar's. Measurements produced by lidars are richers and allow a better reliability on the number and the directions of simultaneous crossings.

8.3 Biology activities

Participants: Eric Wajnberg, Yves Papegay.

8.3.1 Optimized flower visiting strategy of bees

Three years ago, through an international scientific cooperation with Israeli scientists located at the Ben-Gurion University of the Negev, and as explained in an activity report provided previously (2020), we developed a probabilistic model whose aim was to understand a strange - and up to now not understandable - reproductive behavior of the potter wasp insect Delta dimidiatipenne (Hymenoptera). Females of this insect lay their eggs in mud chambers provisioned with caterpillars they capture to feed their young. Experimental observations indicate that many of the caterpillars collected by this wasp are actually parasitized by a small gregarious parasitoid wasp and are providing a lower amount of food for the wasp progeny. As a result, all players in the interaction perish - the young potter wasp cannot fully exploit the caterpillars and presumably starve to death; and the small parasitoids complete their development, but cannot break out of the mud and remain trapped in the sealed pot. Following such observation, we developed a probabilistic model trying to understand under what environmental conditions such a striking phenomenon (i.e., bringing back to the nest parasitized caterpillars), can be maintained, despite the high cost to all players. After several problems to develop this modeling work (some of them were due to the current political situation in Israel), we were able to submit a manuscript to a good international journal (Behavioural Processes). By the end September, we received a decision (minor revision) and a revised version of the text was resubmitted by mid-November. We are now waiting on the editorial decision from the journal.

8.3.2 Other research activities developed this year

Several other activities were developed this (and the previous) years, all lead to publications in international journals:

- A work [12] has been published with Odile Pourtallier, originating from an international scientific cooperation with Israeli scientists located at the University of Haifa to understand the optimal foraging decision of bees foraging for nectar. For this, we developed an optimization deterministic model trying to understand what should be the optimized flower visiting strategy, taking into account the ability of the foraging animals to learn the quality of the different flowers they are visiting.

- It is difficult to optimize the treatment of crops with insecticides again pests, since these chemical compounds also kill the natural enemies of the pests that are present, hence hampering our ability to protect the crop efficiently. With colleagues from different countries (USA, Israel, Finland and India), we developed a theoretical model to optimize the use of pesticides to control crop pests, taking also into account the incomes for the farmers. [13]

- With an international team, we also published a review articles in a top-level international journal [14], discussing how a trait-based approach can be used – mainly based on international databases – to identify which natural enemy species can be used to develop efficient biological control programs against crop pests. Such an approach poses several problems that remain to be solved, and we proposed different way to do this.

- Finally, with Brazilian colleagues (from the University of São Paulo), we published [15] a theoretical model to optimize the used of genetically modified corn plants to control corn pests in the field. The model is based on an individual-based spatially explicit Monte Carlo simulation.

9 Partnerships and cooperations

Participants: Jean-Pierre Merlet, Yves Papegay, Odile Pourtallier, Eric Wajnberg.

9.1 International research visitors

9.1.1 Visits to international teams

Research stays abroad

Eric Wajnberg

Visited institution: University of São Paulo

Country: Brazil

Dates: from 4 September 2023 to 3 May 2024

Context of the visit: Project “Spatial and temporal dynamics of host-symbiont interactions in insects: Toward improving biological control programs against crop pests”

Mobility program/type of mobility: sabbatical

9.2 European initiatives

9.2.1 Other european programs/initiatives

- Hephaistos is part of the euROBIN, the Network of Excellence on AI and robotics that was launched in 2021

9.3 National initiatives

- Hephaistos is part of the EquipEx+ AMI dealing with XXL robots.

10 Dissemination

10.1 Promoting scientific activities

10.1.1 Scientific events: organisation

Member of the organizing committees

- Jean-Pierre Merlet is a permanent member of the International Steering Committee of the International RObotics and System (IROS) conference, of the CableCon conference (International Conference on Cable-Driven Parallel Robots) and chairman of the scientific Committee of the Computational Kinematics workshop.

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

10.1.2 Journal

Member of the editorial boards

- Eric Wajnberg is Editor-in-Chief of the international journal “BioControl” since September 2006, a member of the Editorial Board of the international journal “Entomologia Experimentalis et Applicata”, since 1996, a member of the Editorial Board of the international journal “Applied Entomology and Zoology”, since 2003 and a member of the Editorial Board of the international journal “Neotropical Entomology”, since 2009.

Reviewer - reviewing activities

- Eric Wajnberg is referee for about 60 international scientific journals. He reviewed about 20 manuscripts in 2023.

10.1.3 Invited talks

- Jean-Pierre Merlet has given a talk about AI and robotics and one about interval analysis at the joint ACCENTAURI-HEPHAISTOS seminar at Inria.
- Jean-Pierre Merlet presented the HEPHAISTOS activities on handicap during INRIA Scientific days, during the Handicap week and to the "Conseil de l’Âge".
- Jean-Pierre Merlet talked about the past of robotics activities during the 40th years of INRIA Sophia-Antipolis Méditerrannée research center.
- Eric Wajnberg has given an invited talk entitled "A modeling approach to improve the efficiency of augmentative biological control with arthropod natural enemies" during the Second International Latin-American Conference on Biological Control (Juazeiro, Brazil).
- Eric Wajnberg has given an invited talk entitled "Stochastic Individual-Based Model (IBM) in parasitoid ecology and Genetic Algorithm" during the Third Symposium on ecology, evolution and diversity (Federal University of São Paulo, Brazil).

10.1.4 Leadership within the scientific community

- Jean-Pierre Merlet is a member of the IFToMM (International Federation for the Promotion of Mechanism and Machine Science) technical Committees on History and on Computational Kinematics. He is a member of the IFToMM Executive Council Publication Advisory Board and an IEEE Fellow.
- Jean-Pierre Merlet has got an Emeritus research director position at INRIA and an emeritus senior chair of 3IA Côte d’Azur since December 2023.
- Jean-Pierre Merlet was a member of the scientific committee of the CNRS GDR robotique until September 2023 and is now member of the advisory "Conseil des Sages".

10.1.5 Scientific expertise

- Jean-Pierre Merlet is a Nominator for the Japan’s Prize. He is the head of the robotics GDR Publication Committee that has produced the 2023 report on "recommended supports for publication" for journals and conferences that does not provide a ranking but advice according to robotics topics.
- Jean-Pierre Merlet is active in the "Robotics in Provence" industrial cluster.
- Yves Papegay is a member of the OpenMath Society, building an extensible standard for representing the semantics of mathematical objects.
- Eric Wajnberg is an appointed member of the Academic Committee of the Hebrew University of Jerusalem, since June 2022, for four years. He has been an appointed member of the International Advisory Board of the “International Center for Excellence in Biological Control”, from August 2018 to August 2023.

10.1.6 Research administration

- Yves Papegay is the head of local CUMI (Committe of users of the numerical resources and tools).
- Jean-Pierre Merlet has been an elected member of INRIA Scientific Committee until mid-January.
- Jean-Pierre Merlet has been a corresponding member of INRIA ethical committee (COERLE) and a member of the Ethical Committee of Université Côte d'Azur (CER) until September.
- Odile Pourtallier has been member of the local researcher recruitment jury.
- Odile Pourtallier is a member of the local Transform committee.

10.2 Teaching - Supervision - Juries

10.2.1 Teaching

- Jean-Pierre Merlet has taught 15 hours on parallel robots to Master ISC (M2) at University of Toulon.
- Yves Papegay has taught the "Robotics and AI" course of L3IA at Université Côte d'Azur.
- Yves Papegay has taught the "Oriented-Object Programming" Course of L2Info at University of French Polynesia.

10.2.2 Supervision

- Jean-Pierre Merlet is supervisor of the PhD of Romain Tissot. Together with Yves Papegay, he is supervising the PhD of Clara Thomas.
- Jean-Pierre Merlet has been the supervisor of the internship of Julien Bondyfalat whose purpose was to investigate the use of an IA parallel processor for interval analysis algorithms and deep learning for problems with low training time but requiring multiple neural networks and training sets.
- Yves Papegay is supervising an industrial project of engineering school students, about design and realisation of a modular and multi-scale cable-driven parallel cranes.

10.2.3 Juries

- Jean-Pierre Merlet has been member of the PhD defense committtte of M. Metillon at LS2N Nantes,
- Eric Wajnberg has been member of 10 PhD defense committees at the University of Palermo (Barbaccia P., Consentino B.B., Ponte M., Alinc T., Auteri N., Bambina P., Borgia D., Funsten C.C., Giuga L., Ippolito M., Roma E., Sofia S.).

10.3 Popularization

- Jean-Pierre Merlet presented twice HEPHAISTOS activities to 3eme interns and to Eurecom students. He presented the HEPHAISTOS activities on handicap to INRIA general public as well as a global overview on the advantages and drawbacks of mobility based on electric cars.

10.3.1 Education

- Jean-Pierre Merlet and Yves Papegay are active members of the dissemination initiative Terra Numerica.

10.3.2 Interventions

- Jean-Pierre Merlet has given a general talk about ethics for Unica HR4S program.
- Eric Wajnberg has given two public talks in the scope of Science pour Tous 06, one about "Pourquoi la sexualité ? Le regard de la biologie" in the city of Roussillon, the other one about "Lutter contre les ravageurs de culture - De l'usage des pesticides vers des alternatives plus respectueuses de l'environnement" in Aspremont.

11 Scientific production

11.1 Major publications

[1] J.-P. Merlet. 'Interval Analysis and Reliability in Robotics'. In: *International Journal of Reliability and Safety* 3 (2009), pp. 104–130. URL: http://hal.archives-ouvertes.fr/inria-00001152/en/.

[2] J.-P. Merlet. 'Maximal cable tensions of a N-1 cable-driven parallel robot with elastic or ideal cables'. In: CableCon 2021 - 5th International Conference on Cable-Driven Parallel Robots. Virtual, France, 7th July 2021. DOI: 10.1007/978-3-030-75789-2_7. URL: https://hal.inria.fr/hal-03284191.

[3] J.-P. Merlet. 'Mixing AI and deterministic methods for the design of a transfer system for frail people'. In: Sophia IAsummit. Sophia-Antipolis, France, 17th Nov. 2021. URL: https://hal.inria.fr/hal-03436170.

[4] J.-P. Merlet. 'The kinematics of cable-driven parallel robots with sagging cables: preliminary results'. In: ICRA 2015 - IEEE International Conference on Robotics and Automation. Seattle, United States, 2015, pp. 1593–1598. DOI: 10.1109/ICRA.2015.7139401. URL: https://hal.archives-ouvertes.fr/hal-01259258.

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[7] N. Nevejans, O. Pourtallier, S. Icart and 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* (Dec. 2017). URL: https://hal.inria.fr/hal-01665077.

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

[9] 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.

[10] 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.

11.2 Publications of the year

International journals

[11] S. Briot and J.-P. Merlet. 'Direct Kinematic Singularities and Stability Analysis of Sagging Cable-driven Parallel Robots'. In: *IEEE Transactions on Robotics* 39.3 (1st June 2023), pp. 2240–2254. URL: https://hal.science/hal-04007182.

[12] T. Keasar, O. Pourtallier and E. Wajnberg. 'Can sociality facilitate learning of complex tasks? Lessons from bees and flowers'. In: *Philosophical Transactions of the Royal Society B: Biological Sciences* 378.20210402 (23rd Jan. 2023). DOI: 10.1098/rstb.2021.0402. URL: https://inria.hal.science/hal-03952185.

[13] T. Keasar, E. Wajnberg, G. Heimpel, I. Hardy, L. S. Harpaz, D. Gottlieb and S. van Nouhuys. 'Dynamic Economic Thresholds for Insecticide Applications Against Agricultural Pests: Importance of Pest and Natural Enemy Migration'. In: *Journal of Economic Entomology* 116.2 (1st Apr. 2023), pp. 321–330. DOI: 10.1093/jee/toad019. URL: https://inria.hal.science/hal-04086781.

[14] M. Segoli, P. Abram, J. Ellers, G. Greenbaum, I. C. Hardy, G. Heimpel, T. Keasar, P. Ode, A. Sadeh and E. Wajnberg. 'Trait-based approaches to predicting biological control success: challenges and prospects'. In: *Trends in Ecology and Evolution* 38.9 (Sept. 2023), pp. 802–811. DOI: 10.1016/j.tree.2023.04.008. URL: https://inria.hal.science/hal-04180641.

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International peer-reviewed conferences

[16] J.-P. Merlet and Y. Papegay. 'The new exhibition Blind machines, a large 3D printing machine'. In: *2023 IEEE International Conference on Robotics and Automation (ICRA)*. ICRA 2023 - International Conference on Robotics and Automation. Londres (Grande Bretagne), United Kingdom, 29th May 2023. DOI: 10.1109/ICRA48891.2023.10160478. URL: https://inria.hal.science/hal-04253690.

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Scientific books

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