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Project-Team Coprin

Constraints solving, OPtimization, Robust INterval analysis

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THEME SYM

Activity Report

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COPRIN is a joint project between Certis (École des Ponts et Chaussées) and INRIA.

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2. Overall Objectives

2.1. Overall Objectives

Keywords: *constraints programming*, *interval analysis*, *mechanism theory*, *multi-precision*, *numerical robustness*, *optimal design*, *robotics*, *symbolic-numerical calculation*, *systems solving*, *uncertainty*.

COPRIN is a joint project between Certis (École des Ponts et Chaussées) and INRIA.

Its scientific objective is to develop and implement systems solving algorithms based on constraints propagation methods, interval analysis and symbolic computation, with interval arithmetic as the primary tool. The academic goals of these algorithms is to provide *certified solutions* to generic problems (e.g. to calculate all solutions of a system of equations within a search space) or to manage the *uncertainties* of the problems (e.g. to provide an enclosure of all solutions of a system of equations whose coefficients are intervals). These academic goals may also be declined in applicative goals. For example we may determine a domain that describes all possible dimensions of a mechanism that has to satisfy a set of performance requirements. Being given this domain it will be possible to determine nominal dimensions for the mechanism so that even if there are bounded variation between the real dimensions and the nominal one, then the real mechanism will still satisfy the requirements: hence we will be able to manage manufacturing uncertainties for the real process.

Our research aims to develop algorithms that can be used for any problem or are specific to a given class of problem, especially problems that are issued from application domains for which we have an internal expertise (such as mechanism theory and robotics).

A key point of these algorithms is that they rely heavily on symbolic pre-processing and formal calculation in order to improve the efficiency of the problem at hand. Our long term goal is to be able to synthesize automatically a specific solver according to the structure of the problem that has to be managed.

Implementation of the algorithms will be performed within the framework of general purpose software such as `Scilab`, `Maple`, `Mathematica` and will be based on the already existing library `ALIAS`, that are still being developed mostly for internal use.

Since a theoretical complexity analysis of interval analysis based solving algorithms is usually extremely difficult, the efficiency of the algorithm are systematically experimentally evaluated through `ALIAS` on various realistic test examples.

Dissemination is also an essential component of our activity because interval analysis based methods are not sufficiently known in the engineering and academic communities.

The study of robotics problems is a major focus point of the COPRIN 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
- to develop a design methodology for complex robotic systems that guarantee a required level of performance for the **real** robot. Our methodology aims at providing not a single design solution but a set of solutions offering various compromises among the performances. Furthermore the solutions will be robust with respect to errors in the realization of the real robot (e.g. due to manufacturing tolerances and control errors)

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

We have started this year a strategic move toward **assistance robots**. Our long term goal will be to provide assistive robotized devices that may help disabled, elderly and handicapped people in their personal life. Our goals for these devices are that

- they can be adapted to the end-user and to its everyday environment
- they should be affordable
- they may be controlled through a large variety of simple interface

In summary COPRIN has two major research axes, interval analysis and robotics. The coherence of these axis is that interval analysis is a major tool to manage the uncertainties that are inherent to a robotized device while robotics provides realistic problems which allow us to develop, test and improve interval analysis algorithms.

2.2. Highlights of the year

As highlights of this year we will mention:

- the first controlled motion of our wire-driven parallel robot
- the organization of IROS 2008 in Nice with over 1400 attendees

3. Scientific Foundations

3.1. Scientific Foundations

3.1.1. Interval analysis

We are interested in real-valued system solving ($f(X)=0$, $f(X)\le 0$), in optimization problems, and in the proof of the existence of properties (for example it exists X such that $f(X)=0$ or it exists two values X_1, X_2 such that $f(X_1)>0$ and $f(X_2)<0$). There are few restrictions on the f we can deal with as we are able to manage explicit functions using classical mathematical operators (e.g. $\sin(x+y)+\log(\cos(e^x)+y^2)$ or 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 will be 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 to find all the solutions within the domain as soon as 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 includes one, and only one, solution together with a numerical approximation of this solution, that may further be refined at will using multi-precision.

The kernel of our methods is the use of *interval analysis* that allows one to manipulate expression 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

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

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

For example if $F=x\ sin(x+x^2)$ and $x\in[0.5,1.6]$, then $F([0.5,1.6])=[-1.362037441,1.6]$, meaning that for any x in [0.5,0.6] we guarantee that $-1.362037441\le f(x)\le 1.6$.

The interval evaluation of an expression has interesting properties:

- it can be implemented in such way that the results are guaranteed with respect to round-off errors i.e. in spite of numerical errors induced by the use of floating point numbers property 1 is still valid
- if $A>0$ or $B<0$, then there are now values of the unknowns in their respective ranges that may cancel F
- if $A>0$ ($B<0$), then F is positive (negative) for any value of the unknowns in their range

But there is a major drawback of the interval evaluation: there may be an overestimation of $A(B)$ i.e. there may be no value of $x_1,x_2,...,x_n$ such that $F(x_1,x_2,...,x_n)=A(B)$. This overestimation occurs because in our calculation each occurrence of a variable is considered as an independent variable and consequently if a variable have multiple occurrences, then an overestimation may occur. Such phenomena can be observed in the previous example where $B=1.6$ while the real maximum of F is approximately 0.9144. The value of B is obtained because we are using in our calculation the formula $F=xsin(y+z^2)$ with y,z having the same interval value than x.

Fortunately there are methods that allow one to reduce the overestimation and this 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 will be stored in a list and processed later on. The algorithm will be completed 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 it is shown that for a box $\mathcal{B}$ we have $F(\mathcal{B})\ge 0$).

A generic interval analysis algorithm involves the following steps in sequence on the current box:

1. *exclusion operators*: these operators determine that there is no solution to the problem within a given box
2. *filters*: these operators may reduce the size of the box i.e. decrease the width of the allowed ranges for the variables [39], [19]
3. *existence operators*: they allow one to determine that there is a unique solution within a given box and are usually associated to a numerical scheme that enable to compute 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 COPRIN project is to address all these steps in order to find the most efficient procedures. Our efforts focuses on mathematical developments (adapting classical theorems to interval analysis, proving interval analysis theorems), on the use of symbolic computation and formal proof (a symbolic pre-processing allows one to automatically adapt the solver to the structure of the problem), on software implementation and on experimental tests (for validation purposes).

3.1.2. Robotics

COPRIN has a long-standing tradition of robotics studies, especially for closed-loop robots [44], [43]. We address first theoretical issues with the purpose of obtaining analytical and theoretical solutions, but in many cases only numerical solutions can be considered because of 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 that cannot be tackled by any other method (e.g. singularity analysis)
2. we want to take uncertainties (which are inherent to a robotic device) into account so that we can guarantee that the performance level of the *real* robot will satisfy 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 robot)

Our field of study in robotics focuses on *kinematic* issues such as workspace and singularity analysis, positioning accuracy, trajectory planning, reliability [22], [10], [29], [13], [36] and prominently *appropriate design*, i.e. finding the dimensioning of a robot mechanical architecture that guarantees that the real robot will satisfy a given list of requirements [12]. But the methods that we have developed can be used for other robotic problems, see for example the management of uncertainties in a localization problem with ultrasound [41].

Our theoretical work must be validated through experiments that are essential for the sake of our credibility. A contrario, experiments will feed the theoretical work (quite often COPRIN has been the first robotic group to address some theoretical issues that were pointed out by experiments). Hence COPRIN works with partners for the development of real robots but also develops its own prototypes (approximately one every 6 years).

In term of applications we have focused on the development of special machines (machine-tool, ultra-high accuracy positioning device, spatial telescope). Although this activity will be pursued we intend to move toward *service robotics* i.e. robots that are closer to human activity. In service robotics we are interested in domotics, rehabilitation and medical robots and entertainment that be regrouped under the name of *assistive robotics*. Compared to special machines for pricing is not an issue (up to a certain point), cost is an important element for service robotics. While we plan to develop simple robotic systems, our work will focus on a different issue: the management of the robot *modularity*. The mechanical modularity of a robot is obtained by allowing one to change the arrangement of the robot's elements (whose cost may be quite low) so that it is most appropriate for the task. Many such mechanically modular robots are available (or can be designed at will) but finding the right arrangement of the hardware to fulfill the task requirements in spite of mechanical and control uncertainties is an open problem with no known algorithmic solution and developing such algorithms is our long term goal.

4. Application Domains

4.1. Application Domains

Keywords: *geometric constraints*, *mechanism theory*, *optimal design*, *robotics*.

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 control theory and in quantum mechanics), 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*, including *robotics* and especially *service robotics*. In this domain our research focuses on *optimal design* and geometrical modeling of mechanisms, especially for the machine-tool industry, automotive suspensions, virtual reality and medical robotics, which all involve the management of *geometric constraints*. Other domains exhibiting problems of the same nature as mechanism theory (e.g. molecular chemistry) may also be addressed, without constituting a major research axis of the project.

5. Software

5.1. Introduction

Software is an essential part of the research within COPRIN since a large part of this research can only be validated experimentally. Software developments are addressed along various axes:

1. interval arithmetic: although our purpose is not work in this very specialized area (we generally rely on existing packages) interval arithmetic is an important part of our interval analysis algorithms and we may have to extend the existing packages so as to deal, in particular, with multi-precision and arithmetic extensions
2. interval analysis libraries: we daily use two libraries that have been designed in the project and are still under development. A long term work is to develop a generic programming framework that allows for modularity and flexibility, with the objectives of testing new functionalities easily and of building specific solvers by a simple juxtaposition of existing modules
3. interface to interval analysis: in our opinion interval analysis software must be available within general purpose scientific software (such as `Maple`, `Mathematica`, `Scilab`) and not only as a stand-alone tool. Indeed most end-users will be reluctant to learn a new programming language just to solve problems that are only small elements of a more general problem context. Furthermore interval analysis efficiency may benefit from the functionalities available in the general purpose scientific software.

5.2. Interval analysis libraries

5.2.1. ALIAS

Participants: Jean-Pierre Merlet, David Daney, Odile Pourtallier.

The `ALIAS` library (*Algorithms Library of Interval Analysis for Systems*), whose development has started in 1998, is a collection of procedures based on interval analysis for systems solving and optimization.

`ALIAS` is constituted of two parts:

- `ALIAS-C++`: the C++ library (86 000 code lines) which is the core of the algorithms
- `ALIAS-Maple`: the `Maple` interface for `ALIAS-C++` (50 000 code lines). This interface allows one to specify a solving problem within `Maple` and to get the results within the same `Maple` session. The role of this interface is not only to generate automatically the C++ code, 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.

These libraries can be freely downloaded.

5.2.2. *Int4Sci : a Scilab interface for interval analysis*

Keywords: *Scilab.*

Participants: Raphaël Pereira, David Daney.

In 2006 we have started the development of a Scilab interface to C++ Bias/Profil interval arithmetic package and to the library ALIAS.

The first version of Int4Sci has been released this year – see http://www-sop.inria.fr/teams/coprin/logiciels/Int4Sci/ for linux, MacOS and Windows. This interface provides an interval arithmetic, basic interval manipulation tools as well as solving of linear interval systems. All functions are documented and a tutorial is available.

This year, we focus on the development of functionalities regarding interval polynomials (i.e. polynomials whose coefficients are intervals) and of a high level solver based on ALIAS function.

5.2.3. *Mathematica Interface to Interval Analysis*

Participants: Yves Papegay, Jean-Pierre Merlet, David Daney.

Since 2006, we have been implementing in Mathematica a high-level modular interface to the ALIAS library. The initial aim of providing the Mathematica users community a transparent access to the functionnalities of ALIAS, and of extending the dissemination of our library, has progressively turned into the aim of providing ALIAS advanced users and developers with a high-level modular interface for prototyping, easy testing and quick implementation of new interval analysis algorithms and procedures relying on symbolic computation skills. This includes namely symbolic preprocessing of expressions, and symbolic specializations of interval analysis algorithms.

6. New Results

6.1. Robotics and mechanism theory

6.1.1. *Modeling human postural coordination to improve the control of balance in humanoids*

Keywords: *humanoid robot.*

Participant: Nacim Ramdani.

As part of a collaboration with LIRMM and the EDM group (Univ. Montpellier 1), we have addressed the issue of modeling human postural coordination in order to improve the control of balance in humanoid robots. Recent data in the field of postural coordination shows the existence of self-organized postural states, and transition between them, underlying supra-postural tracking movements. We proposed a closed-loop controller which captures the complex postural behaviors observed in humans and can be used to implement efficient and simple balance control principles in humanoids [20], [40].

6.1.2. *Guaranteed computation of constraints for safe path planning with humanoid robots*

Keywords: *humanoid robot.*

Participant: Nacim Ramdani.

Motion planning can be seen as a Semi-Infinite Programming problem (SIP) since it involves a finite number of variables over an infinite set of constraints. Most methods solve the SIP problem by transforming it into a finite programming one by using a discretization over a prescribed grid. This approach is risky because it can lead to motions which violate one or several constraints, with catastrophic consequences when dealing with, for instance, the balance of humanoid robots. We have introduced, in a joint work with the DEMAR project-team, a guaranteed discretization method which uses interval analysis to ensure that the constraints are satisfied over the whole time interval. We have experimentally analyzed this method by performing a trajectory generation under constraints dedicated to the motion of the HOAP-3 humanoid robot using a 6 degree-of-freedom model [24], [38].

6.1.3. Singularity of parallel robots

Keywords: *parallel robot*, *singularity*.

Participants: Julien Hubert, Jean-Pierre Merlet.

The study of singularity is an old issue for parallel robots and the COPRIN project is a leading team on this subject. There still remain open issues on this subject:

- singularity should be avoided in general because the joint forces of the robot may go to infinity in the vicinity of such a pose, causing a breakdown of the robot. However this will not happen for all poses at which the Jacobian matrix loses rank or for any type of external wrench applied on the end-effector. A better knowledge of the "dangerous" singularities is needed
- the workspace of the robot derived from kinematic constraints (such as the limited motion of the joints) may further be reduced if the workspace is separated by singularity regions that cannot be crossed. Hence the influence of singularity on the useful workspace should be clarified
- singularities may also be classified according to the type of infinitesimal motion that occur at such poses but such classification is not yet known
- can we classify the singularities not only as function of the pose parameters but also as functions of the robot design parameters ?
- can we suggest meaningful indices to quantify the proximity to singularities ?

All these issues are addressed in the ANR `SIROPA` project[1] that we are leading.

This year we have addressed the latter problem by defining a proximity criterion based on the absolute value of the joint forces/torques: we estimate that we are "close" to a singularity if these forces are larger than a given threshold (e.g. the weakest breaking force of all mechanical elements of the leg). According to this definition it becomes interesting to determine the component of the robot's workspace, called the *safe workspace*, in which the joint forces will not exceed the threshold. We have first considered the simple example of a planar $3-RPR$ robot whose end-effector is submitted to a given wrench and we have proposed an algorithm which allows one to compute exactly the border of the safe workspace for a given orientation of the robot [22].

6.1.4. Design of high speed parallel robot in presence of uncertainty

Keywords: *design*, *parallel robot*.

Participants: Nacim Ramdani, Jean-Pierre Merlet.

A collaboration is underway with the LIRMM, which aims at providing numerical tools useful to the design of a family of high speed parallel robots. The objective is to find sets of feasible values for the design parameters unlike more usual design procedures relying on optimization techniques. These tools are mainly based on interval analysis and take into account the dynamics of the parallel robots. Moreover, they can deal with bounded uncertainties that affect some physical parameters involved in the dynamics. Our method has been evaluated while studying a 2-DOF parallel robot [32]. Its use with more complex parallel robot is underway.

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[1] `wiki-sop.inria.fr/wiki/bin/view/Coprin/SIROPA`

6.1.5. Prototype of wire-driven robot

Keywords: *wire-driven parallel robot*.

Participants: Nicolas Chleq, David Daney, Jean-Pierre Merlet.

While usual wire-driven parallel robots use a rotary actuator and a drum to coil and uncoil the wires, our new robot uses only linear actuators and a pulleys system[2]. This robot shows a high mechanical modularity (the location of the wire system may be changed at will and various maximal length changes will be possible) and is very fast. Potential applications of this robot will be domotics (windows washing), entertainment (video game, camera control for movies), virtual reality (haptic device with a large workspace) and medical robotics (e.g. rehabilitation within the 3+3 Med action, see section 8.1.2) to name a few. A general kinematic scheme, including wire elasticity, has been developed, allowing to calculate the forward and inverse kinematics in real-time [25].

This year we have tested our robot in two configurations, using a four wire system:

- for planar, horizontal motion: in this case we have an over-constrained 3 d.o.f. robot
- as a crane: here we get a 4 d.o.f. robot

We have designed control laws for the planar case which allow for high speed trajectory tracking and the use of a joystick for manual monitoring. For the crane case we have experimented the controlled lifting of a wooden model that emulates the behavior of a simple lifting device that may be used as an assistive device for the elderly. The evaluation of these experiments is currently underway.

6.2. Algebraic systems and linear algebra

6.2.1. Bounds on eigenvalues and singular values of interval matrices

Keywords: *Interval matrix*, *eigenvalue bounds*, *interval analysis*, *real eigenvalue*, *singular value*.

Participants: David Daney, Milan Hladik.

Since 2006, we have studied methods to bound the eigenvalues of an interval matrix. This work is a key point for the certification of properties of systems depending on a set of parameters.

This year, we have improved the existing algorithms for bounding real eigenvalues: our contribution is a new *inner test* which allow to prove that each value of a given interval is an eigenvalue of one matrix among the set of matrices defined by the interval matrix [46].

6.2.2. Interval Constraint Programming

6.2.2.1. Exploiting Common Subexpressions in Numerical CSPs

Keywords: *domain contraction*, *symbolic computation*.

Participants: Ignacio Araya, Bertrand Neveu, Gilles Trombettoni.

The symbolic form of the equations is crucial for interval-based solving techniques to efficiently handle systems of equations over the real numbers. On the other hand, common subexpression elimination (CSE) is an important feature of compiler optimization. CSE searches in the code for common subexpressions with identical evaluation and replaces them by auxiliary variables. Vu, Schichl, Sam-Haroud, Neumaier have exploited common subexpressions in interval analysis by transforming the equation system into a unique directed acyclic graph. They claim that, like for code optimization, one can only expect a reduction in the number of operations.

We have proved theoretically and experimentally that, due to interval arithmetics, exploiting certain "useful" common subexpressions, including the widespread plus and times operators, can also bring additional domain filtering/contraction to interval-based solving algorithms.

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[2] see `wiki-sop.inria.fr/wiki/bin/view/Coprin/ROBPACALR` for a picture of the robot

Second, based on a better exploitation of n-ary plus and times operators, we have proposed a new algorithm I-CSE that identifies and exploits all the useful common subexpressions. We show on a sample of benchmarks that I-CSE leads generally to significant gains in performance, of sometimes several orders of magnitude [39], [19].

6.2.2.2. A Box-Consistency Contraction Operator Based on Extremal Functions

Keywords: *constraint propagation*, *domain contraction*, *symbolic computation*.

Participants: Gilles Trombettoni, Yves Papegay, Gilles Chabert, Odile Pourtallier.

Some interval contraction algorithms, often designed by "constraint propagation", come from the constraint programming community and bring in practice significant improvement in the solving time of systems of equations. The main two constraint propagation algorithms are `HC4` and `Box-consistency`. They consider a single equation $f(a,x)=0$ of the system at each step, and propagate the obtained reductions in the rest of the system until no interval can be reduced. `BoxRevise` is the atomic procedure used by `Box-consistency`. It considers a function f and a variable x iteratively. To narrow the interval $[x]$ to $[l,r]$, `BoxRevise` works with $g_{[a]}(x)=f([a],x)$, the interval function defined on a single variable x obtained by replacing the vectorial variable a by the box/interval $[a]$. It computes l (respectively r) as the leftmost (respectively the rightmost) root of $g_{[a]}(x)=0$.

We have proposed a new `PolyBox` (*polynomial Box-consistency*) algorithm that implements a more efficient `BoxRevise` procedure when $g_{[a]}(x)$ satisfies some conditions [37]. These conditions apply for example when $g_{[a]}(x)$ is a polynomial. Instead of working with $g_{[a]}$, `PolyBox` works with the two *extremal functions* of $g_{[a]}$, i.e., the two punctual univariate functions that enclose $g_{[a]}(x)$. According to the degree d of the polynomial, the roots of the extremal functions are then determined either analytically ($d \leq 4$), or numerically ($d \geq 5$). The convergence is faster since the extremal functions are punctual. To do so, a preliminary symbolic computation phase, performed in `Mathematica`, allows one to generate an adequate form of the equations.

Experimental results show the interest of our approach.

6.3. Miscellaneous results

6.3.1. Continuous and hybrid reachability analysis in presence of uncertainty

Keywords: *certified computation*, *hybrid systems*, *reachability*, *uncertainty*.

Participants: Nacim Ramdani, Yves Papegay.

To address *dynamical* issues for parallel closed loop robots in a reliable way, even in presence of uncertainty, we are developing tools to compute reachable sets for continuous and hybrid systems, i.e. complex systems where discrete and continuous dynamics interact.

We have first addressed nonlinear continuous reachability computation. When the size of the uncertainty domains are large, the state-of-the-art validated numerical integration methods based on interval Taylor series can produce effective results only for very particular cases. Hence, we have developed alternatives techniques. They rely on *comparison theorems* for differential inequalities, more precisely the Muller's theorem, in order to bracket the uncertain dynamical between two *coupled* dynamical systems where there is no uncertainty. When the system is a *monotone* dynamical systems, the bracketing systems are *decoupled*.

In general, the derived bracketing systems are piecewise differentiable functions, hence they cannot be directly integrated using interval Taylor series. Our contribution then resides in the use of hybrid automata to model them [33], [15], [18], [16].

Furthermore, symbolic computation is used to derive the hybrid automata which model the bracketing systems in a very efficient and effective way [35].

These new reachability computation tools are also at the core of new solving techniques for set-membership state estimation with uncertain nonlinear continuous-time systems [27], [26].

6.3.2. *Local search for 2D packing problems*

Participants: Bertrand Neveu, Gilles Trombettoni, Ignacio Araya.

The 2D strip packing problem consists in placing predefined rectangles in a strip such that no two rectangles overlap, while minimizing the height of the strip. We have selected this challenging problem to work in collaboration with Maria-Cristina Riff and Xavier Bonnaire from the University of Santa Maria in Valparaiso (Chile) with the financial support from INRIA and CONICYT (Chile) in 2006 and 2007. We developed incomplete algorithms to handle this combinatorial problem [14].

We first developed a method based on a local search algorithm (IDW), that makes rectangles moves in an incremental way by maintaining the set of “maximal holes. This algorithm does not involve any manual parameter tuning.

We have also developed a second solving method based on hyperheuristics. The hyperheuristic manages a sequence of greedy low-level heuristics, such as BLF (Bottom left Fill) or BF (Best Fit), each element of the sequence placing a given number of rectangles. A solution is built by placing the rectangles following the sequence of low-level heuristics. The hyperheuristic implements a hill-climbing algorithm on this sequence by testing different moves (adding, removing, replacing a low-level heuristic) [42].

We combined the two methods, a configuration being first built by the hyper-heuristic and then repaired by the local search [11].

We focused finally on the greedy heuristics used to perform the moves and to compute the first layout before running the local search. This is a variant of the well-known Best-fit (decreasing) (BF), called RBF, in which the criterion (i.e., height, width, perimeter, surface) changes every time a hole is selected [28]. This last method, integrated into our local search algorithm appeared to be competitive with the best known incomplete methods.

6.3.3. *Symbolic tools for modeling and simulation*

Keywords: *accuracy*, *code generation*, *modeling*, *reliability*, *simulation*, *symbolic computation*.

Participant: Yves Papegay.

This activity is the main part of a long-term ongoing collaboration with Airbus whose goal is to directly translate the work of aeronautics engineers into digital simulators to accelerate aircraft design. This project already has applications in the aircraft maker development departments.

Modeling and simulation processes usually begin with using scientific theories which describe physical features in terms of formulae and computation algorithms. Based on these models, numerical codes are then implemented for the simulation and visualization of these features. In an industrial context, the large number of parameters and equations involved in the models make the whole process very long, complex and expensive, all the more so that reliable and safe codes are required.

Since the beginning of our collaboration, in 2002, we have successively developed:

- a model edition environment, based on symbolic computation tools, that makes it possible to enter the formulae and the algorithms of the models and to validate them numerically on a reduced set of data,
- a C code generator which, using these models, automatically generates the numerical real-time simulation engines to be plugged in the flight simulator, as well as the technical documentation associated with such simulations, which is indispensable for corporate memory.

In 2008, to answer the specific needs of model design and tuning, we addressed the problem of automatically generating from the models an highly interactive and modular evaluation code allowing to simulate the models and to visualize the results inside the modeling environment – embedded in Mathematica – with the benefits for the designer of being able to directly use all its computational functionnalities.

7. Contracts and Grants with Industry

7.1. Airbus France

Participant: Yves Papegay.

To improve the production of numerical (flight) simulators from models of aerodynamics, Airbus France is interested in methods and tools like those described in 6.3.3.

Following the contracts signed in 2003, 2005 and 2007 with an aircraft maker, a consulting contract has been signed in 2008, to study the possible development of an industrial tool, based on existing prototypes.

7.2. Amadeus

Participants: Bertrand Neveu, Gilles Trombettoni.

Amadeus is a company that manages flight fares for several airlines and with which we have a long-standing collaboration to develop new optimization algorithms based on constraint programming and graph methods for fare quote problems, and to work on the test suite that is used for software evaluation by Amadeus.

In 2008, we worked on a contract for the development of a software proposing the best prices for an imprecise request that can include hotel and car reservations. In particular, we built a constraint programming prototype for the hotel reservation part.

8. Other Grants and Activities

8.1. International and National initiatives

8.1.1. RobPacaLr COLOR

Participants: Jean-Pierre Merlet, David Daney, Nacim Ramdani.

We have obtained an INRIA grant for a collaborative work with LIRMM which addresses the optimal design and calibration issues for wire-driven parallel robots.

A new cable-driven robot has been developed at LIRMM by replacing the rods of an existing parallel prototype by cables: the new robot acts as an under-mobility under-constrained parallel kinematics crane able to generate Scara motion. The distinctive feature of the new robot is that it can resist against outside forces and torques in all the directions of the 6-mobility world. This feature results from the use of pairs of cables binding the actuators and the traveling plate. This is new since classical under-mobility under-constrained cable robots can balance some perturbations only while the other ones generate eventually uncontrolled motions. We have characterized the static workspace defined as the domain of reachable space where the cables remain taut under the action of gravity [23].

We have also addressed the design of parallel cable-driven robots having more cables than degrees of freedom (DOF). Compared to parallel robots with rigid links, this issue has a distinctive property: the requirement of keeping the cables taut. We have shown how numerical tools developed within the COPRIN project-team, can be used to solve the important practical problem of finding geometries of robots such that a given prescribed workspace is fully included in the wrench-feasible workspace [21].

8.1.2. 3+3 Med Roras project

Participants: Jean-Pierre Merlet, David Daney.

In 2005 we have obtained an INRIA grant for a collaborative work with Cassino University, Monastir engineer school and University of Oran for a preliminary work on the development of a wire-driven parallel robot for rehabilitation[3]. A state of the art on rehabilitation and on rehabilitation protocol has been produced. These documents will be used as main inputs to determine if our hardware is appropriate for such task and, more importantly, to develop an appropriate design software that will allow us to calculate the best robot geometry given a pathology, the patient morphology and the rehabilitation protocol.

The RORAS project has been completed in 2008 but we have applied for a new grant RORAS II on the same topics with an extension to assistive robots that has been accepted. The partners of this new project are Cassino University, Sousse Engineer school and University Mentouri of Constantine.

8.2. Participation to National and International Conferences

8.2.1. International Conferences

- I. Araya has presented papers at the JFPC'08 French Conference on constraint programming (Nantes) and at the CP'08 conference on constraint programming (Sydney, Australia).
- D. Daney participated in the IEEE International Conference on Robotics and Automation (ICRA) at Pasadena, USA and in IROS 2008 in Nice.
- J. Hubert participated in ARK in Batz/Mer and in IROS 2008 in Nice.
- J-P. Merlet participated in the IEEE International Conference on Robotics and Automation (ICRA) at Pasadena, USA, in IROS 2008 in Nice, in ARK in Batz/Mer and the ANR PSIROB workshop.
- B. Neveu participated in the conferences JFPC 2008 in Nantes, CPAIOR 2008 in Paris
- Y. Papegay attended and he gave three talks at the International Mathematica Symposium 08 in Maastricht and at the Mathematica Users Conference 2008 at Urbana Champaign, Illinois, USA.
- N. Ramdani presented papers at: IEEE/ACM Hybrid Systems Computation Control 2008, St Louis, MO USA, IEEE Int Conf. on Humanoid Robots 2008, Daejeon, Korea South, World Congress IFAC 2008, Seoul, Korea South, Advances in Robot Kinematics 2008, France, IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS) 2008, Nice, France, ASME Int. Design Engineering Technical Conferences (IDETC) 2008, New York, NY USA, 9th Int. Mathematica Symp., Maastricht, The Netherlands, 2008, IFAC Int. Conf. on Informatics in Control, Automation Robotics, Funchal, Madeira, Portugal, 2008.
- G. Trombettoni gave presentations at the SCAN'08 conference on interval analysis (El Paso, US), at the CPAIOR'08 conference on constraint programming and operational research (Paris), and at the Coprod'08 worshop on constraint programming and decision making (El Paso, US).

8.3. Other Activities

8.3.1. National Activities

- J-P. Merlet is president of IFToMM France and member of the scientific committee of the CNRS Robotics GDR
- N. Ramdani is co-responsible for the working group ”Méthodes Ensemblistes pour l'Automatique” - GDR MACS[4]. He has co-organised the first edition of the Special Workshop on Interval Methods, SWIM 2008[5], at Montpellier, France.

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[3] see `wiki-sop.inria.fr/wiki/bin/view/Coprin/RORAS`

[4] http://www.lirmm.fr/ensemble

[5] https://www.ensieta.fr/e3i2/Jaulin/swim08.html

8.3.2. INRIA activities

- D. Daney is president of the CUMIR (Comité des Utilisateurs des Moyens Informatiques, Recherche).
- J-P. Merlet is a member of the "Bureau du Comité des Projets" of Sophia, of the National Permanent Training Commission, of the Scientific Communication Commission and of INRIA Evaluation Board (CE).
- O. Pourtallier is a member of the CSD (doctoral students monitoring) and NICE (invitation of long term scientist visitors).

8.3.3. European Activities

- J-P. Merlet is a member of the scientific committee of the European Conference on Mechanism Science (EUCOMES).

9. Dissemination

9.1. Leadership within scientific community

A major point of this year has been the organization of the IEEE IROS Conference in Nice in September 2008. Over 1400 papers were submitted and approximately 1400 persons from 47 countries have attended the conference.

- D. Daney has been the webmaster and Local Organization Chair of IROS 2008
- J-P. Merlet has been General Chair of IROS 2008 and Associate Editor for ICRA 2008. He is also associate editor of the journals Mechanism and Machine Theory and ASME Journal of Mechanisms and Robotics.
- B. Neveu was a member of the program committee of JFPC 2008 conference. He visited the research team of Maria-Cristina Riff Rojas at Federico Santa Maria University in Valparaiso, as invited guest during 10 days in November 2008.
- Y. Papegay is a member of the "commission de spécialistes" number 4 of the University of French Polynesia. He is a permanent member of the International Steering Committee of the International Mathematica Symposium conferences serie. He was a member of the Program Committee of the Computer Algebra Systems and Their Applications, CASA'2008 conference, and Co-Finance Chair of IROS 2008.
- O. Pourtallier is a member of the executive board of the International Society of Dynamic Games.
- N. Ramdani is a member of the IFAC Technical Committee 1.3 on Discrete Event and Hybrid Systems, for the 2008-2011 triennium. He is a member of the editorial advisory board of The Open Mechanical Engineering Journal. He was a member of the program committee of the 12th International Conference on Hybrid Systems: Computation and Control (HSCC'09).
- G. Trombettoni has been the scientific president of the program committee of the French Conference on constraint programming JFPC'08, Nantes. He has also been a member of the program committee of the two main international conferences on artificial intelligence (track on constraint programming): AAAI 2008 and ECAI 2008.

9.2. Teaching

- D. Daney gave a course in medical robotics, Master of Bio-Medical, Univ. Nice Sophia Antipolis (15h) and in robotics at ISIA Superior Institut of Computer Science and Control (Ecole des Mines de Paris) (8h).
- O. Pourtallier has taught 6 hours on game theory to master OSE, at École des Mines de Paris, Sophia Antipolis, 20 hours on game theory to MASS at UNSA and 6 hours on optimization, to DESS IMAFA at UNSA.
- G. Trombettoni is an assistant professor in computer science at IUT R&T (networks and telecoms) of Sophia Antipolis.
- B. Neveu has given lectures on constraint programming in the Computer Science Master at University of Nice Sophia (2 h)

9.2.1. PhD thesis

- J-P. Merlet has been a reviewer of 4 PhD theses and 1 HDR
- B. Neveu has been a reviewer of 2 PhD theses and a jury member of 3 PhD theses.
- N. Ramdani was a jury member for 1 PhD defense.

9.3. PhD thesis

Current PhD theses:

1. I. Araya, Filtering techniques for interval solvers
2. S. Bennour, Modeling of human joints for rehabilitation purposes
3. J. Hubert, Classification of the singularity of parallel robots
4. C. Tavolieri, Appropriate design of parallel robots

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Articles in National Peer-Reviewed Journal

[15] N. MESLEM, N. RAMDANI, Y. CANDAU. *Méthodes intervalles pour le calcul de l'espace atteignable des systèmes dynamiques continus incertains*, in "APII-JESA", to appear, 2009.

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