Still a long way to go on the road for parallel mechanisms

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1 Introduction

After spending alwost 20 years in the laboratories for preliminary studies parallel robots are now used in real-life applications in domains such as fine positioning devices, motion generators, ultra-fast pick and place robot and will probably find their use in the field of machine-tools, medical application, haptic devices...

This interest come from the potentially interesting features of parallel mechanisms, the most noticable being:

- high accuracy, rigidity, speed
- large load carrying capability

which in a very large number of cases may overcome the drawbacks of the more complex kinematics and smaller workspace.

But a fact is that these advantages are only *potential* and any real parallel robot will present in practice impressing performances only if all its components (either hardware or software) present a high level of performance. In this paper we will review some key issues in this field, without pretending to be exhaustive[1].

2 The various layers of a parallel robot system

Like their serial counterpart parallel robots are constituted of various layers (figure 1. The *mechanism* layer is the robot itself with first a theoretical model constituted of :

- the *topology* of the mechanism i.e. how the joints, links and actuators are arranged to produce the desired motion
- the *geometry* of the mechanism i.e. the dimensions of the links, the location of the joints . . .

But the practical realization of the robot will differ from this theoretical model and we will find the real robot with:

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[1] The references in this paper are not exhaustive: further references and information on parallel robot may be found at
`http://www-sop.inria.fr/coprin/equipe/merlet/merlet_eng.html` or
`http://www/parallelmic.org`

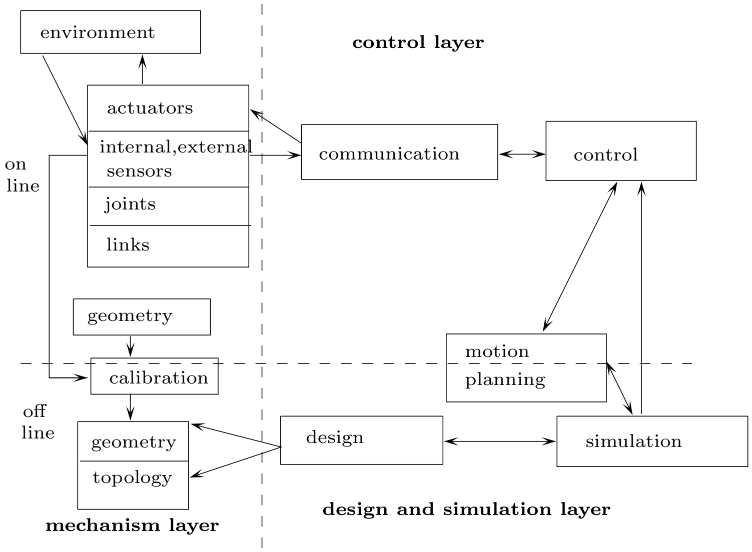

Figure 1: The various layers of a parallel robot

- the *real geometry*
- the *joints* and *links*
- the *actuators*
- the *sensors* which may be *internal* (used mostly for the motion control) or *external* (to get information on the environment of the robot)

The *control* layer is constituted of:

- a *communication* level which allows the transfer of information between the sensors and actuators of the robot and the controller
- a *control* level that may be decomposed into:
  - a *motion planning* level which generates a sequence of motions for the robot
  - a *controler* that ensures the execution of the motions elaborated by the motion planner

The *design and simulation* layer is constituted of

- a *design* module that allows to determine the theoretical topology and geometry that is the best for the tasks to be performed by the robot
- a *simulation* module that allows to simulate the behavior of a robot of given topology and geometry

Optionnaly we may have also a *calibration* layer whose purpose is to obtain a better match between the theoretical model of the geometry and its real geometry by using either the sensors of the robot or additional sensors.

We may also distinguish between *on line* and *off-line* layers (mostly the design and simulation layers) although elements of one category may be used by elements of the other categorie.

At this level of description it may appear that there is no difference between a serial robot and a parallel robot. But we will see that some underlying problems at each layer are very specific for each category of robot.

3 Mechanism

3.1 Mechanical architectures

More than 100 different mechanical architectures of parallel robots have already been proposed and it is probable that not all of them have been discovered. Unfortunatly there are not so many proposed architecture that have only 4 or 5 d.o.f.[2] while many applications require such number of d.o.f. Hence a recent trend is to propose parallel robots with less than 6 d.o.f [12, 14, 28, 40, 57, 68].

This is clearly an interesting research area but many questions arise with this type of robots:

- the proposed structure have *in theory* only 4 or 5 d.o.f. and rely on geometrical constraints to obtain this reduced number of d.o.f. In practice however these constraints will never been perfectly fulfilled and hence these robots will exhibit parasitic motions. Open problems are to determine what will be the maximal amplitude of these parasitic motion being given manufacturing tolerances [54] and the dual problem of determining the amplitude of the manufacturing tolerances so that the maximal amplitude of the parasitic motion will not exceed a given threshold. In my opinion some of the proposed architectures which may sound interesting in theory will be quite difficult to realize

- although having less actuators and sensors may sound economically interesting it is, in my opinion, unclear if more classical robot which are redundant with respect to the task may not be, on the whole, more appropriate. Indeed first all their kinematic chains are identical (which is not the case for 4 and 5 d.o.f. robot) which will reduce the maintenance cost. Then by using the redundancy it is possible to optimize the performances of the robot for a given task: for example for machining operations which require only 5 d.o.f. it is possible to use the extra d.o.f. of a 6 d.o.f. Gough platform so that the overal stiffness over a typical trajectory will be 5 to 25% larger than the stiffness of an identical robot in which the redundancy is not used [50].

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[2] It can be shown that parallel robots with as many identical kinematic chains as d.o.f. cannot have 4 ou 5 d.o.f. except if special kinematic chains are used

Redundancy is also an interesting and open research area [57]. In the field of parallel robot for machine-tools redundancy has been used to increase the workspace of the robot (such as in the Eclipse parallel robot [65]) and to deal with singularities. Another form of redundancy is the concept of *modular robots* [33, 34, 71] in which additional actuators allow to adapt the geometry of the robot according to the task to be performed The main unsolved problem for redundant parallel robot is to determine how to use the redundancy for an optimal use of the robot.

MEMS parallel robots is also an exciting research area. Indeed the motion principle of such mechanism can be used at any scale, from very large motion platform for driving ot flight simulators to micro scale robots. Already parallel robots of millimeters size have been built [3, 6, 44, 60] while the concept of even smaller robots has been proposed [42]. The current technology for actuators and sensors does not allow yet for the development of robot in the millimeter (or lower) size but this will probably change in the near future. The change in size will have a large influence on the physics of such system (gravity will have a very low influence while atomic forces will become preponderent) and new types of analysis will be required.

3.2 Joints, actuators and sensors

Parallel robots require higher kinematic pairs with relatively large amplitude of motion and, in some cases, relatively high load. Current available joints (either ball-and-socket or U-joints) are not completely satisfactory from this view point although recent products like the INA or Hephaist joints have been developed especially for parallel robots [21]. Hence the development of higher kinematic pairs with 2 to 4 d.o.f. is a key issue. As for any mechanical joints these joints must have a low friction, no hysteresis and must have a very reduced backlash. But in addition these joints must be designed so that it is possible to add sensors to measure partly or totally the amplitude of the motion of the joints (which is important for the forward kinematics as mentioned in the next section). Note also that flexible joints is also an interesting field of research, especially for micro-robot [56].

As for the actuators many robot are using linear actuators.In the field of machine tools some parallel robot such as the Urane SX of Renault Automation are using linear electric motor which exhibit impressing accelerations. But there is a lack of linear actuators and sensors for micro parallel robots [44].

Parallel strucures offer also the use of interesting alternate actuators such as:

- *wires*: instead of using rigid links wires may be used as soon as the platform is submitted to an external wrench [2]. They allow for very fast and light robot [36] that may be used as alternate to classical solution. But they also involve to solve more complex problems which are induced by the fact that wires cannot be used to push the platform (this modify for example the workspace of the robot [69])

- *binary actuators*: these actuators have only a finite number of state (for example only 2 states: either fully extended or fully retracted). By combining several platforms using these actuators one can get a robot that can reach a very high number of poses [10]. This allows to obtain very inexpensive robots that may be very fast and constitute an interesting alternative to classical robot for some specific appliations such as pick and place. But the theoretical analysis of such robot is quite difficult [9, 19, 38, 52, 72]
- *spread-band*: this is an interesting concept in which the rolling of a spread-band allow to built a very light and compact actuator [66]. The buckling effect may be a drawback but for specific applications, such as spatial one, the concept is worth investigating

4 Kinematics

4.1 Inverse kinematics

Everybody will agree that *inverse kinematics* (IK) is one of the basic element of any robot controler. Fortunatly it is known that inverse kinematics is usually straightforward for any parallel robot. More precisely in most cases

- there is a unique solution to the IK (in some cases provided that physical constraints are taken into account like for the Delta robot [11]).
- each joint variable may be computed independently being given the desired pose of the robot

The later point is a key difference with serial robot and allows for very fast IK provided that the controler hardware is appropriate. It may be thought that the development of a dedicated IC for the IK will be a major component of an effective parallel robot controler.

4.2 Forward kinematics

The major kinematics problem is the *forward kinematics* (FK), which consists in finding the possible pose of the platform forgiven joint coordinates (the solutions are called the *assembly modes* of the robot for the given joint coordinates). THe FK is a more complex problem than its dual IK counterpart for serial robot. The need of the FK is a controversed question. It may be thought that FK is an academic question that may be usefull only off-line for simulation purposes as a parallel robot will be position controled using IK only. In my opinion pure position control is very difficult for parallel robot especially when there are constraints on both the trajectory and the velocity of the robot (for example when the robot is used as a machining tool). In that case velocity control, which imply solving the FK, is much more appropriate.

FK is an area where a lot of progress has been made thanks to a collaborative work with mathematicians (which has benefited from this problem: solving the

FK of a Gough platform is considered now as a classical bench in algebraic geometry). Although there are many mechanical architecture of parallel robot the FK problem for most of them may be reduced to solve the FK for a few key architecture. For example solving the FK for the Gough platform [25] allows to solve the FK of the Hexa [58] or the Hexaglide [29] although the mechanical architectures of these robots are quite different.

It is now well known that the FK of the Gough platform may have up to 40 solutions [61, 63] and that all these 40 solutions may be real [18]. Numerous works have provided a deep understanding of the problem [20, 39, 51], which in turn has led to efficient algorithms for determining all the solutions of the FK [30, 64, 70] using elimination, Gröebner basis or interval analysis. Although impressing progress have been made these algorithms are not yet real-time and furthermore it cannot be said that FK is a fully solved problem. Indeed the true FK problem is to determine the current pose of the platform being given the joint coordinates. The algorithms provide all the solutions and hence it is necessary to sort the solutions to determine the current pose. *Hence the true unsolved FK problem is to complement the current algorithms with a sort algorithm that will reject solutions that cannot be reached from an initial assembly mode by a singularity and interference free trajectory (and it is unclear if this criteria will be sufficient to eliminate all but one solution).*

For real-time purpose many authors have proposed the use of the Newton-Raphson iterative scheme that assumes that an estimate of the solution is known. This scheme allows for possibly determining one solution of a non-linear square system of equations. There are many ways to model FK equations, not all of them being equivalent in term of quality of the result, computation time or size of the convergence domain [50]. Furthermore it is not so well known that this scheme may converge toward a solution that is not the closest to the estimate, whatever close is the estimate to this desired solution. Interval analysis based methods are good alternate with a similar computation time thant Newton scheme and guarantee on the results. These methods share with the Newton scheme the possibility of a distributed implementation and we believe that this opportunity must be used in a robot controler to speed up the FK which is essential for the control of the robot.

Another interesting possibility is to have a number of sensor which is larger than the number of d.o.f. of the platform. The extra sensors may allow to determine the current pose of the platform (and may also be used for the calibration of the robot, see the corresponding section). But it is necessary to:

1. determine the number and location of the extra sensor(s) so that a unique solution of the FK is found
2. study the influence of the sensor errors on the FK
3. carefully determine the speed-up that the extra sensors allow for the FK

Although this field has been recently investigated [4, 5, 45, 55, 67] many problems are still unsolved, especially for point 2.

5 Singularities

There are various ways to introduce the concept of singularities but the most spectacular one is to consider the static behavior of the robot. Let $\mathcal{F}$ be the wrench applied on the platform of the robot and τ the set of joint forces. These quantities are linearly related by

$$\mathcal{F} = J^{-T}(X)\tau$$

where J^{-T} is the transpose of the inverse jacobian matrix of the robot that is pose dependent. Each componant of the joint forces vector may thus be obtained as a ratio:

$$\tau_i = \frac{A}{|J^{-T}|}$$

where A is the determinant of the minor associated to τ_i. Hence, provided that A is not 0, the joint force τ_i will go to infinity at any pose, called *singular poses*, where the determinant of J^{-T} is 0, causing a breakdown of the robot (in fact the breakdown will occur well before reaching the singularity).

Although the condition $|J^{-T}| = 0$ seems to be a simple condition as the matrix J^{-T} has an analytical form, the full calculation of this determinant leads to a complex expression with a large number of terms (especially if the robot has 6 d.o.f.) which is useless in practice.

We have now a better understanding of singular configurations. They will occur for specific geometrical configurations of the robot that may be determined, whatever is the number of d.o.f of the robot, using line geometry [47]. We have now efficient algorithm that allows to determine if singular configurations exist either in the reachable workspace of the robot or in a specific workspace for the platform [49]. We may also test in near real-time the presence of singularity on any arbitrary trajectory [43].

But this does not mean that all problems related to singular configurations are solved. Forexample:

- a better characterization of singular configurations is needed.Indeed singularity are dangerous if only the denominator of τ_i goes to 0. Indeed if the numerator goest also to 0, then the joint force may still be finite
- it is usually claimed that singularity should be avoided: this is true except that manipulators that are *permanently* singular [35, 31] may also be of interest as they allow to perform complex motion of the platform of the robot with only one actuator, motion that may be of interest for example for machining operation. We believe that such manipulators are worth investigating in practice

6 Workspace

It is well known that a main drawback of parallel robot is their reduced workspace. Furthermore computing this workspace is not an easy task as, at the opposite of classical serial robot, the translational and orientation workspace are coupled. Classicaly a first approach to solve this problem is to fix the values of some d.o.f. until only 3 d.o.f. only are free. This is usually done by fixing either the orientation of the platform or the location of its center. In the first case the geometrical approach that determine geometricaly the possible motion of the center of the platform for each kinematic chains leads usually to the best result as it provides exact calculation with a compact storage and easy representation [24]. Orientation workspace is more difficult to deal with as there is no universal way to represent this workspace.

Another approach is to calculate an approximation either of the border of the whole workspace using a numerical method [1, 26] or interval analysis [48]. The later approach has the advantage to be able to deal also with limits on the motion of the passive joints and to allow for workspace verification (i.e. to check if a desired workspace is included in the workspace of the robot). It has also the flexibility to deal with the calculation of various types of workspace (for example to determine all the possible locations of the center of the platform such that it is possible to have any orientation of the platform within some prescribed ranges for the orientation angles).

In this field remains two unsolved problems:

- a fast algorithm to compute the maximal motion of the platform
- an algorithm that allows to check for links interference. This is a much more complex problem than may be thought. Indeed it is necessary to determine all the hyper-surfaces in the workspace for which a pair of kinematic chain intersects in order to split the workspace in interference-free regions and then to determine in which region the initial assembly modes is located to obtain the workspace of the robot.

7 Motion planning

Motion planning is a classical problem for serial robot. But in the case of parallel robots the problem is somewhat different: while for serial robot obstacle avoidance is the main reason for motion planning, its counterpart for parallel robot is the workspace. Possible problems are:

1. verify if a given trajectory lie completely within the workspace of the robot
2. determine if two poses may be reached by a singularity and interference free trajectory that lie completely within the workspace of the robot

Problem 1 can be solved for almost any arbitrary time-function trajectory using interval analysis [43], while problem 2 has no known solution at this time.

8 Calibration

Calibration is a well known problem for serial robots and is now a well-treated problem. It may be thought that the calibration of parallel robots may rely on the methods developped for serial robot but unfortunatly this is not exactly the case. Indeed there is a major difference between both robots: for serial robot small errors on the geometrical parameters induce large errors on the positioning of the end-effector while for parallel robots these errors will also be small. Simulation for calibration is essential: it allows to determine how much a calibration method is sensitive to noise in the measurements and to numerical errors. It allows for example to show that methods directly adapted from the calibration of serial robots may lead to results that are worse than the initial guess as soon as the simulated measurement noise is realistic ....

There are two types of calibration methods:

- *external*: an external measurement device is used to determine for different configurations of the platform what is the pose of the platform (completely or partially). The differences between the measured pose and the controler input pose give an error signal signal that is used for the calibration [17, 22, 32, 41, 53, 73]
- *self-calibration*: the platform has extra sensors (for example sensors that are used for the FK) and only the robot measurements are used for the calibration [8, 16, 37]

The first method is difficult and tedious to use in practice but may give good results. The second method may be less accurate but is easy to use and has also the advantages that it can be fully automatized.

An interesting theoretical problem is to determine what are the measurement configurations of the platform that will lead to the best calibration. Then there is also the problem to put calibration in use in a realistic, industrial environment.

9 Dynamics

Another advantage of parallel robots is that they can reach a high acceleratio-nand velocity, due to their light mobile mass [13, 29, 59]. But control of such robots is a difficult task: although numerous works have reported methods for computing the dynamic model of a parallel robot they are all computer intensive (and involves also solving the FK problem). An important problem is to determine what should be the computation time of the calculation of the dynamic model so that its use in a control loop will really leads to an increase in the performance of the robot. This is a very complex issue especially if it is considered that the control algorithm is not continuous. The second key issue in this field is to implement the control scheme. In my opinion the involved computation time implies the use of a distributed computation scheme: implementation considerations will hence have a large influence on the choice for the control algorithm and for the dynamic model.

10 Synthesis

It is well known that the performances that will be reached by a mechanism depends upon:

- the *topology* of the mechanism
- the *dimensions* of the components of the mechanism

This is especially true for closed-loop mechanisms that are **highly sensitive** to both factors. Hence to design a parallel mechanism so that its performances fit at best a list of requirements both aspects must be adressed:

- *topological synthesis* i.e. finding the general arrangments of joints, links that will describe the general kinematics of the structure.
- *dimensional synthesis* i.e. finding the precise values for dimensioning the mechanism.

Synthesis of parallel robot is an open field (there is a very limited number of papers adressing this issue) and, in my opinion, one of the main issue for the development of parallel robots in practice. The use of parallel structures in the field of machine-tool has shown that designers which have a deep understanding of open-loop mechanisms but have a total lack of experience in closed-loop have focused only on the development of the basic mechanical components of their machine and have almost completely neglected the analysis part. Many such machines have thus suffered from elementary errors: a direct consequence was a reinforcment of a trend that claim that parallel structures is only an academic field that will never be put in practice. As for any human activity one single failure has more influence than numerous success.

10.1 Topology synthesis

This is a very complex problem for parallel mechanism at the opposite of open-loop mechanism for which the number of possible combinations is relatively reduced. Currently topological synthesis for parallel robots is restricted to find a mechanism with a given number of d.o.f without considering other performance criterion and is still mostly done intuitively. There is total lack of automated tool for topological synthesis and even no existing convention for naming a closed-loop mechanism. Although over 100 mechanical architectures of parallel mechanisms have already been proposed I feel that not all possible combinations have been found

An additional difficulty for closed-loop mechanisms is that topological synthesis cannot be considered independently from dimensional synthesis: it is usually not possible to compare a-priory the performances of two mechanical designs just by inspection of their topology at the opposite of open-loop mechanisms for which such qualitative comparison is sometime possible. For example the workspace volume of a Cartesian robot using 3 linear actuators of stroke

L is roughly L^3 while this volume for a 3R robot whose links has length L is roughly $4\pi(3L)^3/3 \approx 113L^3$: hence in general a 3R robot will have a much more larger workspace than a Cartesian robot, at least for a similar dimensioning.

A first approach to topology synthesis is based on the Gruëbler mobility formula Its use is quite simple but this formula does not take into account the geometry of the arrangment of the kinematic pairs and hence may lead to invalid results. Furthermore a Gruëbler based topological synthesis approach cannot benefit from the use of specific geometric arrangments that allow for specific motions.

Alternative approaches are:

- *group theory* [27] which is based on the mathematics of the motion group. This is an interesting approach that allows for some automated reasoning [15] but which is limited as it is necessary to preserve the group mathematical structure
- *enumerative approach*: in this approach some key elements such as the type of actuators and their location are fixed and all the possible structures are derived [7, 23, 62]. Such approach is very intuitive and it is difficult to ensure that all possibilities are presented

In my opinion this area should be expanded and a standard way of describing parallel structure is needed (especially for an automated analysis of their performances as presented in the next section). Note also that an important point for topology synthesis has already been mentioned in the **Mechanical architectures** section: a structure may be based on special geometrical arrangments of the links leading to some specific properties for the mechanism but in practice the geometry may not exactly fulfill the theoretical constraints. It is hence necessary to examine carefully what will be the effect of the manufacturing errors on the motion of the mechanism.

10.2 Dimensional synthesis

Parallel mechanisms are highly sensitive to dimensioning: a classical example is that by changing the radius of the platform of Stewart-Gough platform by 10% we may change the minimal stiffness of the robot over its workspace by 700%.

I have already discussed existing dimensional synthesis method [46] but, in my opinion, none of them are appropriate for parallel robots which have usually a large number of design parameters. Furthermore these methods lead to a unique solution: in the case of parallel robots we believe that there will be usually not a single solution to a design problem. Indeed:

- some performance criterion are antagonistic. One example of such antagonistic criterion are workspace and accuracy: a very accurate robot will usually have a small workspace and vice-versa. Hence a design solution is only a compromise between various requirements that are difficult to compare

- the designer may not be fully aware of all the requirements (for example their economical impact)

Therefore a design methodology should provide not only one single solution but, if possible, all the possible design solutions, or, at least, an approximation of the set of all design solutions.

10.3 Performance analysis

Whatever is the design methodology it will be necessary to have a *performance analysis* module. Being given a mechanism of known topology and dimensions the aim of a performance analysis module is to determine what are the performances of the mechanism. In the synthesis domain such module is used mostly to compare different design solutions, while for simulation purposes the objective will be to determine the performances of the robot.

Performance analysis is difficult for parallel robot. Indeed most interesting performances index are related to the determination of the optimum of a function over a given set. For example the accuracy index consists in determining the worst case positioning error $\Delta\mathbf{X}$ of the platform being given the sensor accuracy $\Delta\rho$, *over the workspace of the robot.* Both quantities are related by

$$\Delta\rho = J^{-1}(X)\Delta\mathbf{X}$$

where J^{-1} is the inverse jacobian matrix of the robot, which is pose dependent. Hence determining the accuracy index is equivalent to solving a constrained optimization problem. In this case the problem is quite difficult as an analytical form of J^{-1} is usually known, while J (which will allow to obtain an analytical form of the criteria to be optimized) has a complex form. It must be noted that the exact calculation of the accuracy index is still an open problem and that it is the case for most performance index of parallel robots.

A key point for performance analysis for synthesis is that the result must be *guaranteed* as it will be used to compare different design solutions. Hence the usual method of discretizing the workspace and computing the accuracy index at a limited number of points within the workspace is not a valid approach. But guaranteeing the result does not mean that the index should be computed *exactly*, even in the computer science signification of this term (i.e. up to the accuracy of the computer). Indeed as the result will be used for comparison purposes it has to be calculated only up to an accuracy that allows for a right choice between different solutions. For example if is possible to compute for two robots that their accuracy index lie in the ranges $[a_1, b_1]$ for the robot 1 and $[a_2, b_2]$ for robot 2 with $b_1 < a_2$, then we may conclude that the robot 1 is more accurate than the robot 2, even if the width $b_1 - a_1$ of the range (i.e. the accuracy with which we have computed the accuracy index of robot 1) is quite large. In my opinion any performance analysis module should take advantage of this property to speed-up the calculation of the performance index as any design methodology will use extensively the performance analysis module.

10.4 Dimensioning methodology

As mentioned in the previous section a design methodology should allow to determine not one single solution but a set of possible solutions and ideally all the design solutions.

Mathematically speaking let $\mathcal{P}$ be the set of n design parameters and let us introduce the *parameters space* as a n dimensional space in which each dimension corresponds to one of the n design paramters. In the parameters space a point represents an unique robot geometry and the purpose of the dimensioning methodology should be to determine the regions of the parameters space such that if a point belong to a region, then the corresponding robot fulfill the requirements.

Clearly determining these regions is not an easy task but a possible approach is to determine them incrementally: for each requirement i the region $\mathcal{R}_i$ corresponding to the robots that satisfy the requirement are computed and the design region will be obtained as the intersection of all the $\mathcal{R}_i$. Alternatively as soon as one of the $\mathcal{R}_i$ has been calculated it can be used as starting point for the determination of a region $\mathcal{R}_{ij}$ where both the requirements i and j are satisfied and so forth. Such approach has been proven to be effective for the workspace requirement [48, 49].

In my opinion the development of a generic optimal design and simulation software for parallel robot is one of the most exciting tasks in this field. Such software should be able to deal with any mechanical architecture and requirements: clearly this will represent a huge development both at the theoretical and software level that justify a collaborative work of academics (from may different fields), companies that develop parallel robots and end-users. This is why the Computational Kinematics Technical Committee of IFToMM has launched the Parallel Kinematic Initiative (PKI)[3] for encouraging collaborations in this field.

11 Controler

The developments proposed in the previous sections will lead to an effective system only if the robot controler allows for dealing with the specificities of parallel robots. Unfortunatly the current trend, especially in the field of machine tool, is to try to adapt existing hardware for the purpose of controling parallel robots. If this trend may be justified when starting a project with parallel robots it will drasticaly penalize the performance of the system on the long term. If we take as example the machine-tool field we may analyze the errors on the fabricated parts that are due to each element of the system: the CAD system that is used to define the parts and which is generating motions for the platform, the controler that monitor the execution of these motions and finally the platform itself. Using current technology it can be shown that the CAD system is responsible of approximatively 20% of the errors, the platform (if

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[3] `http://www-sop.inria.fr/EJCK/PKI/PKI.html`

optimaly designed) less than 10% while the controler induces 70% of the errors. Hence research should focus on the the CAD system (but existing methods may already improve this part) and mostly on the controler. The hardware of the controler should support:

- the possibility of using appropriate control laws, especially velocity control
- parallel computation (that will drastically improve the sampling time)
- specialized integrated circuits that will be devoted to basic computation tasks such as inverse and forward kinematics

12 Conclusion

In this paper we have tried to outline some open problems in the field of parallel robots (without pretending to be exhaustive). Some of these problems are long term while other are key issue for the short term possibilities of using parallel robots in practice. In the last 20 years we have gained a better understanding of the behavior of these complex closed-loop mechanims but there are still many unsolved and exciting problems. If we compare this 20 years to the 200 years that has been necessary to reach the current level of achievment for serial mechanisms we may conclude that there is still a long way to go on the road for parallel mechanisms.

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