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SEVERAL OPEN PROBLEMS IN PARALLEL ROBOTICS

ABSTRACT:
More than 20 years parallel robots attract the interest of the scientific community and in many applicative domains like, production of motion generators, machine tools, precision positioning devices, medical equipment, pick and place machines, etc., where their potential advantages (high accuracy, rigidity, speed, acceleration and load carrying capability) could be very useful. The objective of this paper is to notify some of the open questions in parallel robotics, which is limitation factor of wider practical application of this type of robots.

KEYWORDS:
parallel robots, open problems, research

INTRODUCTION

A **parallel robot** *is composed of two or more closed-loop kinematic chains in which the end-effector (mobile platform) is connected to the base (fixed platform) by at least two independent kinematic chains. Between the base and end-effector platforms are serial chains (called limbs or legs) [90] (fig.1).*

Parallel robot could be named as hexapod, a Stewart platform, Gough platform, Stewart-Gough platform, a parallel kinematic machine (PKM) or a parallel manipulator. Theoretical work on parallel mechanisms dates back to as early as 1645 by Christopher Wren, then in 1813 by Cauchy and in 1867 by Lebesgue. Variable-length-strut hexapods, as those used in motion simulators [31,84] have existed almost 50 years.

Parallel mechanisms are stronger than serial because the load is distributed among all legs, but also because, for some architectures, the legs are only subjected to axial loads. Also, parallel robots theoretically should be more precise since they are more rigid, and since the errors in the legs are averaged instead of accumulated. Finally, these robots are faster since they usually have their heavy motors mounted on the base (fig.1)

On the other hand, parallel robots have a more limited and complex-shaped workspace. Moreover, the rotation and position capabilities (if both present) of parallel mechanisms are highly coupled which makes their control and calibration extremely complex. Furthermore, parallel mechanisms generally have singularities within their workspace and computing the resulting end-effector position for a given set of actuator inputs is, in general, a very difficult and complex problem allowing up to 40 solutions.

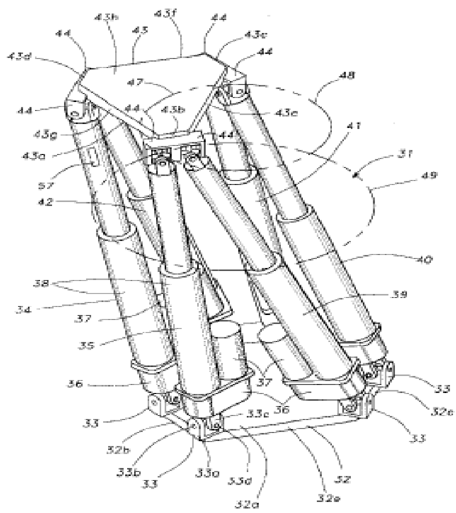

FIGURE 1. A FANUC parallel robot [94] (US patent No. 5987726) [93]

General overview of the main characteristics of the parallel robots are given in the table below:

Table 1.

Feature	Parallel robot
Workspace	Small and complex
Solving forward kinematics	Very difficult
Solving inverse kinematic	Easy
Position error	Averages
Force error	Accumulates
Maximum force	Summation of all actuator forces
Stiffness	High
Dynamics characteristics	Very high
Modelling and solving dynamics	Very complex
Inertia	Small
Areas of application	Currently limited, especially in industry
Payload/weight ratio	High
Speed and acceleration	High
Accuracy	High
Uniformity of components	High
Calibration	Complicated
Workspace/robot size ratio	Low

In the past two decades parallel robots very much attracted the interest in the robotics community. Great interest for parallel robots come from the potentially interesting features of parallel mechanisms: high accuracy, rigidity, speed and large load carrying capability, which in a very large number of cases may overcome the drawbacks of the more complex kinematics, dynamics and smaller workspace. The great interest could be exemplified by a large number of papers published on this subject together with the application of parallel robots in very different domains such as fine positioning devices, simulators, motion generators (platforms), ultra-fast pick and place robots, machine-tools, medical applications, haptic devices, entertainment, force sensors, micro-robots, etc.

But in fact all these advantages of parallel robots are only potential. 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. However in many cases unexpected difficulties in the design and control of such complex system have led to performances which, although still better than conventional serial mechanical architectures, were fare below what was expected. In some cases, for example, the machine tools, performances were even the worst [89].

In the following we will give some examples of some open problems in parallel robotics, which makes limitation of wider practical application of this type of robots.

OPEN QUESTIONS IN PARALLEL ROBOTICS

Mechanical design

A lot of different mechanical architectures of parallel robots, more than 100 according [60] with 2 to 6 DOF have already been proposed and it is probable that not all of them have been discovered. Analysis of the literature shows that more than 80% of the parallel robots are with 3 DOF and 6 DOF. The rest are parallel robots with 5 DOF, 4 DOF, and 2DOF. Unfortunately there are not so many proposed architecture that have only 4 or 5 DOF, while many applications require such number of DOF. For example 4-DOF is sufficient for most pick-and place applications, and 5-DOF is adequate for every machine tool application.

There is a recent trend is to propose parallel robots with 4 and 5 DOF: [19, 69, 16, 18, 26, 50, 99, 21, 98, 104, 10].

It is really an interesting research area but many questions arise with this type of robots:

- *the proposed structures have in theory only 4 or 5 DOF and rely on geometrical constraints to obtain this reduced number of DOF. 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, produced by given manufacturing tolerances, [11, 33] 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 limits.*
- *having less actuators and sensors may sound economically interesting, but it is unclear, if classical parallel robots with 6 DOF which are redundant with respect to the task, are more appropriated. First of all their kinematic chains are identical (which is not the case for the most of 4 and 5 DOF robots). That will reduce the maintenance costs. Then by using the redundancy it is possible to optimize the performances of the robot for a given task*

Redundancy is also an interesting and open research area. In the field of parallel robots redundancy has been used to increase the workspace of the robot (such as in the Eclipse parallel robot [45]) and to deal with singularities [65]. The main unsolved problem for redundant parallel robot is to determine how to use the redundancy for an optimal use of the robot.

Joints

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 joints have been developed especially for parallel robots [25]. Hence the development of higher kinematic pairs with 2 to 4 DOF is a key issue [4, 81]. 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.

Compliant joints are also an interesting field of research, especially for micro-robots [62].

Forward kinematics

The biggest kinematics problem is parallel robotics is the forward kinematics, which consists in finding the possible position of the platform for given joint coordinates. The forward kinematics is a more complex problem than its dual inverse kinematics counterpart for serial robots. The need of the forward kinematics is a controversial question. It may be thought that forward kinematics is an academic question that may be useful only for off-line simulation purposes and a parallel robot will be position controlled using inverse kinematics only. Pure position control is very difficult for parallel robots, especially when there are constraints on both the trajectory and the velocity of the robot (for example when the robot is used as a machine tool). In that case velocity control, which implies solving the forward kinematics, will be much more appropriate.

Although there is much mechanical architecture of parallel robots the forward kinematics problem for most of them may be reduced to solve the forward kinematics problem for a few key architectures. For example solving the forward kinematics for the Gough platform [64] allows to solve the forward kinematics of the Hexa [68] or the Hexaglide [37, 17, 36] although the mechanical architectures of these robots are quite different.

It is now well known that the forward kinematics of the Stewart-Gough platform may have up to 40 solutions and that all these 40 solutions may be real. Numerous works have provided a deep understanding of the problem which in turn has led to efficient algorithms for determining all the solutions of the forward kinematics using elimination, Gröebner basis or interval analysis. Although impressing progress has been made these algorithms are not yet real-time and furthermore it cannot be said that forward kinematics is a fully solved problem. The research continues with the works [58, 100, 40, 30, 79], etc.

The true forward kinematics problem is to determine the current position 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 position. In fact the true unsolved forward kinematics problem is combination of the current algorithms with a sorting algorithm that will reject solutions that cannot be realized physically because of the presence of singularity or of the possible interferences on the trajectory. Also it is unclear if this will be sufficient to eliminate all solutions, or only one.

Another approach to solve the forward kinematics is to add extra sensors to the robot. Each extra sensor will provide an additional equation, leading to an over-constrained system which hopefully will have a unique solution. The problem is here to determine the minimal number of sensors and their location in order to have a unique solution with the simplest analytic form and quite robust with respect to the sensor errors. Some of these problems have been analyzed in [8, 45, 29] but this issue is far from being solved. Adding extra sensors may play also an important role in the robot calibration.

Singularity analysis

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

$$F = J^{-T}(X)\tau \qquad (1)$$

where J^{-T} *is the transpose of the inverse Jacobian matrix of the robot that is position dependent. Each component of the joint forces vector* τ_i *may be obtained as a ratio:*

$$\tau_i = \frac{A}{|J^{-T}|} \qquad (2)$$

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

Although the condition $|J^{-T}|$ *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 DOF).*

This remains an important topic of study although many progress have been made in this field, for example the geometrical classification of the singularities or algorithms for detecting singularities in a given workspace [59]. We should also mention the works of other authors dealing with singularities for different types of parallel robot manipulators like [44, 13, 2, 3, 83, 95, 96, 47, 102, 103, 51, 41].

Singularities for different configurations of parallel robots still remains open field for research.

Another open question is global analysis of singularity in relation with the workspace and trajectory planning. In that field we should mentioned the work of [24].

Workspace

One of the main drawbacks of parallel robots are their reduced workspace. Furthermore computing this workspace is not an easy task. Opposite of classical serial robots, here the translational and orientation workspace are coupled. Classically a first approach to solve this problem is to fix the values of some DOF until only 3 DOF are free. This is usually done by fixing either the orientation of the platform or the location of its centre. In the first case the geometrical approach that determine geometrically the possible motion of the centre 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.

Orientation workspace is more difficult to deal with as there is no universal way to represent this workspace. Here we could mention the works [7] and [70].

Another approach is to calculate an approximation either of the border or of the whole workspace using a numerical method. Some of these approaches have 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). They may also calculate various types of workspace.

Analysis of the workspace for different types of parallel robots is given in [20, 6, 54, 96, 24, 49, 71, 72].

Workspace analysis for different configurations of parallel robots still remains open research field.

Other unsolved problems are:

- *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 in the first moment. 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 interference-free workspace of the robot. This is a difficult task even for robot with very simple kinematic chains [15].*

Motion (trajectory) planning

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

- *verification if a given trajectory lie completely within the workspace of the robot*
- *determine if two positions may be reached by a singularity free 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 [59], while problem 2 has some particular solutions [22, 24, 82, 85]. A lot of work has to be done in this area.

Calibration

Although this problem has been solved for serial robots, this is not the case for parallel robots. Indeed, for a serial robot, small errors in the geometric parameters of the robot lead, in general, to a large difference between the real position of the end-effector and the expected one. This difference may be evaluated by measuring the position of the end-effector and then be used in an optimization procedure which will determine values of the parameters decreasing the positioning errors. Applied to parallel robot this method leads to calibration result that are in general disastrous. One of the advantages of parallel robot is that large errors in geometric parameters may lead to quite small errors in the position of the end-effector. Furthermore the measurement noise has a large influence on the results of the calibration process.

There are two types of calibration methods:

- *external: an external measurement device is used to determine (completely or partially) what is the real position of the platform for different desired configurations of the platform. The differences between the measured position and the desired position give an error signal that is used for the calibration [92, 105, 27, 86, 73, 74, 75, 76, 42, 23, 80, 87].*
- *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 [63, 101, 27, 38].*

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

An interesting theoretical problem is to determine what are the measurement configurations of the platform that will lead to the best calibration. Of course there is an open problem to put the calibration in use in a real, industrial environment.

Dynamics

Another advantage of parallel robots is that they can reach a high acceleration and velocity, due to low mass of the moving elements [37,17].

A first problem here is to determine appropriate dynamic model of the robot. Various formulations may be used [56, 43, 97, 61, 48, 28], although some simplifying assumption have to be made.

A second problem is implementation of control algorithms, so that the use of the parallel robot dynamic model, will really improve the motion control of the robot, compared to more classical control laws [17, 37, 36, 32, 91, 14, 39, 78, 46, 88, 5, 77].

Computing the dynamic model of a parallel robot is time consuming (and involves also solving the forward kinematic problem). An important problem here 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 improvement of the performances of the robot. This is a very complex issue especially if it is considered that the control algorithm is not continuous.

Synthesis and optimal design

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

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

This is especially true for closed-loop, parallel, mechanisms that are highly sensitive to both factors. When we design a parallel mechanism so that its performances should best fit to the list of requirements, both aspects must be take into consideration:

- topological synthesis i.e. finding the general arrangements of joints, links that will describe the general kinematics of the structure.
- dimensional synthesis i.e. finding the appropriate dimensioning of the mechanism.

Synthesis of parallel robot is an open field (there are very limited number of papers dealing with this problem) [1, 9, 26, 57] and the main task for the development of parallel robots in practice.

The problems caused by using parallel structures in the field of machine-tool has shown that designers which have a deep understanding of open-loop mechanisms but, have not experience in closed-loop are focused only on the development of the basic mechanical components of their machine and have almost completely neglected the analysis part.

Topology synthesis is a very complex problem for parallel mechanisms at the opposite of open-loop mechanisms for which the number of possible kinematic combinations is relatively reduced. Currently topological synthesis for parallel robots is restricted to find a mechanism with a given number of DOF without considering other performance criterion(s)

Parallel mechanisms, robots, are highly sensitive to dimensioning. One classical example given by [59] 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% .

According, [59] none of existing dimensional synthesis methods 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 usually will not be a single solution to a design problem and providing only one design solution is not realistic. The main difficulty comes from the criterions which have to be considered: some of them are antagonistic (workspace and accuracy-a very accurate robot will usually have a small workspace and vice-versa), or not continuous (no singularity within the workspace), etc.

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.

With the optimal design (also includes topological synthesis and dimensional synthesis) which is crucial issue for development efficient parallel robots, several interesting problems could be solved, like optimization of:

- robot kinematics (workspace, accuracy, maximal motion of the passive joints, dexterity, accessibility, motion pattern, kinematic error)
- robot dynamic (robot max acceleration, robot max speed, inertia, centre of mass)
- robot flexibility (robot stiffness and robot natural frequencies).

Optimal design is open and actual problem. Very few papers could be find in this area [66, 67, 52, 53, 12, 34].

Controller

Parallel robot will be effective system only if the robot controller allows dealing with the specific characteristics of parallel robots. Unfortunately the current trend, especially in the field of machine tools, is adaptation of existing hardware for the purpose of controlling parallel robots.

If may be, this trend could be justified at the beginning of parallel robotics, long term this will have very bad effect on the robot performances.

Analysis in the machine-tool field have shown that more of the 70% errors on the fabricated parts are induced by controller, CAD system is responsible of approximately 20% of the errors, and the Stewart-Gough platform (if optimally designed) less than 10% [59]. Hence research should be focused mostly on the controller. The hardware of the controller should support:

- the possibility of using appropriate control laws capable to deal with inherent non-linearities of parallel robots,
- 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

CONCLUSION

In this paper we notified some open questions in parallel robotics. Some of the problems are long term, but others should be solved as soon as possible in order to enable wider application of parallel robots in practice.

Serial and parallel robots probably will live parallel a long years. If we compare about 20 years research in parallel mechanisms and more than 200 years in research to reach the current level of knowledge for serial mechanisms, it is easy to conclude that this process of solving problems in parallel robotics will be long term.

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