Parallel manipulators: state of the art and perspectives

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Abstract:

Parallel manipulators have been under increasing developments over the last few years from a theoretical view point as well as for practical applications. In this paper, recent advances are summarized and various applications for this kind of manipulator are illustrated.

1 Introduction

1.1 Definitions

A parallel manipulator is a closed-loop mechanism in which the end-effector is connected to the base by at least two independent kinematic chains

A fully-parallel manipulator is a closed-loop mechanism with an n degree -of-freedom end-effector connected to the base by n independent chains which have at most two links and are actuated by a unique prismatic or rotary actuator.

1.2 Example

Let us consider the mechanism shown in figure 1. The upper plate (end-effector) is connected to the

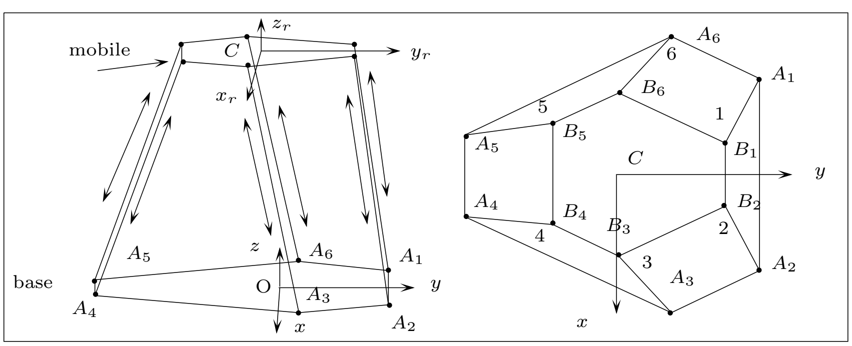

Figure 1: A parallel manipulator with 6 D.O.F: the SSM

base through 6 articulated links. Linear actuators enable to change the link lengths which in turn enable to control the position and orientation of the upper-plate. At the extremities of the links we find an universal joint (with center A_i) and a ball-and-socket joint (with center B_i). A reference frame (O, x, y, z) is attached to the base and a mobile frame (C, x_r, y_r, z_r) is attached to the moving platform. The posture of the moving platform is defined by the coordinates in the reference frame of C together with the rotation matrix defining the rotation between the reference frame and the mobile frame. The manipulator presented in figure 1 is called a SSM and is a special case of the general parallel manipulator as all the A_i (B_i) are coplanar. A general parallel manipulator will have the A_i, B_i in any position on the fixed and moving bodies.

This type of structure has been known for a long time. For example around 1800 the mathematician Cauchy studied the rigidity of an "articulated octahedron"[6]. More recently (1949) Gough [44] used a similar mechanism for the test of tyres. These structures were re-discovered in the 60's as they were the most practical solution for building active flight simulator. In 1965 Stewart [44] illustrated the use of a parallel structure for a flight simulator. Since this time, and although Stewart's mechanism is slightly different from the one in figure 1, parallel link mechanisms are often referred to as "Stewart Platform" although "Gough platform" will be more appropriate.

The choice of a parallel mechanism for a simulator platform is justified by one of its obvious advantages: the high nominal load/weight ratio. Indeed the weight of a load on the platform is approximatively equally distributed on all the links i.e. one link is submitted to only 1/6 of the total weight. Furthermore, the stress in the link is mostly traction-compression which is very suitable for the linear actuators as well as for the rigidity. This feature can be illustrated by referring to one of our parallel manipulator prototype which has a weight of 35 kg and a nominal load of 600 kg.

2 Parallel manipulator advantages

Although the excellent load/weight ratio may be useful, parallel link mechanisms also present other interesting features. A parallel manipulator was first used in a robotics assembly cell by McCallion in 1979 [25] mostly because the position of the end-effector of a parallel manipulator is much less sensitive to the error on the articular sensors than for serial link robots. Furthermore, their high stiffness insures that the deformations of the links will be minimal and this feature greatly contributes to the high positionning accuracy of the manipulator.

Another important feature of parallel manipulators is the possibility of using them as a 6-components force-sensor. Indeed it can be shown that the measurement of the traction-compression stress in the links enables to calculate the forces and torques acting on the mobile platform.

Many different designs of parallel manipulators are possible and the scientific literature on this topic is very rich. All have in common their low cost since most of the components are standard although the assembly of the manipulator has to be done with care. The design is important as some features may be upgraded by an appropriate choice.

3 Current research trends

As the architecture of parallel manipulators is very different from the one used for serial-link manipulators most of the theoretical problems have to be reconsidered. In fact there is a strange duality between parallel link mechanisms and serial link mechanisms: a difficult (simple) problem for one kind is easily solved (with difficulty) for the other kind. This duality has yet to be explained satisfactorily, although some attempts have already been made [47, 50].

3.1 Mechanical design

An interesting problem is to find a method to design a mechanical architecture for a parallel manipulator being given its number and type of degree of freedom. An approach of this problem based on group theory has been presented by Hervé. By using this approach this author has been able to design the new parallel manipulator with 3 translationnal d.o.f. *Star* [15]. But additional works remain to be done especially for designing robot combining translational and rotational d.o.f.

3.2 Kinematics

Two problems can be distinguished for the kinematic aspects: *inverse kinematics* and *direct kinematics*. The inverse kinematics problem i.e. finding the link lengths for a given posture of the mobile platform (a difficult problem for serial-link mechanisms) is straightforward for parallel manipulators. Thus their control is usually very simple. On the other hand the direct kinematics problem is much more difficult. In general, this problem has more than one solution. For example, if we consider a manipulator similar to the one of figure 1 but with a triangular mobile plate, there will be up to 16 different postures of the problem for a given set of link lengths [29]. Lazard [19] showed that there will be no more than 40 solutions for the SSM and more recently Ronga [40] shows that even in the most general case there will be no more than 40 solutions. Some algorithms have been presented to solve special cases [1, 2, 16, 29]. But no closed-form solutions have been discovered except in some very special cases of manipulators [20]. In practice, iterative numerical procedures are used without any problems [39].

Another practical way to solve the direct kinematics problem is to add appropriate orientation sensors in the links enabling to compute the posture of the mobile platform [3, 17, 27].

3.3 Dynamics

As fast parallel manipulators can be designed the calculation of their dynamic model is necessary in order to get a satisfactory control. A full dynamic model in closed-form has yet to be established but fortunately some assumptions can be made enabling simplified but efficient dynamics behavior to be simulated. Recently many researchers have addressed this problem [8, 21, 35, 37, 38, 42, 45].

3.4 Force-feedback control and Compliance

As a parallel manipulator can be equipped with a 6-component force-sensor, it can carry out various tasks involving contact with its surroundings (assembly, surface following) and therefore a force-feedback scheme can be used. Successful experiments have been performed using a parallel manipulator alone [4, 26, 38] but interesting problems remain to be solved when both a macro and micro manipulator are used [38]. An interesting point about parallel manipulators is that, although they are very rigid, passive compliance can be obtained either by using pneumatic actuators [38] or by adding elastic dampers in their links [26]. In either case an appropriate choice of the position of the link's sensors enables the posture of the mobile platform to be calculated precisely whatever are the elastic deformations of the links. Some researchers have also addressed the problem of determining a design which insures that, at least for some postures of the mobile platform, the stiffness matrix is diagonal [11].

3.5 Singular configurations

As for serial link mechanisms, a parallel manipulator can be in a singular configuration i.e. in a configuration where no articular forces can balance an external wrench applied to the mobile platform. It is important to determine these configurations as, in their vicinity the articular forces may tend to infinity causing a breakdown of the manipulator. Singular configurations are characterized by the zeroing of the determinant of the inverse jacobian matrix. Although this matrix is known, the symbolic computation of its determinant yields in most cases a huge expression and finding the closed-form of its roots seems very difficult. A numerical procedure can be used [9] but a geometrical approach enables to establish efficiently the relationships between the position parameters characterizing a singular configuration [28]. An open problem is to determine if there are singular configurations inside the workspace of the parallel manipulator although singular loci and the workspace can be plotted simultaneously for planar parallel manipulators [41].

3.6 Workspace

In contrast to common serial link mechanisms with three intersecting wrist joint axes the workspace of a parallel manipulator cannot be decoupled in two 3D workspaces characterizing the possible translation and orientation motions. Therefore the workspace is completely imbedded in $R^3 \times \mathrm{SO}(3)$ and there is no human readable way to represent it. However some projections of the full workspace can be drawn. For example it is usual to represent the possible translations of the robot in a plane for a fixed orientation and altitude of the mobile platform, either by using a discretization procedure [4, 10] or, more efficiently, a geometrical algorithm [12, 30] which can take into account the limited range of the actuators, the mechanical limits of the passive joints and links interference. It is also possible to assume that one point of the mobile plate is fixed and the possible rotations of the mobile plate around this point can be illustrated [31]. A corollary problem has also been recently solved: verifying that a straight line trajectory lie fully inside the workspace [32].

3.7 Calibration

The accuracy of a parallel manipulator is not only dependent upon an accurate control of its links lengths but also upon a good knowledge of its geometrical characteristics. According to the fabrication tolerances many factors will play a role in the final accuracy of the robot. Wang [49] has shown that up to 132 parameters will be necessary to describe the geometrical features of a Gough platform. However by a careful design these parameters may be reduced to the set of coordinates of the joint centers (36 parameters) and link offsets (6 parameters). The calibration of parallel manipulators remains an open problem although some recent papers have addressed this issue [51, 48, 24]

3.8 Parallel manipulator in truss

An interesting articulated truss can be built by joining parallel mechanism modules [34, 46]. This leads to light, highly redundant manipulators for which interesting kinematics and control problems have yet to be solved. These kinds of manipulators may be interesting in space applications.

4 Practical applications

Although the concept of parallel manipulators is quite recent, many interesting prototypes [3, 10, 14, 17, 18] have been proposed by various laboratories. The parallel manipulators developed at MEL in Japan should be mentioned: one of them being a micro manipulator which linear actuators range are a few micrometers enabling to perform motions of a few nanometers [5] and on the other hand one being a huge manipulator to be used for mining purposes [36].

The first commercial parallel manipulator, the "Gadfly", a 6 d.o.f manipulator intended to be used for the assembly of electronic components, was designed by Marconi [22]. Later this company designed a huge hybrid serial-parallel manipulator, the "Tetrabot" [23]. A fast 3-4 d.o.f. parallel manipulator, the "Delta" robot [43], is now being sold by the Demaurex company. This manipulator is used for very fast pick-and-place tasks of light loads. The nice mechanical design enables it to reach high velocities and accelerations. A 6 d.o.f. manipulator based on a similar design, the *Hexa* is currently under development [37]. A new product the SmarTee is now proposed by Hughes [7].

As application examples let us mention the use of one of our prototype [33] for ophthalmic surgery operation [13] and the use of a more classical Gough platform at the European Synchrotron Radiation Facility (ESRF) for the manipulation of heavy experimental setups with a repetability better than 0.1μm for a load of 230 kg (figure 2).

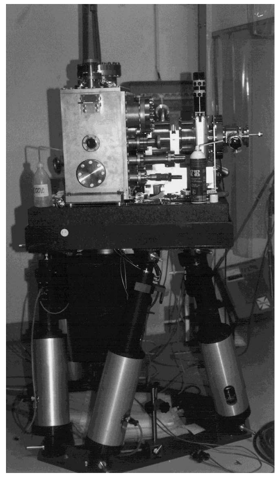

Figure 2: An example of application of a parallel manipulator as a fine positionning device for heavy load: the ESRF robot

5 Conclusion

Parallel manipulators present various advantages which can be useful in many robotic tasks. Although interesting theoretical problems remain to be solved, the current state of the art has enabled prototypes and commercial manipulators to be designed.

Although the concept of parallel manipulator is too recent and too different from the design of most classical manipulators to be widely accepted and frequently chosen by the designers of robotic systems, it is strongly felt that their use in many robotic tasks is so necessary that they will become indispensable in the near future.

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