Parallel manipulators: state of the art and perspectives

J-P. Merlet

INRIA Sophia-Antipolis, 2004 Route des Lucioles, BP 93, 06902 Sophia-Antipolis Cedex, France

Abstract:

Parallel link manipulators are undergoing increasing developments this last few years as well from a theoretical view point as for practical applications. We summarize in this paper what has been discovered recently and illustrate various applications for this kind of manipulator.

1 Introduction

Let us consider a parallel manipulator described in figure 1. Two plates are connected

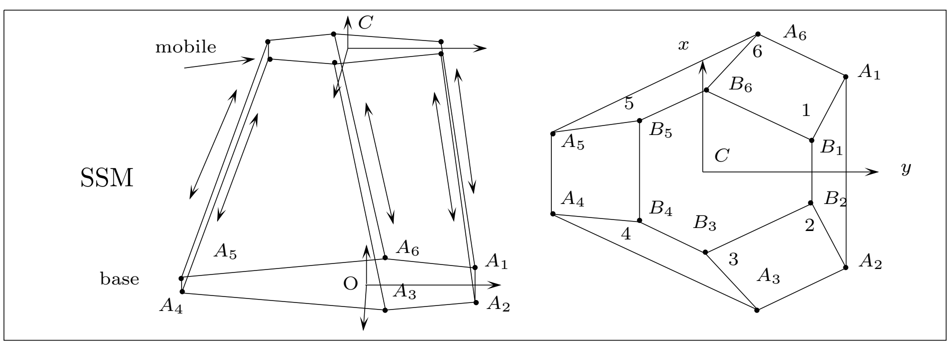

Figure 1: A parallel manipulator with 6 D.O.F.

through 6 articulated links in which a linear actuator enables to change the links lengths. By controlling these lengths we are able to control the position and orientation of the upper-plate with respect to the base plate. Usually the links are joined to the plates by universal joints for the base plate and ball-and-socket joints for the mobile plate.

This type of structure is known since a long time. For example around 1800 the mathematician Cauchy has studied the rigidity of an "articulated octahedron"[4]. More recently (1949) Gough [33] uses a similar mechanism to simulate the constraints exerted on tyres. In 1965 Stewart [33] illustrates the use of a parallel structure for a flight simulator.

The choice of parallel mechanism for simulator platform is justified by one of their obvious advantages: the high nominal load/weight ratio. Indeed the weight of a load on the platform is approximatively distributed on all the links i.e. one link is submitted only to 1/6 of the total weight. Furthermore the stress in the link is mostly traction-compression which is very suitable as well as for the linear actuators as for the rigidity.

Parallel link mechanisms present also others interesting features for robotics applications. A parallel manipulator has been first used in a robotics assembly cell by McCallion in 1979 [21]. As an accurate manipulator is necessary to complete precise assembly tasks parallel link mechanisms are very convenient. Indeed the position of the end-effector of a parallel manipulator is much more less sensible 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.

Many different designs of parallel manipulators are possible but all have in common that their cost is usually low because most of the componants used in the manipulator are standard. But the design is important because some features may be upgraded by an appropriate choice.

The main common drawback of parallel manipulators is their usually small workspace compared to serial link manipulators.

2 Theoretical aspects of parallel manipulators

As the architecture of parallel manipulator is very specific 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 will be easily (difficultly) solved for the other kind. This duality has yet to be explained satisfactorily although some attempts have been made [36, 37].

2.1 Kinematics

Two problems can be distinguished for the kinematics aspects: the *inverse kinematics* and the *direct kinematics*. The inverse kinematics problem i.e. find the links lengths for a given posture of the mobile platform is straightforward for parallel manipulators. At the opposite the direct kinematics problem has not been solved yet although recent papers has given some clues on this topic [22, 26, 17]. In general this problem has more than one solution: for a manipulator with a triangular mobile plate there will up to 16 different postures of the problem for a given set of links lengths. But no closed-form solutions has been discovered except in some very special cases of manipulator. In practice iterative numerical procedures are used without any problem. A practical way to solve the direct kinematics problem is to add orientation sensors in the links [13, 2].

2.2 Dynamics

As fast parallel manipulator can be designed their dynamic model is necessary for the control. A full dynamic model in closed-form has yet to be established but fortunately some assumptions (for example links without mass) can be made enabling to simulate a simplified but efficient dynamics behavior and the design of the robot can be such that these assumptions will be justified. Recently many researchers have addressed this problem [1, 5, 18, 23, 24, 27, 30, 31, 34].

2.3 Force-feedback control and Compliance

As a parallel manipulator can be used as a 6-componants force-sensor by adding force sensor in each link it can realize various tasks involving contact with its surrounding and therefore a force-feedback scheme can be used. Successful experiments has been realized when using a parallel manipulator alone [3, 22, 29] but interesting problems remain to be solved when both a macro and micro manipulator are used [14, 28]. An interesting point about parallel manipulator is that although they are very rigid passive compliance can be obtained either by using pneumatic actuators [29, 22]. In either cases an appropriate choice of the position of the links sensors enables to calculate precisely the posture of the mobile platform at the opposite of serial link mechanisms. Some researchers have also addressed the problem of determining a design which insures that, at least for some posture of the mobile platform, the stiffness matrix is diagonal [6, 16, 8].

2.4 Singular configurations

As serial link mechanisms a parallel manipulator can be in a singular configuration i.e. in a configuration where no articular forces (the stress in the links) can equilibrate an external wrench applied to the mobile platform. It is important to determine the location of these configurations as in the vicinity of a singular configuration the articular forces will tend to infinity. Singular configurations are characterized by the cancellation of the determinant of the inverse jacobian matrix. Although this matrix is known the symbolic computation of its determinant yield in most of the cases to a huge expression. Finding the closed-form of the roots of this expression seems very difficult. A numerical procedure can be used [6] but a geometrical approach enables to find relationships between the position parameters characterizing a singular configuration [22]. An open problem is to determine if they are singular configurations inside the workspace of the parallel manipulator.

2.5 Workspace

At the opposite of serial link mechanisms the workspace of a parallel manipulator cannot be decoupled in two 3D workspaces characterizing the possible translation motions and orientation motions. Therefore representing this workspace is a difficult task. Usually the workspace border are calculated for a fixed orientation and altitude of the mobile platform either by using a numerical procedure [3, 7] or a geometrical algorithm [9, 22].

3 Practical applications

3.1 Research prototypes

Although the concept of parallel manipulators is quite recent many prototypes [2, 7, 10, 11, 12, 13, 15, 25] and even industrial robots have been build. As the list of prototypes developed in laboratories is too long to be presented here let us just mention the two prototypes of parallel manipulators we have build at INRIA The first one is a "left hand" i.e. it is intended to be used in cooperation with a serial link robot to perform force-feedback controlled tasks. The second one is a small parallel manipulator which is used as an active wrist of a serial link manipulator, realizing a macro-micro robotics system. The actuation principle of this robot is slightly different from the one of the "left hand" as the links have a fixed length. Indeed we use linear actuators to move the articulation points near the base along a vertical axis, enabling to have better orientation motions and less links interference. At the other hand we may mention a parallel micro-manipulator developed at MEL in Japan which linear actuators have a range of a few micrometers enabling to perform motion of a few nanometers [3]. Interesting articulated truss can be build by joining parallel mechanisms modules [35]. This yield to light, highly redundant manipulators which may be interesting in spatial applications.

3.2 Commercial robots

The first commercial parallel manipulator was designed by Marconi [19]. The "Gadfly" is a small 6 d.o.f manipulator intended to be used for the assembly of electronic componants. Later this society design a huge hybrid serial-parallel manipulator, the "Tetrabot" [20] with a parallel module for the translation motion. A fast 3-4 d.o.f. parallel manipulator, the "Delta" robot [32], is now being sold by the society Demaurex. This manipulator is used for very fast pick-and-place tasks of light loads. The nice mechanical design enables to reach high velocities and accelerations. A 6 d.o.f. manipulator based on a similar design is currently under development [25]. The french society AICO is currently selling a 6 d.o.f. parallel manipulator, the "SPACE 1" robot, based on the design of Reboulet [29] for assembly purposes. Another french society, LOGABEX, has designed a truss-robot with 4 to 6 6 d.o.f. parallel modules. This highly redundant manipulator is light but is difficult to control.

4 Conclusion

Parallel manipulators present various advantages which can be useful in many robotics tasks. Although interesting theoretical problems remain to be solved the current state of the art has enable to design efficient prototypes and commercial manipulators. Although the concept of parallel manipulator is to recent and too different from the design of most classical manipulators to have been forced upon the mind of the designers of robotics systems our feeling is that their use in many robotics tasks is so necessary that they will become indispensable in the near future.

References

[1] Angeles J. and Gosselin C. Détermination du degré de liberté des chaînes cinématiques simples et complexes. In *7th IFToMM World Congress on the Theory of Machines and Mechanisms*, pages 199–202, Seville, September, 17-22, 1987.

[2] Arai T., Cleary K., and others . Design, analysis and construction of a prototype parallel link manipulator. In *IEEE Int. Conf. on Intelligent Robots and Systems (IROS)*, volume 1, pages 205–212, Ibaraki, Japan, July, 3-6, 1990.

[3] Arai T. and others . Development of a parallel link manipulator. In *ICAR*, pages 839–844, Pise, June, 19-22, 1991.

[4] Cauchy A. Deuxième mémoire sur les polygones et les polyèdres. *Journal de l'École Polytechnique*, pages 87–98, May 1813.

[5] Do W.Q.D. and Yang D.C.H. Inverse dynamic analysis and simulation of a platform type of robot. *J. of Robotic Systems*, 5(3):209–227, 1988.

[6] Douady D. *Contribution à la modélisation des robots parallèles: conception d'un nouveau robot à 3 liaisons et six degrés de liberté*. Ph.D. Thesis, Université Paris VI, Paris, December, 9, 1991.

[7] Fichter E.F. A Stewart platform based manipulator: general theory and practical construction. *Int. J. of Robotics Research*, 5(2):157–181, Summer 1986.

[8] Gosselin C. *Kinematic analysis optimization and programming of parallel robotic manipulators*. Ph.D. Thesis, McGill University, Montréal, June, 15, 1988.

[9] Gosselin C. Stiffness mapping for parallel manipulators. *IEEE Trans. on Robotics and Automation*, 6(3):377–382, June 1990.

[10] Hara A. and Sugimoto K. Synthesis of parallel micromanipulators. *J. of Mechanisms, Transmissions and Automation in Design*, 111(1):34–39, March 1989.

[11] Hayward V. and Kurtz R. Preliminary study of serial-parallel redundant manipulator. In *NASA Conference on Space Telerobotics*, pages 39–48, Pasadena, January, 31, 1989.

[12] Hervé J-M. and Sparacino F. Structural synthesis of parallel robots generating spatial translation. In *ICAR*, pages 808–813, Pise, June, 19-22, 1991.

[13] Inoue H., Tsusaka Y., and Fukuizumi T. Parallel manipulator. In *3rd ISRR*, pages 321–327, Gouvieux, France, October, 7-11, 1985.

[14] Khatib O. Inertial characteristics and dextrous dynamic coordination of macro/micro manipulator systems. In *7th CISM-IFToMM Symposium on Theory and Practice of Robots and Manipulators*, Udine, Italie, September 1988.

[15] Kohli D., Lee S-H, Tsai K-Y, and Sandor G.N. Manipulator configurations based on Rotary-Linear (R-L) actuators and their direct and inverse kinematics. *J. of Mechanisms, Transmissions and Automation in Design*, 110(4):397–404, December 1988.

[16] Kurtz R.L. Kinematic and optimization of a parallel robotic wrist mechanism with redundancy. Research Report TR-CIM-90-2, Université McGill, Montréal, January 1990.

[17] Lazard D. Stewart platform, October, 17, 1991. Communication personelle.

[18] Lee K-M. and Shah D.K. Dynamic analysis of a three-degrees-of-freedom in-parallel actuated manipulator. *IEEE J. of Robotics and Automation*, 4(3):361–368, June 1988.

[19] Marconi . The Gadfly manipulator. Research Report 732, Marconi Research Centre, 1985.

[20] Marconi . Development of the Tetrabot robotic manipulator. Research report, Marconi Research Centre, 1986.

[21] McCallion H. and Pham D.T. The analysis of a six degrees of freedom work station for mechanized assembly. In *5th IFToMM World Congress on the Theory of Machines and Mechanisms*, pages 611–616, Montréal, July 1979.

[22] Merlet J-P. *Les Robots parallèles*. Hermès, Paris, 1990.

[23] Nakamura Y. and Ghodoussi M. Dynamics computation of closed-link robot mechanisms with nonredundant and redundant actuators. *IEEE Trans. on Robotics and Automation*, 5(3):294–302, June 1989.

[24] Pierrot F. *Robots Pleinement Parallèles Légers : Conception Modélisation et Commande*. Ph.D. Thesis, Université Montpellier II, Montpellier, April, 24, 1991.

[25] Pierrot F., Dauchez P., and Fournier A. Towards a fully-parallel 6 d.o.f. robot for high speed applications. In *IEEE Int. Conf. on Robotics and Automation*, pages 1288–1293, Sacramento, April, 11-14, 1991.

[26] Raghavan M. The Stewart platform of general geometry has 40 configurations. In *ASME Design and Automation Conf.*, volume 32-2, pages 397–402, Chicago, September, 22-25, 1991.

[27] Reboulet C. and others . Rapport d'avancement projet VAP, thème 7, phase 3. Research Report 7743, CNES/DERA, January 1991.

[28] Reboulet C. and Pigeyre R. Hybrid control of a 6 d.o.f. in parallel actuated micro-macro manipulator mounted on a Scara robot. In *ISRAM*, volume 3, pages 293–298, Burnaby, July, 18-20, 1990. ASME Press Series.

[29] Reboulet C. and Robert A. Hybrid control of a manipulator with an active compliant wrist. In *3rd ISRR*, pages 76–80, Gouvieux, France, October, 7-11, 1985.

[30] Seguchi Y., Tanaka M., and others . Dynamic analysis of a truss-type flexible robot arm. *JSME Int. J.*, 33(2):183–190, 1990.

[31] Sklar M. and Tesar D. Dynamic analysis of hybrid serial manipulator system containing parallel modules. *J. of Mechanisms, Transmissions and Automation in Design*, 110(2):109–115, June 1988.

[32] Sternheim F. Tridimensionnal computer simulation of a parallel robot. Results for the Delta 4 machine. In *18th Int. Symp. on Industrial Robots (ISIR)*, pages 333–340, Lausanne, April, 26-28, 1988.

[33] Stewart D. A platform with 6 degrees of freedom. *Proc. of the Institution of mechanical engineers*, 180(Part 1, 15):371–386, 1965.

[34] Sugimoto K. Kinematic and dynamic analysis of parallel manipulators by means of motor algebra. *J. of Mechanisms, Transmissions and Automation in Design*, 109(1):3–7, March 1987.

[35] Tanaka M. and others . Motion/configuration control of a truss-type parallel manipulator with redundancy. In *Japan-USA Symposium on Flexible Automation*, pages 329–336, ISCIE, Kyoto, 1990.

[36] Waldron K.J. and Hunt K.H. Series-parallel dualities in actively coordinated mechanisms. *Int. J. of Robotics Research*, 10(2):473–480, April 1991.

[37] Zamanov V.B and Sotirov Z.M. A contribution to the serial and parallel manipulator duality. In *8th IFToMM World Congress on the Theory of Machine and Mechanisms*, pages 517–520, Prague, August, 26-31, 1991.