Review of parallel manipulator for various applications

Mayank Kumar Patel*[2], Krishan Kumar Gotewal[1], Manoah Stephen M.[1], Parth Patel[2]

[1]Remote Handling and Robotics Technology Development Division, Institute for Plasma Research, Gandhinagar, India
[2]Department of Mechanical Engineering, LDRP – Institute of Technology and Research, Gandhinagar, India

Presented in International Conference on Advancements and Futuristic Trends in Mechanical and Materials Engineering held at Indian Institute of Technology Ropar (IITR), Rupnagar, during December 5-7, 2019.

KEYWORDS

Parallel manipulator,
Delta robot,
Fusion,
Medical,
Industry.

ABSTRACT

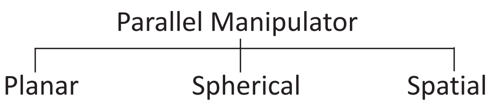
This paper highlights, various applications of parallel manipulator having multiple degrees of freedom (DOF). Parallel manipulators are used in various fields such as industry, space, medical, fusion reactor, and virtual reality. Here the focus is given to nuclear fusion applications. A review of kinematic analysis and dynamic analysis has been described. Also, there is a discussion on the use of a flexible joint to increase the performance of the system.

1. Introduction

The parallel manipulator is a closed-loop structure used for the manipulation of end-effector. It has a fixed and mobile platform (end-effector) are connected with each other by at least two or more kinematic chains. Kinematic links are connected using universal joint, revolute joint, spherical joint or prismatic joint. These links control the position and orientation of the mobile platform. In 1954, Gough developed six DOF parallel manipulator with hydraulic jack for universal tire testing machine. In 1962 parallel mechanism was designed by Willard L.V. Pollard for automatic spray painting. The mechanism had five DOF, namely three positions and two rotations. In 1965, a paper was published by Steward on six DOF parallel platform for flight simulator (Merlet, 1993).

2. Classification of Parallel Manipulator

The parallel manipulator is categorized according to their nature of motion in three categories.



1. Planar parallel manipulator: The parallel manipulator in which kinematic links are on the same plane is defined as a planar parallel manipulator. It has a maximum of three degrees of freedom.
2. Spherical parallel manipulator: In spherical parallel manipulator, kinematic links are in the curve shape and motion of the mobile platform is controlled spherically. It has three degrees of freedom.
3. Spatial parallel manipulator: In spatial parallel manipulator, the mobile platform is moved in space with respect to the fixed platform. The spatial manipulator has more than three degrees of freedom, therefore, it has many applications.

*Corresponding author,
E-mail: mayankpatel5505@gmail.com

3. Kinematic Analysis

The kinematic analysis deals with only the motion of the manipulator without considering the torques or forces. The study of the kinematics of the parallel manipulator is made for obtaining motion of the mobile platform. Kinematic analysis for the parallel manipulator is divided into two categories, forward kinematics and inverse kinematics (Peidong Wu, 2008). In forward kinematics, the joint variable is known, and the position of end-effector is obtained, while in the inverse kinematic position of end-effector is known and the value of the joint variable is obtained. Inverse kinematics for the parallel manipulator is easy but forward kinematics for the parallel manipulator is quite difficult because of multiple positions occurring for the same joint variable.

Peidong Wu et al. developed a method for solving the kinematics by forward kinematics for parallel manipulator using Homotopy theory. Generally, 6 DOF parallel manipulator has many solutions to forward kinematics. Most of the obtained solutions have many imaginary domains. The major benefit of this method is that it does not rely on the initial conditions or values of the system (Peidong Wu, 2008).

4. Dynamic Analysis

The development and analysis of the dynamic model are important for the study of the parallel manipulator. There are many ways to understand the importance of the dynamic model. A dynamic model is used for computer simulation of the system and the tests can be done without actually preparing the model (Bhaskar Dasguptaa, 2000) (Furqan, Suhaib, & Ahmad, 2017).

Various methods to study the dynamics of the parallel manipulator are Newton-Euler method, Lagrange formulation, virtual work principle and Kane's method (Furqan & Suhaib, 2014). Newton-Euler method is easy to understand and work with. This approach needs to have all the constraints and joints defined. Due to a large number of symbolic computation, Lagrange Formulation method becomes quite tedious and unsuitable. The virtual work principle method is based on the computation of the energy of the whole system. For dynamic analysis of steward platform, this method is efficient. Kane method is used to analyse the multibody system for calculation of acceleration, partial velocities of mass centres, and partial velocity of all links.

5. Parallel Manipulator With Flexible Joint

Typically, universal or ball joints are used in the parallel manipulator. Due to the presence of manufacturing and alignment errors, the accuracy of the parallel manipulator is reduced. To overcome these errors, one can use flexible joints. The advantages of the flexible joint are negligible backlash and self-lubrication. Flexure may also be sensitive to the working temperature.

Wang Dan designed a parallel manipulator with a flexible joint. It is a closed-form non-linear model which is describing the load- displacement relations of spatial beam flexure hinge. Due to the use of flexure hinges, it can achieve better accuracy in the workplace (Dan & Rui, 2016).

6. Finite Element Method Analysis

The finite element method is applied for the analysis of a parallel manipulator to determine its static and dynamic characteristics. It is used to find the natural frequency, static stresses in the component also mode shapes of the parallel manipulator. The finite element model of the parallel manipulator is constructed to describe the stress distribution of the legs.

Dohner et al. proposed a finite element model for the analysis of the chatter on which spindle is mounted in a milling machine. To actively control the chatter, they added a flexible actuator on the periphery of the spindle in their model. The explicit relation governing the vibration behaviour of the hexapod was not explained here (Dohner, Kwan, & Regelbrugge, 1996).

Mohd. Furqan et al., explained the finite element analysis of steward platform with a flexible joint as shown in Fig. 2. The result obtained was that the hyperbolic flexible joint is the most accurate

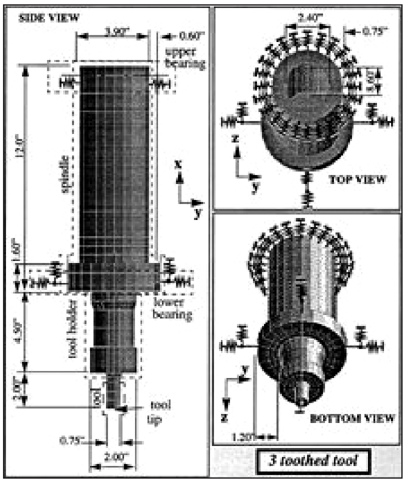


Fig. 1. Finite element model of the spindle with a flexible tool (Dohner, Kwan, & Regelbrugge, 1996).

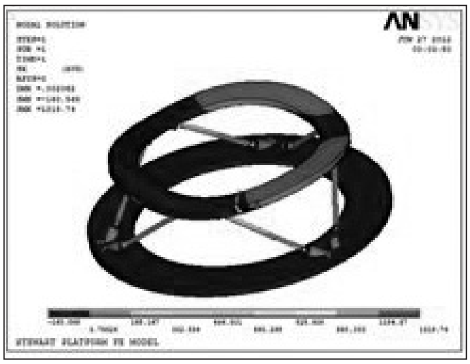


Fig. 2. Stress pattern of the X-Component in the legs (Furqan & Alam, 2013).

Fig. 3. Hexapod (Patel & George, 2012).

Fig. 4. Delta robot (Patel & George, 2012).

Fig. 5. Cable driven robot (Tang, 2014).

geometrical profile for multibody analysis and maximum stress is developed at the hyperbolic joint(Furqan & Alam, 2013).

7. Applications

The parallel manipulator spent almost 20 years in laboratories for preliminary research studies. Now a day it is used in real-life applications because of their advantages like high load carrying capacity, high accuracy, high rigidity, speed, etc. It also has some drawbacks like complex kinematic, dynamics and smaller workspace.

The current applications of parallel manipulator are in a fine positioning device, simulator, motion generator, ultra-fast pick and place robot, machine tool, medical application, haptic device, micro-robots, articulated trusses, etc.

7.1. Industrial application

The parallel manipulator is used in industry for assembly, packaging, testing, welding, milling, etc. Hexapod, Delta robots, and cable-driven robots are widely used in industries.

7.1.1. Hexapod

Hexapod is a kind of parallel manipulator, which is used increasingly in manufacturing, inspection, and research. As shown in Fig. 3 hexapod has six extensible legs, which is connected to a fixed and mobile platform. It provides large motion in six degrees of freedom for heavy payloads with high accuracy and repeatability. Various hexapods are present on the basis of their load capacity (0.5 kg to 1500 kg) and actuator range (130 mm to 3 m) (Patel & George, 2012). It used in machine tool manufacturing, simulator, and precision machining.

7.1.2. Delta Robot

In 1980 Reymond Clavel designed a parallel manipulation robot using a parallelogram mechanism with four DOF, three positions and one orientation. Delta robot is an example of a successful parallel kinematic structure.

A parallelogram mechanism allows an output link have to orientation with respect to a fixed input link. As shown in Fig. 4, Delta robot is made from such three parallelogram mechanisms; it can archive three DOF. The input link of the parallelogram mechanism is mounted on rotating joints and motors or linear actuators (Patel & George, 2012) actuates them. The actuators are placed at the base therefore acceleration and working speed of the delta robot is high, so they are used for fast pick and place application. Delta robot is used in the packaging industry, working with electronic components. It is also used in Pharmaceutical industries and the medical field.

7.1.3. Cable driven robot

In 1989 a parallel manipulator was designed for under water applications. It was actuated or driven using cables. Now cable driven robots are used in processing machinery, port cargo handling, bridge construction, welding and to control cameras in stadiums.

As shown in Fig. 5, a cable-driven robot's mobile platform is connected with actuators using cable. The cable is connected to an actuator that is placed on fix platform. When we actuate the cable, the position and orientation of the mobile platform changes accordingly (Tang, 2014). In generally a cable- driven robot has n degree of freedom which are driven by m cables. Various conditions of constraints for Cable Driven robot are

- When n+1>m then it is in under constrained condition.
- When n+1=m then it is in fully constrained condition.
- When n+1<m then it is in redundantly constrained condition (Qian, Zi, Shang, & Xu, 2018)

7.2. Space application

The parallel mechanism is used in a satellite tracker system and simulation of the space vehicle. Katsuyoshi Tsujita et al. developed a test system where a parallel robot is used for gravity compensation of a space-craft (Tsujita, Shigematsu, & Kishimoto, 2014). The vibration caused due to Omni wheel of the parallel robot is isolated by the parallel robot itself as shown in Fig. 6.

7.3. Medical application

The parallel manipulator can be used in neurosurgery, spine surgery, ophthalmology, orthopaedic for total knee and hip replacement surgery. As shown in Fig. 7, Parallel manipulators are also used for surgical operations. It can manipulate the needle in six DOF. Due to high accuracy and precision, it provides minimum pain and higher efficiency by reducing the surgery time (Zhang,, Huang,, & Li, 2018).

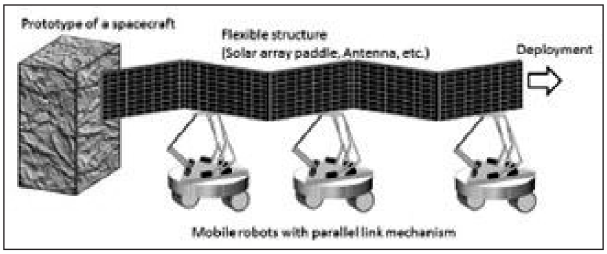


Fig. 6. System architecture (Tsujita, Shigematsu, & Kishimoto, 2014).

7.4. Virtual reality application

Dongsu Wu et al. developed a parallel manipulator for assisting head and neck motion by using a head-mounted device for virtual reality. As shown in Fig. 8, Dongsu Wu used 6-3 Universal-Prismatic-Spherical (UPS) Steward Platform. It consists of six powered legs, an upper platform, and a lower platform. Lower platform is attached with helmet (Wu,, Wang, & Li, 2016). The position and orientation of lower platform is controlled with the help of six legs.

7.5. Parallel manipulator in fusion application

Huapeng Wu et al. developed a Penta- WH parallel robot as shown in Fig. 9, for assembly or repair inside the tokamak vacuum vessel. It is used to perform welding, cutting, edge machining, smoothing and NDT control. This parallel robot can handle a weight of welding device up to 200kg for e-beam welding and for cutting, it can handle dynamic force up to 3 kN. The design of parallel robot Penta-WH consists of two parallel mechanisms, first for positioning in three axes and second for orientation in two axes. The third mechanism is for driving a robot on the carriage. Thus, Penta-WH parallel robot has six degree of freedom (Wu, Handroos, Pessi, Kilkki, & Jones, 2005).

Stanislao Grazioso et al., developed a hybrid kinematic mechanism. It is the combination of

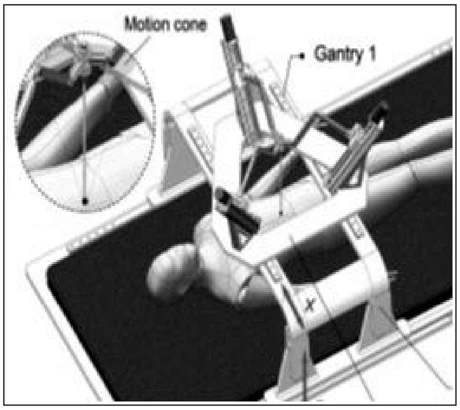


Fig. 7. Surgical robot for needle insertion (Zhang,, Huang,, & Li, 2018).

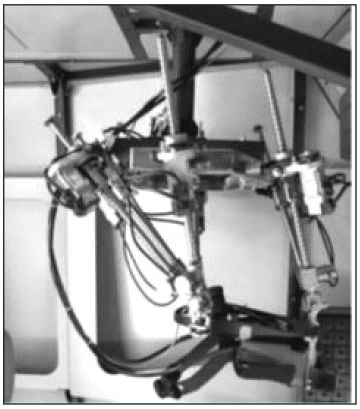


Fig. 8. Six DOF exoskeleton (Wu,, Wang, & Li, 2016).

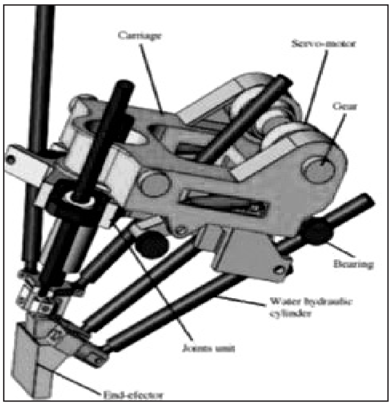


Fig. 9. Penta-WH parallel robot (Wu, Handroos, Pessi, Kilkki, & Jones, 2005).

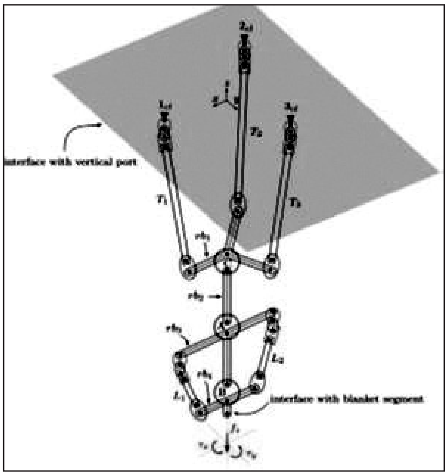


Fig. 10. Model of the hybrid kinematic mechanism (Graziosoa, Gironimoa, Iglesiasb, & Sicilianoa, 2019).

parallel and serial manipulator as shown in Fig. 10. The parallel section is used for positioning in space. At the end of the parallel manipulator, the serial manipulator is connected for providing rotation about the three axes. For the dynamics of hybrid kinematic mechanism, screw based formulation is used to prepare a dynamic model for simulation. It used as overhead cranes for the ex-vessel operations (Graziosoa, Gironimoa, Iglesiasb, & Sicilianoa, 2019).

8. Conclusion

This review work showcases different areas of applications of a parallel manipulator. It is used for gravity compensation in space and medical applications. In space, it is also used to create zero gravity condition and for vibration isolation in deployment of solar array panels. In medical field, it is used to counter balance manipulator's self-weight in gravity field for any configuration to the ease of operation on a patient by surgeons. Hexapods are used in flight and on-road vehicle simulators to give an immersive feeling to the user along with actual vibrations and jerks experienced in driving the same in real conditions. In the air force, it is used to train the newly recruited pilots, before handling the real fighter jets. Cable driven parallel robots are used in processing machinery, port cargo handling, bridge construction, welding and also used to control the cameras in stadiums. Penta-WH parallel robot is used for heavy payload handling and manipulation in fusion application. Hybrid combination of serial-parallel manipulator is used in which parallel manipulator is used for proper position in space and serial manipulator for providing rotation about the three axes. It also helps in understanding the different methods to solve the kinematics and dynamics of a parallel manipulator. This work is useful in further design and development of a parallel manipulator for heavy payload handling.

Acknowledgement

Thanks to Institute for Plasma Research, Gandhinagar for allowing me to carry out review work and Remote Handling and Robotics Technology Division Members for their full-hearted co-operation in providing all the necessary data and detailed guidance during this review work.

Disclaimer

The views and opinions expressed herein do not necessarily reflect those of Institute for Plasma Research, Gandhinagar.

References

1. Dasguptaa, B.T.M., & Mruthyunjaya, T.S. (2000). The Stewart platform manipulator: a review. *Mechanism and Machine Theory, 35(1)*, 15-40.
2. Wang, D., & Fan, R. (2016). Design and Nonlinear Analysis of a 6-DOF Compliant Parallel Manipulator with Spatial Beam Flexure Hinges. *Precision Engineering*, 45, 365-373 10.1016/j.precisioneng.2016.03.013.
3. Dohner, J.L., Kwan, C.M., & Regelbrugge, M.E. (1996). *Active chatter supression in an octahedral hexapod milling machine: a design study*. Proceedings Volume 2721, Smart Structures and Materials 1996: Industrial and Commercial Applications of Smart Structures Technologies; (1996) https://doi.org/10.1117/12.239144
4. Furqan, M., & Alam, D.N. (2013*). Finite Element Analysis of a Stewart Platform using Flexible Joints. 1st International and 16th National Conference on Machines and Mechanisms* (iNaCoMM2013), 1044-1049, IIT Roorkee.
5. Furqan, M., & Suhaib, M. (2014). Some Studies on Parallel Manipulator – A Review. *Journal of Basic and Applied Engineering Research*, 1(3), 99-104.
6. Furqan, M., Suhaib, M., & Ahmad, N. (2017). Studies on Stewart platform manipulator: A review. *Journal of Mechanical Science and Technology, 31* , 4459-4470.
7. Graziosoa, S., Gironimoa, G.D., Iglesiasb, D., & Sicilianoa, B. (2019). Screw-based dynamics of a serial/parallel flexible manipulator for DEMO blanket remote handling. *Fusion Engineering and Design*, 139, 39-46.
8. Merlet, J.P. (1993). Parallel manipulators state

of the art and perspectives. *Journal of Advanced Robotics, 8(6),* 589-596.

9. Patel, Y.D., & George, P.M. (2012). Parallel Manipulators Applications—A Survey. *Modern Mechanical Engineering,* 2(3), 57-64. 10.4236/mme.2012.23008.
10. Wu, P., Wu, C., & Yu, L. (2008). Method for Forward Kinematics of Stewart Parallel Manipulators. *Intelligent Robotics and Applications* (ICIRA 2008). Lecture Notes in Computer Science, 5314, Springer-*Verlag Berlin Heidelberg*. https://doi.org/10.1007/978-3-540-88513-9_19
11. Qian, S., Zi, B., Shang, W.W., & Xu, Q.S. (2018). Review on Cable-driven Parallel Robots. *Chinese Journal of Mechanical Engineering*, 1-11.
12. Tang, X. (2014). Overview of the Development for Cable-Driven Parallel Manipulator. *Advances in Mechanical Engineering*, 1-9.
13. Tsujita, K., Shigematsu, H., & Kishimoto, N. (2014). Development of a gravity compensation system for the prototype test of spacecraft by using mobile type multi robots. *MOVIC 2014 - 12th International Conference on Motion and Vibration Control*. *Researsh Gate*, 1-7.
14. Wu, H., Handroos, H., Pessi, P., Kilkki, J., & Jones, L. (2005). Development and control towards a parallel water hydraulic weld/cut robot for machining processes in ITER vacuum vessel. *Fusion Engineering and Design*, 75-79, 625-631.
15. Wu, D., Wang, L., & Li, P. (2016). 6-DOF Exoskeleton for Head and Neck Motion Assist with Parallel Manipulator and sEMG based Control. *CoDIT'16,* 341-344.
16. Zhang, N., Huang, P., & Li, Q. (2018). Modeling, design and experiment of a remote-center-of-motion parallel manipulator for needle insertion. *Robotics and Computer–Integrated Manufacturing*, 50, 193-202.

Mr. Mayank Kumar Patel is currently pursuing a Bachelor of Engineering in Mechanical Engineering from LDRP – Institute of Technology and Research, Gandhinagar, India. He also worked as Project Trainee at the Institute for Plasma Research for 6 months. He has presented a paper at '7th International Conference on Advancements and Futuristic Trends in Mechanical and Materials Engineering' held at the Indian Institute of Technology Ropar, Rupnagar, India during December 5-7, 2019.

Mr. Krishan Kumar Gotewal is currently working at the Institute for Plasma Research, Bhat, Gandhinagar at a position of Scientific Officer – SF. He is the division head of the Remote Handling and Robotics Technology Development Division (RHRTD) at the Institute for Plasma Research. He has completed his B.Tech. in Mechanical from A.M.U. Aligarh, U.P. India in June 1999. He has a working experience of 19 years in the field of Mechanical Engineering. He has 4 publications in peer-reviewed journals and conference proceedings. He has guided five M. Tech. Projects. He was deputed to ITER Organization, France (Nov-2007 to June-2014) through IPR. He was awarded an award for excellent performance by ITER, France in 2012.

Mr. Manoah Stephen currently works at the Institute for Plasma Research, Gandhinagar at a position of Scientific Officer – E. He works as a Mechanical Engineer in the Remote Handling and Robotics Technology Development Division (RHRTD). He is currently pursuing M.Sc. Engineering (Mechanical) by Research from Homi Bhabha National Institute, India. He has work experience of 9 years. He has 2 publications in peer-reviewed journals and 13 publications in peer-reviewed conference proceedings. He has guided three M. Tech. Projects. He has handled various international as well as domestic projects in Fusion Reactor Studies Division, Cryopump Division and RHRTD Division.

Mr. Parth Patel has been working as Assistant Professor in Mechanical Engineering Department at LDRP Institute of Technology and Research. A constituent institute of Kadi Sarva Vishwavidyalaya, under the aegis of Sarva Vidyalaya Kelavani Mandal. He completed his M.Tech. (CAD/CAM) from Ganpat University, Kherva. His topic for research was "Parametric Optimization of Belt Conveyor Supporting Structure Using FEA-DOE Hybrid Modelling". He has 6 years of teaching experience and has published/presented research papers in international journals & conferences.