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Parallel Manipulators Applications—A Survey

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ABSTRACT

This paper presents the comparison between serial and parallel manipulators. Day by day, the applications of the parallel manipulator in various field is become apparent and with a rapid rate utilized in precise manufacturing, medical science and in space exploration equipments. A parallel manipulator can be defined as a closed loop kinematic chain mechanism whose end effector is linked to the base by several independent kinematic chains. The classification of various parallel manipulators is presented herewith. The prime focus of the paper is to realize the parallel manipulators applications for industry, space, medical science or commercial usage by orienting manipulator in the space at the high speed with a desired accuracy.

Keywords: Parallel Manipulator; Hexapod; Reconfigurable Parallel Robot; Delta Robots

1. Introduction

Parallel manipulators are widely popular recently even though conventional serial manipulators possess large workspace and dexterous maneuverability. The basic problems with serial one are their cantilever structure makes them susceptible to bending at high load and vibration at high speed leading to lack of precision and many other problems. In this paper, parallel manipulators advantages over the serial one are compared. Hence, in applications demanding high load carrying capacity and precise positioning, the parallel manipulators are the better alternatives and the last two decades points to the potential embedded in this structure that has not yet been fully exploited. Willard L. V. Polard [1] designed and patented the first industrial parallel robot as shown in **Figure 1**. The development of *parallel manipulators* can be dated back to the early 1960s, when Gough and Whitehall [2] first devised a six-linear jack system for use as a universal tire testing machine. Later, Stewart [3] developed a platform manipulator for use as a flight simulator. Since 1980, there has been an increasing interest in the development of parallel manipulators. This paper highlights the potential applications of parallel manipulators include mining machines, walking machines, both terrestrial and space applications including areas such as high speed manipulation, material handling, motion platforms, machine tools, medical fields, planetary exploration, satellite antennas, haptic devices, vehicle suspensions, variable-geometry trusses, cable-actuated cameras, and telescope positioning systems and pointing devices. More recently, they have been used in the development of high precision machine tools [4] by many companies such as Giddings & Lewis, Ingersoll, Hexel, Geodetic and Toyoda, and others. The Hexapod machine tool [5,6] is one of the widely used parallel manipulators for various industries.

2. Serial vs Parallel Manipulators

Parallel kinematic manipulators offer several advantages over their serial counterparts for certain applications.

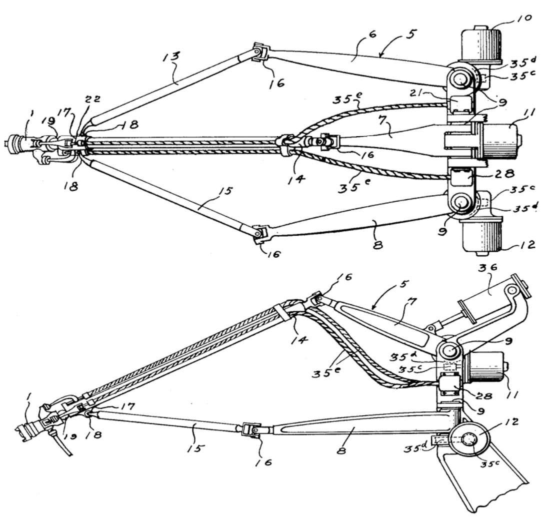

Figure 1. Pollard's spatial industrial robot [1].

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Among the advantages are greater load carrying capacities as total load can be shared by number of parallel links connected to fixed base, low inertia, higher structural stiffness, reduced sensitivity to certain errors, easy controlling and built-in redundancy but smaller and less dexterous workspace due to link interference, physical constraints of universal and spherical joints and range of motion of actuators and suffer from platform singularities. The abundant use of multi DOF *spherical* and *universal* joints in parallel manipulator not only simplify the kinematics, but they also make sure that the legs in the Stewart-Gough platforms [7] experience only compressive or tensile loads, but no shear forces or bending and torsion moments. This reduces the deformation of the platform, even under high loads. The fully parallel designs of robots have all actuators in or near the base, which results in a very low inertia of the part of the robot that has actually to be moved. Hence, a higher bandwidth can be achieved with the same actuation power. This is why parallel structures are used for, for example, flight simulators and fast pick-and-place robots. Parallel architecture is always lucrative for many practical applications to improve robot performance beyond the reach of serial manipulators as apparent from **Table 1**. Parallel kinematic robots have another structure. From the fixed base, a number of arms and links are coupled in parallel to the Tool Centre Point. All drive motors/gearboxes can then be located on the fixed base are used for drilling, welding, tapping with greater accuracy and repeatability. In particular, parallel manipulators with fewer than six degrees of freedom have recently attracted researchers' attention, as their employ may prove valuable in those applications in which a higher mobility is uncalled-for. Arms/links can then be lightweight and very stiff, minimizing inertia. Ball joints means link loads restricted to pure tension/compression, further improving the stiffness/mass ratio. Errors will not be amplified throughout a parallel structure.

For a parallel kinematic mechanism, the kinematic equations will be considerably more complex due to the closed kinematic loops, than for an open (serial) kinematic structure. Parallel manipulators are also termed as closed loop manipulators. For development of high performance robots, models will be required for simulation and performance prediction, and for model based compensation in the control system to obtain advanced performance. Any mechanical systems composed of conventional joints, traditional parallel manipulators suffer from errors due to backlash, hysteresis, and manufacturing errors in the joints. In contrast to serial manipulators, there can be presence of un-actuated or passive joints. The presence of passive joints and multi-DOF joints makes the kinematic analysis very different from kinematic analysis of serial manipulators. Direct kinematics is much harder & involves elimination of passive joint variables in parallel kinematics. Compare to direct kinematics the inverse kinematics is much simpler in parallel manipulators. Parallel robots are intrinsically more accurate than serial robots because their errors are averaged instead of added cumulatively due to many parallel links as well as closed loop architecture. These robots possess many intrinsic characteristics over serial robots, hence lot of scope of applications in near future in various fields can be envisaged.

Table 1. Comparison between parallel and serial manipulators.

	Type of manipulator	
	Parallel manipulator	Serial manipulator
Type of manipulators	Closed loop	Open loop
End effectors	Platform	Gripper
Natural description	In Cartesian space	In joint space
Location of actuators	Near the immobile base	On the links
Inertia forces & stiffness	Less and high respectively	High and less respectively
Design considerations	Structure, workspace considerations, singularities, link interference	Strength and stiffness considerations, vibration characteristics
Preferred property	Stiffness	Dexterity
Use of direct kinematics	Difficult and complex	Straightforward and unique
Use of inverse kinematics	Straightforward and unique	Complicated
Singularity	Static	Kinematic
Direct force transformation	Well defined and unique	Not well defined; may be non-existent, unique or infinite
Preferred application	Precise positioning	Gross motion

Classification of Parallel Manipulators

Symmetric Planar Spherical Spatial

Symmetrical manipulators has number of limbs equals to number of degree of freedom, which is also equals to total numbers of loops. A planar parallel manipulator is formed when two or more planar kinematic chains act together on a common rigid platform. Now days, each leg of a planar parallel manipulator is replaced by a single wire, the manipulator is referred to as a planar wire-actuated (or wire-suspended) parallel manipulator. Spherical manipulators are just able to make the end effectors movement according to controlled spherical motions. Especially, spatial parallel manipulators with *fewer degrees of motion* than six, but more than three, attracted the attention of both, the researchers and users.

In the most of the research work, kinematic analysis is carried by either kinematic constraint equations, screw theory method, DH Parameters or using the concept of dual unit quaternion which is really a most efficient for representing screw displacements of lines for spatial manipulators [8]. Using the inverse dynamics, the forces and torques of the actuated joints can be computed for closed loops configurations of parallel architecture. As per the literature review, Newton Euler approach is relatively more economical compared to Euler Lagrange formulation for parallel as well as hybrid manipulators.

3. Industrial Applications

In 1942, a patent was issued to Willard L. V. pollard [1] for his novel design of automatic spray painting. In fact, it was never built. It has five degree-of-freedom motion—three for the position of the tool head, and the other two for orientation. In 1954, Dr. Eric Gough, an employee of Donlop Rubber Co., England had developed a six degree of freedom—the first octahedral hexapod for universal Tyre Testing Machine [2]. In 1965, Stewart published a paper in which he proposed a six degree of freedom parallel platform as a flight simulator [3]. The Stewart platform comprises six pods, six spherical joints and six universal joints with 6 degree of freedom as shown in **Figure 2** [9]. Stewart platform has also been used for the Agile Eye (a spherical Parallel mechanism) —pointing devices developed by Gosselin and Hamel [10] at robotics laboratory at Laval University, Canada, has low inertia and inherent stiffness, the mechanism can achieve angular velocities superior to 1000 deg/sec and angular accelerations greater than 20,000 deg/sec^2, largely outperforming the human eye. An American engineer, Klaus Cappel is considered as a third pioneer in field of parallel robotics. He has developed an octahedral Hexapod Manipulator as motion simulator & was patented in 1967 as shown in **Figure 3** [11]. Stewart Platform is also used for underground excavation device by Arai in 1991 and another application such as milling machines by Aronson in 1996.

3-DOF spherical parallel mechanism [12] as shown in **Figure 4** has interesting characteristics for practical applications like worktable, a manipulator, a camera orienting device, a wrist or a motion simulator. Parallel Robots can offer many advantages for high-speed laser operations as shown in **Figure 5** due to their structural stiffness and limited moving masses with less power consumption [13].

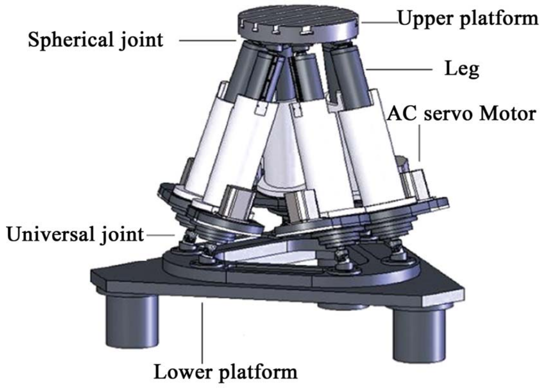

Figure 2. Typical Gough Stewart platform [9].

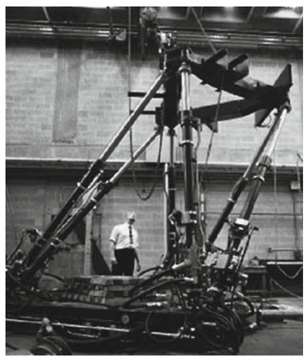

Figure 3. First design of an octahedral hexapod for flight simulator (courtesy of Klaus Cappel) [11].

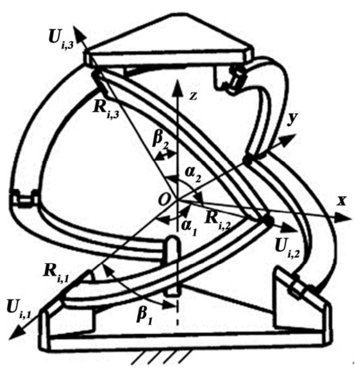

Figure 4. Three DOF spherical parallel manipulators [12].

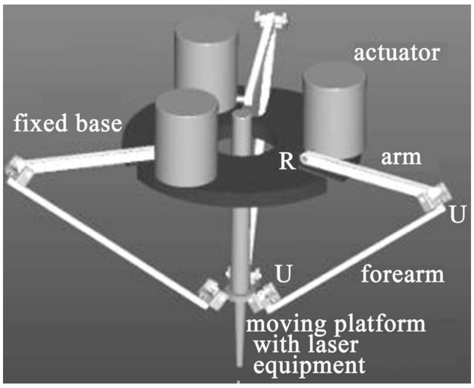

Figure 5. Three RUU kinematic chains usage in delta robot for laser cutting [13].

Figure 6 depicts the parallel cube-manipulators [14] have characteristics of no singularities in the workspace, simple form of forward kinematics and existence of a compliance centre x = y = z = 0 with a added advantages of high stiffness and compactness used in the fields of micro-motion manipulators, remote center compliance (RCC) devices, assembly, planar kinematics machines and so on.

3.1. Hexapod

The hexapod is one form of parallel manipulator that is used increasingly in manufacturing, inspection and research. The ultimate hexapod would provide large motions for massive payloads in up to six degrees of freedom with high accuracy, resolution and repeatability. Recently, during the inverse kinematics error simulation results indicated that hexapod machine tool could be positioned with an error less than 0.03 mm and could be oriented with an error less than 0.000003 rad. The **Figure 7** shows hexapods with various actuators with range in size from 130 mm to 3 m, with load capacities between 0.5 and 1500 kg.

3.2. Delta Robots

3-RPS mechanism is utilized in the machine tool, which was analyzed using Bezout's elimination approach for solving trigonometric non linear equations by Meng-Shiun Tsai *et al.* [16] during their research work. The hybrid machine tool developed by Industry Technology Research Institute (ITRI) is shown in **Figure 8** using the stated 3-PRS mechanism. The configuration shown in **Figure 9** is utilized as a 3-axis PKM for drilling-tapping machine tool for point to point high speed accurate control. Same concept was applied to a machine tool prototype developed by Renault Automation Comau, France with a velocity of 120 m/min. Parallel or delta robotics is used mainly in the packaging industry, in working with electronic components, and in the medical and pharmaceutical

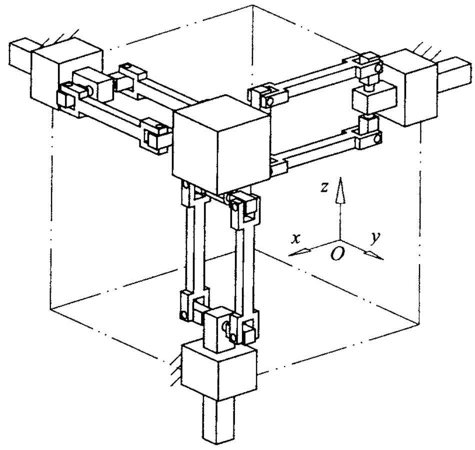

Figure 6. Cube manipulators [14].

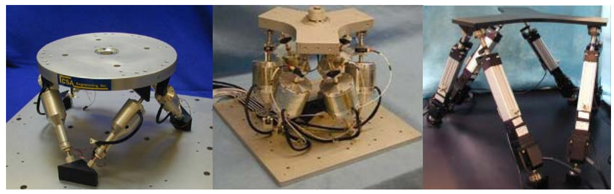

Figure 7. Hexapods using piezoelectric, electromagnetic and motor-driven screw actuators [15].

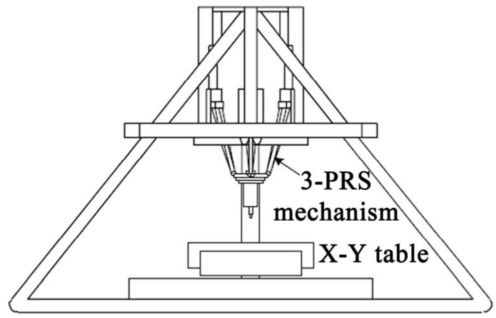

Figure 8. The machine tool designed by ITRI in Taiwan [16].

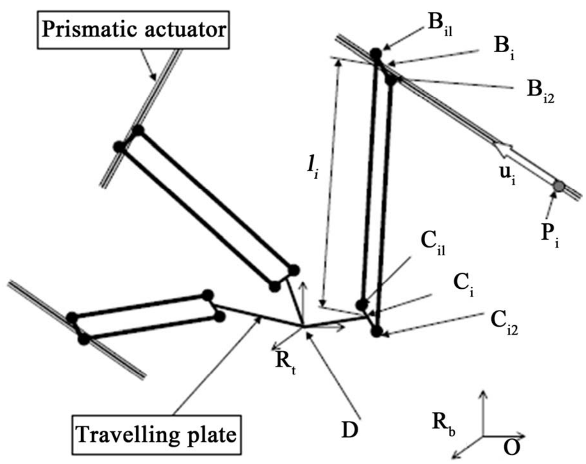

Figure 9. Use of linear drives in delta structure for 3-axis parallel machine tool [17].

industries. Most of the time delta robotics is mounted in a hanging position. This will allow the effector arm to extend down to a work area, like a conveyor belt. The robot is made up of two bases, one larger and one smaller. The smaller end is where all the work is done. These two platforms are connected by the linkages. Each of these linkages is powered by a single motor. The linkages are attached to the main base by a universal joint. This gives the linkages a great deal of flexibility in the range of movement, provided it is in unison. The latest versions of delta robotics have been designed to reduce maintenance and cleaning. They have been given a smaller footprint so that occupied space can be kept to a minimum. Various styles of delta robots have been created, such as the stainless steel model that allows for easy wash down when used in food applications. In sort, this type of configuration is widely applicable as a sorting and collating in various types of packaging and food industry. **Figure 10** shows "FlexPicker", a 3- or 4-axes axis pick and place parallel robot for handling of drugs, food, electronic components etc developed by ABB [18].

As shown in **Figure 11**, the table tennis game can be played with a visual feedback using parallel manipulators. Lagrangian's dynamics is used for its dynamic analysis and simulation.

4. Reconfigurable Parallel Robot

A reconfigurable parallel robot consists of a set of independently designed modules, such as actuators, passive joints, rigid links (connectors), mobile platforms and end-effectors that can be rapidly assembled into various configurations with different kinematic characteristics and dynamic behaviors.

Cable-Driven Robots

There are several applications of cable-suspended manipulators [20] such as; Cutting, Excavating and Grading, Shaping and Finishing, Lifting and Positioning, Flexible Fixturing, cleanup of disaster sites, access to remote areas, manipulation of heavy payloads. Cable-direct-driven robots (CDDRs) are a type of parallel manipulator wherein the end-effector link is supported in-parallel by *n* cables with *n* tensioning motors. Cable-driven robots are very attractive because of their capabilities for high payloads (comparable to construction cranes), large range of motion, rapid deployment and easy reconfiguration.

One of the biggest application areas of cable-suspended robots is cargo handling. The idea of a Stewart platform is replicated in a cable suspended robot as shown in **Figure 12** at University of Delaware. **Figure 13** shows spatial design of 7-cable-suspended robot, with closed form forward pose kinematics, for automated machining, construction, sculpting, and related applications. S. Lahouar *et al.* [22] have determined the new method of collision detection between cable and object recently.

Figure 10. "FlexPicker" [18].

Figure 11. Prototype of robot tennis system [19].

Figure 12. Cable-suspended robot designed and assembled at University of Delaware [20].

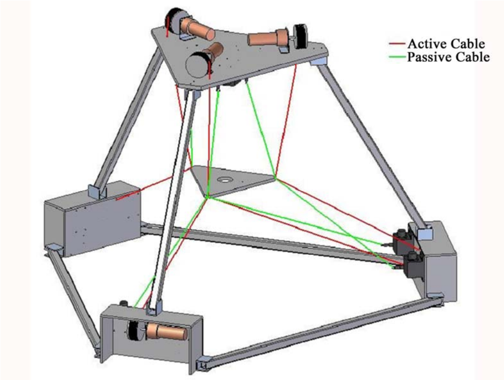

Figure 13. Seven-cable robot with 6-cable passive metrology (2004) [21].

5. Space Applications

Figure 14 shows the Canterbury satellite tracker [23] system uses parallel mechanism for better orientation. Now days, the scope of parallel manipulators for spatial applications is lucrative for researchers. The reconfigurable parallel robot (**Figure 15**) is developed at *National Research Council of Canada* for purpose of exploring its space applications. The robot is made up of two modular units: 1) slide: a three-DOF prismatic joint system with fixed-leg length 2) swing: a three-DOF revolute joint system. The design allows emergency behavior lead to the saving in building, launching and operating costs for space applications. The reconfigurable configurations are considered as part of ultimate intelligent systems.

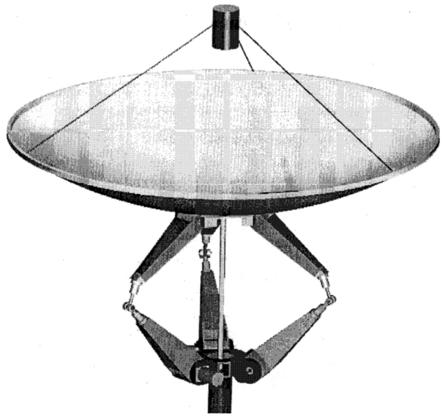

Figure 14. Satellite tracker [23].

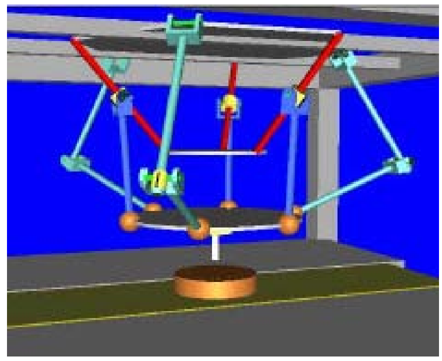

Figure 15. The re-configurable parallel robot [24].

6. Medical Science

N. Sima'an *et al.* [21] had investigated best fits robot for medical applications using parallel architecture. The RSPR robot is best suitable compared to URS and double circular triangular robot due to reduce actuator forces & singular positions. The kinematic structure of Hexapod robot shown in **Figure 16** provides 6 DOF with working area of 100 × 100 × 50 mm and 15˚ rotation with position accuracy of 20 µm for different kinds of surgical instruments [25]. The other applications may include in neurosurgery, ENT, Ophthalmology, Spine surgery and orthopedics for total knee and hip replacement surgery. The application of the mechanism shown in **Figure 17** was inspired by the human biological elbow operation and it was intended to be a medium to seek for functional restoration in patients with transhumeral amputation.

3-PUU translational parallel manipulator concept is used in CPR for chest compression as a rescue breathing with compression frequency of 100 times per minute as shown in **Figure 18**. The same parallel manipulator Design problems for human-machine interfaces are considered for end-effectors in cable-based parallel manipulators in physiotherapy applications [28] as shown in **Figure 19** developed at the Robotics & Mechatronics Laboratories of the University of Padua, Italy. Parallel robot architecture for Ultrasound 3D systems are being developed by Simon Lessard, Ilian Bonev and Pascal Bigras to potentially replace traditional 2D equipments in the diagnosis of vascular disease using multiple 3D ultrasound examinations on a human patient [29]. Parallel manipulator usage in self propelling endoscope with hydraulic actuation is noteworthy. Moreover, 3DOF ISOGLIDE3 as a parallel manipulators are developed with fuzzy and PID controller for clinical use [30].

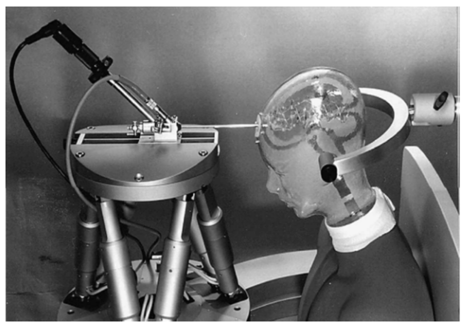

Figure 16. Use of Stewart platform for precision surgery [25].

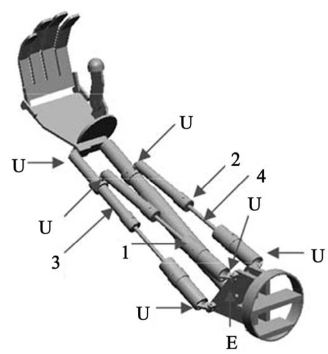

Figure 17. Elements of prosthesis using parallel topology with 3 line actuators [26].

7. Miscellaneous Applications

Some applications require service robots that are capable of moving along a vertical plane e.g., wall painting,

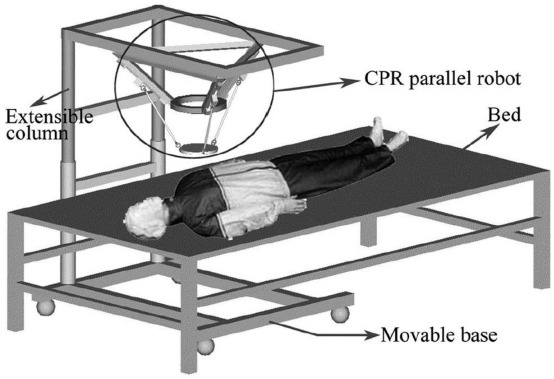

Figure 18. Conceptual design of Cardio-pulmonaryresuscitation (CPR) operation [27].

Figure 19. MariBot—a platform for upper arms using cable-based parallel manipulator [28].

window washing, non-destructive testing (NDT), surveillance, etc. Ship cleaning/inspection, Welding robot, Airplane cleaning and inspection, Oil tank inspection, Nuclear plant inspection, Steal bridge inspection, Cleaning and Inspection of glass wall and inspection of pipes with ultrasonic probe in chemical plants.

NINJA-1 is composed of legs based on a 3D parallel link mechanism capable of producing a powerful driving force for moving on the surface of a wall or glass. Welding tasks at time of assembly as well as during maintenance are accomplished using a hybrid parallel robot developed for an international thermonuclear experimental reactor (ITER), which is a Vacuum Vessel.

8. Conclusion

Several parallel mechanisms have been conceived and investigated in the last two decades. Automated welding, grinding, cutting, inspection, material handling, pipe fitting, oil-well fire fighting, ship building, bridge construction, air craft maintenance, ship-to-ship cargo handling, steel erection, etc. are the various areas of applications. Many prototypes of innovative manipulators and machine based parallel architecture have been built and presented in literature. One of the basic features of parallel mechanisms like Stewart platform, Hexaglides, hexapods and delta robots consist of suitable behavior for dynamical applications where high speed operation makes important the dynamics of the system. Because of the stated advantages, with the applications of micromachines running at very high speed, mechatronics and parallel structured manipulators in medicine are widely spread in clinical use. Deep-sea maintenance of oil and gas facilities can be improved and be more effective by exploration of parallel manipulators applications in this area. Wire driven parallel robotics pay attention for the space applications for current state of research. A continued and incessant effort by researchers will grow and evolve in increasing the capability and effectiveness of various parallel robotics applications to push towards new horizons for robotic industry.

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