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Error Modeling and Accuracy of Parallel Industrial Robots

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1. Introduction

Most industrial robots are open-chain mechanisms constructed of consecutive links connected by rotational or prismatic joints of one degree of freedom. These serial manipulators have large workspace, high dexterity and good maneuverability. However, due to their serial structure they exhibit low stiffness and poor positioning accuracy. As a result, their use in applications that require large loads (e.g. machining) and high accuracy, is limited. In the case of a parallel manipulator, the end-effector is attached to a moveable plate which is supported in-parallel by a number of actuated links. As a result, these parallel manipulators are anticipated to possess the following advantages, compared with serial manipulators: 1) high force/torque capacity since the load is distributed to several in-parallel actuators; 2) high structural rigidity; and 3) better accuracy due to less cumulative joint errors.

A large number of publications dealing with the accuracy of the serial manipulators appeared in the past. These include topics on error modeling effects of manufacturing tolerance on pose accuracy and numerous calibration strategies. However, very few publications dealing with the same issue as related to parallel manipulators can be found. Since high accuracy is generally believed to be one of their advantages compared to that of serial manipulators, it is important to address this issue. The purpose of this research is to establish the kinematic and error models for evaluating the effects of manufacturing tolerances, installation errors and stiffness effect on the accuracy of a parallel robotic system.

In order to evaluate the accuracy of parallel robotic system, it is necessary to develop a kinematic model which will accommodate the above errors. Based on this model, algorithms for forward, inverse kinematics and error modeling of the parallel robot are presented. These algorithms with a set of typical tolerances were used to compute the pose errors which include three translational and three angular errors.

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Manufacturing tolerances, **installation errors** and **link offsets** cause deviations with respect to the nominal kinematic parameters of the robot system. As a result, if the nominal values of these parameters are used within the robot system control software, the resulting pose of the system will be inaccurate. Accuracy of a robot is the closeness with which its actual pose matches the pose predicted by its controller. A robot normally designed for repeated work such as spray painting, pick and place, etc., has high repeatability but low accuracy. An accurate robot is required in applications where off-line programming is involved. To a large extent, robot inaccuracy is induced by the propagation of *geometric errors*, *compliance errors* and *time-variant thermal errors.* The geometric errors of a robot come from manufacturing imperfections, misalignments or joint wear. Compliance errors are due to the flexibility of robot joints and link deflection under self-gravity and external load. The compliance errors also depend on the robot's changing position. Thermal errors result from thermal distortion and expansions of robot components due to internal and external heat sources such as motors, bearings and ambient temperature change.

Link and joint flexibility has a significant impact on robot performance and stability. Link gravity and external payload cause the deflection of links and flexible joints, and therefore degrade the robot performance. Link compliance effects are represented by six differential component changes: three translational and three rotational changes. This paper presents a systematic methodology for estimating the compliance characteristics of serial and parallel manipulators due to external concentrated load/deflection. In related experiments, special measurement tools and sensors are necessary to identify the stiffness of driving joints.

Also in this paper a general methodology is presented to calibrate and compensate for robot compliance errors and thermal errors in addition to geometric errors, An error synthesis model based on the Denavit-Hartenberg (D-H) convention is derived for simultaneously considering geometric errors, compliance errors and thermal errors. Based on this model a general methodology is developed to calibrate geometric errors, compliance errors and thermal errors. Experimental results show that the accuracy of the robot is improved by an order of magnitude after the compensation.

1.1 Serial and Parallel Robots

Robots are representative of mechanics devices which integrate aspects of manipulation, sensing, control, and communication. Rarely have so many technologies and scientific disciplines focused on the functionality and performance of a system as they have done in the fields of robot development and application. Robotics integrates the state of the art of many front-running technologies. Large efforts have been made to define an industrial robot and to classify its application by industrial branches so that remarkably precise data and monitoring are available today.

The task of an industrial robot in general is to move a body (workpiece) with six maximal Cartesian spatial DOF (three translations, three rotations) to another point and orientation within a workspace. The complexity of the task determines the required kinematic configuration. The number of DOFs determines how many independently driven and controlled axes are needed to move a body in a defined way. Industrial robots normally have up to four principal arm axes and three wrist axes. While many exciting robot structures use serial kinematic chains, some parallel kinematic structures have been adopted for a variety of tasks. Typical configurations of industrial robots are shown in Figure 7. Most closed-loop kinematics is based on the so-called hexapod principle (Stewart platform, 1965), which represents a mechanically simple and efficient design. The structure is relatively stiff and enables relatively high positioning accuracy and high speeds, but workspace or working volume is limited.

Parallel or closed-chain linkages and serial or open-loop kinematic chains have been substantially investigated over last several decades. A closed-chain linkage, which usually has a limited number of degrees of freedom, is not applicable as a general-purpose robot kinematic configuration. A serial kinematic chain can provide a large workspace, but with less rigidity and load-carrying capacity compared with a parallel kinematic chain. The fully parallel-driven manipulators such as Stewart-platform have been investigated by many researchers. In general, the workspace of a robot arm consisting of only parallel kinematic chains is relatively small. Currently, there has been an increasing interest in the design of hybrid or serial-parallel robot manipulators which can provide salient features of both serial and parallel kinematic chains. An appropriately designed hybrid robotic manipulator will have a large load-carrying capacity and workspace, and yet be comparatively small and lightweight.

The TAU parallel configuration (Figure 1) is rooted in a series of inventions and was masterminded by Torgny Brogardh, 2000; 2001; 2002. The configuration of the robot simulates the shape of "τ" like the name of the Delta robot named after the "∇" shape configuration of the parallel robot. As shown in Fig. 1.1, the basic TAU configuration consists of three driving axes, three arms, six linkages, 12 joints and a moving (tool) plate. There are six chains connecting the main column to the end-effector in the TAU configuration. The TAU robot is a typical 3/2/1 configuration, which configuration is shown in Figure 11 of Section 2. There are three parallel and identical links and another two parallel and identical links. Six chains will be used to derive all kinematic equations. Table 1 highlights the features of the TAU configuration.

On the subject of D-H modeling, Denavit J. & Hartenberg, H, 1955, Tasi, L. 1999, Raghavan, M. 1993, Abderrahim M. & Whittaker, A. R. 2000 have applied the method and studied the limitations of various modeling methods. On the subject of **forward kinematics**, focus has been on finding *closed form solutions* based on various robotic configurations, and *numerical solutions* for difficult configurations of robots. It can be found in the work done by Dhingra A. K. et al. 1998, 2000, Shi, X. & Fenton, R. G. 1994, Didrit, O. et al, 1998, Zhang, X. & Song, S. 1991, Nanua, P. et al, 1990, Sreenivasan, S. V. et al, 1994, Griffis, M. & Duffy, J. 1989, and Lin, W. et al, 1992. On the subject of error analysis, Wang, J. & Masory, O. 1993, Gong, C. et al, 2000, Patel, A. J. & Ehmann, F. E. 2000 used *forward kinematic solutions* to obtain errors. **Jacobian matrix** was also used in obtaining errors. On the subject of the variation of parallel configurations, based on the work done by Dhingra, A. K. et al, 1999, 2000, Geng, Z. & Haynes, L. S. 1994, the influence of the configurations on the methods of finding closed form solutions can be found.

In this paper, the D-H model (Figure 2) is used to define the TAU robot configuration, a complete set of parameters is included in the modeling process. Kinematic model and error model are established for including all types of errors using **Jacobian matrix method** for the TAU robot. Meanwhile, a very effective **Jacobian Approximation Method** is introduced to calculate the forward kinematic problem instead of the Newton-Raphson method. It denotes that a closed form solution can be obtained instead of a numerical solution. A full size Jacobian matrix is used in carrying out error analysis, error budget, and model parameter estimation and identification. Simulation results indicate that both Jacobian matrix and Jacobian Approximation Method are correct and have an accuracy of micrometers. ADAMS simulation results are used in verifying the established models.

A six-degrees-of-freedom precision measuring system is introduced in this study as an application of all methods mentioned above. The methods are also applied to explore new robotic applications such as grinding and machining. These new developments also revive the interest in robotic performance evaluation. Given the mechanical configurations of industrial robots with their popular six degrees of freedom, industrial robots have to be evaluated with metrology device or system of 3 or more degrees of freedom. Evaluation methods and equipment are needed to measure the spatial pose of robot efficiently with low cost.

Several methods are available for characterizing robot performance in accordance with ISO 9283 "Manipulating Industrial Robots Performance Criteria and Related Test Methods". Eight major performance measuring methods and techniques are introduced in the technical report ISO TR 13309, including the accurate, easy-to-use but costly laser tracking technique. The pros and cons of existing multi-degrees of freedom measuring systems, including laser tracker, straight edges, multi-probes at certain check points, image and scanning techniques etc, are well documented [Lau and Hocken, 1984; Van Brussel, 1990; Jiang et al, 1988]. Pose measurement of robotic end-effecter has been the focus [Ziegert and Datseries, 1990; Zhu and Cui, 2001, 2003].

Precision booster (Figure 3) a 6-DOF piezoelectric ultraprecision positioning drive is developed to provide industrial robots with 6-DOF fine positioning capability. It is designed to mount at the end of the forearm of a robot before its end-effector. With the added fine positioning capability, the accuracy of industrial robots can be greatly enhanced. Working with more accurate feedback sensors or calibration processes, the booster enables industrial robot to reach micrometer accuracy – one or two orders of magnitude higher than those of conventional serial robots. The accuracy of the precision booster can be designed in the range of sub-micrometer or micrometer over a range of millimeters enough to cover the sub-millimeter positioning resolution offered by existing industrial robots. The booster features monolithic flexure construction and the flexure structure functions as a spatial motion mechanism. This monolithic motion mechanism is backlash free and stick-slip free. High strength and high stiffness piezoelectric actuators are used to power the booster to perform fine positioning.

	TAU robot
Work area	1.5 m * 3 m
Repeatability	15 μm
Path accuracy	30 μm
Acceleration	5 g
Maximum positioning speed	180m / min
Excitation frequency	> 40 Hz
Cost	< 250 KUSD

Table 1. Specifications of the TAU Robot Based on Certain Applications

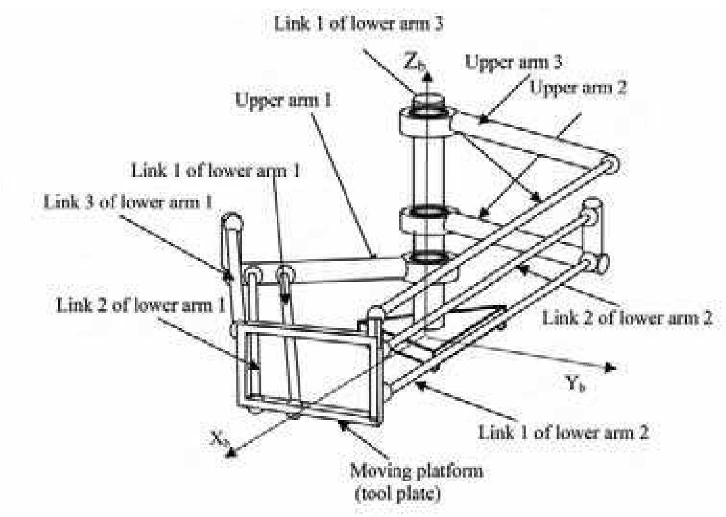

Figure 1. One of the TAU Robot Configurations

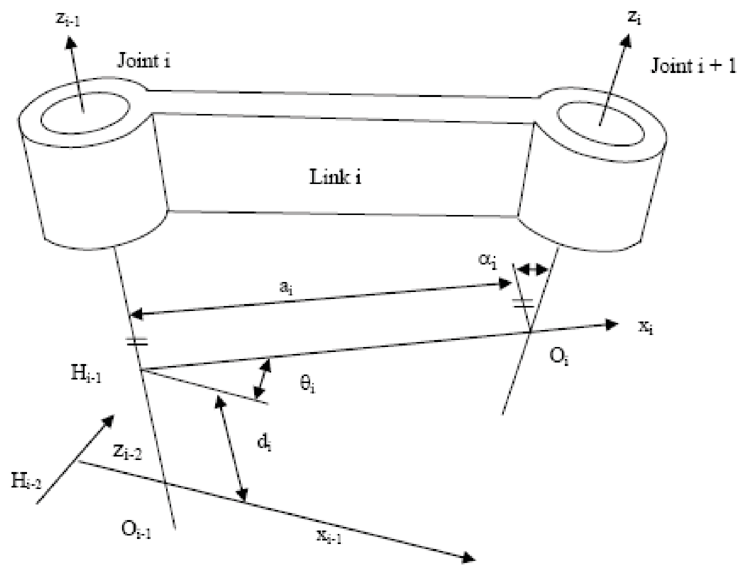

Figure 2. Definition of the Parameters in D-H Model

1.2 Kinematic Configurations of Parallel Robots

Gough-Stewart parallel robot, or so-called 'hexapod' shown in Figure 3 (Gough 1957 and Stewart 1965), is an assembly consisting of a fixed base with universal joints connecting the base to six linear-actuated limbs that support a moving platform through six ball-and-socket joints. This configuration allows the platform to move with six degrees-of-freedom employing the fewest number of actuators while maintaining stiffness by using only two-force-members. It is a closed-loop kinematic system with parallel links and is considered to be far more rigid than that of its serial counterparts of the same size and weight. Its force-output-to-manipulator-weight-ratio is generally an order of magnitude bigger than that of most industrial robots (Liu, 1993). *The same closed-loop kinematic configuration that gives its rigidity also complicates the solution of the forward kinematics in such a way that no closed-loop solution for this problem has been found* (Lacaze, Tasoluk and Meystel, 1997).

Tricept robot, shown in Figure 4, logically derived from the Tetrabot (Thornton, 1988), has a 3-DOF (degree of freedom) configuration of the parallel type to execute translational motions and a 3-DOF spherical wrist to execute rotational motions (Neumann and Neos Robotics, 1998). Its workspace is to be considered relatively large compared to the size of the robot. In order to further enlarge the size of the workspace, the addition of a revolute joint at the fixed base has been envisaged, introducing kinematic redundancy into the robotic manipulator. Its translational part can be thought as a reduced Stewart platform with only three limbs. Like the Stewart platform, its kinematics has not been completely obtained: the inverse kinematics problem admits an analytical solution whereas the direct kinematics problem may require the use of iterative algorithms (Siciliano, 1999).

Delta robot, patented in U.S. in 1990 (Clavel, 1990), is shown in Figure 5. The basic idea behind the Delta parallel robotic design is the use of parallelograms. A parallelogram allows an output link to remain at a fixed orientation with respect to an input link. The use of three such parallelograms restrains completely the orientation of the mobile platform, which remains only three purely translational degrees of freedom. The input links of the three parallelograms are mounted on rotating levers via revolute joints. The revolute joints of the rotating levers are actuated in two different ways: with rotational (DC or AC servo) motors or with linear actuators. Finally, a fourth leg is used to transmit rotary motion from the base to an end-effector mounted on the mobile platform.

The use of base-mounted actuators and low-mass links allows the mobile platform to achieve accelerations of up to 50-G in experimental environment and 12 G in industrial applications. This makes the Delta robot a perfect candidate for pick and place operations of light objects. The Delta design has been applied to industry robot for several years. Its kinematics and dynamics also have been developed (Hunt 1973 and Codourey 1998).

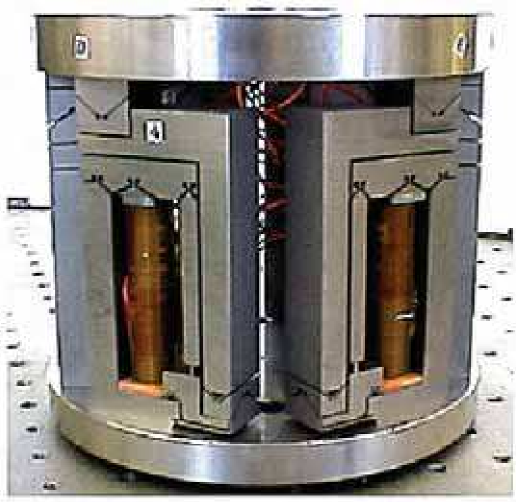

Figure 3.Piezo Driven Flexure Based Hexapod (Zhu and Cui, 2001)

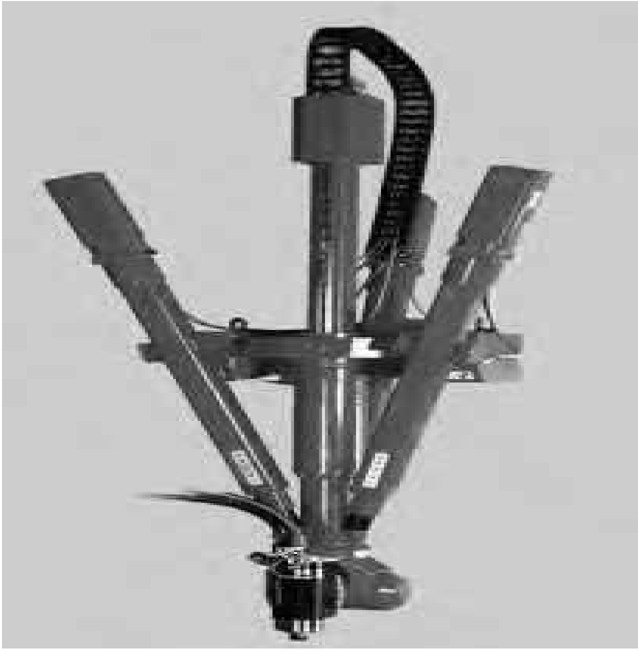

Figure 4. Tricept Robot (Neumann and Neos Robotics, 1998)

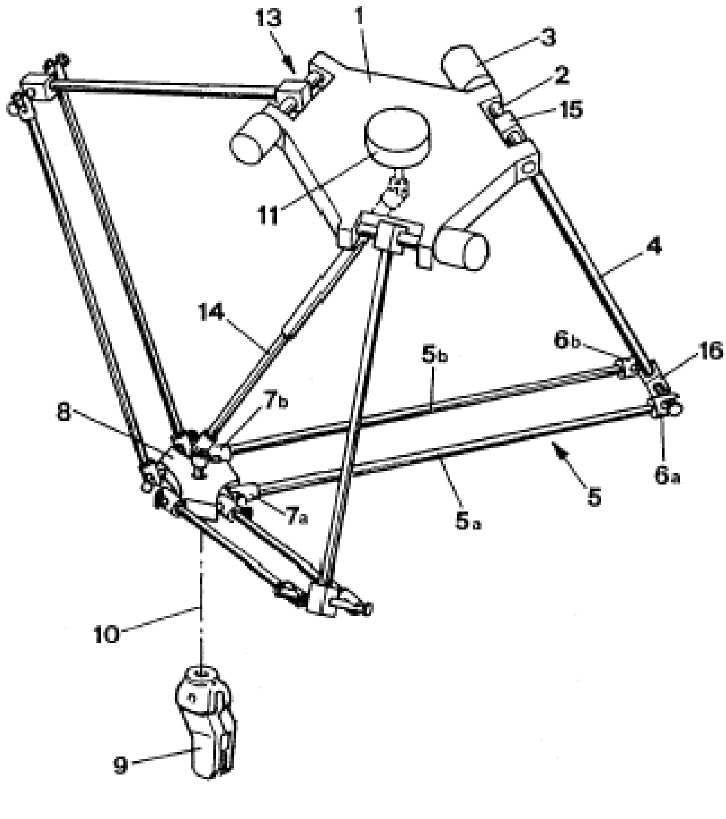

Figure 5. Delta Robot from US patent No. 4,976,582

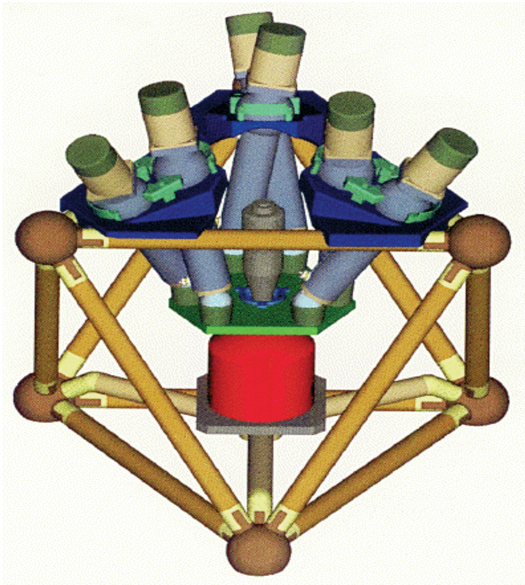

Figure 6. Octahedral Hexapod (NIST)

Octahedral Hexapod as shown in Fig. 1.6 is a demonstration machining center with six DOFs. It is a small, portable machine based on an octahedral framework. Machine motion is achieved by a Stewart Platform style actuation system. The framework and machining system can achieve high overall stiffness due to the fact that the structural members are generally in tension or compression with a minimum amount of bending stress. This structure allows the machine's capabilities to be independent of its foundation. Six identical struts with spherical pivots are mounted to the framework to drive the machining spindle, providing six-axis machining capability. The machine has a work volume of approximately 5" diameter X 3.5" high. The assembled machine will fit in a 24" X 24" X 25" volume. The machine completely disassembles and stores in a case approximately 24" X 16" X 10".

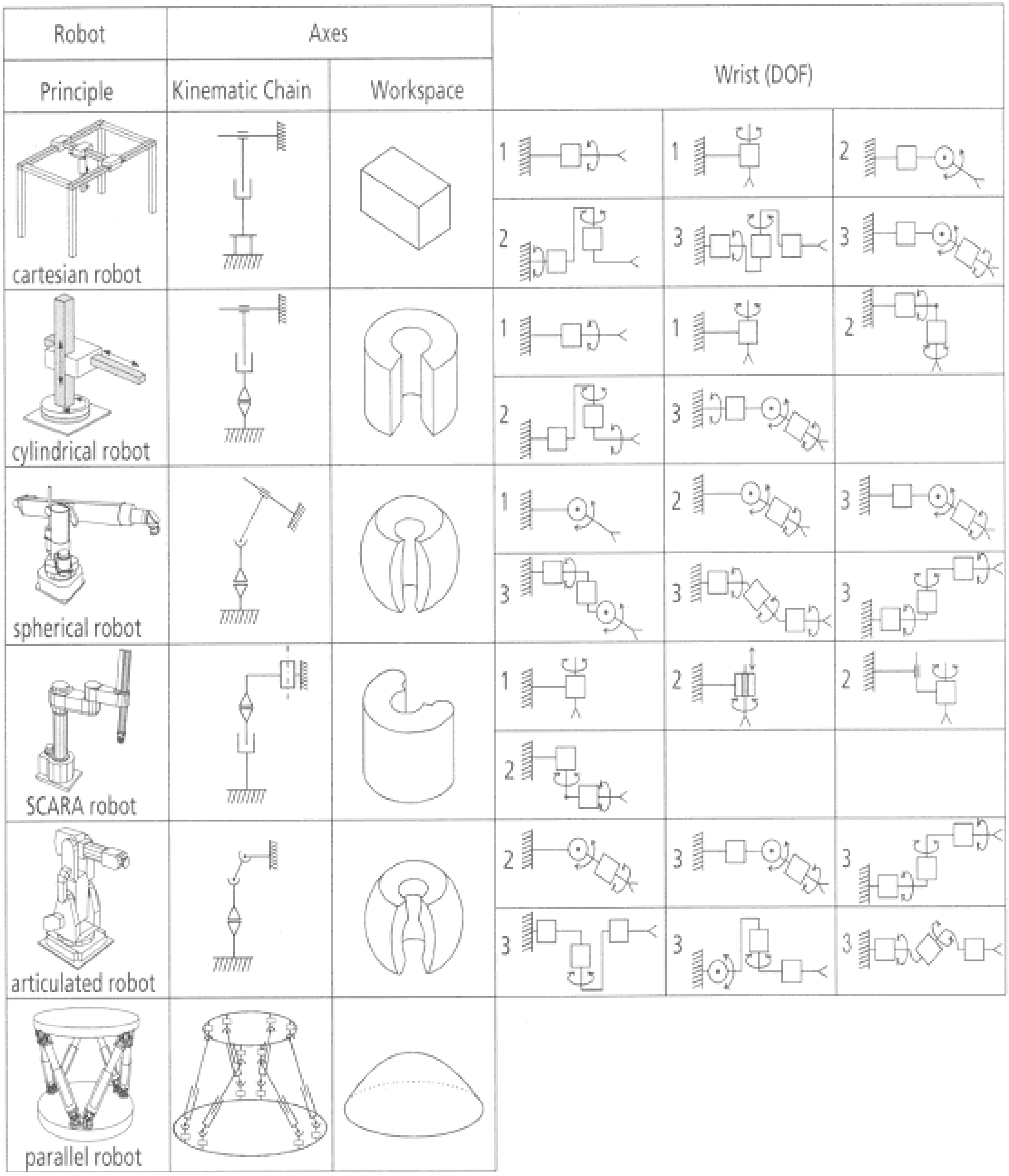

Figure 7 Typical Arms and Wrist Configuration of Industrial Robots (Handbook of Industrial Robotics)

2. Tau Configuration Design

Hybrid manipulators are parallel-serial connection robots that give rise to a multitude of highly articulate robotic manipulators. The robotic manipulators have a strength-to-weight ratio many times larger than the value currently available with industrial or research manipulators. This is due to the fact that these hybrid manipulators are stress compensated and ultralight in weight, yet are extremely stiff due to the fact that the force distribution in their structures is mostly axial.

Serially connected robot manipulators in the form of an open-loop kinematic chain with computer-controlled joint actuation have been utilized extensively in robot industry. For parallel manipulators, a classic example is the Stewart platform, which has been kinematically and, to some extent, dynamically investigated by many researchers.

The major advantages of existing parallel robots, compared with serial robots, are smaller mass and higher stiffness of the arm system. This is very important to achieve a shorter cycle time with lower actuator power together with more accurate movement.

The disadvantage is a relative small workspace in relation to the volume of the arm system. In the process of improving the robotic performance by diminishing the disadvantages, the basic features in design should include the following:

1. All the actuators are mounted on a fixed platform, which minimizes the mass of the moving arm system.
2. The links connected to the actuated platform are two-force members transmitting only compression and tensile forces and do not carry bending and twisting loads, which makes it easy to achieve a moving arm system of high in stiffness and low in mass.
3. The joints can be implemented as ball and socket bearings, which makes it possible to obtain high precision in addition to high stiffness and low mass for the joint arrangement.
4. The actuated platform is positioned with 3 translational DOFs in a parallel fashion without angular displacement.

2.1 The Link Clustering Design Approach

Systematic clustering of the links connected to the actuated robot platform has been studied. Based on this design approach new parallel arm structures have been identified and some new robot concepts have been found (Brogardh, T, 2000).

Figure 8 shows schematically the basic components needed to achieve the

Delta parallel arm robot with the kinematic features listed above. The actuated platform is connected to 6 links of type A by means of ball and socket joints that each has 3 DOFs. Type A means that the links are designed to be stiff only for forces along their axial direction in the structure. This force loading characteristic in the links of type A is guaranteed since a ball and socket joint cannot transmit bending moment or twisting torque to the link it is connected to.
The actuators in Figure 8 are mounted on the fixed platform and the moving part of the actuators is connected to the links of type A via links of type B. The type B links are designed to be stiff against also bending moment and twisting torque. All the links of type B do not need to be connected to actuators, but 3 of them must, otherwise the actuated platform cannot be manipulated in 3 DOFs.

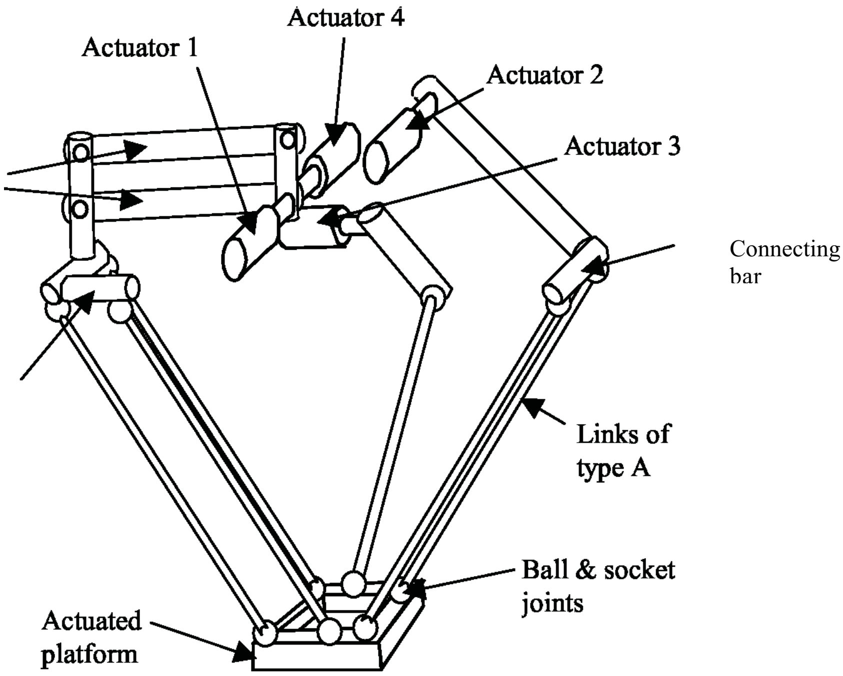

Figure 8. Components for the Design of Structures with the Same Features as the Delta Robot. (Courtesy of Brogardh, T, 2000).

Each of the links of type B (Figure 8) can be connected to one or more of the links of type A. One could say that each link of type B can be connected to a cluster of links of type A and it is possible to introduce a simple clustering scheme, where for example 2/2/2 means that the links of type A are clustered with 2 links to each of the 3 links of type B. To achieve parallel movements of the actuated platform (to preserve the tilt angles), type A links belonging to the same cluster must be parallel and have the same length. Moreover, to avoid a

collapsing parallel arm structure because of kinematic singularities, the placement of the type A link joints on the actuated platform must be optimized as well as the relative directions between the type A links of the different clusters. The 6 links of type A can be clustered in 3 ways: 2/2/2, 3/2/1 and 4/1/1. The 4/1/1 clustering will not fulfill the kinematic demands for a controllable structure and can be omitted. However, the 2/2/2 and the 3/2/1 clustering according to Figure 10 are kinematically useful. Using the 2/2/2 clustering scheme for the design will end up with the Delta structure. The optimized link placement in this case is achieved when the lines between the joints of each cluster on the actuated platform have an angle of 120 degrees between each other. The arm structure will collapse if the angle between two joint lines is 0 (180) degrees instead of 120 degrees. If instead the 3/2/1 clustering is used for the design of a parallel arm robot, the placement of the joints of the type A links on the platform surface is not critical. The only demand is that the 3 lower joints of cluster 1 are not allowed to be on a straight line on the platform. The optimum is achieved when these 3 joints of cluster 1 form a triangle with equal side length. This robustness with respect to the link placement on the actuated platform opens up new possibilities for the robot design.
In Figure 9 the actuated platform is considered to have a plane design, which means that the links of type A connect to the platform surface in a plane. However, the actuated platform could also be designed as a 3-D framework as depicted in Figure 10. This framework does not need to be a cube as in the figure, but the cube drawing makes it easier to see the configurations of the links. As in the case with a plane platform design, there are also in this case 2 useful clustering possibilities for an actuated 3-D platform: 2/2/2 and 3/2/1.

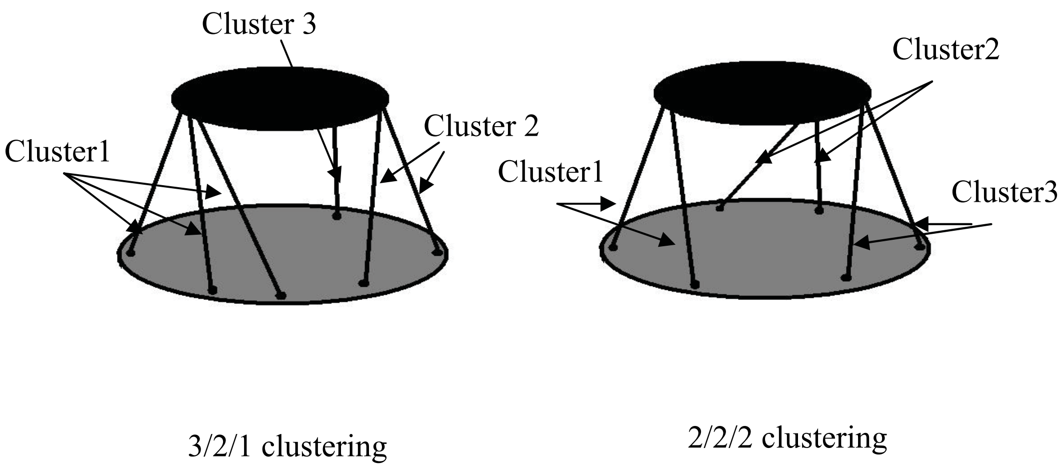

Figure 9. Useful Clustering Strategies When the Links of Type A Are Attached to the Actuator Platform in a 2-D Pattern.

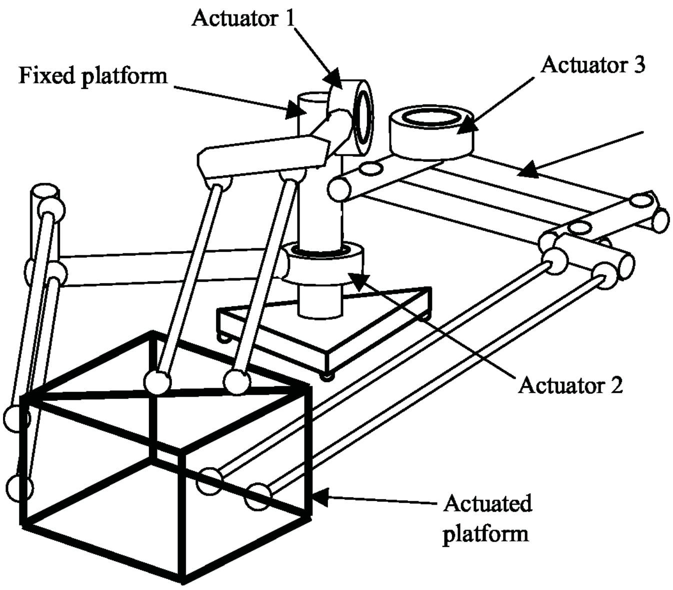

Figure 10. Useful 2/2/2 Clustering Strategies when the Links of Type A are Attached to the Actuator Platform in a 3-D pattern. (Courtesy of Brogardh, T, 2000).

2.2 TAU 3/2/1 Configuration

A new class of parallel robot, namely, TAU robot, has been created based on the 3/2/1 configuration. It combines the performance advantages of parallel arm mechanism (e.g., high stiffness, high accuracy) with the large workspace of serial robot.

As shown in Figure 11, the primary design of the TAU prototype robot has three actuators mounted on the base fixture and arranged in a line, which is called an I-configuration TAU. From bottom to top, actuators and upper arms (type B link) are numbered as 1, 2 and 3, and connected with 3, 2 and 1 lower arm(s) (type A link) respectively. This configuration basically performs a 3-DOF motion in its workspace. The 3-DOF parallel robot has a small footprint but with an enhanced stiffness.

The six links (lower arms) connected to the tool plate are driven by the three upper arms rotating around Z-axis. This structure has 3 DOFs in its workspace. With its geometric constraint, the DOF of a TAU robot is equal to (Tsai, 1999)

$$\text{DOF} = \lambda(n - j - 1) + \sum_{i=1} f_i$$

λ: degree of freedom of the space in which a mechanism is intended to function

n: number of links in a mechanism, including the fixed link
j: number of joints in a mechanism, assuming that all the joints are binary.
f_i: degree of relative motion permitted by joint i.

Joints between fixture and upper arms are 1-DOF rotational joints. Joints connecting upper and lower arms are 2-DOF universal joints. 3-DOF spherica-joints connect lower arms and moving plate.

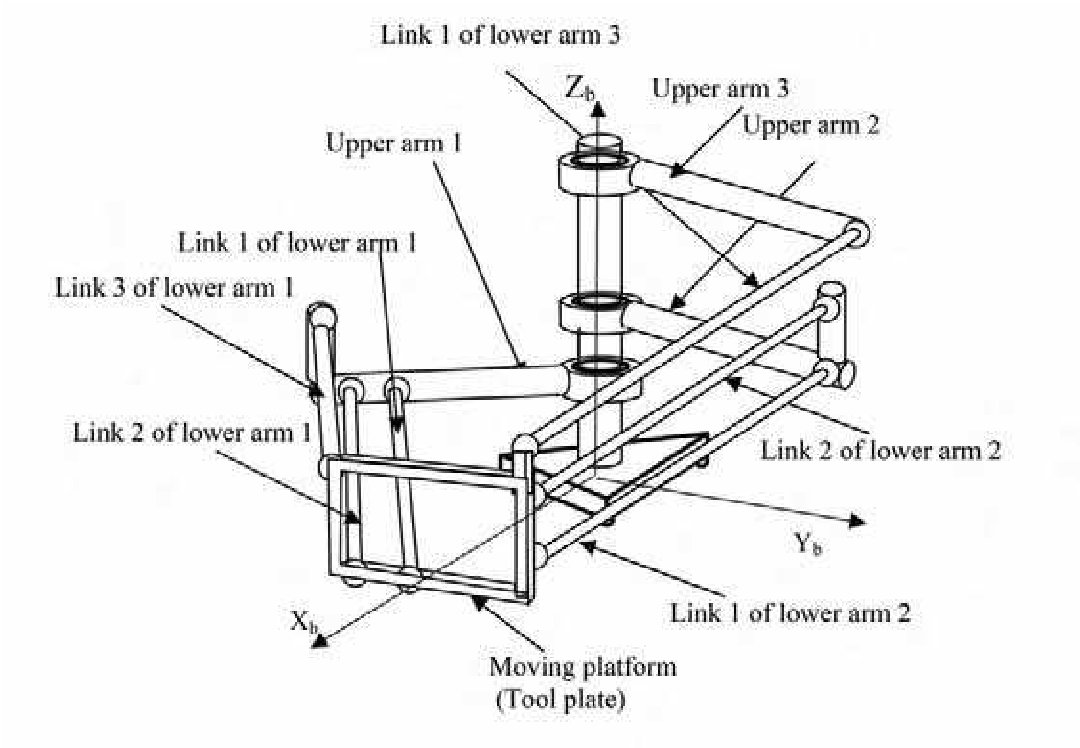

Figure 10.TAU Robot Based on Clustering Design Approach

2.3 Features of the TAU Configuration

The parallel robotic configuration for translational motion has a higher stiffness compared to the serial robotic configuration. It also has the following features: Large workspace, 360 degree around its base axis like a serial robot, analytic kinematic solution and analytic rigid-body dynamic solution.

Applications and Design Requirements

With these new features, the robot has the possibility to work with several conveyors and feeders placed around the robot. This is just one example of how a SCARA like parallel arm robot could be used to increase the productivity in an existing production line just by replacing conventional SCARA robots used today with its parallel arm cousins.

Typical Applications

Spot welding and painting are among the earliest application for industrial robot. Their payload is usually less than 50 kg. Repeatability requirement is in the range of 100 µm.

Pick and place and packaging have relatively low requirement on repeatability and stiffness. Payload varies from 1 to 500 kg. High speed is preferred for high productivity.

Machining or material removal including deburring, grinding, milling and sawing, requires high stiffness. Stiffness and accuracy of the robot decide the quality of the machined product.

Potential Applications

Laser cutting or welding, as a non-contact process requires an accuracy/repeatability less than 100 µm. Payload, which is the laser gun and accessories, is usually less than 50 kg. Speed required is not high in such applications.

Coordinate measuring function is typically performed by a CMM. It has a strict accuracy requirement of less than 50 µm for both static and path following at a low speed.

Fine material removal is as precision machining application now dominated by CNC machines. It requires the highest stiffness and system accuracy.

Design Objectives

The mechanism design is application orientated. Three typical future applications were selected and studied in the design phase: 2-D laser cutting, CMM for automobile vehicle and material removal applications. Each of them represents a typical application with certain requirements. Accuracy is a dominating factor reflecting the level of performance of any measurement system. The accuracy is low for current articulated robot arms. Material removal application requires high stiffness. Current serial configured CNC machines or parallel-configured machines have a limited workspace.

	TAU robot	Linear motor gantry
Work area	1.5 m * 3 m	1.5 m * 3 m
Repeatability	15 µm	17 µm
Path accuracy	30 µm	50 µm
Acceleration	5 g	2 - 4 g
Maximum positioning speed	180 m / min	100 - 200 m / min
Excitation frequency	> 40 Hz	13 Hz
Cost	< 250 KUSD	250 KUSD

Table 2. Performance Comparison with 2-D Laser Cutting Gantry Robot

Table 2 shows the performance comparison between the TAU robot and the gantry robot currently used in laser cutting application, which indicates the potential applications instead of using linear gantry robot. The performance of TAU covers all advantages of the Linear Motor Gantry.

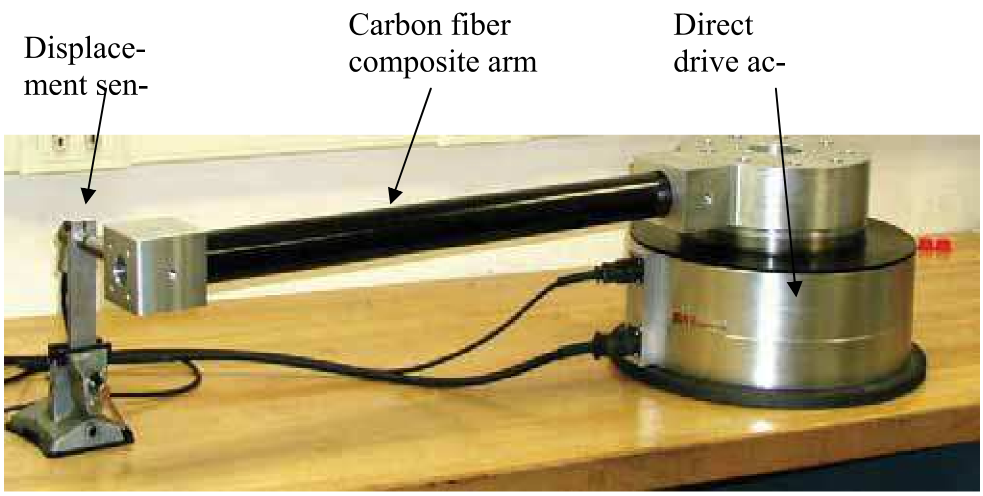

Figure 12. Single Arm Test Platform for Drive Motor Error Analysis

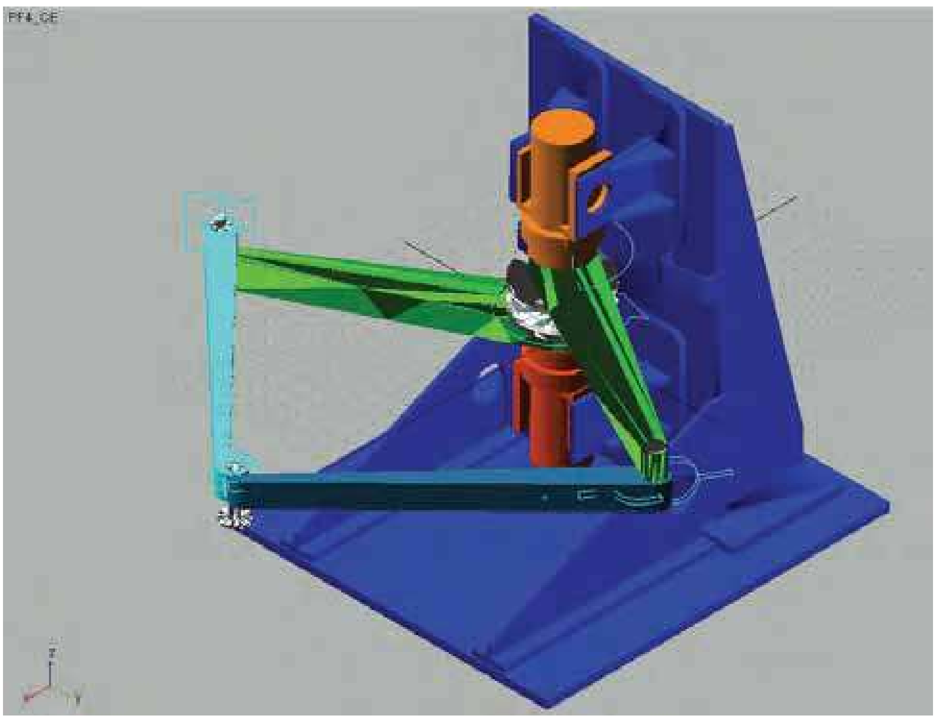

Figure 13. ADAMS Simulation Model for Two-Arm Test Platform