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# Teaching the Design of Parallel Manipulators and Their Controllers Implementing MATLAB, Simulink, SimMechanics and CAD*

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*The teaching of parallel mechanisms and their controllers is a difficult task because of the complex mathematics that must be solved for the direct and indirect kinematics problems. In order to help students understand the kinematics and the dynamics of parallel manipulators and their controllers, we have designed a final-year robotics course based on MATLAB, Simulink and SimMechanics. Students are given specifications of the parallel manipulator that they must design, such as parameters of the DC motors to be used, the type of controller to be implemented, the number of degrees-of-freedom (DOF) of the developed robot, etc. Each group is then required to design a parallel manipulator of its choice in MATLAB, Simulink, SimMechanics and/or CAD. Finally, they are required to design the manipulator's controller for simulation purposes. Some mechanical components of the best robot are rapid prototyped on the Dimension 3-D printer. The mathematical analysis of the best mechanism is then studied in detail. This is compared with the simulation of the integrated manipulator in MATLAB. This paper presents the mechanical design, analysis and controller design of the parallel manipulator that was developed in MATLAB.*

## INTRODUCTION

A SERIAL MANIPULATOR consists of a group of rigid bodies, called struts or links, with the first link connected to a supporting base and the last link connected to a platform that holds a terminal device or tool. Each link of a serial manipulator is connected to, at most, two others by implementing a joint, so that closed kinematics loops or chains are not formed. Parallel manipulators contain kinematics loops, which are formed when some of the links are connected to three or more other links [1]. A closed-loop path can be found between the first link connected to the supporting base and another link connected to another, or the same, supporting base. An example of a commercial parallel manipulator is Fanuc F-200i, which is based on the Steward Platform (Fig. 1).

One of the ways in which parallel manipulators are described is according to the joints implemented on their kinematics chains. Kinematics chains are described by the sequence of the types of joints from the base upwards. Either different or the same kinematics chains can be used in the design of a parallel manipulator. If *R* represent a revolute joint, *P* represents a prismatic joint and *S* represents a spherical joint, then the different kinematics chains in Fig. 2 have the following sequence of joints: *RRR*, *RPR*, *RRP*, *RPP*, *PRR*, *PPR* and *PRP*.

The first parallel manipulators were sold with the argument that they were as accurate as machine tools and would therefore become a serious threat to conventional machine tools. This is not the case and many of the machines sold do not have the same accuracy or rigidity to be able to compete with the machine tools. Suitable applications for parallel manipulators are mainly within the area of reconfigurable manufacturing systems, five axis machining, handling of heavy work-pieces and manufacturing that requires high-strength assembly equipment.

The factors that make the teaching of parallel manipulators difficult are:

- the high cost of developing or acquiring a parallel manipulator;
- the complex mechanical design and structure of parallel manipulators; and
- the complexity of the controllers for developed parallel manipulators.

At Massey University, we have developed an undergraduate final-year course based on SimMechanics, Simulink and MATLAB for the simulation and design of parallel manipulators and their controllers in the Bachelor of Engineering in Mechatronics curriculum. This approach is low-cost and effective, as students can develop, design,

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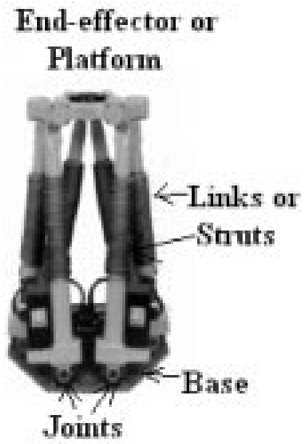


Fig. 1. Fanuc F-200i ( based on the Steward Platform) and its components.

verify and simulate their designs in one integrated platform.

## SIMMECHANICS AND OTHER SIMULATION SOFTWARE

The literature repeatedly refers to the simulation and modelling of parallel manipulators. The difficulties in modelling complex mechanical systems are many and far-reaching. Most of the simulation software that has been developed is implemented in C or FORTRAN and specializes in simulations of six DOF systems that model specific aspects of the physical system (e.g. stiffness model of a Stewart platform [3]), how heat affects the deformation of Tripod Robot [4], etc. Although these simulations work well for the particular application for which they were developed, it is often difficult to apply the models to new systems, or to make design changes outside the scope of the original implementation, or to reuse the models in new development tasks such as controller development/simulation.

SimMechanics from MathWorks Inc. is a recently developed MATLAB library based on Simulink. It is a modelling software for mechanical systems that provides a single simulation environment for the construction of reliable mechanical

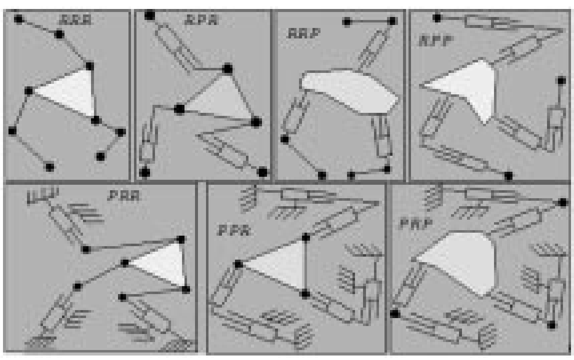

Fig. 2. Some examples of 3 DOF parallel manipulators [2].

and controller models. These models can be reused by converting them into compact, efficient C code for embedded controller implementations and hardware-in-the-loop testing applications [5]. SimMechanics includes a computer-aided-design (CAD)-to-SimMechanics translator that facilitates the automatic creation of SimMechanics models from SolidWorks or CAD assemblies [6].

Students enrolled in our Robotics course are required to design and model a parallel manipulator and its controller using Solidworks, SimMechanics, Simulink and MATLAB only. Students are grouped into groups of three to five students.

## PARALLEL MANIPULATOR DESIGN PROCESS AND DIFFERENT SOFTWARE TOOLS OF EACH DESIGN STAGE

The process of designing parallel manipulators can be divided into six stages (Fig. 3). In the first stage, the values of the minimum and maximum parameters that the parallel manipulator must have are specified. Minimum and maximum values of parameters such as workspace, acceleration, velocities, torques, DOF, resolution etc. are specified according to the task that will be carried out. The next sections elaborate on the different stages of the design process.

The second stage involves the design of the topology of the parallel manipulator, including the number of kinematics chains, the number of links used per each kinematics chain, the type of joints used to join different links, and the positions of the base and the platform. Values of geometric parameters such as lengths of different links, limits of different joints' movements, and positions of attaching different kinematics chains to the base and platform are also specified. Solidworks is used to facilitate the implementation of this stage. The advantage of using Solidwoks is that a 3-D model of the mechanical design assembly of the parallel manipulator can be achieved and inspected. This gives the designers, or students, the ability to use their intuition about the ability of the developed parallel manipulator to achieve the required motions or tasks.

The CAD-to-SimMechanics translator can be used to convert the developed mechanical design into a SimMechanics model so that kinematics and dynamics analysis of the manipulator can be done. Otherwise a SimMechanics model of the developed parallel manipulator can be directly implemented in SimMechanics. The advantage of using the CAD-to-SimMechanics translator is that it eliminates the errors that are usually encountered in the analysis of parallel manipulators, such as inexact relative positions of joints coordinates, incorrect mass and inertia tensors of links, etc. However, the designer or the student must make sure that the SimMechanics model developed with the CAD-to-SimMechanics translator is analysed and understood so that the results of the simulation can be

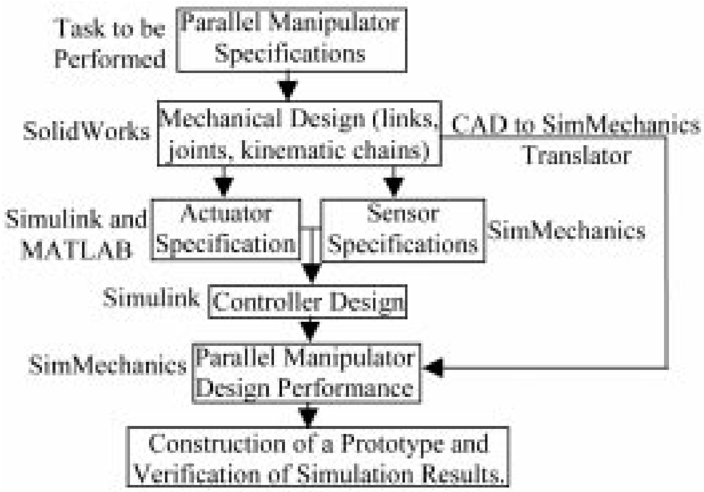


Fig. 3. Flow chart of the design process and the different tools used during the different stages of the design process.

interpreted and that the actuators and sensors can be correctly added to the SimMechanics model.

The third stage involves the specification or selection of actuators that are used to achieve the motion of the different joints of the developed parallel manipulator. The modelling of different actuators is implemented in Simulink and MATLAB. Their performance can be monitored using scopes in Simulink and/or SimMechanics. Sensors are then used to monitor the critical manipulator's parameters for simulation purposes. Sensors are added in the SimMechanics model. Their outputs can be monitored either in Simulink or SimMechanics.

The fourth stage involves the design of a controller for the parallel manipulator. This normally involves designing controllers for all actuators that are implemented in the design of the parallel manipulator. The controllers are developed in Simulink.

The fifth stage involves the integration and simulation of the mechanical design, actuation techniques, sensory techniques, and controller of the developed parallel manipulator in one environment, SimMechanics. The last step involves verification of the results of the fifth step by implementing the real prototype of the parallel manipulator.

## DESIGN STATEMENT

The students are given the specifications of the parallel manipulator that they must design. This includes the DC motor's parameters to be used, the type of controller to be implemented, the overall dimensions of the manipulator, the number of DOFs of the developed manipulator and the minimum number of kinematics chains that the developed manipulator must have.

The number of parameters that are required to fully describe a general serial manipulator is 132 [7]. It is very difficult to optimise each and every parameter of a manipulator, due to the large number of parameters that are involved. Some criteria that are pose dependent are normally used to analyse and design the manipulator's performance. They rely on the six dimensional operational space and are computer-intensive and not accurate.

Some of the performance criteria that have been used for parallel manipulator design are:

- Dynamics: Acceleration is maximised, while a specific minimum acceleration is guaranteed. Analysis of the acceleration and inertia characteristics of a manipulator is carried out against a cost function that quantifies the dynamic performance of the manipulator. A numerical procedure would then be used to find parameters that optimise the average cost function, as calculated over a finite number of poses [8].
- Workspace: The manipulator's workspace is maximised by optimising the geometric parameters of the manipulator, such as its overall size, workspace, motion range, joints, etc. Sometimes there is the requirement that the design parameters be optimised, so as to make sure that a given set of points belongs to the workspace [9]. One of the drawbacks of parallel machines compared to serial machines is the limited workspace. This increases the importance of workspace evaluation, both in the design stage and when implementing a parallel mechanism in a manufacturing process.
- Dexterity: The manipulator's design parameters are optimised such that maximum velocities and minimum velocities are guaranteed. The design parameters can be minimised so as to reduce the condition number of the inverse kinematics Jacobian matrix. This in turn gives the required joints' velocities a certain characteristic called isentropy [10].
- Stiffness: The design parameters are optimised so as to achieve maximum forces or torque. This is achieved by reducing the number of design parameters to three and then using the stiffness

matrix to define various criteria and calculating their average value by using a dicretisization method [11]. Parallel manipulators can carry a higher payload than conventional serial manipulators. This is due to the fact that parallel manipulators have a higher stiffness than their serial counterparts. This property is, however, highly nonlinear in space. The stiffness of a machine can be defined as the force required to displace a point in space at a specific distance. Stiffness is directly proportional to the accuracy of parallel manipulators. Parallel manipulators were introduced with the argument that they had a better accuracy than conventional manipulators and stiffness in the same range as machine tools. Due to the complicated kinematics chain in a parallel machine, it is very hard to achieve the accuracy sought after. The main problem is that the kinematics model does not coincide with the physical machine. There are several reasons why the model does not match reality, such as a flexible base, incorrect links' length entered into the controller, etc. [12].

- Combination: A combination of the above methods can be used [10].

Implementation of analysis of all the above performance parameters is straightforward in SimMechanics, except analysis of the workspace.

## OUR DESIGN

The best design of one student group is used as a case study for the Robotics course. It is analysed and some of its parts are rapid prototyped on the Dimension 3-D printer. Figure 4 is a SolidWorks (or CAD drawing) of the best parallel manipulator that was designed by one group of students. The advantage of the CAD model is that it helps students to visualise their design concepts. The designed manipulator is similar to the one proposed by Kohli [13], but the first joint on the base is a prismatic joint. This manipulator is designed for reconfigurable manufacturing applications that require pick and place operations, with optimised workspace. Figure 5 is a SimMechanics model of one leg of the same parallel manipulator. The developed parallel manipulator can be classified as ***PR**RS* (where the bold letter indicates that the joint is actuated). The advantage of using the SimMechanics model is that sensors can be positioned on every joint of the manipulator's model in order to simulate any parameter of the joint, such as forces, torques, linear and rotary displacements, etc., depending on the design requirement. The design principle can be simulated and verified before the actual manipulator is built.

## MOTOR CONTROL

The manipulator's actuators and their controllers can be modelled in Simulink. These models can be integrated into the manipulator's SimMechanics model for simulation of the integrated model. All the actuated joints of the manipulator use the same DC motors with integrated gear as actuators. The prismatic joints are driven by linear motors that use the same DC motors and linear screws. Figure 6 shows the Simulink model of the actuators and the controllers that are used. A simple positional controller for the DC motor is used. All the outputs of the Simulink models of DC motors and their controller are MUX-ed, and they are the inputs to the parallel manipulator SimMechanics model that are applied to the actuated joints.

## KINEMATICS ANALYSIS

Kinematics analysis of parallel manipulators is divided into forward kinematics and reverse kinematics. The inverse kinematics gives the solution for the joints' parameters (angles and displacements), given the orientation and the position of the platform. Determination of the joints' parameters is important for position control of parallel manipulators. The forward kinematics gives the solution to the orientation and position of the platform, given the joints' parameters. Forward

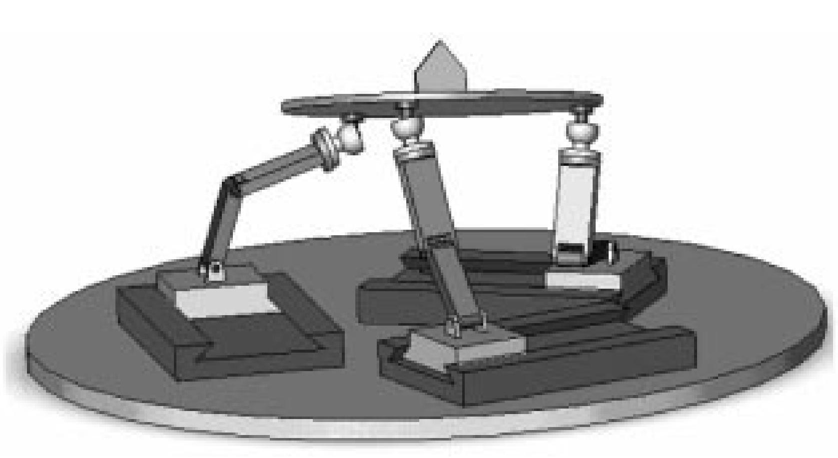

Fig. 4. SolidWorks model of the Parallel Manipulator designed by one of the students' groups.

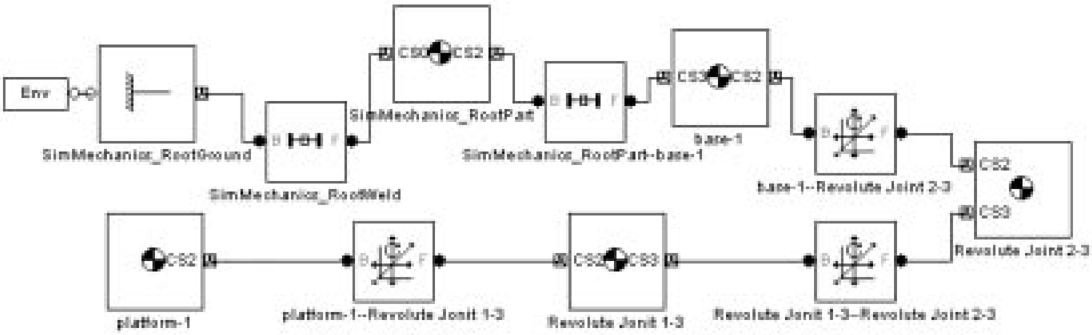


Fig. 5. SimMechanics model of one leg of the developed *PRRS* parallel manipulator.

kinematics is important for the orientation and velocity control of manipulators. The inverse kinematics is straightforward, while the forces and kinematics solution requires a numerical solution.

Kinematics analysis of parallel manipulators has been extensively researched. We will only give the results from literature in this section. Figure 7 is a schematic of the students' proposed manipulator, with Denavit-Hartenberg coordinates assigned to each joint $B_{ii}$.

*Inverse kinematics*

Let $A$ be the origin of the body-attached coordinate system (the platform), and $O$ be the origin of the reference coordinate system that is on the stationary base (Fig. 7). The position and orientation of the platform is measured from the coordinate system $A$ on the platform with reference to the coordinate system $O$ on the base. Let $B_{ij}$ represent the end of the coordinates of each strut/link in a kinematics chain $A_i$. $A_i$ also represents the end of the chain that is linked to the moving platform. By construction the coordinates of $B_{i1}$ are known fixed in a reference frame, while the coordinates of $A_i$ may be determined from the moving platform's position and orientation. If **X** represents the moving platform's generalised coordinates using the roll, pitch and yaw angles, i.e. ($x_A$, $y_A$, $z_A$, $\varphi_A$, $\theta_A$, $\psi_A$), we have:

$$\overrightarrow{B_iA_i} = \overrightarrow{B_iO} + \overrightarrow{OA_i} = H_1(X) \quad (1)$$

This gives the coordinates of the extreme points on all the chains for which we want to solve $\mathbf{X}_{ii}$ (generalised coordinates of chain links). The direct kinematics of each link need to be calculated and the solutions for each kinematics chain can be independently determined [6]. Let ${}^{i\text{-}1}\mathbf{A}^{i}{}_{0}$ be the initial transformation matrix that describes a point in the $i^{th}$ coordinates frame in terms of the $i$-$1^{th}$ coordinate frame and $\mathbf{Y}_i$ represent the linear displacement matrix for a joint in a chain. The direct kinematics of each chain can be found by multiplication of the successive transformation matrices. For example, the direct kinematics for the joint $B_{23}$ is:

$$\mathbf{P}_4 = ({}^{0}\mathbf{A}^{1}{}_{0}\ \mathbf{Y}_1)({}^{1}\mathbf{A}^{2}{}_{0}\ \mathbf{Y}_2)(\ {}^{2}\mathbf{A}^{3}{}_{0}\ \mathbf{Y}_3)\ (\ {}^{3}\mathbf{A}^{4}{}_{0}\ \mathbf{Y}_4) \quad (2)$$

where $\mathbf{P}_4$ represents the coordinates of a point in the coordinate frame of joint $B_{23}$.

*Forward kinematics*

Sensor-based solutions can be implemented to determine the forward kinematics by implementing

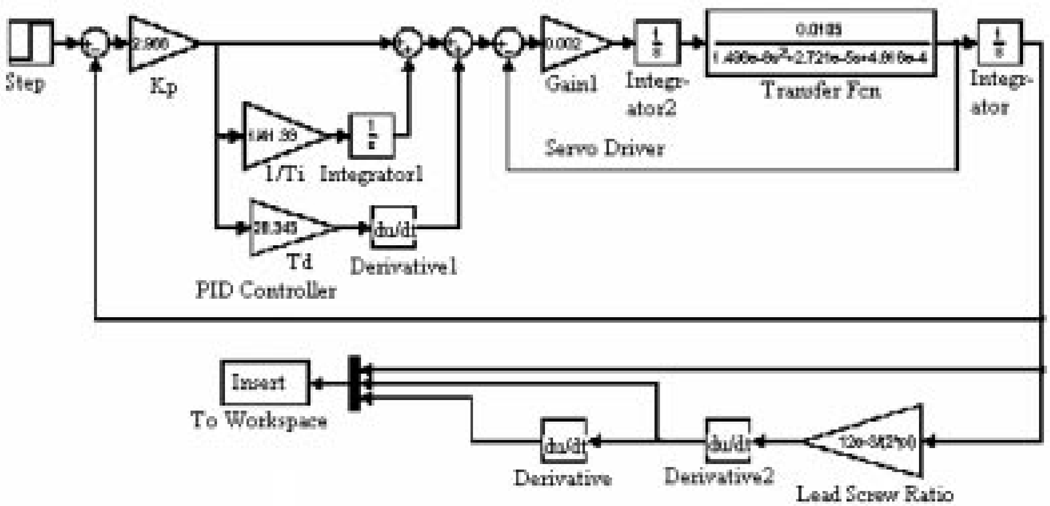


Fig. 6. Simulink model of DC motors and their controllers.

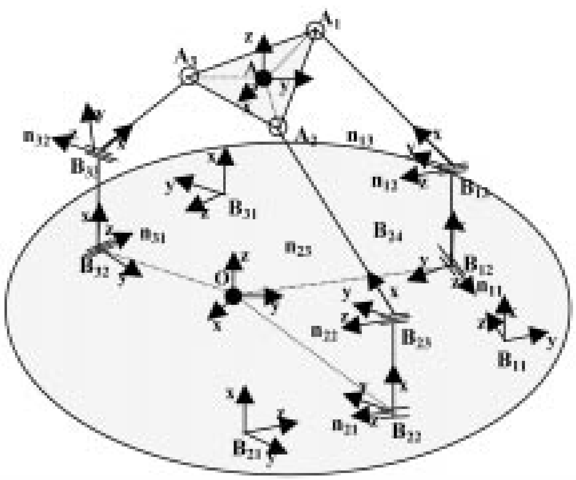

Fig. 7. A three-legged parallel manipulator.

displacements measured by the angular encoders in all the joints to compute the forward displacement of the platform. The forward kinematics problem of parallel manipulators then becomes the same as the forward kinematics problem for serial manipulators. The transformation matrix from frame $B$ to frame $A$ can be determined and used.

The numerical solution is more difficult and requires an iterative solution. One method of solving it is to use the Newton-Raphson method, which uses the following equation:

$$\boldsymbol{x_{k+1}} = \boldsymbol{x_k} - \frac{\boldsymbol{f(x)}}{\boldsymbol{f'(x)}}, \qquad \boldsymbol{k = 0, 1, 2, \ldots} \tag{3}$$

where $f(x)$ is described according to some particular characteristic geometry of the manipulator, e.g., $\| \overrightarrow{A_1A_2} \|^2 = (\boldsymbol{P_2} - \boldsymbol{P_1})^{\boldsymbol{T}}(\boldsymbol{P}_2 - \boldsymbol{P}_1)$, and $x$ is one of the generalised coordinates.

Using the generalised coordinates of the joints, $\mathbf{X}_{ii}= (x, y, z, \varphi, \theta, \psi)$, as before, the resulting equation becomes:

$$\begin{bmatrix} x \\ y \\ z \\ \varphi \\ \theta \\ \psi \end{bmatrix}_{k+1} = \begin{bmatrix} x \\ y \\ z \\ \varphi \\ \theta \\ \psi \end{bmatrix}_{k} - \frac{\begin{bmatrix} f_1(x,y,z,\varphi,\theta,\psi) \\ f_2(x,y,z,\varphi,\theta,\psi) \\ \vdots \\ f_6(x,y,z,\varphi,\theta,\psi) \end{bmatrix}}{\begin{bmatrix} \frac{\partial f_1}{\partial x} & \frac{\partial f_1}{\partial y} & \cdots & \frac{\partial f_1}{\partial \psi} \\ \frac{\partial f_2}{\partial x} & \frac{\partial f_2}{\partial y} & \cdots & \frac{\partial f_2}{\partial \psi} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_6}{\partial x} & \frac{\partial f_6}{\partial y} & \cdots & \frac{\partial f_6}{\partial \psi} \end{bmatrix}} \tag{4}$$

A good set of start values is the home position of the robot [14]. Denavit-Hartenberg parameters can be found for each chain in the manipulator. The matrices ${}^{i-1}\mathbf{A}^{i}_{0}$ which have been defined in the previous section can be used to solve the direct kinematics problem.

*Singularity analysis*

Singularity analysis for parallel manipulators is very important, because, in contrast to serial linked manipulators, which lose a degree of freedom in a singular configuration, a parallel manipulator gains one degree of freedom. The singular configuration is defined as when the determinant of the Jacobian matrix is zero. The two Jacobians for parallel manipulators that can be identified are for the inverse kinematics problem, and one for the direct kinematics problem [15]. This results in three types of singularity: det $(J_{\text{dir. kin.}}) = 0$, or det $(J_{\text{inv. kin.}}) = 0$, or both the determinants equal to zero.

The danger with singular configurations is the fact that, even though the joints' velocities are all zeros, the platform can still move around an axis [16]. Figure 8 describes how the platform gains an extra degree of freedom because it can rotate around the axis $B_3, B_5$ in the left view perpendicular to the surface of the paper in the right view. $B_i$ indicates the connection points on the movable platform. The major hazard with a singular configuration is the danger of mechanical damage, because the stiffness of the parallel manipulators is close to zero if the force is applied perpendicular to the leg $L_{1,2}$ in the papers plane, as shown in Fig. 8 [14].

## RESULTS

A full analysis of designs of parallel manipulators can be implemented in SimMechanics, as presented above. In SimMechanics, any parameter of any joint or link can be monitored by attaching a relevant SimMechanics sensor to it. Figure 9 shows an example of the results from the simulation processes. The manipulator's controller controls the initial and final positions of the actuated joints. The positions, $(x, y, z)$s, and poses, $(\varphi, \theta, \psi)$s, of the end-effectors are monitored with reference to the global coordinates. The resolutions of the manipulators are investigated by applying the minimum input reference signal to the controllers of the actuators that can cause

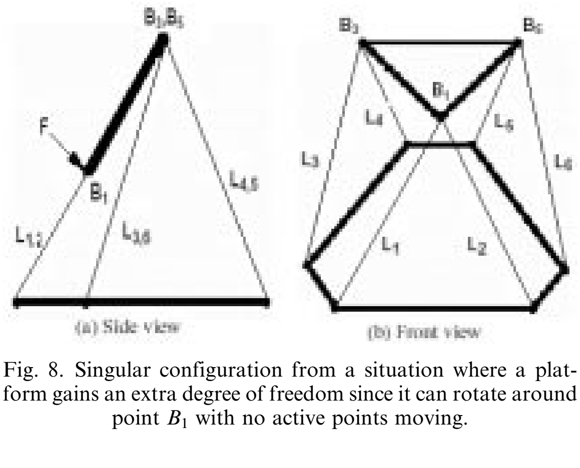


Fig. 8. Singular configuration from a situation where a platform gains an extra degree of freedom since it can rotate around point $B_1$ with no active points moving.

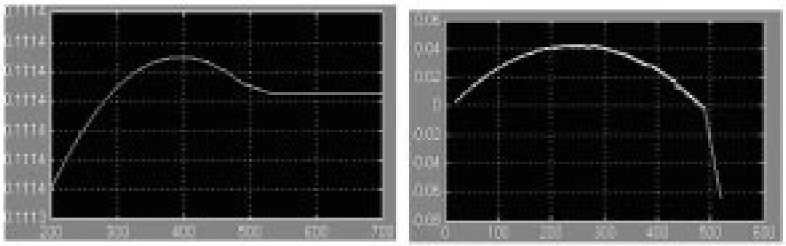

Fig. 9. Position and pose of ***PRRS*** end-effector (a) Z and (b) $\psi$.

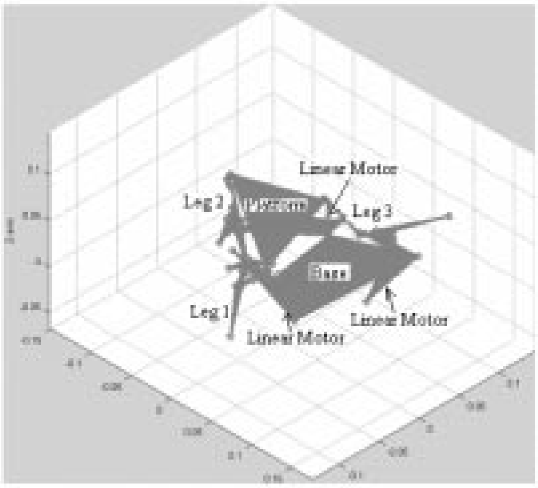


Fig. 10. Results of animation of the developed parallel ***PRRS*** manipulators.

minimum motion of the robot. This solves the problem of the direct kinematics of the developed parallel manipulators, which is not easy to solve because it has multiple solutions. The resulting motion of the parallel manipulators can be animated while under simulation. Figure 10 shows the animated ***PRRS*** parallel manipulator. SimMechanics uses convex hulls or equivalent ellipsoids to represent bodies or links.

## CONCLUSION

Developing and teaching parallel manipulators implementing CAD enhances the student's understanding of the design of parallel manipulators. This is further reinforced by the SimMechanics model. However, the differences between the SimMechanics model and other conventional mathematical models must be understood. SimMechanics models the mechanical bodies using their mass centres, and positions the origins of the coordinate frames of each body at its mass centre. This is different to the way coordinate frames are assigned using conventional mathematical models such as a Denavit-Hartenberg representation.

Actuators and their controllers' model can be developed in Simulink. Simulation of the integrated system is done in SimMechanics. Depending on the design or simulation requirement, different parameters can be optimised and their effects simulated.

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