A New Fighter Simulator Based on a Full Spinning Six Degrees-of-freedom Parallel Mechanism Platform

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ABSTRACT

This paper presents an innovative motion base for flight simulator, which is based on the new six degrees-of-freedom parallel mechanism, called 'Eclipse-II'. Most conventional simulators adopt the Stewart platform as its motion base. The Stewart platform is a six degree-of-freedom parallel mechanism that enables both translational and rotational motions. However, the motions such as continuous 360-degree overturn of the aircraft or continuous 360-degree spin of the flight are impossible since the platform can only tilt as much as ±20-30 degrees. The Eclipse-II mechanism created by the authors allows continuous 360-degree rotation in *A*, *B* and C-axis as well as *X*, *Y* and *Z*-axis translational motions.

The paper introduces briefly the kinematic design issues of the Eclipse II platform including singularity avoidance problems. Then, the design and development issue of the working sample machine is followed. It is a miniature machine, which demonstrate successfully the original idea regarding the general motion simulation.

Finally, the paper presents the design and development issue of the real one-man riding flight simulator, which will be completed by the summer of 2005. This Eclipse flight simulator is the only one by which all the motions in the space can be simulated. The conceptual design accommodates a fighter's cockpit inside the machine. It is controlled by a set of joystick and pedal input. All the translational and rotational motions of the platform can be synchronized in real time with the dynamic images of the Microsoft Flight Simulator 2002.

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I. Introduction

Motion simulators are virtual reality systems that assume the appearance of a real situation by using audio-visual effects and movements of a motion base. Such devices are used for many purposes, e.g., flight and driving simulators to name only a few. The former are used for pilot training by providing the pilot with motions that reflect the state of the aircraft while the later reproduce the actual driving conditions for vehicle design and human factors studies. Broadly speaking a motion simulator consists of an auditory system to generate sound, a visual system to display images, and a motion base system to generate movements as a result of motion cues.

Most current simulators have adopted the Stewart-Gough platform shown in Fig. 1, as the motion base. This platform is a six degree-of-freedom parallel mechanism that allows both translational and rotational motions. The platform can only tilt as much as ±20-30 degrees and large motions, as the 360-degree overturn, are impossible. That is, the overturn motion of the aircraft or the 360-degree spin of the roller coaster cannot be reproduced by the Stewart platform.

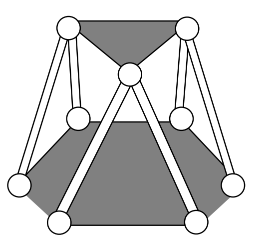
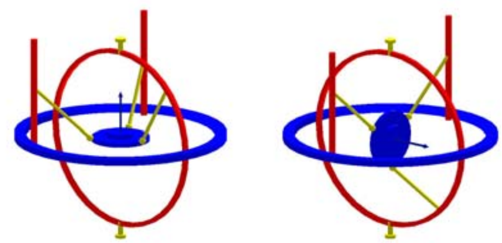
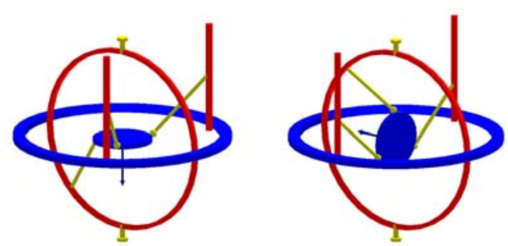


Figure 1. Structure of Stewart-Gough platform

Some other parallel mechanisms that display relatively large translational or rotational motions are the Delta robot and the spherical parallel mechanism. Yet, the kinematic mobility of these mechanisms is not six and they are used either for positioning or orienting applications. Closer to the spirit of our design is the redundantly actuated Eclipse-I mechanism, devised specifically for machining applications. This mechanism has a large workspace and all closed trajectories on five faces of a cube can be traced without breaking contact. Though the spindle can rotate 360 degrees around the fixed z-axis and tilt concomitantly, the tilting angle of the upper plate does not exceed 90 degrees with respect to the vertical. Hence, large overturn motions are impossible.



(a) Rotation angle 0° (b) Rotation angle 90°



(c) Rotation angle 180° (d) Rotation angle 270°

Figure 2. Eclipse-II mechanism and its 360-degree continuous rotational motions

The objective of the present research is to develop a mechanism capable of 360-degree tilting motion of the platform as well as translational motion. Fig. 2 shows the Eclipse-II mechanism and an example of its rotational motion capability. Since there are no limits in the rotational motion, it is possible to design a more realistic and higher fidelity motion simulator.

The paper is organized as follow. In Section 2, we describe the kinematic structure of the Eclipse-II, including the computational procedures for the forward and inverse kinematics. The singularity analysis and a method for eliminating the singularities are presented in Section 3. In Section 4, we describe the workspace analysis and present a structure for maximizing the workspace. Finally, some concluding remarks follow in Section 5.

II. Kinematic design and Singularity Avoidance problems

The architecture of the Eclipse-II mechanism is shown in Figure 2. The Eclipse-II consists of three *PPRS* serial sub-chains that move independently on a fixed circular guide. Here, *P*, *R*, and *S* denote prismatic, revolute, and spherical joints, respectively.

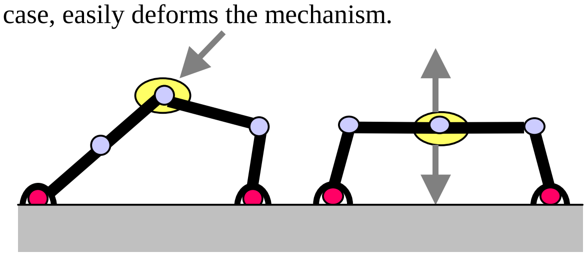
The Eclipse-II has six degrees-of-freedom. The six actuated joints are the three *A* joints (*P*) along the horizontal circular guide, the C_2 and C_3 joints (*P*) on the vertical columns and another *P* joint (C_1) on the vertical circular column. All six actuated joints can be found in Figure 2 and are indicated by arrows. The connecting links C_iB_i are attached to the circular and vertical columns, respectively, through revolute joints. The other ends of these links are mounted to the moving platform via three spherical joints (points B_i in Figure 2).

Mounting one circular column and two linear columns on the circular guide results in the Eclipse-II having a large orientation workspace. Thus, the platform can rotate 360 degrees continuously about the *y*-axis in the moving frame {*M*} (center of the moving platform) and the *Z*-axis in the fixed frame {*F*} (center of the fixed horizontal track), respectively, as shown in Figure 3.

The detailed results of the kinematic analysis are already described in a previous paper regarding Eclipse-II mechanism. In this paper, only the design issues regarding the singularity avoidance problems are presented. A singularity is a configuration in which the degrees-of-freedom of a parallel mechanism changes instantaneously, which must be eliminated in the workspace of the mechanism.

In general, there are two types of singularities in parallel mechanisms: end-effector singularities and actuator singularities.

Figure 3 illustrates the concept of the two types of singularities. If the end-effector is at the configuration as shown in Figure 4(a), it loses one d.o.f. in the arrow direction shown in the figure. Theoretically, regardless of how large the load force is in that direction, the end-effector does not move. However, if the end-effector is at the configuration as shown in Figure 4(b), it gains an additional d.o.f. in the arrow direction shown in the figure, that is, a self-motion is possible. The load force in that direction, for example, the gravity force in this case, easily deforms the mechanism.



(a) end-effector singularity (b) actuator singularity

Figure 4. Two types of singularities in parallel mechanisms.

In the Eclipse-II mechanism, two types of singularities coexist in the workspace. In this section, the singular

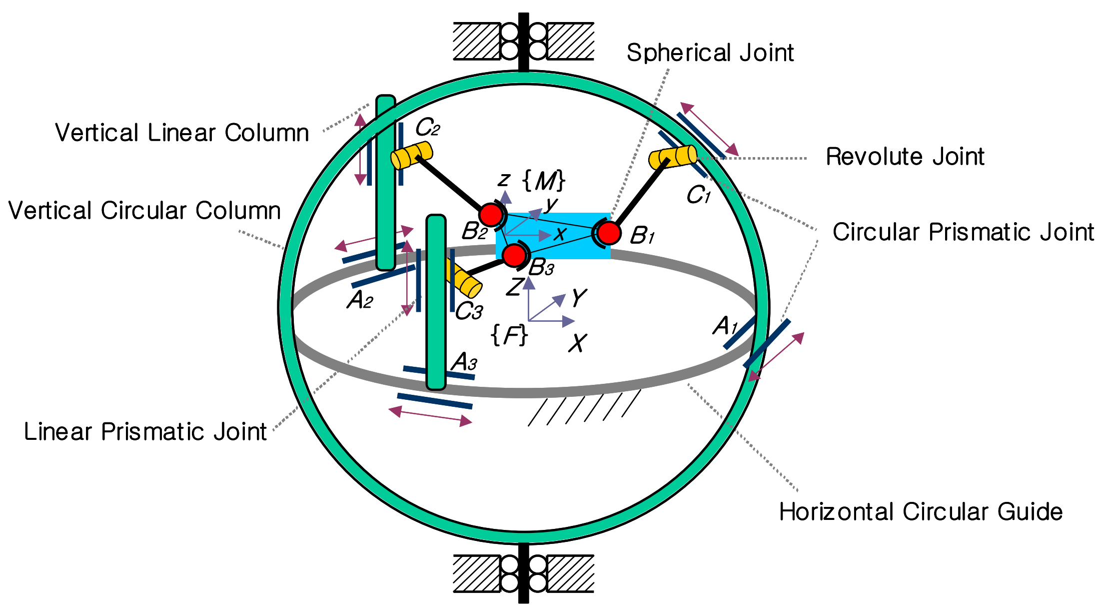
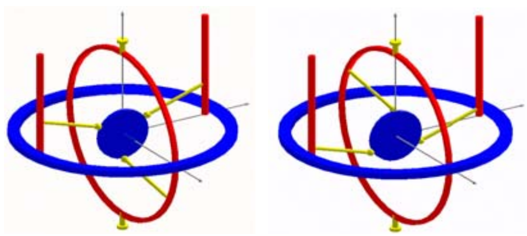


Figure 3. Architecture of the Eclipse-II mechanism

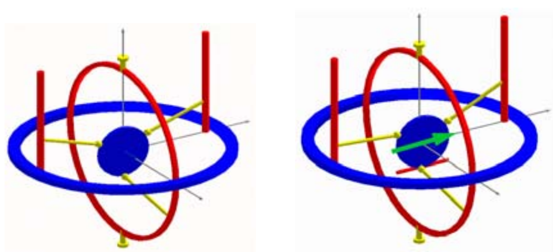
configuration of the Eclipse-II mechanism and the method for eliminating singularities are described.
Figure 4 shows two typical configurations of the end-effector singularities. The singular configurations occur in positions where, with the platform tilted at 90° or 270°, one of the spherical joints is located on the *Z*-axis of the fixed frame.



(a) platform titlting 90º (b)platform titling 270º

Figure 5. Examples of the end-effector singular configuration.

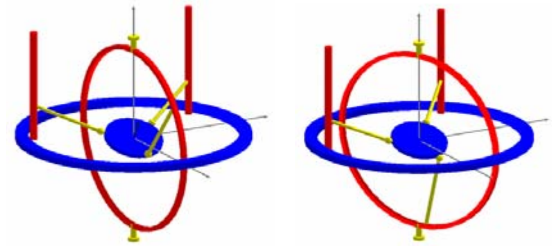
As shown in Figure 6(a), the platform cannot translate along the *y*-direction in the moving frame, which is the same concept as shown in Figure 4(a). Hence, an actuator is added to change the position of the spherical joint that is connected to the circular column; that is, one degree-of-freedom is added to the original Eclipse-II. With this addition, the platform can now move along the *y*-axis direction at the end-effector singular configuration since the position of the spherical joint can be changed along the linear guide [see Figure 6(b)]. The additional actuator results in the elimination of the end-effector singularity within the workspace of the mechanism.



(a) 6 d.o.f Eclipse-II (b) 6+1 d.o.f. Eclipse-II

Figure 6. *y*-direction motion in the moving frame: (a) impossible with the 6 d.o.f Eclipse-II (b) possible with the modified Eclipse-II

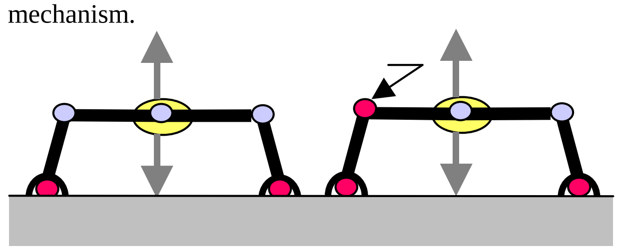
Figure 7 shows two typical configurations of an actuator singularity. The actuator singular configurations occur in positions where, with the platform rotation angle about the z-axis of the moving frame 0°, the tilting angle is 25° as shown in Figure 6(a), and where, with the rotation angle 180°, the titling angle is 225° as shown in Figure 7(b). For other singular positions, please refer to.



(a) tilting angle 25° rotation angle 0° (b) tilting angle 225° rotation angle 180°

Figure 7. Examples of the actuator singular configurations

In actuator singular configurations, the platform cannot sustain its static equilibrium position in the presence of external force, which is the same concept as shown in Figure 4(b). In this case, the platform seems to have extra degrees of freedom. Since the forward kinematic solutions are divided into two or more directions, along the path crossing the actuator singular configuration, there exist multiple forward kinematic solutions with the same active joint values. Hence, there is a chance that the platform moves along an undesired direction.
One method for eliminating the actuator singular configurations is to redundantly actuate the mechanism by adding an actuator to one or more of the passive joints as shown in Figure 8(b). In the case of the Eclipse-II, an additional actuator is added to one revolute joint on one of the linear columns. The modified Eclipse-II becomes a redundantly actuated mechanism.



(a) actuator singularity (b) actuator singularity eliminated

Figure 8. Adding one more actuator eliminates the actuator singularity.

In conclusion, by adding two more actuators, both the end-effector singularity and the actuator singularity are completely eliminated in the workspace of the Eclipse-II mechanism.

III. Working Sample Development

Figure 8 shows the photograph of the working sample of the Eclipse-II mechanism. It has been manufactured to verify the original idea.

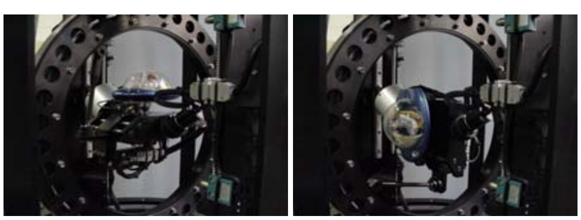
The main specifications of the working sample are as follows:

- overall size: 1350(L) x 900(W) x 1970(H) mm
- platform size: 210 x 180 mm
- kinematic workspace: ϕ37.2 x 80 mm
- max. linear speed: 4 m/min
- max. linear acceleration: 230 mm/sec^2 (0.023g)
- max. angular speed: 200 deg/sec (33.3 rpm)
- max. angular acceleration: 700 deg/sec^2
- number of axes: 9
- actuators: AC servo motors

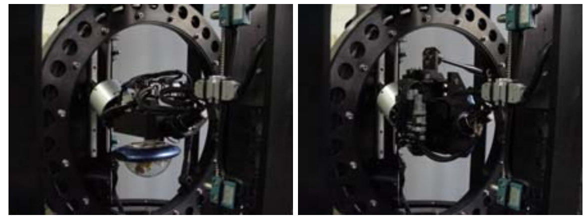
Figure 9. Photograph of the Eclipse-II working sample.

Figure 10 presents a real 360-degree continuous rotational motion of the platform of the working sample. With the translational motion in the *X*, *Y*, and *Z*-axis, the working sampe enables complete six degree-of freedom motion including continous overturning about the *A*, *B* and *C*-axes. Figure 2 shows the conceptual motion of the Eclipse-II mechanism, which has been described by the kinematic drawings. This is the unique feature of the Eclipse-II parallel mechanism.

The working sample of the Eclipse-II mechanism is able to reproduce any six degrees-of-freedom motion including any overturn motions (for example, that of an aircraft or the 360-degree spin motion of roller coaster, see Figure 10). This is impossible by any other parallel mechanisms developed so far.



(a) Rotation angle 0° (b) Rotation angle 90°



(c) Rotation angle 180° (d) Rotation angle 270°

Figure 10. Platform of the Eclipse-II working sample and its continuous rotational motion

To verify the motion of Eclipse-II, we used real roller coaster motions. Figure 11 shows the coordinates of a real roller coaster path, which is in operation at an amusement park in Daegu, South Korea. It contains one 360-degree overturn pitching and two 360-degree side-turn rolling loops. This path was used to verify the general motion simulation idea based on the Eclipse-II mechanism. Figure 12 presents the coordinate values of the working sample platform in the fixed frame {*F*} (see Figure 2), which simulates the motion of the roller coster shown in Figure 11.

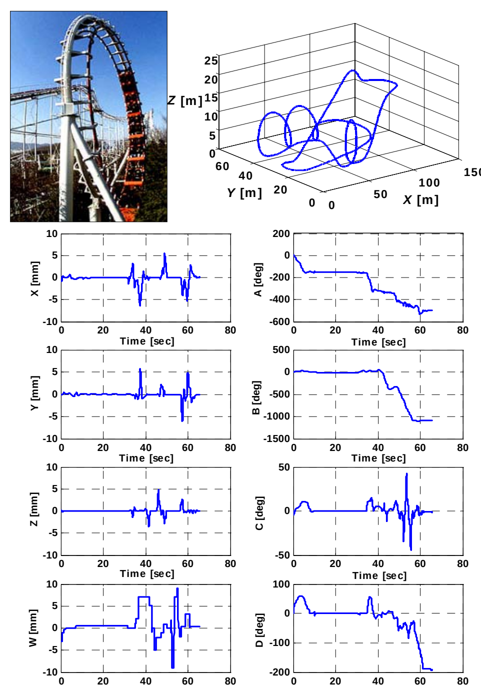


Figure 11. A scaled model and coordinate values of the roller coaster installed in the Woo-Bang Amusement Park, Daegu, Korea.

In Figure 11, it can be noted that the Eclipse-II working sample is capable of simulating six degree-of-freedom general motion including continuous 360-

degree spins. About the *A*-axis and *B*-axis, respectively, the maximum spin angles are 540° and 1100°. Actually, the working sample can simulate an infinite spin angle.

IV. One-man Ride Machine Development

Eclipse-II working sample is not designed to be controlled by user's real time input because of its limitations of linear accelerations. To overcome this problem, nowadays real one-man ride machine for flight simulator is developing. Figure 11 shows the drawing of the one-man ride machine of Eclipse-II.

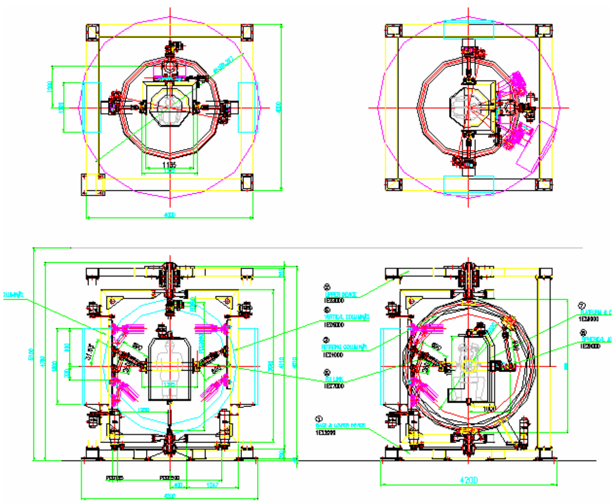


Figure 11. Assembly drawing of the Eclipse-II one-man ride machine

The main specifications of the one-man ride machine are as follows:

- overall size: 4200(L) x 4000(W) x 5100(H) mm
- platform size: 1125 x 940 mm
- kinematic workspace: ϕ ϕ236.6 x 491.3mm
- max. linear speed: 36 m/min
- max. linear acceleration: 0.5 g
- max. angular speed: 120 deg/sec
- max. angular acceleration: 500 deg/sec^2
- number of axes: 9
- actuators: AC servo motors

It is developed focusing flight simulators like fighters. Therefore it will be controlled by rider's joystick handling, and its linear acceleration is 0.5g. Actually it is firstly designed that its linear acceleration is 1.0g, but the linear acceleration has been reduced because of budget problem. The manufacturing and assembly will be completed by this September.

V. Conclusion

This paper presents a new six degree-of-freedom platform, which is based on the Eclipse-II parallel mechanism. The unique feature of the platform is that it enables unlimited continuous spin around any rotational axis plus finite *X*, *Y*, and *Z*-axis translation motion.
The important design issue is the singularity avoidance problem. The Eclipse-II has both types of singularities : end-effector and actuator singularities in the workspace. These singularities can be eliminated by adding two more actuators.
A working sample has been designed and developed to verify the original idea. The size of the platform of the working sample is 210 x 180 mm. For demonstration purposes, it is applied to simulate the real motion of a roller coaster, whose path contains several over-turning pitching and rolling loops.
Based on kinematic ideas and experimental data of working sample, we are now developing one-man ride machine for the flight simulator like fighter simulator. Its manufacturing and assembly will be completed by this September.

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