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# Design of a Parallel Mechanism Platform for Simulating Six Degrees-of-freedom General Motion Including Continuous 360-degree Spin

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**Abstract**
This paper presents a new six degree-of-freedom parallel mechanism platform, which can be used as a basis for general motion simulators. The unique feature of the platform is that it enables unlimited continuous 360-degree spin in any rotational axes plus finite *X*, *Y*, and *Z*-axis translation motion. The first part of the paper deals with the kinematic design issue of the platform including singularity avoidance problems. The second part describes the design and development issues of the working sample structure. It has been assembled and tested successfully to verify the original idea of general motion simulators. For demonstration purposes, the real motions of the platform are synchronized with those of the real roller coaster in operation, whose path contains several overturning pitching and rolling loops.

Keywords: Parallel mechanism, Kinematic design, Motion simulation

## 1 INTRODUCTION

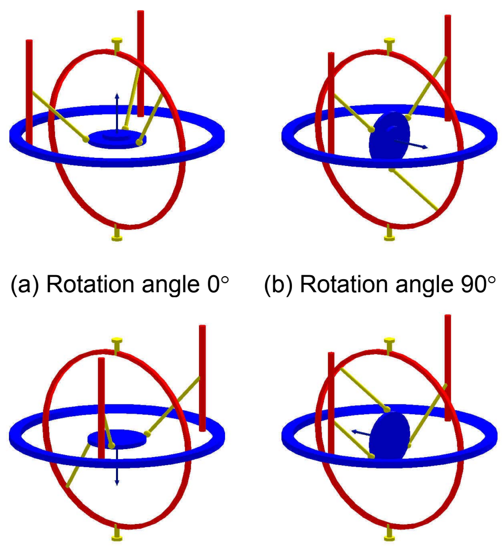
Motion simulators are virtual reality systems that assume the appearance of a real situation by using audio-visual effects and movements of a motion base. Such devices are used for many purposes, e.g., flight and driving simulators to name only a few. The former are used for pilot training by providing the pilot with motions that reflects the state of the aircraft, while the latter reproduce the actual driving conditions for vehicle design and human factor 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 based on motion cues.

Most current simulators have adopted the Stewart-Gough platform as the motion base (see [1] and [2]) for a survey on parallel mechanisms and list of references). This platform is a six degree-of-freedom parallel mechanism that allows both translational and rotational motion. The platform can only tilt as much as ±20-30°; overturn motions of an aircraft, or the 360-degree spins of a roller coaster, cannot be reproduced by the Stewart platform.

Some other parallel mechanisms that display relatively large translational or rotational motions are the Delta robot [3] and the spherical parallel mechanism [4, 5]. However, the kinematic mobility of these mechanisms is less than 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 (see [6] and [7]), 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 concurrently, the tilting angle of the upper plate does not exceed 90 degrees with respect to the vertical. Hence, overturn motions are impossible.

The objective of the present research is to develop a mechanism capable of 360-degree tilting motions of the platform as well as translational motion. Figure 1 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.



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

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

Figure 1: Eclipse-II mechanism and its 360-degree continuous rotational motion.

The paper is organized as follow. In Section 2, we describe the kinematic design issues of the Eclipse-II, especially the singularity avoidance problem. Section 3 describes the design and development issues of the working sample, which has been manufactured to verify the original idea regarding the Eclipse-II mechanism. In Section 4, a real example of motion simulation will be presented by using the scaled model of a roller coaster. Finally, some concluding remarks follow in Section 5.

## 2 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.

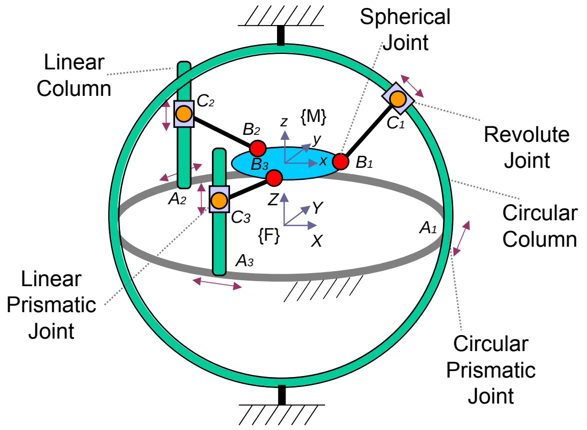



Figure 2: Architecture of the Eclipse-II mechanism.

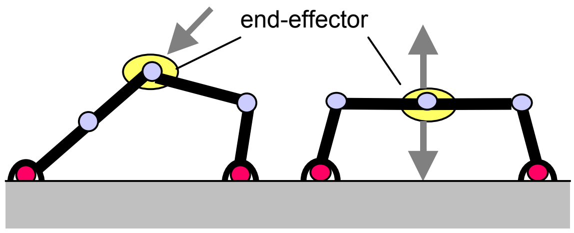
The Eclipse-II has six degrees-of-freedom. The six actuated joints are the three *A* joints (*P*) along the horizontal circular guide, the $C_2$ and $C_3$ joints (*P*) on the vertical columns and another *P* joint ($C_1$) on the vertical circular column. All six actuated joints can be found in Figure 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 2.

The detailed results of the kinematic analysis are already described in a previous paper [8]. 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 [2]: 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 3(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 3(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.

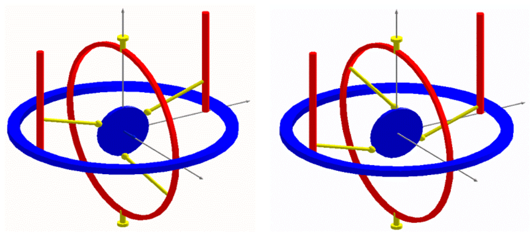



(a) end-effector singularity (b) actuator singularity

Figure 3: 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 configuration of the Eclipse-II mechanism and the method for eliminating singularities are described.

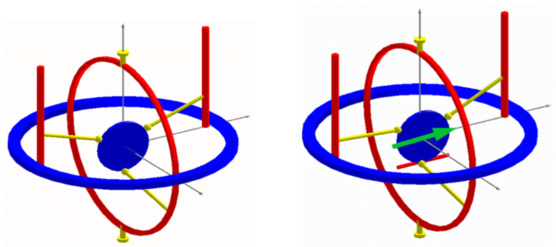
Figure 4 shows two typical configurations of the end-effector singularities. The singular configurations occur in positions where, with the platform tilted at 90° or 270°, one of the spherical joints is located on the *Z*-axis.



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

Figure 4: Examples of the end-effector singular configuration.

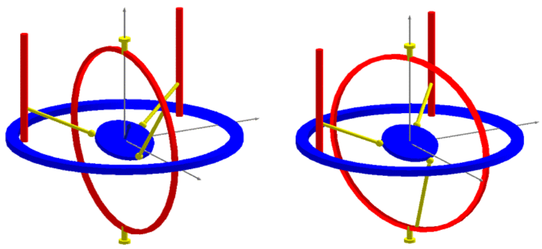
As shown in Figure 5(a), the platform cannot translate along the *y*-direction in the moving frame, which is the same concept as shown in Figure 3(a). Hence, an actuator is added to change the position of the spherical joint that is connected to the circular column; that is, one degree-of-freedom is 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 5(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 5: *y*-direction motion in the moving frame is:
(a) impossible with the 6 d.o.f Eclipse-II
(b) possible with the modified Eclipse-II.

Figure 6 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 6(b). For other singular positions, please refer to [8].



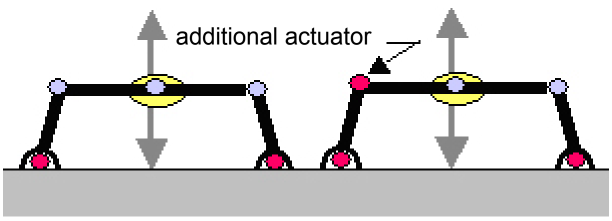
(a) tilting angle 25°
rotation angle 0°

(b) tilting angle 225°
rotation angle 180°

Figure 6: 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 3(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 7(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

Figure7: 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.

## 3 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: $\phi$37.2 x 80 mm
- max. linear speed: 4 m/min
- max. linear acceleration: 230 mm/sec$^2$ (0.023g)
- max. angular speed: 200 deg/sec (33.3 rpm)
- max. angular acceleration: 700 deg/sec$^2$
- number of axes: 8 (plus one, actually, for rotaing the rider's chair)
- actuators: AC servo motors

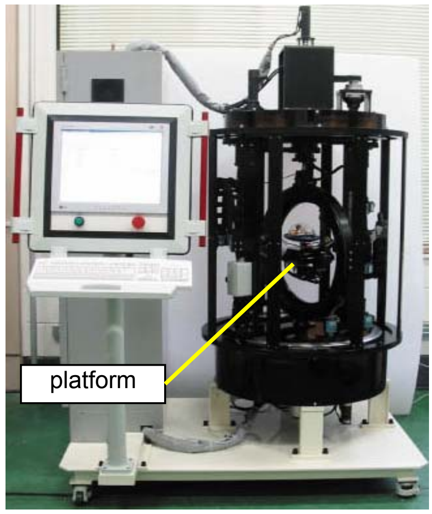
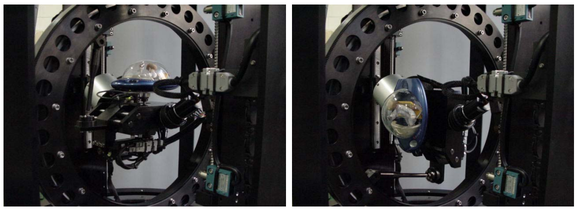
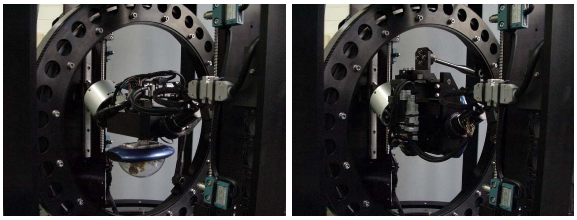



Figure 8: Photograph of the Eclipse-II working sample.

Figure 9 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 1 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.



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



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

Figure 9: Platform of the Eclipse-II working sample and its 360-degree continuous rotational motion.

## 4 MOTION SIMULATION EXAMPLE

The working sampe 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.

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*}, which simulates the motion of the roller coster shown in Figure 11.

Figure 10: An example of 360-degree side-turn rolling loops of the roller coaster.

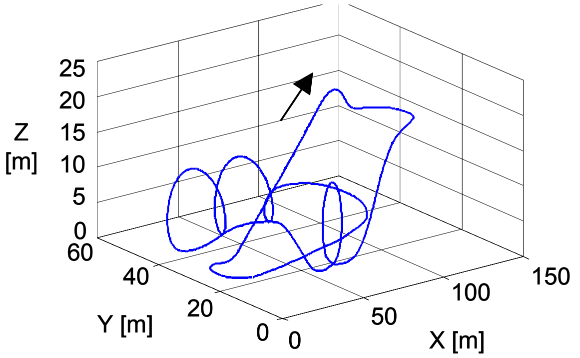



Figure 11: A scaled model of the roller coaster installed in the Woo-Bang Amusement Park, Daegu, Korea.

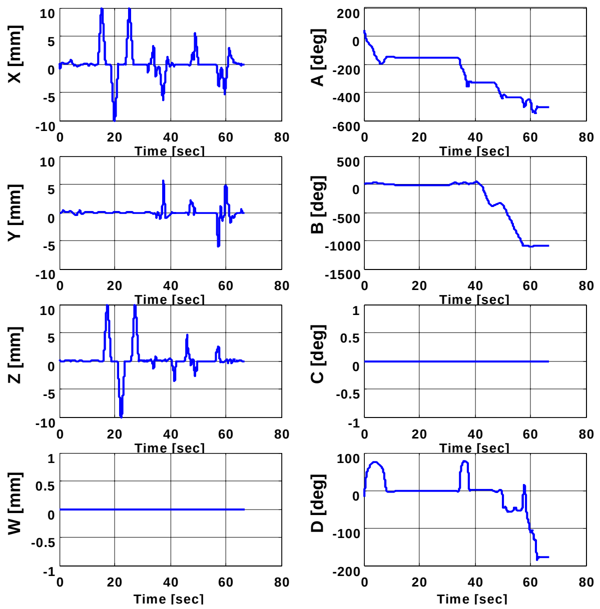



Figure 12: the coordinate values of the working sample platform in the fixed frame.

In Figure 12, 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.

The linear motion in the *W*-axis in Figure 12 presents the movement of the spherical joint in Figure 5, which is added to eliminate end-effector singularities. Since the path used in the real roller coaster (Figure 11) does not include any end-effector singular configuration, the linear movement in the *W*-axis is zero in the entire path. The angular motion in the *D*-axis in Figure 12 presents the rider's chair rotational angle with respect to the platform.

This motion is necessary to keep the rider's viewpoint constant to the proceeding direction of the roller coaster. However, a detailed discussion on this issue is beyond of the scope of this paper.

The current problem of the working sample is that the maximum linear acceleration is 230 mm/sec$^2$ (0.023g). Currently, a one-man riding motion simulator is being developed based on the Eclipse-II mechanism by the authors, and the target linear acceleration is 1.0g, which is thought to be sufficient to simulate any type of six degree-of-freedom general motion.

## 5 CONCLUSIONS

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 sigulairities 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.

## 6 ACKNOWLEDGMENTS

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