Design and Analysis of Decoupled Parallel Mechanism with Redundant Actuator

Sun Ho Kim[1], Hyun Pyo Shin[1], Woosung In[1], Dongsu Jeon[1], Jongwon Kim[2,#]
1 School of Mechanical and Aerospace Engineering, Seoul National University, Seoul, South Korea
2 School of Mechanical and Aerospace Engineering, Seoul National University, Seoul, South Korea
Corresponding Author / E-mail: jongkim@snu.ac.kr, TEL: +82-2-880-7138, FAX: +82-2-875-4848

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This paper presents a six degrees of freedom parallel kinematic mechanism with decoupled motion architecture. This parallel mechanism can rotate 360 degrees continuously in any direction with six degrees of feedom, and its kinematic architecture is partly decoupled. The decoupled parallel mechanism usually has simple kinematics and easy control algorithm. Redundant parallel kinematic mechanism has the problem not to able to select the unique motion of actuator for the motion of the end-effector, also coupled parallel mechanism is hard to control in realtime. Therefore it need motion planning algorithm to choose a specific motion. In this paper, a modified redundant kinematic parallel mechanism and its kinematic analysis to have decoupled motion from its original structure is proposed, and its motion planning is presents using new methodology for partly decoupled redundant parallel mechanism. This methodology can reduce the calculation time of its motion planning, and also it makes its motion control be easy.

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1. Introduction

Parallel mechanisms consist of several serial chains that connect a base to a moving platform. Because of their structure, parallel mechanisms are in general capable of very fast and accurate motion, possess higher average stiffness characteristics throughout their workspace, and can carry heavier payloads than their serial counterparts. These advantages however come at the expense of a reduced workspace, singularity configurations, difficult mechanical design, and more complex kinematics and control algorithms.

A singularity configuration 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. One method for enlarging workspace by eliminating the singular configurations is to redundantly actuate the mechanism by adding an actuator to one or more of the passive joints.

The Eclipse-II mechanism is a parallel mechanism capable of 360-degree tilting motions of the platform as well as translational motion, which is designed for the motion base of a motion simulator. This mechanism is originally designed with six degrees-of-freedom, but two degrees-of-freedom are added to eliminate limited motions and one actuator is added to a passive joint to eliminate actuator singularity configuration. Therefore the Eclipse-II mechanism is finally modified to be 8 degrees-of-freedom and 9 axes parallel mechanism.

According to these design issues, Eclipse-II one-man ride machine is developed. Development of Eclipse-II one-man ride machine is focused to motion simulator such as flight simulator. Verification of Eclipse-II mechanism is already accomplished using Eclipse-II working sample machine (See, [5]). Based on results from working sample machine, Eclipse-II one-man ride machine is developed and manufactured.

Since Eclipse-II one-man ride machine has problems in real time motion planning and control due to its structural complexity. To overcome these control difficulties modified Eclipse-II structure is presented. It has partially decoupled kinematic structure using redundant actuator. Therefore real time motion planning and control is possible.

In this paper, novel 6-d.o.f parallel mechanism is presented. This mechanism called Eclipse-II is consisted of 9 actuators to get the partially decoupled motion and to overcome its singularities. The paper is organized as follow. In Section 2, we describe the kinematic structure of the Eclipse-II, including singularity analysis and a method for eliminating the singularities. Section 3 describes the design and development issues of the one-man ride machine, which has been manufactured to verify the original idea regarding the Eclipse-II mechanism and designed as motion simulator. In Section 4, development issues of new one-man ride machine. The purpose of modification is to get easier motion planning and real time control issue using decoupled motion structure. Finally, some concluding remarks follow in Section 5.

2. 6-d.o.f Redundant Parallel Mechanism: Eclipse-II

2.1 Basic Kinematic Structure

The architecture of the Eclipse-II mechanism is shown in Figure 1. 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

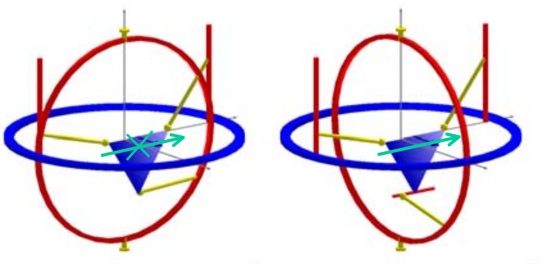
and C_3 joints (P) on the vertical columns and another P joint (C_1) on the vertical circular column. All six actuated joints can be found in Fig. 1 and are indicated by arrows. The connecting links C_iB_i are attached to the circular and vertical columns, respectively, through revolute joints. The other ends of these links are mounted to the moving platform via three spherical joints (points B_i in Fig. 1).

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 Fig. 1.

2.2 Singularity Analysis and Redundant Eclipse-II mechanism

Generally, a parallel mechanism platform has two types of singularity [1]: end-effector singularity and actuator singularity. Fig. 2 illustrates the concept of the two types of singularities. If the end-effector is at the configuration shown in Fig 2(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 shown in Fig. 2(b), it gains an additional d.o.f. in the arrow direction shown in the figure; that is, self-motion is possible. The load force in that direction -- for example, the gravity force in this case -- easily deforms the mechanism.

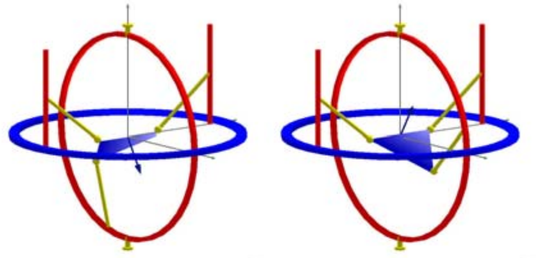
In the Eclipse-II mechanism, two types of singularities coexist in the workspace. As shown in Fig. 3(a), the platform cannot translate along the y-direction in the moving frame, which is the same concept as shown in Fig. 2(a). Hence, an actuator is added to change the position of the spherical joint that is connected to the circular column; that is, one d.o.f. is added to the original Eclipse-II mechanism. 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 Fig. 3(b)). In addition, there is a limited rotational motion, so one more d.o.f. is added to rotate along z –axis on the moving platform.



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

Fig. 3 y-direction motion in the moving frame

Fig. 4 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 is 0°, the tilting angle is 25° as shown in Fig. 4(a), and where, with the rotation angle 180°, the titling angle is 225° as shown in Fig. 4(b). For other singular positions, please refer to [3].



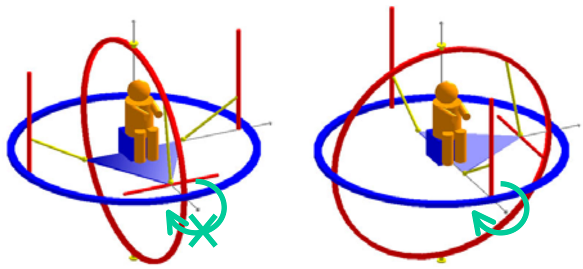
(a) tilting angle 25° rotation angle 0° (b) tilting angle 225° rotation angle 180°

Fig. 4 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 Fig 2(b). In this case, the platform seems to have extra degrees of freedom. 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. For Eclipse-II, an additional actuator is added to a revolute joint on one of the linear columns. The modified Eclipse-II becomes a redundantly actuated mechanism.

In addition to the Eclipse-II making continuous rotational motions by the z-axis and y-axis, there's a limitation in x-axis rotational motion at the home position of the mechanism. The Eclipse-II mechanism is originally designed to be applied as a motion simulator, therefore this rotational limitation should be overcome. For this, one redundant actuator is added on the bottom of the platform (see Fig. 5).



(a) 7 d.o.f. Eclipse-II (b) 8 d.o.f. Eclipse-II

Fig. 5 X-axis rotation of the Eclipse-II

In conclusion, by adding three more actuators to eliminate two

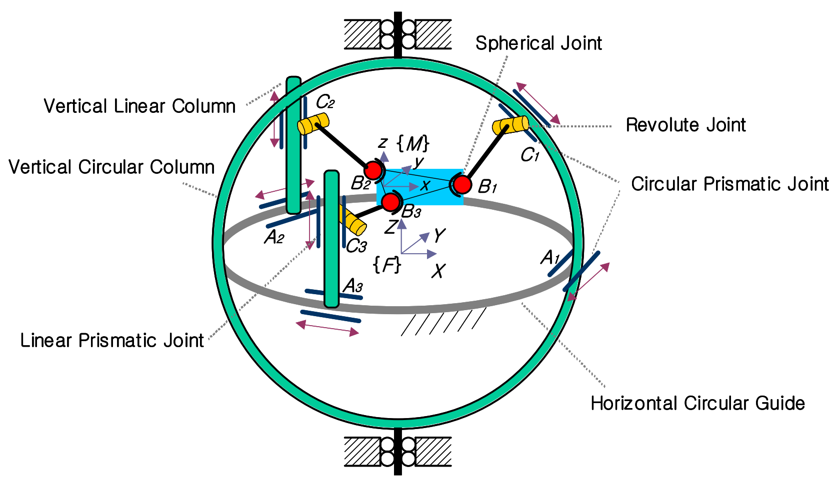


Fig. 1 Architecture of the Eclipse-II 6-d.o.f parallel mechanism

type singularities and the limited rotation problem, Eclipse-II is modified to be an 8-d.o.f and 9 axes redundant parallel mechanism. (see Fig. 6).

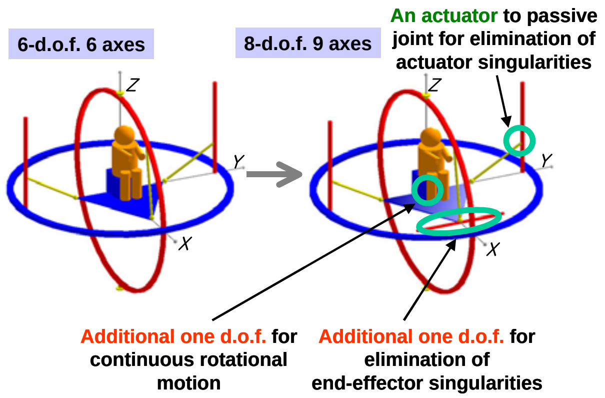


Fig. 6 8-d.o.f, 9axes Eclipse-II mechanism

3. Eclipse-II One-man Ride Machine Development

Fig. 8 and Fig. 9 show the assembly drawing and photographs of the one-man ride machine of the Eclipse-II mechanism. Prior to one-man ride machine development, working sample machine is developed to verify original idea. The specific discussion about working sample machine is mentioned in previous paper. Please refer to [5] (see Fig. 7).


Fig. 7 Photograph of the Eclipse-II working sample

Based on experimental data with working sample machine, Eclipse-II one-man ride machine is designed and manufactured. This machine is located in Seoul National University.

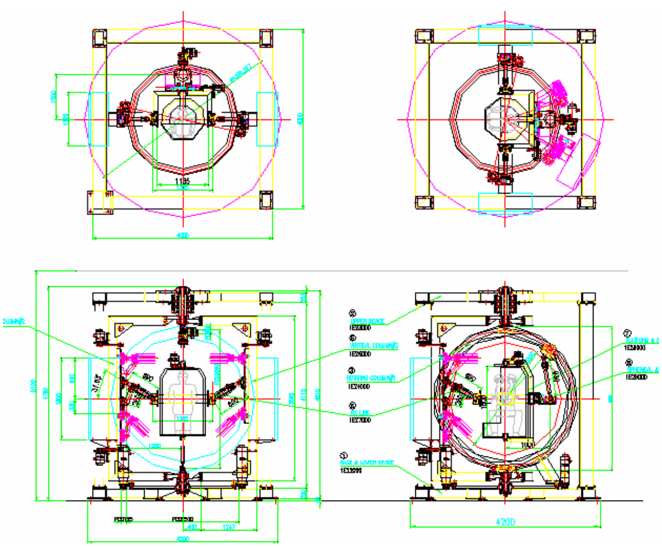


Fig. 8 Assembly drawing of Eclipse-II one-man ride machine

The main specifications of the working sample are as follows:

- overall size: 4200(L) x 4000(W) x 5100(H) mm
- platform size: 1125 x 940 mm
- kinematic workspace: 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

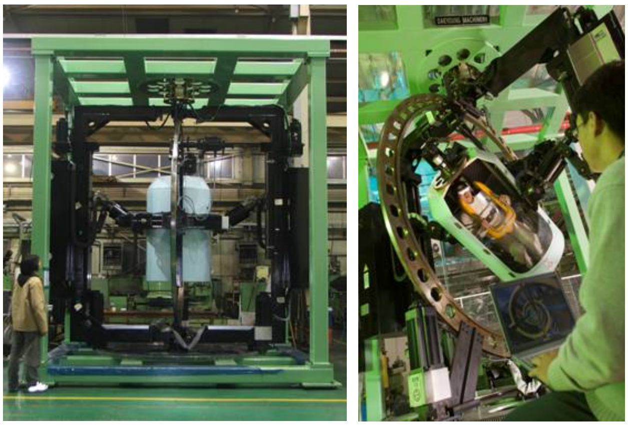


Fig. 9 Photographs of the Eclipse-II one-man ride machine

One-man ride machine is designed motion simulator such as flight simulator for military purpose or roller coaster simulator for entertainment use. It can simulate 6-d.o.f motion according to prepared path through washout algorithm filter and motion planning algorithm. But it has difficulties in real time control and motional planning because of its original structural complexity with redundant actuators. Therefore modification using decoupled kinematic structure is considered to overcome its real-time control difficulties.

4. Modification of Eclipse-II One-man Ride machine to Decoupled Architecture

Flight simulator, such as fighter simulator, needs real-time control according to pilot's motion input through control stick. To apply flight simulator as mentioned, a new kinematic structure of Eclipse-II is presented. Decoupled parallel manipulators can achieve separate control in position and orientation (see, [6]). It has advantage in control and it can help getting real-time control in parallel manipulator. The kinematic decoupling of parallel manipulators can be classified into three types: strong decoupling, complete decoupling, and partial decoupling. The case of Eclipse-II selects partial decoupling because it is focused enabling real-time motion planning and control for flight simulator application. According to this objective, modified Eclipse-II one-man ride machine is designed (see, Fig. 10)

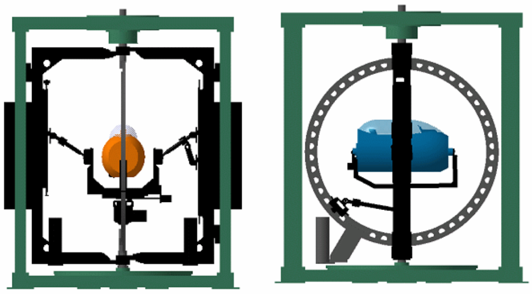


Fig. 10 Modified Eclipse-II one-man ride machine

In case of original Eclipse-II one-man ride machine, the redundant actuator which is used to rotate chair on platform is used for yawing rotational motion. But in case of the modified Eclipse-II one-man ride machine, it is charged of rolling motion, therefore we can be decoupled *y*-direction translational motion and rolling rotational motion. Original Eclipse-II one-man ride machine has difficulty in real-time control because of rolling rotational motion that is coupled with y-direction translation motion. Therefore with modification using decoupled structure synthesis the real-time control difficulty can be solved.

Since platform design has been changed to get partial decoupled structure, its kinematic analysis including singularity analysis and workspace analysis are required. According to singularity analysis, there is no difference in singular positions, therefore the same method is performed to avoid singularity configurations. In case of workspace, there is change in workspace because its platform size has been changed. Platform size has to be changed from 1125 x 940 to 1600 x 1250(mm). The result of workspace analysis is shown in Fig. 11. As a result, the workspace is changed from ϕ236.6 x 491.3 to ϕ300 x 280(mm).

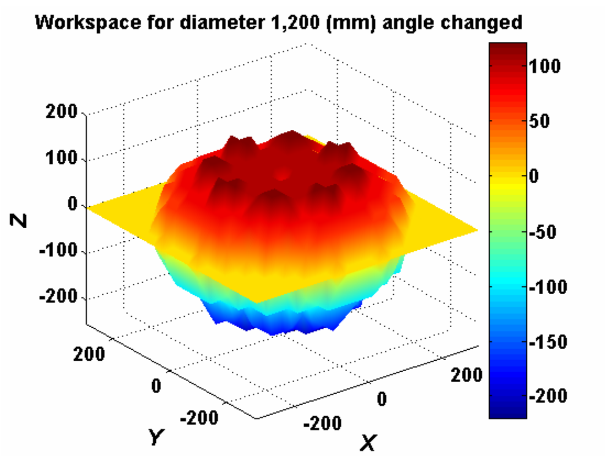


Fig. 11 Workspace of modified Eclipse-II one-man ride machine

4. Conclusion

This paper presents a redundant 6-d.o.f parallel mechanism, the Eclipse-II. The unique feature of the Eclipse-II is that continuous 360-degree rotational motion of the platform is possible in addition to translational motion. The original Eclipse-II mechanism shows both end-effector and actuator singular configurations within its workspace. Hence, a linear guide, where one spherical joint moves, is added to the mechanism to eliminate the end-effector singularity. An actuator is also added to each of two passive joints of the Eclipse-II to eliminate the actuator singularities. Based on kinematic ideas and verification experimental data using working sample, Eclipse-II one-man ride machine developed. It is designed for motion simulator application, but it has difficulties in real-time motion planning and control. To solve this control limitation issue, modified Eclipse-II one-man ride machine is suggested using partially decoupled parallel kinematic mechanism structure and performed kinematic analysis. Therefore the real-time motion planning and control can be accomplished with modified Eclipse-II one-man ride structure.

ACKNOWLEDGEMENT

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