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Development of the Eclipse-II motion simulator

DONGSU JEON
School of Mechanical and Aerospace Engineering,
Seoul National University, Seoul, South Korea
dsjeon@rodel.snu.ac.kr

JONGWON KIM
School of Mechanical and Aerospace Engineering,
Seoul National University, Seoul, South Korea
jongkim@snu.ac.kr

WOOSUNG IN
SUN HO KIM
HYUN PYO SHIN

Abstract: *This paper presents the development of an innovative motion simulator, based on the Eclipse-II mechanism, which is a redundantly actuated parallel kinematic mechanism, with a partially decoupled architecture in its rotational motion. This parallel mechanism can generate six degrees of freedom motion, including continuous rotation through 360 degrees, and translation in any direction. After all verification, such as kinematics, singularity and dynamics analysis, the Eclipse-II one-man ride machine has been manufactured having eight degrees of freedom, and nine axes, by using redundant actuators. It simulates specific motion from the input path produced by a washout filter and motion planning system. The washout filter, which converts the real world motion trajectory to the realizable motion of the simulator, is designed to minimize human sensation error. Also, the motion planning algorithm is designed to choose the specific control inputs from finite candidates, caused by using two additional degrees of freedom of the Eclipse-II mechanism. This motion planning algorithm of the Eclipse-II machine leads to difficulty in achieving real-time control performance due to its structural complexity. This paper finally presents a modified Eclipse-II one-man ride machine, having a partially decoupled architecture in its rotational motion by using the redundant actuators to realize effective real-time control performances.*

1 Introduction

Over the last thirty years, various types of motion simulators have been developed to serve different needs. Although pilots and air crews have been the primary beneficiaries, motion simulators have been steadily expanding their presence in novel applications such as prototype testing, human behavior studies, etc (Barbagli, F. et al., 2001). Recently, motion simulators have been staking their territory in the amusement park arena, gradually replacing the bulky and costly riders (Rock, I., 1975). However, current amusement flight simulators focus on the visual and audio systems, rather than precise reproduction of actual motions (Young, L. R., 1977). Therefore, a novel motion simulator that simulates real world motion more precisely is eagerly anticipated.

Generally, the motion simulator consists of a visual system to provide the images for the riders, an auditory system to generate sound, and a motion base to generate movement as a result of motion cues. Most of the current motion simulators adopt a Stewart-Gough platform as their motion base. This platform has a six degrees of freedom mechanism which enables it to rotate and translate in the X, Y and Z axes. However its rotation angles are limited to a maximum ±20°~30°, leading to unrealistic spin motions such as those for simulating overturns of fighter planes, and 360° spin motions of roller coasters.

The objective of this research is to develop the motion base system that can generate real world motions more precisely than any of the existing motion bases. The Eclipse-II mechanism is a parallel mechanism capable of a 360-degree rotational motion of the moving platform as well as translational motions, designed for the motion base of the motion simulator. This mechanism was originally designed with six degrees of freedom, however, two additional degrees-of-freedom have been added to eliminate the end-effector's singular configurations, and to improve the capability of the rotational aspects of the motions. In addition, an additional actuator is added to a passive joint to eliminate the actuator's singular configuration, and so the final Eclipse-II mechanism possesses eight degrees of freedom, and is a nine axes parallel mechanism (Kim, J. et al., 2002).

The Eclipse-II one-man ride machine, based on the Eclipse-II mechanism, is developed primarily for use in motion simulator applications such as flight simulators and roller coaster simulators for recreational use. Its development is based on the results of theoretical analysis of the Eclipse-II mechanism with actuation redundancy, and experimental verification using a working sample machine (Kim, J. et al., 2003).

Typically, the motion simulator needs the reproducing system of an input motion trajectory, which is called the washout filter. The limited workspace of a motion simulator does not allow for direct duplication of real world motion on the simulator platform, and so this has prompted the development of the washout filter. The function of a washout filter is to accept real world motions as inputs and then, to produce desired simulator motions so that the sensations on the simulator are as close as possible to those experienced in actual riding (Levision, W. H., and Junker, A. M., 1978).

Despite the Eclipse-II one-man ride machine being able to realize any motions with a continuous 360-degree rotational motion in any direction with six degrees of freedom, it has problems in achieving real-time motion planning and control performance due to its structural complexity. The modified Eclipse-II one-man ride machine is presented here, which aims to overcome these problems of achieving real-time executions speeds for running the algorithms. The modification is performed to enable three rotational axes of the moving platform to be controlled by independent actuators through the use of the redundant actuator.

This paper is organized as follows. In section 2, the kinematic structure of the Eclipse-II, with its characteristics of redundant actuation and its verification by use of a working sample are presented. Section 3 describes the design and development issues of the Eclipse-II one-man ride machine, including the washout filter and the motion planning algorithm, and section 4 presents the modified structure, followed, finally, by the concluding remarks in section 5.

2 Eclipse-II Mechanism and Verification by Working sample

2.1 Basic Kinematic Structure

The architecture of the Eclipse-II mechanism is shown in Fig. 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, and the six actuated joints are the following: three prismatic joints (A_i) along the horizontal circular guide, two prismatic joints (C_2, C_3) on the vertical columns, and another one prismatic joint (C_1) on the vertical circular column. All six actuated joints can be seen in Fig. 1, indicated by arrows. One end of each connecting link B_iC_i is attached to the circular and vertical columns through the revolute joint. The other end of these links is mounted to the moving platform via a spherical joint (B_i).

Mounting the circular column, and the two linear columns, on the circular guide gives the Eclipse-II a large orientation. The moving platform can rotate through 360 degrees continuously about the *y*-axis in the moving frame {*M*} and the *Z*-axis in the fixed frame {*F*}.

In general, a parallel mechanism has two types of singularity: an end-effector singularity and an actuator singularity [3]. In the Eclipse-II mechanism, these two types of singularities coexist in the workspace (Kim, J. et al., 2002). To avoid the end-effector singularity, the additional branches with actuated joints are added onto the moving platform, and to eliminate the actuator singularity, the extra actuator is added onto the passive joints between the vertical column and the connecting link. In addition, one redundant actuator is added onto the moving platform to improve the capability of the rotational motion, which is the continuous 360 degree

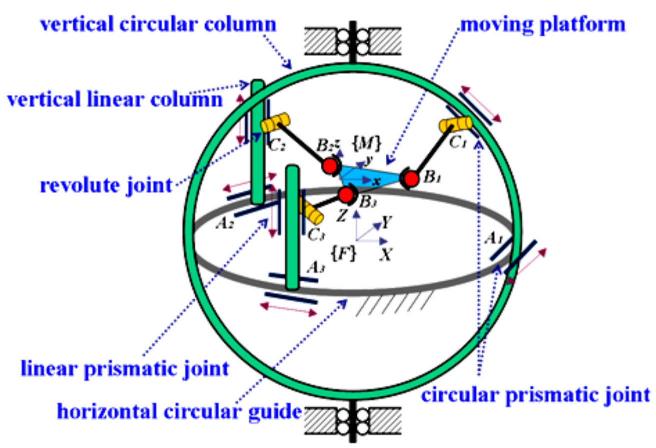


Fig. 1 Architecture of the Eclipse-II mechanism

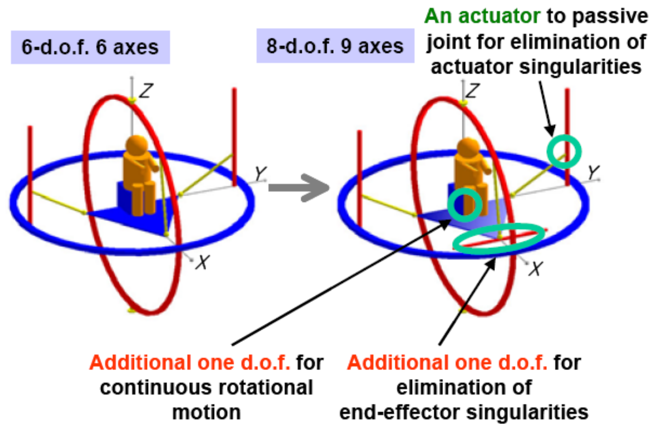


Fig. 2 8-DOF, 9-axis Eclipse-II mechanism

rotational motion of the moving platform. As a result, the Eclipse-II mechanism becomes an eight degrees-of-freedom, nine-axis redundant parallel mechanism, as shown in Fig. 2. A more detailed explanation has been discussed in a previous paper (Kim, J. et al., 2003).

2.2 Working sample Development

Figure 3 shows a photograph of the working sample of the Eclipse-II mechanism, which has been manufactured to verify the original idea. The main specifications of the working sample are shown in Table 1.

With the translational motion in the X, Y, and Z axes, the working sample is able to complete six degree-of-freedom motions including continuous overturning about the A, B and C-axes. The working sample of the Eclipse-II mechanism is able to reproduce any six degrees-of-freedom motions, including overturn motions, for example, that of an aircraft. This is impossible to achieve in any of the other parallel mechanisms developed so far.

Fig. 3 Eclipse-II working prototype example

Table 1 Specifications of the Eclipse-II working prototype

Overall size: 1350(L) x 900(W) x 1970(H) mm
Platform size: 210 x 180 mm
Kinematic workspace: 37.2 x 80 mm
Max. linear speed: 4 m/min
Max. linear acceleration: 230 mm/sec2 (0.023g)
Max. angular speed: 200 deg/sec (33.3 rpm)
Max. angular acceleration: 700 deg/sec2
Number of axes: 9
Actuators: AC servo motors.

3 Eclipse-II One-man Ride Machine Development

3.1 Developed prototype

Figs. 4 and 5 present photographs of the Eclipse-II one-man ride machine, and its assembly drawing, respectively, and the device has been designed based on the Eclipse-II mechanism using experimental data of a working sample machine. This machine can be applied to emulate a motion simulator, such as a flight simulator for military purposes, or a roller coaster simulator for recreational use. The machine is located in Seoul National University in Korea.

The main specifications of the Eclipse-II one-man ride machine are shown in Table 2. It can simulate any six degrees-of-freedom motion with a 360-degree rotational motion about any direction. It is operated according to the prepared path, which is made by passing the real-world path through a washout filter and motion planning algorithm. Since it has two additional degrees of freedom, as mentioned in Section 2, the motion planning and control algorithm is crucial in finding the optimal eight control inputs from the six degrees-of-freedom rider's command inputs.

3.2 Washout filter design

A motion simulator enables a pilot sitting on the platform to experience the real-world motion sensations. Due to its lack of dynamic and spatial abilities, such as its limitation of workspace, a motion simulator does not attempt to reproduce the real-world motion directly. The washout filter prevents the simulator from being driven off its pre-determined boundaries, or from generating excessive torques. The washout filter converts real world motions into realizable motions for the simulator to perform, while minimizing the sensational differences between the real world and simulated motions.

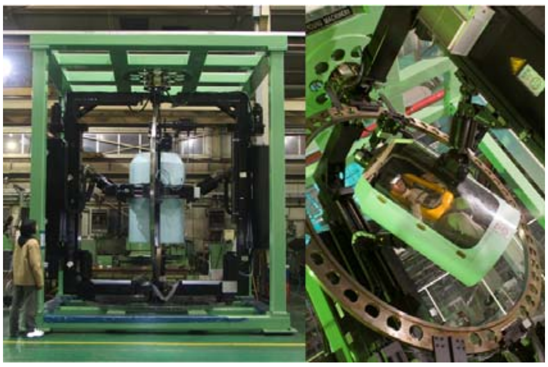


Fig. 4 Photographs of the Eclipse-II one-man ride machine

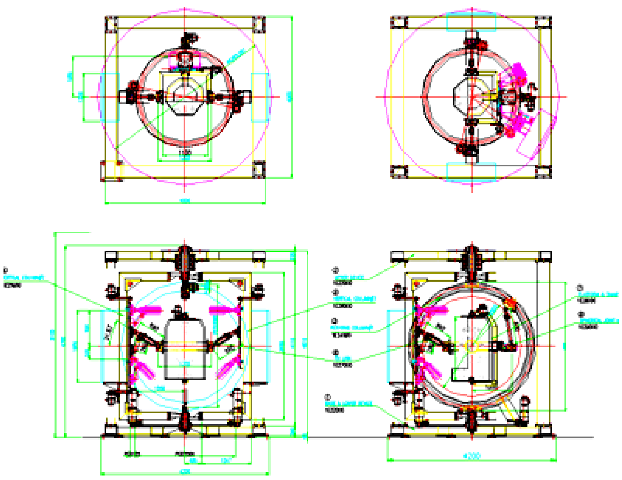


Fig. 5 Assembly drawing of the Eclipse-II one-man ride machine

Fig. 6 represents the procedure of converting the real world motions into realizable motions on the simulator, by using the washout filter. To consider human sensation when formulating the washout filter design problem, a mathematical vestibular model is necessary. This calculates the human sensation using specific forces and angular velocities. From the reference path, the washout filter of the Eclipse-II produces the realizable path of the simulator, while minimizing human sensation error, between the reference path and the converted path which is then used in the motion planning procedure as the input trajectory.

3.3 Motion planning for Off-line control

The basic motion planning algorithm using the rotation matrices of *z-y-x* and *z-y-x-z'* Euler angles for rotational motion is as follows:

$$
\begin{aligned}
\boldsymbol{R}_{control} &= \boldsymbol{R}_{input} \\
\boldsymbol{R}_{input} &= \mathbf{Rot}_Z(\alpha)\mathbf{Rot}_Y(\beta)\mathbf{Rot}_X(\gamma) \\
\boldsymbol{R}_{control} &= \mathbf{Rot}_Z(\alpha')\mathbf{Rot}_Y(\beta')\mathbf{Rot}_X(\gamma')\mathbf{Rot}_{Z'}(\delta') \qquad (1)
\end{aligned}
$$

where α, β and γ are the rotation angles about the z, y and x axes of the rider's frame, α', β', γ' and δ' are the rotation angles about the z, y, x and z' axes of the moving frame of the Eclipse-II one-man ride machine. The z' axis is the additional rotational axis of the chair on the moving platform.

The input rotation matrix, to be denoted as $\boldsymbol{R}_{input} \in \Re^{3\times 3}$ in equation (1), is obtained from the washout filter. The output rotation matrix, $\boldsymbol{R}_{control}$ has the same dimension as the input matrix. Each component of the output matrix is expressed as a function of the output angles, namely, α', β', γ' and δ'. There are four unknown output variables, but equation (1) is calculated by only three independent components, of the nine components of the rotation matrix. This causes the output angles not to be determined as a unique solution. There exists the possibility of infinite control output sets, due to the redundant axis, which is added along the z-axis in the moving frame for the improvement of rotational capacity in X-axis. So, it takes significant time to determine the optimal control values, α', β', γ' and δ', from the infinite number of possible

Table 2 Specifications of the Eclipse-II one-man ride machine

Overall size: 4,200 (L) × 4,000 (W) × 5,100 (H) mm
Platform size: 1,125 × 940 mm
Kinematic workspace: Ø236.6 × 491.3 mm
Max. linear speed: 36 m/min
Max. linear acceleration: 0.5g
Max. angular speed: 120 deg/sec
Max. angular acceleration: 500 deg/sec^2
Number of axes: 9
Actuators: AC servo motors

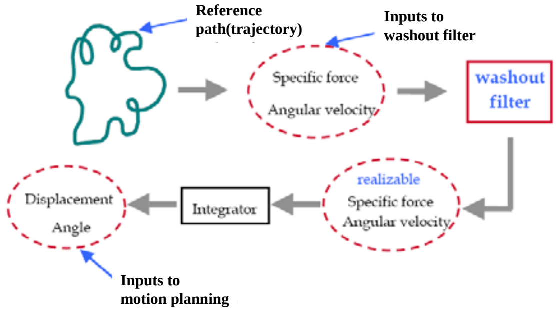


Fig. 6 Procedure of converting the path by the washout filter

candidates, while considering limited workspace and actuator capabilities. This brings about difficulty in real-time motion planning and control for the Eclipse-II one-man ride machine, therefore, it is only useful for the motion simulator operated by predefined paths, such as the roller coaster simulations for recreational use. The modification of the Eclipse-II one-man ride machine has been given considerable focus in order to realize real-time control.

4 Modification of Eclipse-II One-man Ride Machine for Real-time operating

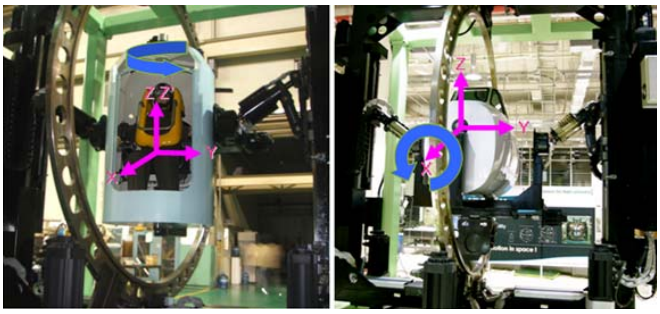
4.1 Modification for real-time operating

A flight simulator needs a real-time control algorithm that deals with the rider's inputs from a control stick and throttle. In particular, a fighter simulator for military purpose needs real-time response for the extreme input motions, such as turning movements with high acceleration.

Since the Eclipse-II one-man ride machine has difficulties in achieving real-time control performance, as mentioned in section 3, a modified kinematic structure is proposed. The objective of this modification is to accomplish decoupled rotational motion architecture, meaning that each rotational axis can be operated by different actuators. This can be achieved by using a redundant actuator attached on the chair of the moving platform for the X-axis rotation in the moving frame $\{M\}$. In the case of the original Eclipse-II one-man ride machine, the redundant actuator is used for the yaw motion that is the rotational motion about the Z-axis in the moving frame $\{M\}$. This modification is shown in Fig. 8.

As a result of the modification, the motion planning algorithm for the rotational motion is no longer required, as shown in equation (2).

$$\begin{aligned} &\boldsymbol{R}_{modified\_control} = \boldsymbol{R}_{input} \\ &\boldsymbol{R}_{input} = \mathbf{Rot}_Z(\alpha)\mathbf{Rot}_Y(\beta)\mathbf{Rot}_X(\gamma) \\ &\boldsymbol{R}_{modified\_control} = \mathbf{Rot}_Z(\alpha'')\mathbf{Rot}_Y(\beta'')\mathbf{Rot}_X(\delta'') \end{aligned} \qquad (2)$$



(a) Previous Eclipse-II (b) Modified Eclipse-II

Fig. 8 Rotation axis of the redundant actuator on the chair of the moving platform

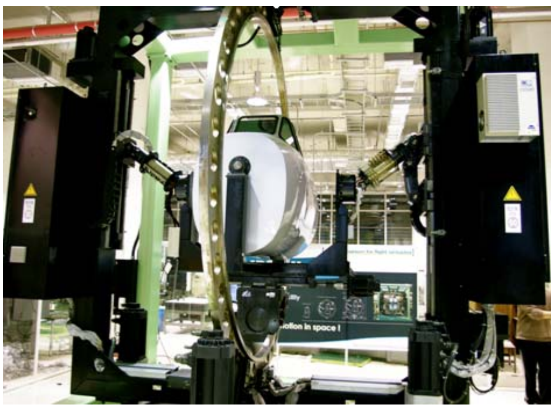


Fig. 9 Photograph of the modified Eclipse-II one-man ride machine

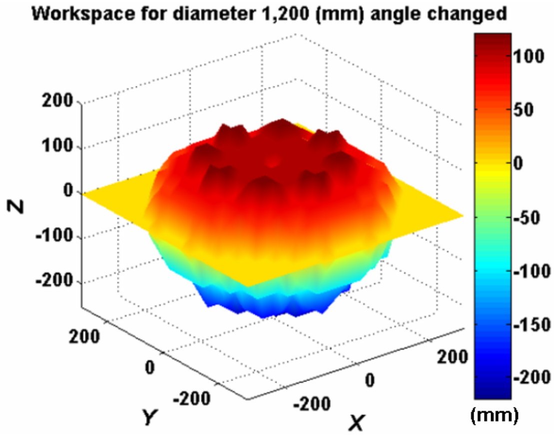


Fig. 10 Workspace of the modified Eclipse-II one-man ride machine

where α'', β'' and δ'' are the rotation angles about the z, y and x axes of a moving frame of the modified Eclipse-II one-man ride machine. This enables the modified Eclipse-II one-man ride machine to be operated in a real-time motion planning and control mode. The modified Eclipse-II one-man ride machine has been designed and manufactured as shown in Fig. 9.

4.2 Kinematics of the modified Eclipse-II one-man ride machine

Since the kinematic structure of the Eclipse-II one-man ride machine has been modified, its kinematic analysis for the modified mechanism, including singularity analysis and workspace analysis, is required. It has been identified that there is no difference in the singularity positions between the original and the modified mechanism. Therefore, the same redundant actuation technique is adopted to avoid singularity configurations. However, the machine's workspace is changed, as the size of the cockpit, frames and links were also changed. The size of cockpit expanded from Ø 940 × 1,125 (mm) to Ø 1,200 × 1,600 (mm), and the workspace was changed from Ø 236.6 × 491.3 (mm) to Ø 300 × 280 (mm), as shown in Fig. 10. This is a dexterous workspace, defined as the region the end-effector is able to reach with full rotational capacity.

5 Conclusions

This paper has presented a redundant 6-DOF parallel mechanism called the Eclipse-II. The unique feature of Eclipse-II is that it is able to perform a continuous 360-degree rotational motion about any direction of the moving platform, in addition to translational motions. The redundant actuation has been used to eliminate both the end-effector and the actuator singularities, and to increase the capability of the rotational motion. Based on the results from the kinematic analysis, and experimental verification, using a working sample machine, the Eclipse-II one-man ride machine has been developed along with the washout filter and motion planning algorithm. However, its difficulties in real-time motion planning, and achieving effective control, have led to the modification of the Eclipse-II one-man ride machine. The modified machine can be used successfully in a fighter simulator, or rollercoaster simulator, with extreme motions.

ACKNOWLEDGEMENT

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