Research Article

Design and Development of a 3-DOF Personal Motion Simulator

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Abstract: This study describes the design and development of a motion simulator with 3 degrees of freedom as a personal riding motion simulator. While the conventional motion simulator mainly pursues high precision with high performance specifications, we propose a simple and cost effective riding motion simulator to replace the expensive conventional motion simulator. In this paper, we propose a new motion platform with a parallel mechanism that can be implemented stably because the mechanism structure has higher inertia moment and force transmission efficiency than the serial type mechanism. The proposed motion simulator needs to be configured to have minimal degree of freedoms while a user experiences a proper motion. Therefore, we design a three-degree-of-freedom parallel mechanism that can be implemented stably due to high inertia moment and force transmission efficiency, and verify the performance of the simulator through experiments.

1. Introduction

Motion Simulator has been mainly developed for military flight control training and has been used as a tool to assist pilot training. Therefore, it requires high precision and stability of the simulator, but it is difficult to be popularized because it requires expensive high-performance equipment and wide installation space **(Alexander Huesmann and Josef Nauderer, 2007)**. Today, motion simulators are expanding various fields of application to not only military, but also education in engineering and welfare and entertainment with virtual reality technology. For the use of this new emerging application fields, new design method of a motion simulator aimed at a low-end type with the minimum degree of freedom for the user to feel immersive is needed to reduce manufacturing cost and overcome the constraints according to the minimum installation space.

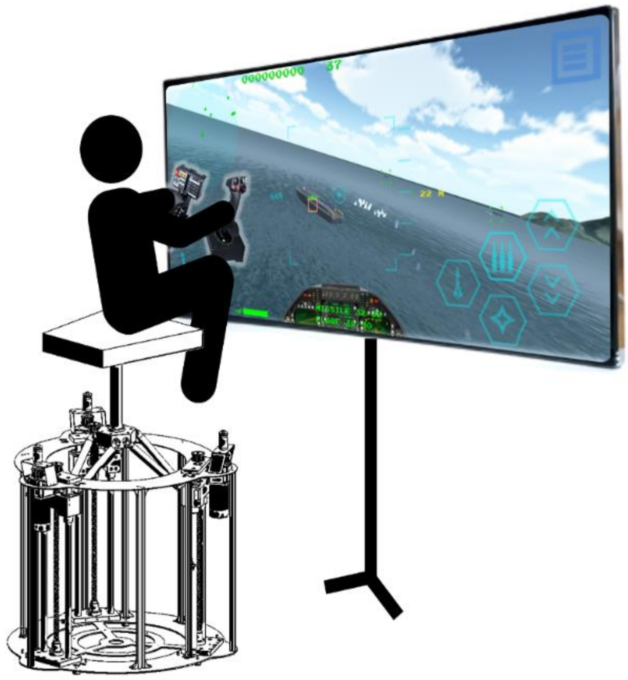
This study aims to design and develop a low-end personal riding motion simulator. To accomplish this, it is necessary to reduce the manufacturing cost, and it is necessary to develop them by limiting the range of motion. Parts with a high proportion of manufacturing cost are substituted to reduce unit cost and reflect in the design to have a limited payload based on the determined range of use.

In the mechanism of motion simulator, it can be largely classified into two types, serial and parallel mechanism. Parallel type mechanism has advantages in structural stability, rigidity, and precision by distributing the load. On the other hand, the serial type mechanism requires a high-performance power unit with a higher torque in order to operate with the same performance as the parallel type mechanism, and has a disadvantage in that the operating radius is restricted due to an increase in the load according to the operating angle. Motion simulator performs repetitive motions for starting, stopping, and rotating at the same time as it is driven, and has a moment of inertia generated by the repulsive force of the object according to the motion **(Roza, Z.C., 2005)**. Therefore, this study describes the design and development of the mechanism of a personal riding motion simulator with a parallel mechanism that is easy to overcome the moment of inertia.

For the popularization of motion simulators, considerations in design are to reduce manufacturing costs and to derive the minimum degree of freedom by considering the constraints according to the installation space and method **(A.M. Parkes and A. Flint, 2004)**. The degree of freedom of simulator varies depending on the intended use, but the minimum degree of freedom for multi-purpose use is 3 degrees of freedom along the roll, pitch, and yaw axes.

The proposed motion simulator is configured as shown in the following Figure 1, and has a total of 3 degrees of freedom with 2 degrees of freedom rotational motion for roll and pitch and 1 degree of freedom linear motion for yaw. The simulator is composed into two parts, and it is divided into a base platform that supports the total load and a motion platform that actually operates. The base platform consists of a driving part and an exoskeleton that supports the load, and the motion platform consists of a link and an end effector.

Figure.1. showing the concept of personal motion simulator

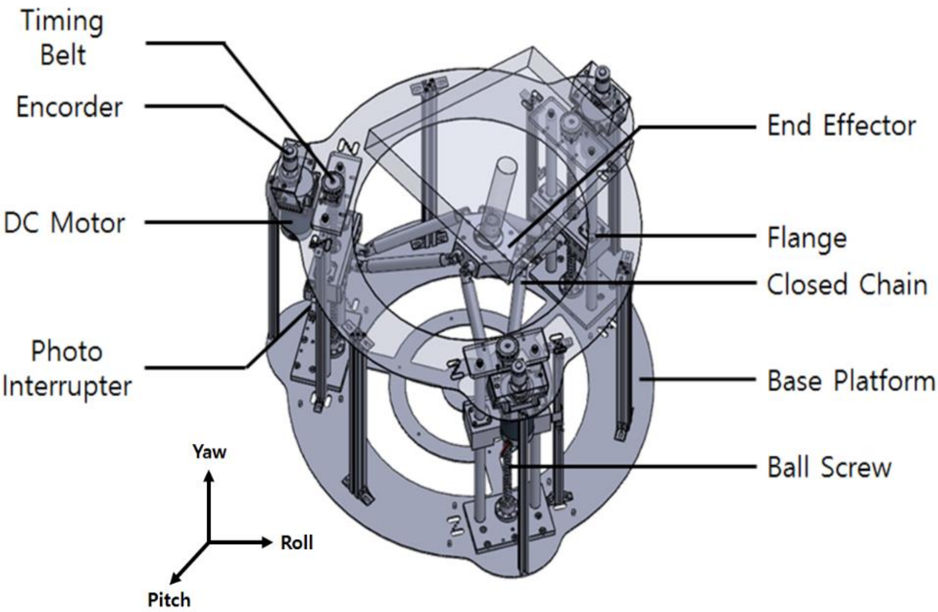


This paper is organized as follows. First, the design and specifications of the proposed motion simulator are presented, and the kinematic analysis of the motion simulator, control system and software are explained. Finally, the performance of the motion simulator is verified through the experimental results, and in the conclusion, the results of this study are summarized and future studies are presented.

2. Design and Specifications of Personal Riding Motion simulator

The proposed motion simulator is largely classified into two parts. It is divided into a base platform that supports the entire load and a motion platform that actually operates. The base platform consists of a driving part and an exoskeleton that supports the load, and the motion platform consists of a link and an end effector. The simulator is configured as shown in Figure 2, and it is configured to have a total of 3 degrees of freedom with two degrees of freedom rotational motion for roll and pitch and one degree of freedom linear motion for yaw.

Figure.2. showing the motion simulator configuration



The motion simulator consists of a parallel mechanism structure to distribute the load of the occupants. The designed parallel mechanism is composed of a closed chain structure similar to that of the Stewart platform. This structure has an advantage in realizing stable motion as it lowers the moment of inertia that occurs during motion of the motion simulator and facilitates high force transmission characteristics. It is composed of a structure that combines a universal joint and a ball bearing to have three degrees of freedom at both ends of the link as shown in Figure. 3 and Figure. 4 to form a closed chain structure.

Figure.3. showing the link structure connecting to a base platform

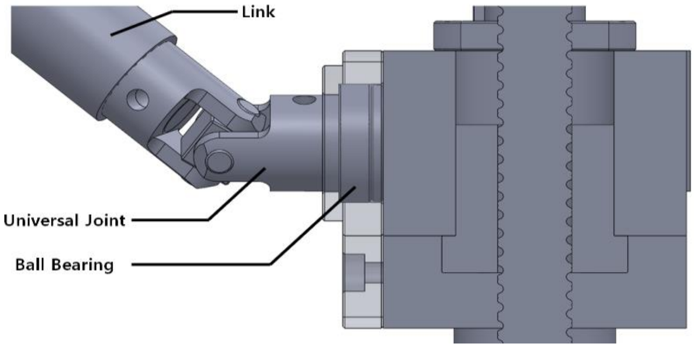
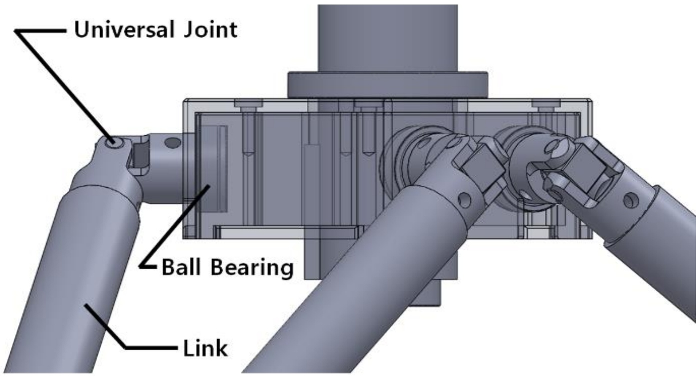


Figure.4. showing the link and end effector connection structure



Specifications of the developed motion simulator are shown in Table 1. The maximum height for the allowable operating radius of the simulator is 1175.69mm, as shown in Table 1 and Figure 5, and the total weight of the motion simulator is 78.22kg, and the diameter is Ø1028, so it has structural stability in realizing the movement. In addition, the overall height of the base platform is 880.75mm and the weight is 58.72kg. In consideration of the prototype design, the speed was set relatively slow for the safety of passenger and stable motion control, and the maximum payload of the simulator was designed as 100 kg. The top view and side view of the motion simulator are shown in Figure 5. The outlook of the developed motion simulator are shown in Figure 6.

Table.1. showing the specifications of the developed motion simulator

Item	Unit	Specifications
Dimension	mm	Ø1028 × 1175.69
Total weight	kg	78.22
Base platform dimension	mm	Ø1028 × 880.75
Base platform weight	kg	58.72
Operating angle	°	30
Operating speed	mm/sec	4.88 ~ 9.76
Payload	kg	100
Supply voltage	V	24
Torque	Nm	24.69

Figure.5. showing the top view(left) and the side view(right) of the motion simulator

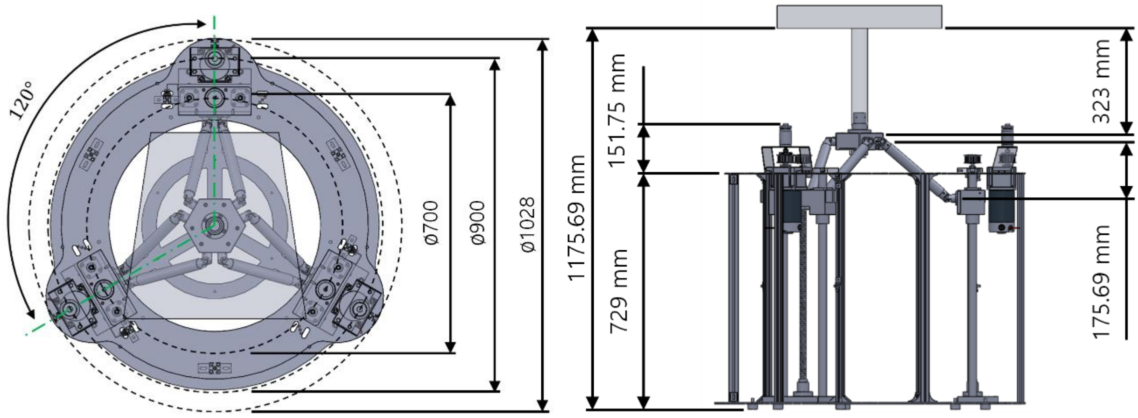
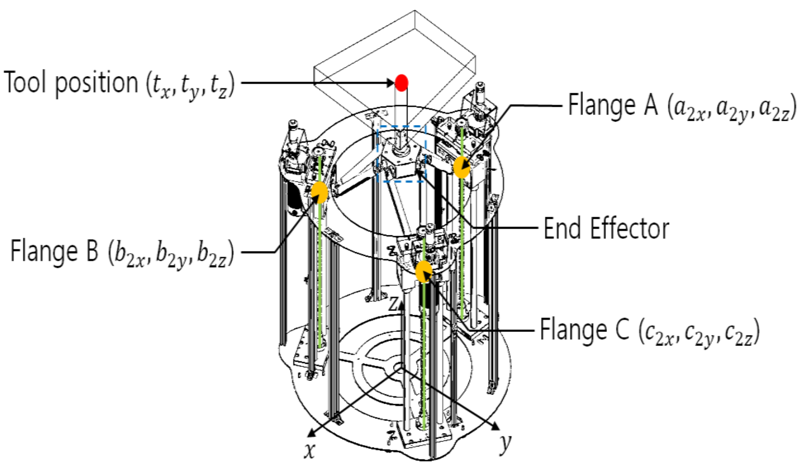


Figure.6. showing the outlook of the developed motion simulator

3. Kinematic Analysis of the Motion Simulator

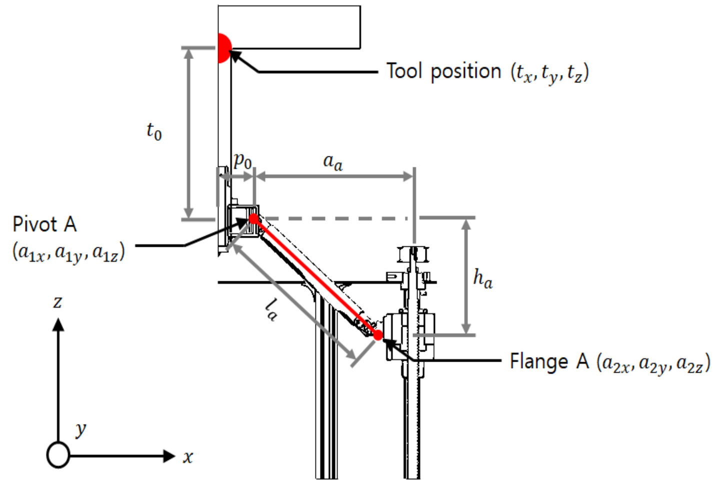
The inverse kinematics of the proposed motion simulator is to change the coordinates (t_1, t_2, t_3) of the tool position by moving the flange of each driving part up and down as shown in Figure 7. The pivot, the point at which the end effector connected with the link from the flange of each drive, is arranged at 120° intervals.

Figure.7. showing the coordinates of the motion simulator



Since the flanges are located on three parallel columns, only the z-axis coordinate, which is the height coordinate, is calculated as shown in Figure 8. If all six coordinates of the flange and pivot are known, then, a_a, a_b, a_c can be expressed according to the equation Pythagorean theorem. In the case of the flange A, the distance of a_a can be found through the Pythagorean theorem of a_{2x}-a_{1x} and a_{2y}-a_{1y}, and in the same way, the equation representing both flange B and flange C is substituted and expressed as Equation 1. By substituting the coordinates in Table 2 in Equation 1, the target flange position can be found.

Figure.8. showing the right side view and its coordinates of motion simulator



Equation.1.

$$\begin{bmatrix} a_{2z} \\ b_{2z} \\ c_{2z} \end{bmatrix} = \begin{bmatrix} t_z + t_0 + \sqrt{l^2 - (a_{2x} - a_{1x})^2 + (a_{2y} - a_{1y})^2} \\ t_z + t_0 + \sqrt{l^2 - (b_{2x} - b_{1x})^2 + (b_{2y} - b_{1y})^2} \\ t_z + t_0 + \sqrt{l^2 - (c_{2x} - c_{1x})^2 + (c_{2y} - c_{1y})^2} \end{bmatrix}$$

Table.2. showing the flange and pivot coordinates

Item	Unit	Specifications
Dimension	mm	Ø1028 × 1175.69
Total weight	kg	78.22
Base platform dimension	mm	Ø1028 × 880.75
Base platform weight	kg	58.72
Operating angle	°	30
Operating speed	mm/sec	4.88 ~ 9.76
Payload	kg	100
Supply voltage	V	24
Torque	Nm	24.69

4. Control System and Software

The configuration of the motion simulator control system is shown in Figure 9. Photo Interrupter is used for the origin calibration when the simulator is started, and the encoder data and the photo interrupter signal are transmitted to the MCU, and the absolute position of the motion simulator is calculated based on both data. GUI of the developed control software is shown in Figure 10. The software outputs the distance value data in mm in real time through the console window to check the actual operating distance and the error rate of the command **(Kim, Y. J. and Seo, Y. H. ,2013)**.

Figure.9. showing the configuration of the motion simulator control system

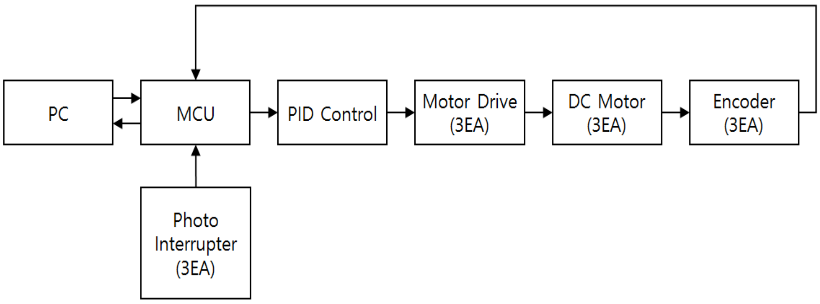
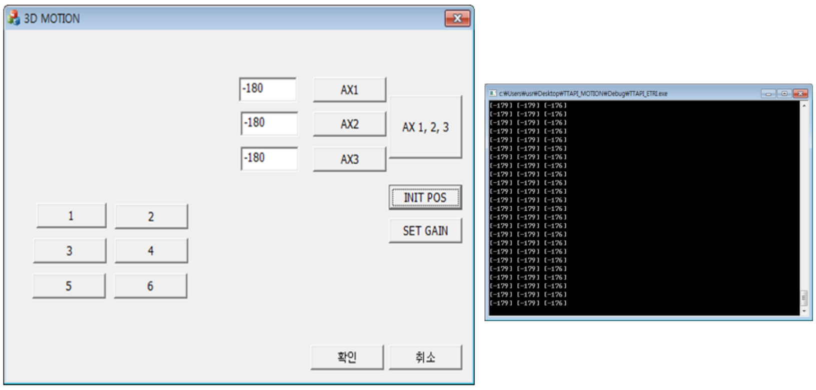


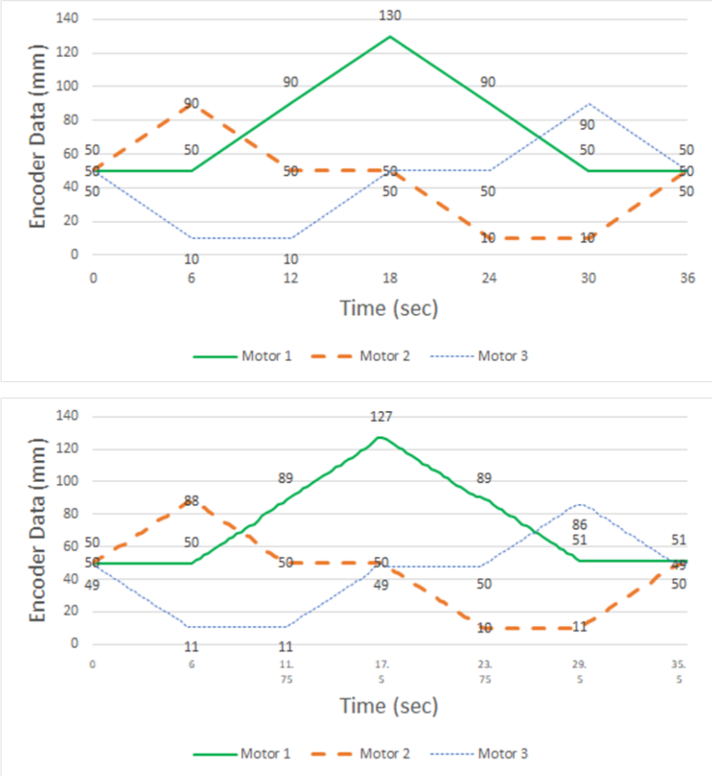
Figure.10. showing the GUI of the developed control software



5. Experimental Result

An experiment was performed to perform continuous motion by operating all three axes of the motion simulator. Figure 11 shows the result of the experiment to check the error rate by comparing the actual encoder data and the commanded value.

Figure.11. showing the 3-axis drive operation command (top) and encoder data accordingly (bottom)



Next, an experiment to measure the sensibility of boarding a continuous motion according to the operation of the three axes of the driving unit was performed to review the safety of the developed simulator as shown in Figure 12 **(J.C.F. de Winter, P.A. Wieringa, J. Dankelman, M. Mulder, M.M. van Paassen, and S. de Groot ,2007)**. A total of 26 passengers participated in the experiment, and more than 65% of the respondents from the survey result of ‘Experience according to angle change’ showed that ‘12° and 15° are less likely to feel safety’. At the time of the experiment, the average speed of the motion simulator was 8.54 mm/sec, which was relatively slow considering the speed of the existing motion simulator. However, the developed motion simulator is capable of wider angle control, and as a result of the survey, 70% of passengers answered that 'the motion of the simulator is interesting'.

Figure.12. showing the experiment to measure sensibility for continuous motion

6. Conclusion

This paper proposed a motion simulator with an optimal mechanism design through analysing the advantages and disadvantages of the existing parallel mechanism for an entry-level personal motion simulator. In addition, the proposed motion simulator's performance was demonstrated and verified through a passenger riding experiment and a questionnaire to review the safety of the developed simulator. As a further work, design changes that can improve safety of motion simulators and add degrees of freedom to improve its performance are planned so that the developed simulator can be applied to actual applications such as flight or gamming simulation contents.

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