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DYNAMIC MODELING AND MOTION PLANNING FOR REDUNDANT PARALLEL KINEMATIC MECHANISM USING JOINT TORQUE DISTRIBUTION

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ABSTRACT

This paper presents the dynamic modeling of Eclipse-II and motion planning algorithm for the redundant parallel kinematic mechanism using joint torque distribution that satisfies a path of the end-effector. The redundant parallel kinematic mechanism has more numbers of actuator than numbers of degrees-of-freedom, and it has the advantage of bigger workspace than non-redundant parallel kinematic mechanism by eliminating singularities. The redundant parallel kinematic mechanism, however, has the problem not to able to select the unique motion of actuator for the motion of the end-effector. In this paper, the method of motion planning is presented, that is to find out joint torque distribution with dynamic modeling and to find out unique motion of actuators for minimizing the energy of actuators. The dynamic modeling is compensated with the frictional effects, and is verified by comparing torques and energy with measured values.

NOMENCLATURE

Dynamic Analysis, Eclipse-II, Motion Planning, Parallel Kinematic Mechanism

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 motions, 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.

To overcome the limit of motion, a redundant parallel mechanism is attached to additional d.o.f. But redundant parallel kinematic mechanism has infinite solutions of inverse kinematics. That means each joint’s value against the end-effector configuration cannot be determined.

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 passive joint to eliminate actuator singularity configuration. Therefore Eclipse-II mechanism is finally modified to be 8 degrees-of-freedom and 9 axes parallel mechanism.

In case of Eclipse-II, the joints’ values also cannot be determined for the end-effector’s movement. It can move with redundant actuators or without them. This paper presents the motion planning to determine the all joints’ values including redundant actuators.

Eclipse-II is also over-actuated parallel mechanism, and dynamics for over-actuated parallel mechanism is different from that of serial mechanism and that of non over-actuated parallel mechanism. Ryu [2] had developed basic dynamic equations for over-actuated parallel mechanism of 2-d.o.f. parallel mechanism and Eclipse-I parallel mechanism. But still the dynamics for Eclipse-II mechanism and dynamic analysis with the real parallel mechanism machine are required.

For motion planning problems, there are many relative researches about redundant or non-redundant serial robots (see [3] and [4]). However there is not previous work on motion planning for redundant parallel mechanism.

In this paper, the method of motion planning is presented, that is to find out joint torque distribution with dynamic modeling and to find out unique motion of actuators for minimizing the energy of actuators. Case experiments with a redundant parallel kinematic mechanism, Eclipse-II, are also performed to verify the motion planning.

This paper is organized as follow. In Section 2, Eclipse-II redundant parallel kinematic mechanism is introduced. Section 3 describes the dynamic analysis of Eclipse-II mechanism. In Section 4, we will describe motion planning for redundant parallel mechanism with two application cases. Finally, some concluding remarks follow in Section 5..

ECLIPSE-II PARALLEL MECHANISM WITH REDUNDANT ACTUATORS

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.

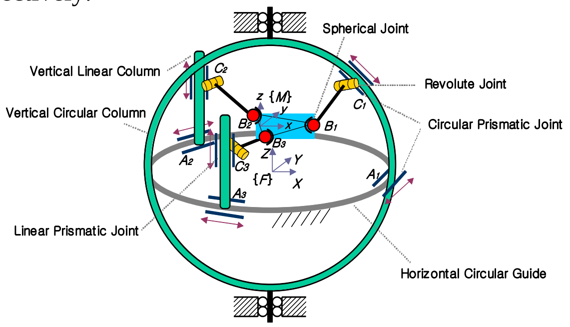
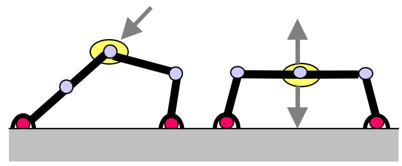


Figure 1. Architecture of the Eclipse-II mechanism

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 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. The detailed results of the kinematic analysis are already described in a previous paper [5].

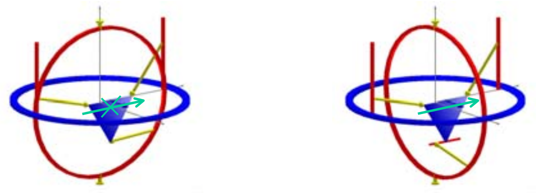
Generally, parallel mechanism platform has two types of singularity [1]: end-effector singularity and actuator singularity. Fig. 2 illustrates the concept of the two types of singularities. If the end-effector is at the configuration as shown in Fig 2(a), it loses one d.o.f. in the arrow direction shown 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 as shown in Fig. 2(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 2. Two types of singularities in parallel mechanisms

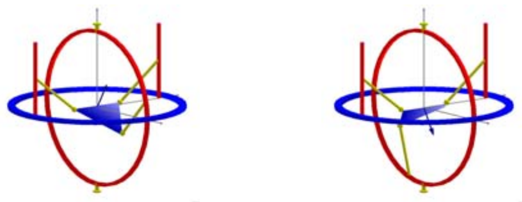
In the Eclipse-II mechanism, two types of singularities coexist in the workspace. As shown in Fig. 3(a), the platform cannot translate along the y-direction in the moving frame, which is the same concept as shown in Fig. 2(a). Hence, an actuator is added to change the position of the spherical joint 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 d.o.f. is added more to rotate rider's chair on the platform.



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

Figure 3. y-direction motion in the moving frame is:

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 [5].



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

Figure 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 as shown in Fig. 5(b). 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 conclusion, by adding three more actuators to eliminate two type singularities and limited rotation problem, Eclipse-II is modified to be 8-d.o.f and 9 axes redundant parallel mechanism. (see Fig. 6).

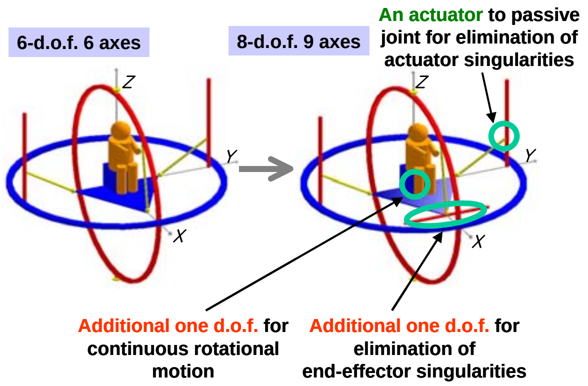


Figure 6. 8-d.o.f, 9axes Eclipse-II mechanism

Fig. 7 shows the photograph of the working sample of the Eclipse-II mechanism. It has been manufactured to verify the original idea. This machine is used to verify the dynamic analysis and motion planning which are described following sections.

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/sec2 (0.023g)**
max. angular speed: **200 deg/sec (33.3 rpm)**
max. angular acceleration: **700 deg/sec2**
number of axes: **9**

Figure 7. Eclipse-II working sample

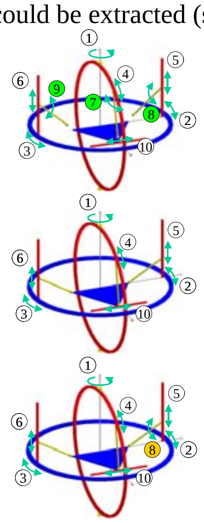
DYNAMIC ANALYSIS

To solve dynamics for parallel mechanism, reduced system is used. The reduced system is to divide parallel mechanism on passive joint and to make it serial chains as shown Fig. 8(a), torques for each serial chain are found out with assumption of all joints are active. Finally serial chains are combined and torque on active joints can be found out using D'Alembert principle.

But in case of over-actuated parallel mechanism, the number of active joints is larger than that of independent joints which are found out before. Thus the principle for torque distribution is need, and torques on all active joints with over-actuated joints could be calculated with minimal torque distribution.

For the dynamic modeling for Eclipse-II mechanism, 3 steps: reduced system, original system and over-actuated system could be made out. In first step, Eclipse-II platform is divided to 3 serial chains, and each torque on all 10 actuators, including passive joints, can be found out by Lagrangian and Newton equations (see Fig 8(a)).

In second step, by D'Alembert principle, torques on 7 independent joints, excluding 3 passive joints, are determined as shown in Fig. 8(b). Final step, using minimal norm torque distribution, 8 actuators with one over-actuated joint values could be extracted (see Fig. 8(c)).



(a) Step 1: Reduced System.

$$F_e = M_p \ddot{P}_c + C_p + N_p + F_b \qquad (1)$$

(b) Step. 2: Original System

$$\tau_{ori} = \tau_{ru} + \Phi^T \tau_{rv} + J_f^T F_e \qquad (2)$$

(c) Step. 3: Over-actuation system

$$\tau_{act} = w^{-1}\Gamma(\Gamma^T w^{-1}\Gamma)^{-1}\tau_{ori} \qquad (3)$$

Figure 8. Three steps for dynamic analysis for Eclipse-II redundant parallel kinematic mechanism

To verify torques of dynamic modeling with real machine, the experiments are carried out for the 5 simple motions and 1 complex motion: alpha-axis rotation, beta-axis rotation, z-axis translation, y-axis translation, delta-axis rotation, and complex motion. As the result, RMS torque errors between dynamic modeling and real machine are around 3 to 6% on all 9 actuators. The energy between dynamic model in and the working sample machine is also checked, and there is only 4.0% error.

MOTION PLANNING

Eclipse-II mechanism is developed as motion simulator, so paths of platform for each stage are given, and each joint's value for each stage should be determined. Minimal energy path for each stage, and combined each stage's path for optimal path (see Fig.9).

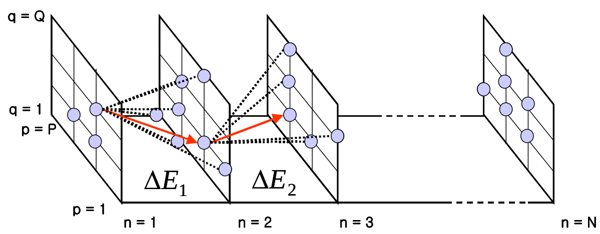


Figure 9. Dynamic Programming

To find out optimal path to minimize energy for each stage, the cost function and 5 constraints [(i) each actuator's torque limit, (ii) each actuator's velocity is less than max. velocity, (iii) Each actuator's acceleration. is less than maximum acceleration, (iv) Each joint's value is less than its limit, and (v) Spherical joint's stroke is less than its limit] are set as shown in Eq. (4).

$$\min E \equiv \sum \min \Delta E \qquad (4)$$

$$E = \int |\tau_a|^T W_a dq_a = \sum_{i=1}^{N} |\tau_a(i)|^T W_a \Delta q_a(i)$$

$$\tau_a \le T_{\max},\ \dot{q}_a \le V_{\max},\ \ddot{q}_a \le A_{\max},\ D_{\min} \le q_a \le D_{\max},\ a_b \le BALLLIMIT$$

To verify the result of dynamic modeling and motion planning, the test path for Eclipse-II is used. It includes rotation motions with more than 360 degrees continuously, and extreme condition in maximum velocity and acceleration of Eclipse-II working sample. Also this path is designed to use full strokes in the workspace of Eclipse-II working sample. Fig. 10 shows a scaled data of the test path and its optimized coordinate values which are applied by motion planning to minimize energy with the working sample platform.

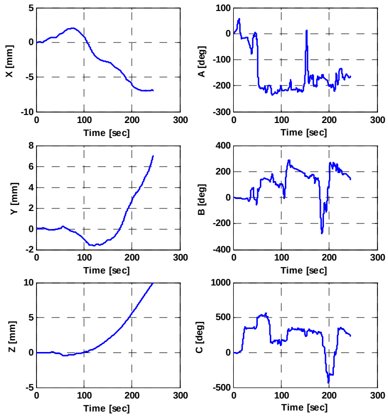


Figure 10. (a) A scaled data of the test path for the Eclipse-II working sample.

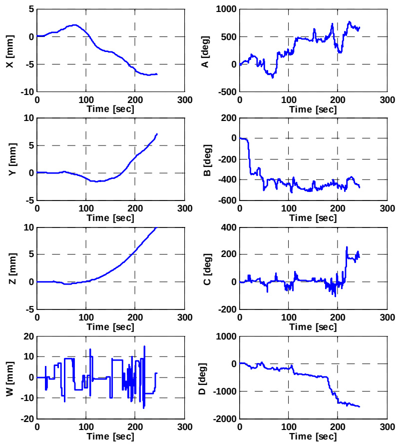


Figure 10. (b) An optimized coordinate values of the test path

To verify the dynamic modeling, the measured energy of Eclipse-II working sample platform is compared with the calculated energy of dynamic modeling. Fig. 11 shows the result of verification, and the error between two data is only 2.4% as shown in Table. 1.

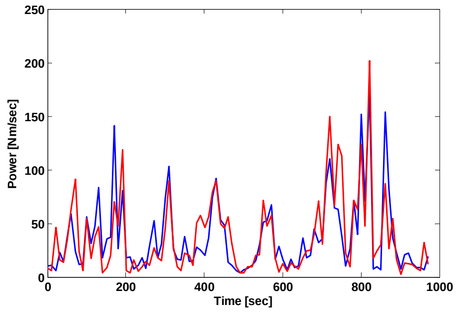


Figure 11. Calculated energy for optimal path (solid line) and calculated energy for normal path (dashed line) in the test path

Table 1. Sum of energy of the working sample in the roller coaster motion

Sum of calculated energy	**3553.3 Nm**
Sum of measured energy	**3641.6 Nm**
Error	**2.4%**

CONCLUSION

This paper presents a redundant parallel kinematic mechanism, based on Eclipse-II mechanism that is added 2 deegrees-of-freedom and 3 actuators to eliminate singularities and motion limit.

For the redundant parallel kinematic mechanism, motion planning to minimize energy is presented, and it is verified with the test path of Eclipse-II working sample machine.Put conclusion here.

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