11.3 Energy saving by using a redundantly actuated parallel mechanism

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Abstract
In this work, energy saving by using a redundantly actuated parallel mechanism is presented. The redundantly actuated parallel mechanisms have more actuators than the degrees of freedom of the mechanisms. We show that the excessive actuators can be used to save operating energy of the mechanism by distributing the operating torques against the gravitational force. The energy saving is verified by experiments for a 2-DOF parallel mechanism with three actuators, which is operated against the gravity. The results show that the redundant actuation scheme can save about 25% of average energy in various pathways with respect to the non-redundant analogue.

Keywords:
Parallel kinematics, Energy efficiency, Redundant actuation

1 INTRODUCTION
Parallel mechanisms consist of several serial chains that connect a base to a moving platform. Because of their structure, parallel mechanisms are known to be capable of very fast and accurate motions and to carry heavier payloads than their serial analogues is capable. These advantages however come at the expense of a reduced workspace from singularity configurations, difficulty in mechanical design procedure, and more complex control algorithms. A singularity is a configuration in which the degrees of freedom of a parallel mechanism change instantaneously, which must be eliminated for enlarging workspace of the mechanism. One method to eliminate the singular configuration is to add one or more actuators into one or more of the passive joints [1-3].

Reducantly actuated parallel mechanism usually increases cost of the mechanism system because of additional actuators. Thus, the more energy efficient control algorithm is needed to compensate the manufacturing or purchasing cost of the redundant parallel mechanisms [4-6]. Approach to the motion generation methodology can be categorized into two concepts: minimum torque and minimum consumed energy. The minimum torque approach is focused on lowering the maximum torque of the actuators to be installed. This approach has an advantage in reducing the initial cost in building a machine. However the positioning platforms such as router and spot welding robot need to reduce the operational expenditure rather than initial cost. In this paper, the minimum energy strategy is adopted to reduce actuating energy by adding an excessive actuator in a parallel manipulator.

There are some relative researches about trajectory planning of redundant or non-redundant serial robots [7-11]. However there seems to be not so many previous works on energy efficiency for redundant parallel mechanism. In this paper, the energy saving feature by using redundantly actuated parallel mechanism is presented. By adding additional actuators, the parallel mechanism can consume lower energy compared to non-redundant systems do. Experimental verification has also been done with a 2-DOF redundantly actuated parallel mechanism machine.

This paper is organized as follow. The kinematic and dynamic analysis is presented for a 2-DOF redundant actuated parallel mechanism in Section 2. In Section 3, simulation results for energy saving by redundant actuation is presented. The experimental verification with seven test path is depicted in Section 4. Finally, some concluding remarks follow in Section 5.

2 METHODS
2.1 Kinematic analysis
A planar 2-DOF parallel manipulator is used for verifying the energy saving feature by redundant actuation. Figure 1 shows the schematic diagram of the 2-DOF planar manipulator, which consists of a triangular plate platform, a base frame, and three serial l11, l2, l3 chains. The serial chains l11 and l2, consist of two links (l111, l112) and (l21, l22), respectively, but the chain l3 consists of only one link. In the case of non-redundant control, two active actuators are enough to realize the 2-DOF motion. However, three to eight actuators can be attached and the mechanism will be operated with the over-actuated control. The equations of motion for the suggested mechanism can be derived from the constraint equation, which represents geometrical constraint of the mechanism during the operation. In case of the 2-DOF mechanism, the constraint equation \( \kappa(x) \) can be written as equation (1).
The equation means the distance among the point $p_1$, $p_2$, and $p_3$ from the base coordinate should be equal to the side of the triangular platform. $p_1$, $p_2$, and $p_3$ are the triangular position of the platform. $D_i$ is the length of a side of the platform. Then, a Jacobian is defined as the linear relationship between the time derivatives of the related variables. The detailed derivation of equations is given in previous works [12].

Constraint Jacobian is the velocity relationship between the independent joint vector $q_i$ and the dependent joint vector $q_r$. This relationship can be obtained by the time derivative of the geometric constraint equations $g()$. By differentiating the constraint equation, the relationship between the velocity of the independent and actuating joint angles can be derived such as equation (2).

$$
\dot{q}_i = \Phi \dot{q}_r \quad \text{where} \quad q_i \quad \text{and} \quad q_r \quad \text{are the independent joint vector and actuating joint vector respectively.} \quad \Phi \quad \text{is a Jacobian mapping independent joints to dependent joints. Here} \quad \Gamma \quad \text{is a Jacobian mapping independent joints to actuating joints. These Jacobians will be used to perform dynamic analysis. The Jacobian matrix of above equations considered can be used to obtain the elements of dynamic analysis as mass, Coriolis force, and a generalized force of system.}
$$

\begin{align}
\left[\begin{array}{c}
\dot{q}_1 \\
\dot{q}_2 \\
\dot{q}_3
\end{array}\right] = \left[\begin{array}{c}
\left[\begin{array}{c}
\|p_1 - p_2\|^2 - D_2^2 \\
\|p_2 - p_3\|^2 - D_3^2 \\
\|p_3 - p_1\|^2 - D_1^2
\end{array}\right] = 0
\end{array}\right]
\end{align}

(1)

Figure 1: Schematic diagram of a 2-DOF planar manipulator

2.2 Dynamics analysis

The dynamics of a robot manipulator describes how the robot moves in response to these actuator forces. The dynamics analysis is generally classified into forward and inverse dynamics analysis in robotics literature. The forward dynamics analysis is to find the resulting motion of the end-effector as a function of time by given control inputs, which are generally actuator torques and forces. In contrast, the inverse dynamics analysis is performed to find the control inputs required to produce desired end-effector motion. It can be analyzed from the given joint values and time derivatives by solving the inverse kinematics for the desired end-effector motions.

The dynamics analysis of the redundantly actuated parallel mechanism is performed based on the results of the non-redundant case. To obtain the general motion equation of the redundantly actuated parallel mechanism, the actuating and passive joints values have to be expressed as the function of the generalized coordinates. But in case of redundantly actuated parallel mechanism, the number of active joints is larger than that of independent joints. Thus the principle for torque distribution is needed, and torques on all actuating joints with redundantly actuated joints could be calculated with minimal torque distribution [4]. From minimal torque distribution algorithm, torques of the redundant system $\tau_r$ can be expressed with Jacobian $\Gamma$ which maps velocity of the independent joints to velocity of the redundantly actuated joints.

$$
\tau_r = \Gamma^T \tau_i \quad \text{(3)}
$$

where $\tau_r$ is torque of the actuators in non-redundant case. If there is no internal forces in the system the torques of redundant system can be expressed as equation (4).

$$
\tau_r = \Gamma(\Gamma^T \Gamma)^{-1} \tau_i \quad \text{(4)}
$$

Then dynamic equation of redundantly actuated parallel manipulator can be established finally.

$$
M\ddot{q}_i + C\dot{q}_i + N = \Gamma^T \tau_r \quad \text{(5)}
$$

With the torques of redundantly actuation discussed in this Section, the trajectory planning based on dynamic modelling can be carried out.

2.3 Energy analysis

In the manipulator system, electric motors are usually exploited to actuate the joints. The absolute value of the power signal that is calculated by multiplying torques and the angular velocity of the actuating joints can be used for the energy calculation such as equation (6).

$$
E_p = \int \left( \sum_{i=1}^{n} |r_i| \dot{q}_i | \right) dt 
$$

(6)

where $r_i$ is the torque and the $\dot{q}_i$ is angular velocity of the i-th actuating joint, respectively.

In the case of non-redundant actuation for the 2-DOF mechanism in this work, the energy can be written as equation (7).

$$
E_p = \int \left( |r_{i_1}| \dot{q}_{i_1} + |r_{i_2}| \dot{q}_{i_2} | \right) dt 
$$

(7)

where $r_{i_1}$ and $r_{i_2}$ is the torques of the independent actuators in non-redundant case. For the redundantly
actuated case, the energy equation can be obtained as equation (8).

\[ E_r = \int \left( |r_1 \dot{\theta}_1| + |r_2 \dot{\theta}_2| + |r_3 \dot{\theta}_3| \right) dt \]  

(8)

where \( r_1 \), \( r_2 \), and \( r_3 \) is the torques of the actuating actuators in the redundant case. These torque vectors should satisfy the relationship suggested in equation (2) and (5) if the both actuation method can produce same motion of the manipulator.

The work done by the actuators can also be defined as follows:

\[ W_r = \int \left( \sum r_i \dot{\theta}_i \right) dt \]  

(9)

3 SIMULATION

Simulations are carried out to compare the consumed energy of redundant actuation and non-redundant actuation. In case of the non-redundant actuation, the two actuators are assumed to be installed in the base position of \( B_1 \) and \( B_2 \) in Figure 1. The additional actuator is assumed to be installed on \( B_3 \) in the case of redundant actuation.

The 2-DOF redundantly parallel manipulator is designed to apply the external forces to the mechanism system. With vertical configuration of the mechanism, simulations with the proposed mechanism are performed to obtain the consumed energy caused by external forces, which is gravity in this case.

Seven linear pathways are proposed as Figure 2 so as to verify the energy saving by redundant actuation. The start points and end points of test paths are selected so that all the point during each pathway should be included in the workspace of the system and so that avoid the singularity region. The dark region in Figure 2 represents the actuator singularity of non-redundant system, yet there is no actuator singularity in the workspace of the redundant system.

The specific discussion about singularity of the parallel mechanism can be found in previous works [2], [12].

In Table 1, simulation results of the energy consumption for the two systems are compared. From the results of the simulation, the redundant system is observed to require smaller energy than that of non-redundant system in all the pathways. As an example, work done by actuators and consumed energy in both cases of redundant and non-redundant actuation during the pathway are depicted in Figure 3. The end-effector starts from point (-150mm, 400mm) and arrives to the point (-30mm, 100mm) in the end of the pathway. In the figure, the red solid line represents the power by non-redundant actuation during the pathway, where only two actuators at the \( B_1 \) and \( B_2 \) in Figure 1 are used for the manipulation. The green dashed line represents the power by redundant actuation with respect to time, which used three actuators at \( B_1 \), \( B_2 \) and \( B_3 \). From the simulation results, the consumed energy of both cases can be calculated as the area below each graph, that is, the integration of the power with respect to the operation time.

The simulation results show that the work by actuators in both cases is almost equal to each other, which presents the same result in Section 2. In contrast, the consumed energy
The difference of reduction ratio among the test paths is influenced by configuration of mechanism during the trajectory. The consumed energy efficiency of redundant system can be increased in comparison to non-redundantly actuated system, if configuration of redundant actuator is designed for desired point-to-point path of system.

4 EXPERIMENTAL RESULTS
To verify the simulation result of optimization, experiments are carried out with the 2-DOF redundantly actuated parallel mechanism machine as Figure 4. The experiments were executed with this machine. The torques and velocity of actuators were measured from the Clipper PMAC2 controller of DeltaTau. Then the torques and angular velocity were multiplied with each other and integrated with operation time to generate the consumed energy of the actuators. The detailed experimental results are depicted in Table 2. The measured consumed energy in the case of 6th pathway is suggested in Figure 5.

The experimental results presents that the consumed energy by the redundant actuation is saved about 23% in average for the test cases. However, consumed energies of redundant actuation in the 5th and 7th cases are higher than the non-redundant case.

The difference between simulation result and experimental result seems to be caused by friction of joint mechanisms. In case of the go-up paths as path number 3, 5, and 7 the friction usually induces excessive actuation torque. Therefore the friction makes measured energy greater than estimated consumed energy.

On the other hands, the friction in go-down paths as path number 2, 4, and 6 causes the decrease of torques of actuators. That is why the measured data with these paths is smaller than estimated data. To overcome these errors, the friction calibration model should be considered in the dynamic modelling as a future work.

5 CONCLUSION
This paper presents the energy saving feature by using redundantly actuated parallel mechanism against gravitational force. Experimental results are suggested with the vertical 2-DOF redundant parallel machine.

The optimization based on dynamic modelling with minimal torque distribution is used to obtain the minimum consumed energy path. Also this paper shows that consumed energy of redundantly actuated parallel mechanism is less than non-redundantly actuated system with continuous external force such as gravity force. The reason of this consumed energy reduction is that torque distribution with additional actuators of redundantly actuated parallel mechanism can reduce the geometry work of electrical actuators of system. This result will be another advantage of redundantly actuated parallel mechanism in an energy perspective as well as a workspace perspective which is considered previous researches.

The vertical 2-DOF redundant parallel machine is used to verify the algorithm. Both the simulated and experimental results in Figure 3 means geometry work of redundantly actuated system is reduced compared to non-redundantly actuated system because of torque distribution among the actuators installed including the additional actuators.

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results show that the redundant parallel manipulator has advantage in reducing consumed energy compared to non-redundant parallel manipulator.

6 ACKNOWLEDGMENTS
This work was supported by research program of Kookmin University in Korea, the IGPT Project (N0000005) of the Ministry of Knowledge Economy in Korea and National Research Foundation (NRF) grant funded by the Korea government (MEST) (No. 2012-0000348).

7 REFERENCES


