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Energy saving effect mapping of redundant actuation in workspace

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This paper shows the mapping results of the energy saving effect of redundant actuation in a workspace. In redundant actuation, a system uses more actuators than the degrees of freedom (DoF). This system can distribute the actuating torques, which are concentrated on the normal system's actuators, to the redundant actuators. This distribution can reduce the overall energy loss of the actuators, which can increase the overall energy efficiency of the system. The distribution performance depends on the end-effector position of the system. A 2-DoF normal manipulator and redundant manipulator are designed to analyze the energy loss of each actuation type, depending on the end-effector position in the workspace. The mapping of the energy saving effects of the redundant manipulator is conducted by comparing the energy losses of the two types of manipulators.

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Keywords: Manipulators; Energy saving; Redundant actuation; Mapping**1. Introduction**

Saving energy is becoming increasingly important. Thus, it is desirable to improve the energy efficiency of industrial manipulators. An improvement in the energy efficiency of an industrial robot can be realized by reducing the electric power loss that occurs in electronic devices. This energy loss mainly consists of the coil loss of servo motors and conduction loss of servo drivers, and it is proportional to the square of the current flow [1-3]. Generally, the current flow is proportional to the torque. Therefore, the total electric power loss is proportional to the sum of the squares of the individual torques.

The electric power loss can be reduced by optimized path generation. Many researchers have studied the optimal paths for normal manipulators [4, 5]. These studies have shown that an optimized path can be derived by minimizing the normal torque value, which is the square root of the sum of squares of the individual torques, along the path. However, the method cannot reduce the energy for a given path, because the actuating torque vector is uniquely dependent on the path.

We presented a new energy saving method [6]. The electric power loss can also be reduced by using redundant actuation technology, which involves the use of more actuators than the

mechanism's degrees of freedom (DoF) [7-10]. This technology can reduce the sum of the squares of the torques by distributing the torques to the overall actuators including the redundant [11, 12]. This technology can reduce the electric power loss for a given posture and path. Therefore, it is more efficient and convenient than a path generation algorithm.

The reduction effects of redundant actuation are not equal throughout the workspace, but differ with the posture of the mechanism according to the end-effector position. Therefore, it is important to verify the energy saving effect in the main workspace of the target mechanism.

In this paper, the energy saving effect of reducing the electric power loss is visually mapped according to the end-effector position in the workspace. A 2-DoF test manipulator is selected as a simulation target. The energy saving effect can be visually checked using this process. This visual map can also be used for path planning to improve the energy saving effect.

This paper is organized as follows. The energy-saving theory of redundant actuation is presented in Section 2. A kinematics and dynamics analysis of the 2-DoF test manipulator is presented in Section 3. In Section 4, the simulation result for the energy saving effect map of redundant actuation is presented. Finally, the concluding remarks follow in Section 5.

2. Concept

The input energy of a robotic system is not only used as the output power of a motor, but is also dissipated as electric power loss in electronic devices. This power loss mainly occurs through the coil loss of servo motors and the conduction loss of servo drivers, and it can be calculated using equation (1).

$$P_{coil} = \sum_{i=1}^n R_i I_i^2, \quad P_{conduction} = \sum_{i=1}^n \mu_i I_i^2, \quad (1)$$

where R_i is the i -th resistance of the coil of the motor, μ_i is the i -th coefficient for the conduction loss, and I_i is the current of the i -th actuator.

The total electric power loss can be expressed as the sum of the two kinds of electric power loss, and it is proportional to the square of the current. Because the current is proportional to the actuating torque, the total electric power loss can be replaced by equation (2).

$$P_{loss} = P_{coil} + P_{conduction} = \sum_{i=1}^n \lambda_i I_i^2 = \sum_{i=1}^n \kappa_i \tau_i^2 \quad (2)$$

where λ_i and κ_i are the i -th coefficients of the models, and τ_i is the current of i -th actuator.

As shown in equation (2), the total electric power loss can be reduced by minimizing the sum of the squares of the torques. Redundant actuation can reduce this value by distributing the actuating torque to redundant actuators.

An example of the reduction of the sum of the squares of the torques using redundant actuation is shown in Fig. 1. Two kinds of manipulators are presented, which have the same postures, but different actuation mechanisms. Fig. 1(a) shows the normally actuated manipulator. The actuating torques of this manipulator are uniquely determined to be -250 Nm and 510 Nm, and the sum of the squares of these torques is calculated to be 322,600 Nm². However, the redundantly actuated manipulator, which is represented in Fig. 1(b), can optimally distribute the actuating torques, which minimizes the sum of their squares. In this case, the distributed actuating torques are 230 Nm, 40 Nm, and 220 Nm, and the sum of the squares of these torques is calculated to be 102,900 Nm².

In this way, the sum of the squares of the torques is reduced by 68% for the same operation, and this reduction induces a reduction in the electric power loss. The saving effect varies with the posture of the robot according to the position of the end-effector. This is because the null space of the torque vector is changed according to the posture of the robot.

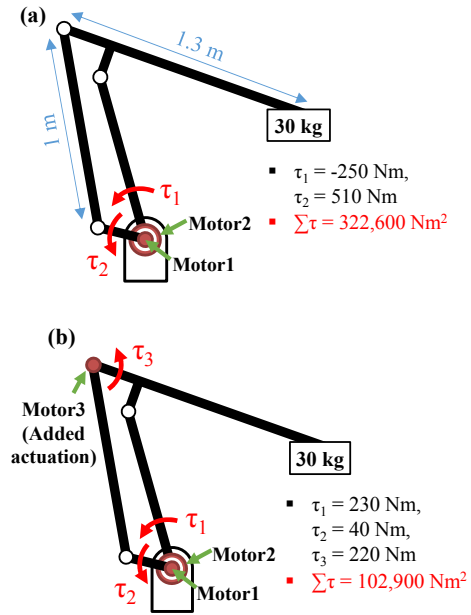


Fig. 1. Example of reduction in sum of squares of torques by redundant actuation: (a) normal actuation and (b) redundant actuation.

3. Model

3.1. Kinematic model

A parallel type 2-DoF manipulator is used to simulate the energy saving effect and derive the energy saving effect map of the redundant actuation. Fig. 2(a) shows a schematic of the 2-DoF test manipulator. The main link l_3 is connected by two chains, l_{11} and l_{12} , and l_{21} . Two actuators are installed at B_1 and B_2 for normal actuation. For the redundant actuation, an additional actuator is installed at B_3 , which is labeled J_2 in the normal actuation case. This manipulator is based on the main link mechanism of a commercial manipulator (IRB1410 by ABB). The detailed specifications of the test manipulator are listed in Table I.

The equations of motion for the proposed test manipulator can be derived from the constraint equation, which represents the geometrical constraint of the mechanism during its operation. The notations are shown in Fig. 2(b). The mechanism consists of two serial chains from the base to the center of the platform. Two chains are marked as blue and green, respectively. The ends of these two serial chains are coincident at one point. Assuming that the end coordinates of the i -th chain are $P_{ii}(x_{ii}, y_{ii})$, the kinematics of each chain is as shown:

$$\begin{aligned} x_{ii} &= l_{i1} \cos q_i + l_{i2} \cos(q_i + q_{i+2}) + x_{i0i} + x_{0i}, \\ y_{ii} &= l_{i1} \sin q_i + l_{i2} \sin(q_i + q_{i+2}) + y_{i0i} + y_{0i}, \\ \phi_1 &= q_1 + q_3 + q_5 = \theta, \quad \phi_2 = q_2 + q_4 = \theta + \pi/2, \end{aligned} \quad (3)$$

where l_{22} is 0, and $i = 1, 2$. x_{i01} , x_{i02} , y_{i01} , and y_{i02} are calculated using equation.

$$\begin{aligned} x_{i01} &= (l_{32} + l_{33}) \cos(q_1 + q_3 + q_5), y_{i01} = (l_{32} + l_{33}) \sin(q_1 + q_3 + q_5), \\ x_{i02} &= l_{31} \cos(q_2 + q_4) + l_{33} \cos(-\pi/2 + q_2 + q_4), \\ y_{i02} &= l_{31} \sin(q_2 + q_4) + l_{33} \sin(-\pi/2 + q_2 + q_4), \end{aligned} \quad (4)$$

These equations can be shown as three kinematic constraint equations:

$$g(q_{all}) = 0: \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix} = \begin{bmatrix} x_{i1} - x_{i2} \\ y_{i1} - y_{i2} \\ \phi_1 - \phi_2 + \pi/2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \quad (5)$$

where the whole joint vector $q_{all} = [q_1 \ q_2 \ q_3 \ q_4 \ q_5]^T$. The velocity relationship between the joint angles can be calculated by using the constraint Jacobian relationship [13]. This relationship can be obtained using the time derivative of the geometric constraint equation. The relationship between the velocities of the independent joint vector $\dot{q}_u$ and actuating joint vector $\dot{q}_r$ can be obtained by selecting the actuating joints from the independent joints $\dot{q}_u$ and the vector for the dependent joints with actuators $\dot{q}_r$. This relationship can be written as follows.

$$\dot{q}_r = \begin{bmatrix} \dot{q}_u \\ \dot{q}_r \end{bmatrix} = VU \begin{bmatrix} I_{2 \times 2} \\ \Phi \end{bmatrix} \dot{q}_u = \Gamma \dot{q}_u, \quad (6)$$

where U is a transfer matrix from the independent and dependent joint vectors to all of the joint vectors. V is a selection matrix for the actuating joints from all of the joint vectors. Φ is a Jacobian mapping from the independent joint vector to the actuating dependent joint vector. Γ is a Jacobian mapping from the independent joints to all of the actuating joints.

3.2. Dynamic model

A dynamic model of the 2-DoF normally actuated test manipulator can be derived by replacing the overall structure's dynamic model with the constraint Jacobian [11]. The substituted dynamic model of the normally actuated robot is shown as follows.

$$M(q)\ddot{q}_u + C(q, \dot{q})\dot{q}_u + N(q) = \tau_u \quad (7)$$

where τ_u represents the actuating torques of the normally actuated manipulator.

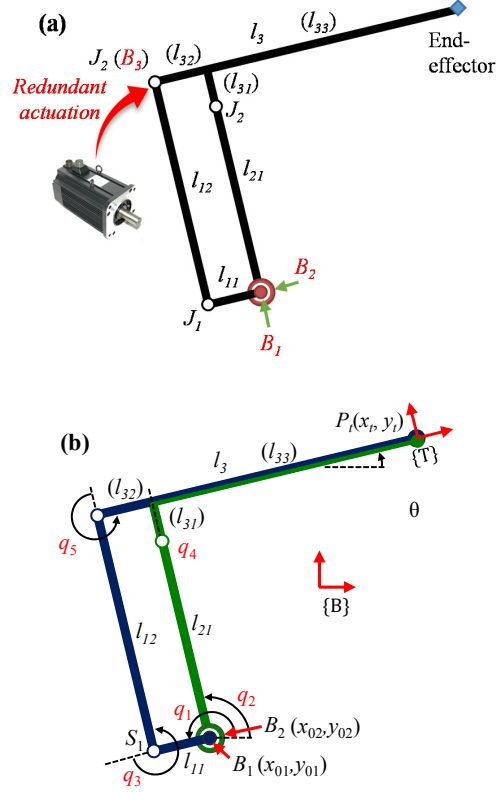


Fig. 2. Configuration of 2-DoF test manipulator: (a) schematic and (b) notation.

Table I. Specifications of 2-DoF test manipulator

Part	Length (mm)	Weight (kg)	Moment of Inertia (kgm ²)
l_{11}	230	3.7	0.07
l_{12}	960	3.7	1.21
l_{21}	800	16	2.61
l_3	1310	21	6.99

The number of active joints is larger than the number of independent joints in the case of the redundantly actuated manipulator. Therefore, the actuating torques of the redundantly actuated manipulator have non-homogenous solutions, and are constrained by equation (8).

$$\tau_u = \Gamma^T \tau_r, \quad (8)$$

where τ_r represents the actuating torques of the redundantly actuated manipulator. The dynamic model of a redundantly actuated manipulator can be derived by replacing the dynamics of the normally actuated manipulator with constraint equation (9). The new dynamic model is shown in the following.

$$M(q)\ddot{q}_u + C(q, \dot{q})\dot{q}_u + N(q) = \Gamma^T \tau_r, \quad (9)$$

4. Simulation result

The energy saving ratio attained by redundant actuation in the workspace is simulated to derive the energy saving effect map. The energy saving ratio η_{save} at one end-effector position is calculated using equation (10).

$$\eta_{save} = (P_{loss}^{general} - P_{loss}^{redundant}) / P_{loss}^{general} \quad (10)$$

where P_{loss}^{normal} and $P_{loss}^{redundant}$ are the electric power loss values of the normal and redundant actuations, respectively. The energy saving ratio is derived for the workspace according to the end-effector position.

P_{loss}^{normal} can be derived using the kinematic and dynamic model of the normally actuated manipulator. Based on the end-effector position in the workspace, P_{loss}^{normal} can be expressed as shown in Fig. 3(a).

$P_{loss}^{redundant}$ can be derived using the optimal distribution of the actuating torques, which is calculated using the kinematic and dynamic model of the redundantly actuated manipulator, to minimize the sum of the squares of the torques. Based on the end-effector position in the workspace, $P_{loss}^{redundant}$ can be expressed as shown in Fig. 3(b). The electric power loss has a high value near the singularity region.

The coefficients κ_i of the normal and redundant actuations represent the electric power loss models of the i -th actuator. Furthermore, these are assumed to be the same for the convenience of the calculation. The weight of the redundant actuator is assumed to be 8 kg when considering the required power. A light color is a high value, and a dark color is a low value. A checked region denotes an area nearby singularity.

By using these two kinds of simulation results, the energy saving effect of redundant actuation according to the end-effector position can be derived as shown in Fig. 4.

5. Conclusion

In this paper, the energy saving effect map of redundant actuation was derived, which represented the energy saving effect in the workspace. The electric power losses of the normal and redundant actuations were simulated, and the energy saving effect of the redundant actuation was calculated using the two kinds of simulation results. The energy saving effect map could be used to verify the energy saving effect of the target manipulator in the main workspace. Moreover, energy efficient path planning could be performed by using this efficient map.

The results showed that the area described by x positions ranging from 0.2 m to 1.3 m and y positions ranging from 0.2 m to 2 m had a high energy saving effect. However, the area described by x positions ranging from 1.2 m to 2 m and y positions ranging from -0.5 m to 0.3 m had a low energy saving effect. This was due to the variation in the distributing capacity according to the posture of the test manipulator. In the future, the regular distribution of the energy saving effect and movement of the area with a high energy saving effect will be considered for the optimal design of a linkage structure.

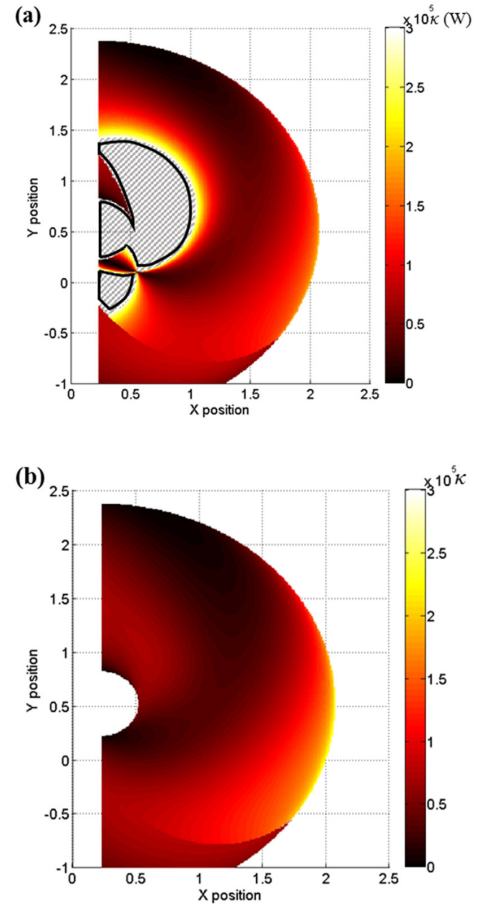


Fig. 3. Electric power loss of 2-DoF test manipulator: (a) normal actuation and (b) redundant actuation.

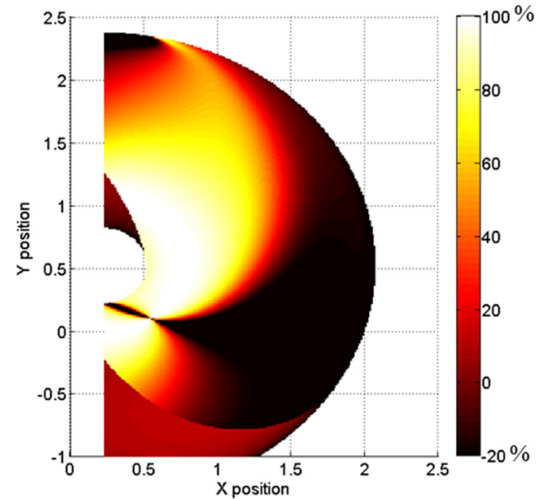


Fig. 4. Energy saving effect map representing energy saving ratio of redundant actuation.

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