2025 IEEE/SICE International Symposium on System Integration (SII)
January 21-24, 2025, Munich, Germany

Location Optimization of Manipulator to Minimize Energy Considering the Path Direction

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Abstract— **This study presents a novel Directional Energy Index (DEI) to optimize the energy efficiency of manipulators operating within constrained environments. The DEI evaluates the manipulator's energy consumption along a specified path, with the advantage of not requiring consideration of the system's dynamics, i.e., any time-related factors. Through simulations involving a planer two-link manipulator and the Yaskawa HC10, the DEI effectively identifies the optimal manipulator's location that minimizes energy usage. This index supports the development of energy-efficient robotic systems, aligning with resource conservation and carbon neutrality goals.**

I. INTRODUCTION

Industrial robots operate in most factories to address labor shortages. Conventional factories provide environments that are well-suited for robotic manipulators. As manipulators' prices have decreased and their implementation has become more accessible, the number of manipulators has increased, and not the factories but the manipulators have become well-suited to the factories. To integrate into a factory, the manipulator must fit into the determined space and specific tasks for a purpose. Therefore, optimizing the usage of the manipulator or the manipulator itself for the determined purpose is crucial.

This study proposed the manipulator's location optimization, maximizing manipulability when given a specific path. When considering the specific path, the optimization should utilize the manipulability ellipsoid instead of manipulability, as the latter lacks any direction components. When the manipulability ellipsoid has a large gap between the major and minor axes, even if the manipulability is large, the manipulator does not always move easily to the targeting direction of the specific path. This study proposed a Directional Manipulability Index (DMI) that considers the direction of the path to evaluate how easy it is for the manipulator to move in the target direction of the specific path. Using the DMI, this study optimized the manipulator's location to the easiest position to move along the specific path. However, the optimization considered only how easy it was to move, not considering how efficient it was. Thus, this paper discusses efficiency by focusing on energy consumption. For practical use, the discussion of energy consumption is not avoidable due to the global demands of energy-saving, resource-saving.

*This work was supported by JSPS KAKENHI Grant Number 23K03755.

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Many studies discuss how to find the trajectory with the minimum energy of the manipulator. There are two main categories of minimization of the manipulator's energy consumption: trajectory optimization and location optimization. A trajectory optimization searches for the optimal shape of the path, velocity, and acceleration given a specified starting point and a destination. Fung et al. optimized trajectory generation to minimize the energy of robots handling LCD glass [1]. They optimized points of interpolation function by Real-coded GA to minimize the energy. Also, Alam et al. searched by RRT* for minimum energy trajectory for the pick-and-place problem [2].

On the other hand, location optimization searches for the optimal layout of the path and the manipulator. Izui et al. proposed a cycle time minimization method to discuss the layout of multiple workpieces and destinations on the job for the manipulator [3]. Each layout is discussed as a minimum bounding rectangle and optimized using Multi-Objective GA to maximize the workspace's manipulability. Also, Gadaleta et al. proposed the location optimization of the manipulator considering the given trajectory to minimize energy consumption with the motor model [4]. The optimization evaluated the cycle time and energy consumption and demonstrated effectiveness for car assembly. As previously mentioned, the manipulator typically obtains the specific path. Also, the environment and the conditions are challenging to change. Therefore, the paper discusses the location optimization to minimize the energy consumption.

Many studies discussed evaluating energy consumption in trajectory optimization or location optimization. Akbari et al. approximated the energy consumption using the square of acceleration [5]. Also, some studies calculated energy consumption using the product of the manipulator's joint torque and angular velocity [6][7]. With the detailed model, which considers the manipulator dynamics and the motor-approximated circuit equation, some cases employed the more precise energy consumption calculation method [8][9]. Furthermore, some studies detailed a motor model as the calculation considering the copper loss and the iron loss [10][11]. Some used electromagnetic and mechanical models, considering copper loss and joint friction loss [12], and others even considered loss in the power-electronics system [13]. A more specific one discusses energy consumption from the potential energy transition of the manipulator's links in a pre-quantized space [14].

The latter mentioned have detailed and more accurate models, but their computational cost increases. Optimization calculates the evaluation of the objective function multiple times in an iteration. Therefore, the high computational cost of a single calculation is extremely disadvantageous. From this point of view, there is a tradeoff between the accuracy of the energy consumption calculation and the computational speed. A calculation for energy consumption that achieves high accuracy and low computational cost is desirable.

The assumptions of this study are below.

- For making the problem easier, i.e., the computational cost smaller, not the trajectory, but the path is taking account. Consequently, the time elements disappear from the model.
- Since the path and task are predefined, the manipulator is allowed a confined space. Consequently, the system cannot freely generalize the path.

The previous methods, however, are:

- Assuming the trajectory and calculating with physical quantities containing time elements such as velocity and current.
- Setting a boundary condition by the manipulator's workspace entirely or without any condition.

Therefore, this study must employ a different energy calculation method. To realize the method for the specified path in a confined space, we propose a novel index, the Directional Energy Index (DEI), to evaluate the manipulator's energy.

II. INDEX CONSIDERING PATH DIRECTION

To consider the general manipulator, let us assume that the Degrees of Freedom (DoF) of the manipulator are $m \in \mathbb{N}$ DoF for the end-effector and $n \in \mathbb{N}$ DoF for the joints of the manipulator. Here, $m \leqq n$ and n DoF can achieve m DoF for the end-effector. The relationship of them are follows:

$$ {}^{o}\dot{\boldsymbol{p}}_e = \boldsymbol{J}\dot{\boldsymbol{q}} \tag{1} $$

where ${}^{o}\dot{\boldsymbol{p}}_e \in \mathbb{R}^m$ is the velocity of the end-effector, $\boldsymbol{J} \in \mathbb{R}^{m\times n}$ is the Jacobian matrix, and $\boldsymbol{q} \in \mathbb{R}^n$ is the angular velocity. The Jacobian Matrix $\boldsymbol{J}$ can be interpreted as a transformation matrix from the joints to the end-effector.

A. DMI: Directional Manipulability Index

The manipulability ellipsoid was proposed to indicate the direction and extent of ease of operation at the end-effector [15]. It can be derived as follows:

$$ {}^{o}\dot{\boldsymbol{p}}_e{}^T(\boldsymbol{J}^+)^T\boldsymbol{J}^+\,{}^{o}\dot{\boldsymbol{p}}_e \leq 1 \cap {}^{o}\dot{\boldsymbol{p}}_e \in \mathrm{Range}(\boldsymbol{J}) \tag{2} $$

where $\boldsymbol{J}^+ \in \mathbb{R}^{n\times m}$ is the pseudo-inverse matrix of the Jacobian matrix, and $\mathrm{Range}()$ defines the range of possible values. Here, the manipulability ellipsoid represents the set of all velocities of the end-effector ${}^{o}\dot{\boldsymbol{p}}_e$ that can be achieved using angular velocities $|\dot{\boldsymbol{q}}| \leq 1$ for $\dot{\boldsymbol{q}} \in \mathbb{R}^n$.

Also, manipulability is an index of how easily the manipulator can move at an end-effector position. Manipulability can be calculated from Eq. (3) using the Jacobian matrix.

$$ w = \sqrt{\det \boldsymbol{J}\boldsymbol{J}^T} \tag{3} $$

From Eq. (1), the Jacobian matrix can be regarded as a transformation matrix from the joint space to the operational space. Since manipulability is defined by the determinant of the Jacobian matrix, it represents the expanding rate of the space from joint space to operational space. Many studies employ manipulability to indicate how easily the manipulator can move.

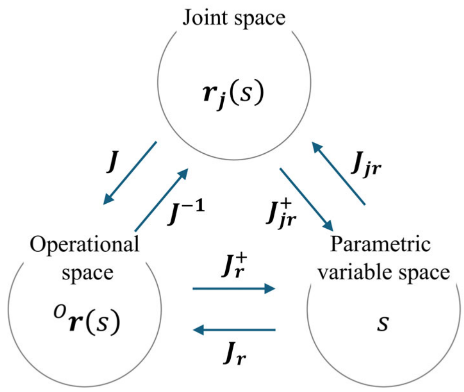


Fig. 1. Relationship between joint space, operational space and parametric variable space

However, manipulability is a scalar quantity proportional to the volume of the manipulability ellipsoid and cannot account for the manipulator's moving direction. Conversely, the manipulability ellipsoid has a direction and can consider directional terms. The major axes of the manipulability ellipsoid indicate the velocity vector with the largest magnitude. Therefore, by extracting the directional term from the Jacobian matrix used for the manipulability ellipsoid, it is possible to derive the velocity of the end-effector from the angular velocity while considering the direction of the path. This approach can thus indicate the ease of moving along the path direction.

Without consideration of the time term for simplify, the trajectory ${}^{o}\boldsymbol{p}_e(s(t))$ is considered as the path vector ${}^{o}\boldsymbol{r}(s) \in \mathbb{R}^m$ using the parametric variable $s(t) \in \mathbb{R}$. For the calculation of the variation in the path vector, the differential of ${}^{o}\boldsymbol{r}(s)$ with respect to s is derived as follows:

$$ \frac{d\,{}^{o}\boldsymbol{r}(s)}{ds} = \boldsymbol{J}_r \tag{4} $$

Eq. (5) can be obtained by transforming Eq. (4).

$$ d\,{}^{o}\boldsymbol{r}(s) = \boldsymbol{J}_r ds \tag{5} $$

$\boldsymbol{J}_r$ can be regarded as a Jacobian matrix between ${}^{o}\boldsymbol{r}(s)$ and s, and rewritten as Eq. (6).

$$ ds = \boldsymbol{J}_r^+ d\,{}^{o}\boldsymbol{r}(s) \tag{6} $$

Eq. (6) represents the parametric variable's rate with respect to the infinitesimal position displacement along the path.

Fig. 1 shows the relationship between each space. As the figure, $\boldsymbol{J}$ maps from the joint space to the operational space, and $\boldsymbol{J}_r^+$ maps from the operational space to the parametric variable space. Thus, the minimum variation of the parametric variable along the path due to the minimum angular displacement can be calculated with Eq. (7).

$$ ds = \boldsymbol{J}_r^+\boldsymbol{J}d\boldsymbol{q} \tag{7} $$

Using the displacement of the parametric variable, we proposed the Directional Matrix Index (DMI) $\hat{w}$ with Eq. (8) to evaluate manipulability along the moving direction.

$$\hat{w} = \sqrt{ds \cdot ds^T} = \sqrt{\boldsymbol{J}_r^+ \boldsymbol{J} \boldsymbol{J}^T \boldsymbol{J}_r^{+T}} \tag{8}$$

DMI can evaluate the manipulability in the parametric variable space, representing the length of the chord of the manipulability ellipsoid in the operational space.

B. DEI: Directional Energy Index

Using a similar theoretical approach to DMI, the Directional Energy Index (DEI) can be considered. The link coordinate system Σ_i is defined on each i^{th} joint ($i \in \mathbb{N}, i \leqq n$). The link coordinate system Σ_{gi} is defined on the center of gravity of each i^{th} link. ${}^o\boldsymbol{p}_{gi} \in \mathbb{R}^6$ and ${}^o\boldsymbol{p}_e \in \mathbb{R}^6$ denote the position/orientation of the i^{th} link coordinate system and the operational coordinate system defined on the end effector, respectively.

The coordinates of the center of gravity of each i^{th} link can be calculated using forward kinematics, and the relationship between velocity and angular velocity can be obtained by differentiating the kinematics as follows:

$${}^o\dot{\boldsymbol{p}}_{gi} = \boldsymbol{J}_i \dot{\boldsymbol{q}} \tag{9}$$

The Jacobian matrix $\boldsymbol{J}_i \in \mathbb{R}^{6\times m}$ can be regarded as a transformation matrix from the joint space to the operational space on each link.

Herein, we introduce the parametric variable $s(t) \in \mathbb{R}$, which changes with time, to separate the trajectory into path and time components. When the trajectory ${}^o\boldsymbol{p}_e(s(t))$ is given at the end-effector, the joint angle $\boldsymbol{q}_e(s(t))$ can be calculated from inverse kinematics. The trajectory in joint space $\boldsymbol{q}_e(s(t))$ can be separated using $s(t)$ as shown in Eq. (10).

$$\dot{\boldsymbol{q}}_e(s(t)) = \frac{d}{ds}\boldsymbol{q}(s)\frac{ds}{dt} \tag{10}$$

where $\boldsymbol{q}(s)$ is the path in the joint space. From Eq. (10), the differential of the path in the joint space with respect to the parametric variable is regarded as a variation of the path in the joint space with the parametric variable. Thus, Eq. (10) is rewritten as Eq. (11) using the Jacobian matrix $\boldsymbol{J}_{jr}$.

$$\dot{\boldsymbol{q}}_e(s(t)) = \boldsymbol{J}_{jr}\dot{s} \tag{11}$$

From the above equation, the Jacobian matrix $\boldsymbol{J}_{jr}$ can be interpreted as a transformation matrix from the parametric variable space to the joint space.

When the inertia matrix of the end-effector is $\boldsymbol{M}_e \in \mathbb{R}^{m\times m}$ in the operational space, the kinetic energy $E_e \in \mathbb{R}$ associated with the end-effector velocity ${}^o\dot{\boldsymbol{p}}_e$ can be calculated as follows:

$$E_e = \frac{1}{2}\,{}^o\dot{\boldsymbol{p}}_e{}^T \boldsymbol{M}_e\,{}^o\dot{\boldsymbol{p}}_e \tag{12}$$

By substituting Eq. (1), the following equation is derived.

$$E_e = \frac{1}{2}\dot{\boldsymbol{q}}^T \boldsymbol{J}^T \boldsymbol{M}_e \boldsymbol{J}\dot{\boldsymbol{q}} \tag{13}$$

To consider the kinetic energy at each i^{th} link $E_{li} \in \mathbb{R}$, the kinetic energy of links $E_l \in \mathbb{R}$ can be described as the sum of E_{li}.

$$E_l = \sum_{i=1}^{n} E_{li} = \sum_{i=1}^{n} \frac{1}{2}\,{}^o\dot{\boldsymbol{p}}_{gi}{}^T \boldsymbol{M}_i\,{}^o\dot{\boldsymbol{p}}_{gi} \tag{14}$$

From Eq. (1), (9), the operational space can be transformed to joint space using $\boldsymbol{J}$ on end-effector, and $\boldsymbol{J}_i$ on i^{th} link, respectively.

$$E_l = \sum_{i=1}^{n} \frac{1}{2}\dot{\boldsymbol{q}}^T \boldsymbol{J}_i{}^T \boldsymbol{M}_i \boldsymbol{J}_i \dot{\boldsymbol{q}} \tag{15}$$

By combining the Eq. (13) and (15), the total kinetic energy can be derived as follows:

$$E = \frac{1}{2}\dot{\boldsymbol{q}}^T \boldsymbol{J}^T \boldsymbol{M}_e \boldsymbol{J}\dot{\boldsymbol{q}} + \sum_{i=1}^{n} \frac{1}{2}\dot{\boldsymbol{q}}^T \boldsymbol{J}_i{}^T \boldsymbol{M}_i \boldsymbol{J}_i \dot{\boldsymbol{q}} \tag{16}$$

Furthermore, by considering e as the $(n+1)^{\text{th}}$ joint and letting $i = 1, \cdots, n, e$, it can be expressed as follows:

$$E = \sum_{i=1}^{e} \frac{1}{2}\dot{\boldsymbol{q}}^T \boldsymbol{J}_i{}^T \boldsymbol{M}_i \boldsymbol{J}_i \dot{\boldsymbol{q}} \tag{17}$$

Also, from Eq. (11), the joint space transforms to the parametric variable space with $\boldsymbol{J}_{jr}$.

$$E = \frac{1}{2}\dot{\boldsymbol{s}}^T \sum_{i=1}^{e} \left\{ \boldsymbol{J}_{jr}{}^T \boldsymbol{J}_i{}^T \boldsymbol{M}_i \boldsymbol{J}_i \boldsymbol{J}_{jr} \right\} \dot{\boldsymbol{s}} \tag{18}$$

From the above equation, the kinetic energy of the manipulator can be calculated in the parametric variable space.

Based on the above discussion of kinetic energy, we propose a new index $\hat{w}_e$ as DEI to evaluate the energy in Eq. (19).

$$\hat{w}_e = \sum_{i=1}^{e} \boldsymbol{J}_{jr}{}^T \boldsymbol{J}_i{}^T \boldsymbol{M}_i \boldsymbol{J}_i \boldsymbol{J}_{jr} \tag{19}$$

DEI $\hat{w}_e$ represents a scalar value of kinetic energy when the magnitude of $\dot{\boldsymbol{s}}$ is 1. Additionally, DEI indicates the displacement of energy in the parametric variable space. DEI in the optimization problem can be used to minimize energy consumption and search for optimal locations.

III. VERIFICATION THROUGH OPTIMIZATION

A. Problem setup

The two-link manipulator is employed to validate the proposed index. Here, the degree of freedom in the operational space m is 2 DoF, and the degree of freedom in the joint space n is also 2 DoF. Two paths are considered: a straight line and a circle. Each path is represented by a series of discrete points, with the position vector of each point referenced in the global coordinate system. The manipulator's location, precisely its base's position, is determined through optimization.

The objective function in the optimization process utilizes four indices: the manipulability index, the DMI, the proposed DEI, and energy consumption E. For comparison, the other three indices were also calculated during the optimization

TABLE I

OPTIMIZATION RESULTS FOR EACH INDEX ON THE STRAIGHT-LINE PATH

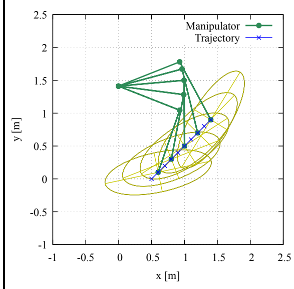
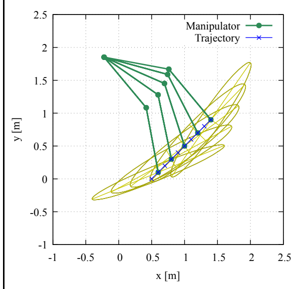
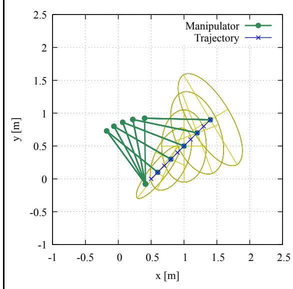
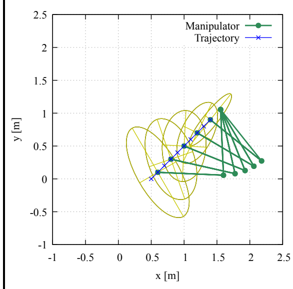
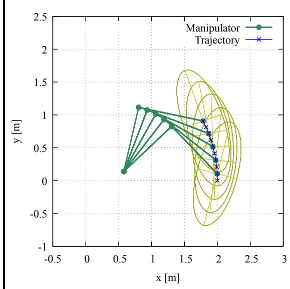
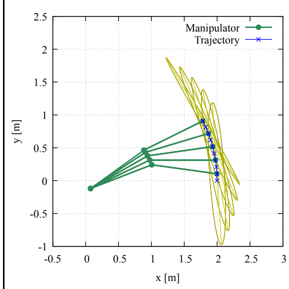
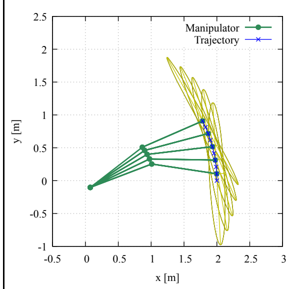
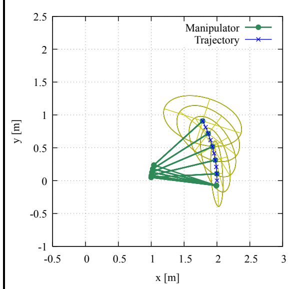
Index	Manipulability	DMI	DEI	Energy
Posture and Manipulability Ellipsoide				
Manipulability	**0.995**	0.242	0.156	0.229
DMI	1.517	**2.028**	0.875	0.861
DEI	15.164	19.982	**11.908**	12.18
Energy consumption [Nm]	1.831	2.339	1.272	**1.267**

TABLE II

OPTIMIZATION RESULTS FOR EACH INDEX ON THE CIRCULAR PATH

Index	Manipulability	DMI	DEI	Energy
Posture and Manipulability Ellipsoide				
Manipulability	**1.000**	0.009	0.118	0.076
DMI	1.569	**2.196**	2.191	0.998
DEI	8.228	5.661	**5.601**	7.860
Energy consumption [Nm]	0.879	0.665	0.610	**0.609**

based on each index. All Jacobian matrices – including the Jacobian matrix from the operational space to the joint space at the endpoint $\boldsymbol{J}$, for each link $\boldsymbol{J}_i$, from the parametric variable space to the operational space $\boldsymbol{J}_r$, – and from the parametric variable space to the joint space $\boldsymbol{J}_{jr}$, are computed numerically rather than using analytical solutions. As an example, the Jacobian matrix $\boldsymbol{J}_{jr}$ is calculated as follows:

$$\boldsymbol{J}_{jr} = \frac{\boldsymbol{f}_{ik}\left(\boldsymbol{f}_p(s+\epsilon)\right) - \boldsymbol{f}_{ik}\left(\boldsymbol{f}_p(s-\epsilon)\right)}{2\epsilon} \tag{20}$$

where $\epsilon \in \mathbb{R}$ is an arbitrary positive infinitesimal displacement, typically ranging from 10^{-5} to 10^{-7}, $\boldsymbol{f}_p(s) \in \mathbb{R}^m$ is a function of the path position determined by the parametric variable s, and $\boldsymbol{f}_{ik}({}^o\boldsymbol{p}_e) \in \mathbb{R}^n$ is a function representing the inverse kinematics of the manipulator.

Additionally, the manipulator !Senergy consumption E is calculated and evaluated using Eq. (21):

$$E = \int \sum_{i=1}^{2} |\tau_i \dot{q}_i| \, dt \tag{21}$$

Here, the manipulator's regenerative energy is not considered, and both acceleration and deceleration are assumed to be driven by the motor's active torque. Thus, it is assumed that all energy during deceleration is dissipated as heat. Furthermore, when evaluating energy consumption, the end-effector position along each path is determined based on fifth-order polynomial interpolation.

B. Optimization problem

The optimization problem is described as follows:

$$\begin{aligned} \underset{\boldsymbol{x}}{\text{minimize}} \quad & f_{obj}(\boldsymbol{x}) \\ \text{subject to} \quad & \boldsymbol{x} \in [\boldsymbol{x}_{\min}, \boldsymbol{x}_{\max}] \end{aligned} \tag{22}$$

where $f_{obj}(\boldsymbol{x}) \in \mathbb{R}$ is the objective function, $\boldsymbol{x} = [x, y] \in \mathbb{R}^2$ is the design point, i.e., the location of the manipulator, and $\boldsymbol{x}_{\min} \in \mathbb{R}^2, \boldsymbol{x}_{\max} \in \mathbb{R}^2$ are the lower and upper bounds of the design point, respectively. The bounds are adapted flexibly to the problem.

The objective function is designed using each index. For example, the objective function for the DEI is designed as follows:

$$f_{obj}(\boldsymbol{x}) = \hat{w}_e \tag{23}$$

By replacing the DEI $\hat{w}_e$ with the manipulability $1/w$, the DMI $1/\hat{w}$, or energy consumption E, the objective function for each index is constructed. Here, larger values are optimal for manipulability and DMI, but smaller values are optimal for DEI and energy consumption.

C. Optimization method

This study employs the DIRECT method: DIvided RECTangle method [16] for optimization. The DIRECT method is an optimization technique that searches for the optimal solution by repeatedly dividing the search region with the smallest objective function value and comparing the objective function values at representative points in search regions of the same size. This method can find the global minimum value even if the objective function exhibits multimodality. Additionally, the method can be applied to multi-dimensional problems.

D. Optimization conditions

This paper considers a manipulator with an upper arm and forearm measuring 1 m long. The design values, specifically the x and y coordinates of the manipulator's base, are constrained within the range of [-6, 6]. The iteration limit for the DIRECT method is set to a maximum of 300 iterations. This study employs two target paths: straight-line and circular paths. The straight-line path's starting position is [0.5, 0.0], and the destination is [1.5, 1.0]. The circular path has the center located at [0.0, 0.0] with a radius of 2 m. The arc of the circular path begins at an angle of 0 rad and ends at $\pi/6$ rad. Indices that do not require time elements, such as the DMI and the DEI, are calculated at ten evenly distributed points along each path. Additionally, energy consumption is evaluated along the trajectory using fifth-order interpolation over a travel time of 5 s.

E. Optimization result

Tables I and II present the optimization results for the manipulator's optimal location and the values for each index and energy consumption. Each column displays the optimization results based on the index listed in the top row. The graphs depict the manipulator's postures at various points along its path, with green lines and circular dots representing the postures, while blue lines and cross points indicate the path itself. Dark yellow ellipses illustrate the manipulability ellipsoids corresponding to each posture of the manipulator. The lower rows of the tables show the average values for each index obtained during the optimization process. Note that the values in bold font are designated for optimization, while the other three are for comparison.

As shown in Table I, the results of the optimizations using manipulability and the DMI indicate that the major axis of the manipulability ellipsoid is sufficiently long along the target path. The longer major axis along the path means that the manipulator converges at a position where it can move easily along the target path. Conversely, when the optimization uses the DEI and energy consumption as the optimization index, the minor axis of the manipulability ellipsoid tends to align with the direction of the target path. In these configurations, the manipulator can exert a greater force on the object attached to the end effector, which allows for more efficient movement of the object. Notably, optimizations that utilize the DEI and energy consumption as criteria demonstrate significantly lower energy consumption than the other optimization methods, with energy consumption values achieving an accuracy of 10^{-2}. This indicates that using the DEI to assess energy consumption is adequate, even without direct calculations of energy consumption itself. Typically, evaluating energy consumption involves complex calculations related to the trajectory dynamics, including time elements. In contrast, calculating the DEI relies solely on kinematics. Therefore, the DEI proves to be more advantageous than methods that compute energy consumption, as it offers lower computational costs while maintaining sufficient accuracy.

In optimizing the circular trajectory, as shown in Table II, the location is optimized to utilize the links' swinging motion when considering manipulability and the DMI, which considers maneuverability.Specifically, the DMI optimization results in a position close to a singular point, utilizing the increase in the Jacobian matrix's magnitude. On the other hand, the energy minimization result optimizes the location along the trajectory extension to minimize joint movements. However, the manipulability in this case becomes extremely small. In contrast, the DEI optimization result considers the directional component of the trajectory, utilizing the swinging motion while achieving a consumption energy level almost equivalent to energy minimization. This demonstrates that DEI optimization achieves a position where energy consumption is minimized while considering the direction of motion.

IV. SIMULATION VERIFICATION

A simulation assuming a manipulator was performed to verify the feasible utilization of the proposed index. Using the physics engine MuJoCo 3.2.3, a simulation model of the Yaskawa HC10 manipulator was developed. The model is based on CAD data provided by Yaskawa Electric Corp. The inertia of each link is estimated based on the total weight and the shape or volume of the CAD model. The limits of angular displacements comply with the specifications of the actual HC10.

The target paths are the straight path that reciprocates a 0.3 m line for two cycles, and the test path for a manipulator specified by ISO 9283 [17]. Using the same problem and method as the previous section, the optimization algorithm optimizes only the three-dimensional location $\boldsymbol{x} \in \mathbb{R}^3$, not the orientations. The simulation evaluates energy consumption at the optimized location. The traveling time on every side is 1 s. The target posture of the end-effector is fixed to ensure that it is oriented vertically. The ranges of the design values are defined as $x, y \in [0, 6]$, and $z \in [-3, 0]$. The maximum number of iterations for the DIRECT method is set to 300.

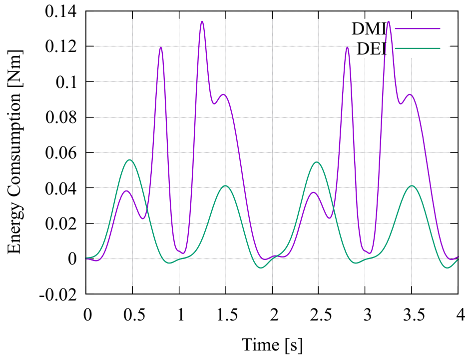


Fig. 2. Power consumption during the straight movement on each optimum location based on DMI and DEI

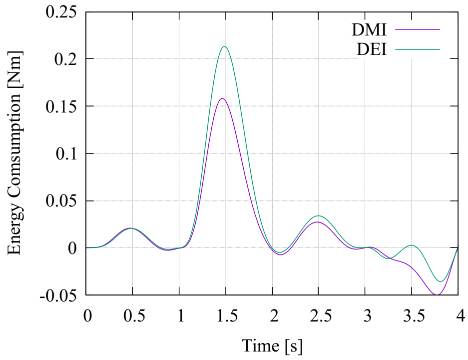


Fig. 3. Power consumption during the cube movement on each optimum location based on DMI and DEI

TABLE III

OPTIMIZED LOCATION AND POWER CONSUMPTION AT EACH PATH

Path	Index	Optimum Location of Manipulator [m]	Total Power [W]
Cube	DMI	[1.037, 0.100, -0.628]	64.92
Cube	DEI	[0.964, 0.049, -0.029]	106.24
Straight	DMI	[0.103, 0.282, -1.333]	173.41
Straight	DEI	[1.037, 0.222, -0.000]	69.92

Fig. 2 and Fig. 3 illustrate the time variation of the power consumption of all joints based on DMI and DEI optimizations on the straight line and the test path, respectively. Table III presents the optimized locations along with the total power consumption. According to the evaluations conducted in the previous section, the DEI optimization is expected to identify a more energy-efficient location than the DMI optimization. However, as noted in the results of this section, depending on the condition, the energy consumption of the DEI optimization exceeds that of the DMI optimization. In feasible cases, the manipulator faces constraints not only on the outer boundaries of the workspace but also towards its center. Consequently, the optimization does not converge to the true optimum value but instead to the nearest feasible point within the solution space.

V. CONCLUSIONS

This study proposed the DEI: Directional Energy Index, as a novel method for evaluating the energy efficiency of manipulators operating in constrained environments. The DEI offers the advantage of evaluating energy consumption along a specified path without considering complex dynamics. Simulations using a two-link manipulator and the Yaskawa HC10 demonstrated that the DEI effectively identifies the optimal manipulator's locations that minimize energy consumption. Future work will focus on refining the DEI for broader applications and integrating it with other optimization techniques to enhance its effectiveness in various robotic systems.

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