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Design methodology for workspace adjustment of industrial robot arms using a long end-effector: implementation in a dishwashing robot system

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Abstract

System integrators (SIers) design and build robotic systems by integrating robotic arms with peripheral devices to perform tasks within specific operational environments. In this context, the reachable workspace of a robot arm is a fundamental constraint in the system design. To ensure a sufficiently large workspace, integrators often resort to large-scale robot arms or multiarm configurations, even when handling lightweight objects. However, these choices inevitably increase the system costs and impose stricter installation constraints. To avoid such over-specification, this study utilizes an existing small-scale robot arm and introduces a long end-effector (LEE) as a design variable for the workspace adjustment. We propose a system-level design methodology that extends the effective workspace through the geometric configuration of the end-effector (EE) rather than by increasing the size or complexity of the arm itself. First, we analyzed the robot arm specifications from major manufacturers to systematically summarize the constraints regarding reachable workspaces and installation conditions. Next, based on a kinematic model, we present a method for determining the link length and mounting angle to satisfy the task workspace requirements. To validate the effectiveness of this approach, we developed a prototype system for a dishwashing task in a restaurant's kitchen. We demonstrated that a small robot arm equipped with an LEE can successfully execute the required motion sequences. The key contribution of this study is the provision of a system-integration-oriented design guideline that satisfies workspace requirements without relying on larger robot arms or increased degrees of freedom.

Keywords System integration · Design methodology · Long end-effector · Workspace adjustment · Industrial robot

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1 Introduction

Industrial robot arms excel in controllability, durability, and versatility, making them a great success in factory automation [1]. Various types of robot arms are available on the market, including orthogonal, selective compliance assembly, and vertical articulated types, each suitable for different tasks. These robot arms are categorized based on the payload and maximum reach radius. A system integrator (SIer) selects a model that is suitable for a specific task space and target object. Similarly, an appropriate end-effector (EE) is selected according to the target object. By combining these elements, SIers can design efficient systems that perform various tasks effectively.

However, with the diversification of task environments, a system design that differs from the conventional standard form of factory automation is required [2–6]. In such cases, it is necessary to consider various factors, including the installation space required for the robot arm [7], method of robot arm installation [8], initial cost of implementation of the robot system [9], and safety [10]. For example, in the restaurant kitchen dishwashing task, which is the focus of this study, the target objects (dishes) may be relatively lightweight, but the task space is large. Ideally, customizing the robot arm's degree of freedom (DoF), link length, structure, and other aspects is desirable. However, the cost of designing and producing such customized robot arms is often beyond the means of many users. Therefore, multiple robot arms are used for conventional dishwashing tasks in restaurants to satisfy large task spaces [11–16]. When selecting commercially available industrial robot arms and EEs, each element must demonstrate sufficient performance. This leads to the over-specification of the overall system, resulting in high cost and complexity.

One of the reasons for overspecification is the relationship between the maximum reach radius and payload of the existing robot arm series. To increase the reach of the robot arm, as in the task described above, the robot arm must be selected based on the maximum reach radius. Generally, the payload tends to increase as the maximum reach radius increases. Consequently, when the target object is lightweight, the robot arm itself becomes unnecessarily large and heavy. In such cases, selecting solely based on the maximum reach radius leads to excessive specifications for other elements.

In this study, we propose a system that combines a compact 6 DoF robot arm with a long end-effector (LEE) to address the issue of size increase that occurs when selecting a robot arm based on the motion range conditions. The LEE has a gripper at the end of a long link, and the reachable position can be easily adjusted by

changing the link lengths. Furthermore, because it lacks active joints other than the gripper, it can be manufactured with a relatively low weight and cost. However, when the LEE is mounted at the end of a robot arm, the following problems are expected.

- (1) Reduced stiffness of the EE The payload of a small robot arm is relatively small, thus the weight of the long link should be reduced. If the gripper weight is too large, there is a concern that the accuracy may decrease and vibration problems may occur.
- (2) Posture constraints of the EE Since the LEE does not have active joints for weight reduction, there is no DoF around the gripper to control the posture. Even when the position range of a typical 6 DoF robot arm is expanded, the postural range could be relatively limited.

These problems are highly dependent on the target tasks. In this study, we focus on a typical pick & place task and present a system design method for using the LEE. An example of a system based on the proposed design method is the automated dishwashing system. The contributions of this study are as follows:

- (1) We characterized the use of large-scale robot arms or excessive degrees of freedom to address workspace limitations as a form of over-specification, which we explicitly sought to avoid. Instead, we propose a system-level design methodology that meets task-specific workspace requirements by introducing the LEE as a design variable while utilizing an existing small-scale robot arm.
- (2) To validate the proposed design methodology, we developed a prototype system for commercial dishwashing. The design process considers the link length, mass, and configuration of the LEE as key variables. While the robot arm is selected based on evaluations of the joint torque limits, structural deflection, and vibration characteristics stemming from the LEE, the detailed parameters of the LEE is determined via kinematic analysis of the required workspace.

The remainder of this paper is organized as follows: Section 2 describes the design method, including an investigation of existing robot arms. Section 3 presents the design preparation required to implement the proposed method in the target environment. Section 4 presents an analysis of the motion range of the LEE using the proposed design method. The development of a dishwashing system using LEEs is demonstrated in Section 5. Finally, Section 6 concludes the paper and discusses the future work.

2 Design method

2.1 Design principle

In conventional factory system design, the surrounding environment can be configured with a certain degree of freedom, allowing many of the conditions required for the target task to be defined clearly at an early stage. Consequently, the workspace can be optimized according to the range of motion and installation layout of the robot arm [17]. In contrast, in emerging fields such as food processing and small-scale production, where experience with robot integration is limited, various constraints, such as compatibility with existing equipment and operator skill levels, make it difficult to configure the environment freely. Under such circumstances, design requirements tend to be diverse and uncertain, making the application of advanced optimization methods impractical from the initial stage. Moreover, the implementation of optimization-based approaches often requires specialized knowledge and computational resources, resulting in high costs that can be burdensome, particularly for small- and medium-sized enterprises. Therefore, in the early stages of system design, practical design methods that incorporate on-site constraints and empirical knowledge are required. In such situations, heuristic design guidelines provide an effective means for rapidly establishing a realistic initial design [18].

2.2 Investigation of existing robot arms

Guided by the proposed design principle, we identified the technical limitations and challenges inherent in existing robot arms. To this end, we conducted a comprehensive survey of robot arm specifications based on publicly available catalogs from ten major manufacturers, current as of September 2023: ABB Ltd. [19], DENSO WAVE INCORPORATED [20], Seiko Epson Corp. [21], FANUC CORPORATION [22], Kawasaki Heavy Industries, Ltd. [23], KUKA Aktiengesellschaft [24], Mitsubishi Electric

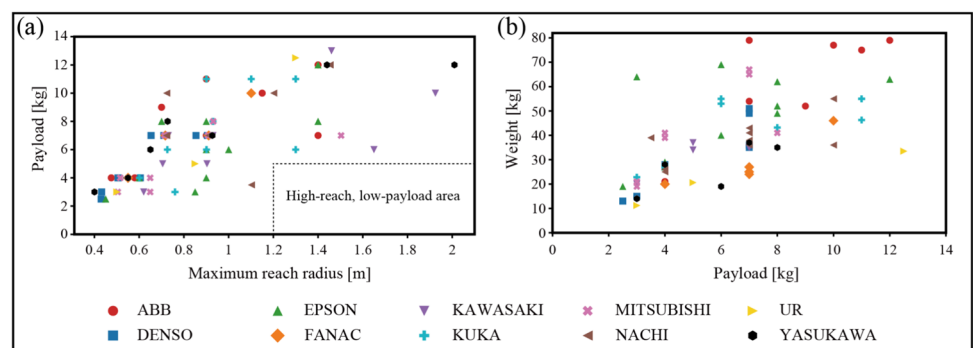
Corporation [25], NACHI-FUJIKOSHI CORP. [26], Universal Robots [27], and YASKAWA ELECTRIC CORPORATION [28]. From these, we arranged the relationship between the payload and the maximum reach radius, as shown in Fig. 1(a) and between the payload and the weight of the robot arm, as shown in Fig. 1(b). Existing robot arms are limited to vertically articulated 6 DoF robot arms with a payload of 15.000 kg or less, which are often used for general pick & place tasks. As shown in Fig. 1(a), none of the robot arms from the investigated manufacturers have a payload of 4.000 or 5.000 kg and a maximum reach exceeding 1.200 m. If the reachable position of the EE was 1.2 m or more, a larger robot arm with a payload of 6.000 kg or more had to be installed. A robot arm with a payload of 6.000 kg corresponds to an average self-weight of 47.000 kg, as shown in Fig. 1(b). A robot arm with a payload of 4.000 kg has an average self-weight of approximately 27.000 kg, which offers advantages in terms of ease of transport and cost. It can be seen that, in general, when the maximum reach radius is increased, the payload and the weight of the robot arm also increase excessively. Therefore, we addressed this problem by installing the LEE.

2.3 Design procedure

In this study, considering the design principles and problems with existing robot arms, we propose the following procedure for designing the range of motion of a robot system using the LEE to suit the task environment by utilizing the knowledge from general pick & place tasks.

- (1) **Clarifying the task environment** The overall size of the task environment is checked. Then, the approximate location of the robot arm is determined, along with the task space most frequently used for performing pick & place tasks. The task space is expressed in a Cartesian coordinate system, where the robot arm is at the center of the coordinates. Next, a list of the types of objects is created, and basic parameters, such as the weight and shape of each object, are clarified.

Fig. 1 Survey of existing industrial robot arms: (a) shows the relationship between the payload and the maximum reach radius, and (b) shows the relationship between the weight and payload



- (2) **Clarify the handling conditions** From the object parameters, the user considers the appropriate shape for the gripper. Because increasing the weight of the LEE is undesirable from the standpoint of payload and allowable torque, a gripper that is as lightweight as possible should be used. Then, based on the shape of the object to be grasped and the shape of the gripper, the range of constraints on the EE posture during grasping is expressed in terms of the roll, pitch, and yaw ranges.
- (3) **Selection of the existing robot arm** The payload capacity of the robot arm is determined by assuming the mass of the object to be grasped, the mass of the gripper, and the approximate mass of the long link. Next, the robot arm with the smallest payload capacity that satisfies the conditions from the robot arm series shown in Fig. 1(a). However, increasing the length and weight of the LEE may result in exceeding allowable joint torque limits, degrading EE positioning accuracy due to structural deflection, and deteriorating vibration performance—specifically regarding the first natural frequency. Consequently, it is essential to evaluate these effects a priori using simplified models.
- (4) **Selection of the LEE design parameters** Select the design parameters of the LEE to be attached to the robot arm. The main design parameters are expected to be the long link length, installation angles between the gripper and long link, and installation angles between the flange and long link. However, there are many parameters to be selected. In such cases, we assume a typical robot arm motion posture and constrain the parameters based on the knowledge gained by Slers and other organizations in general pick & place motion.
- (5) **Analysis of the motion range** The user utilizes both the forward and inverse kinematics [29, 30] of the robot arm to explore combinations of LEE parameters that enable the EE to reach specified positions and postures within the workspace. For each candidate set of LEE parameters, the existence of feasible joint angle solutions is examined to verify whether the desired task-space position and posture satisfied the conditions defined in (1) and (2). Through this analysis, the feasible range of LEE parameter combinations that allow the robot arm to achieve the specified position and posture within the workspace is identified. Any combination within this feasible range can be selected based on the system requirements. During actual system deployment, the identified feasible workspaces and corresponding recommended parameter ranges are presented to the user as selectable options.

In procedure (5), we also considered the use of optimization-based tools [31]. Optimization tools can automatically

determine the LEE parameters that satisfy specified workspace conditions by defining an appropriate cost function. Nevertheless, the use of such tools requires advanced expertise and extensive parameter tuning, leading to high implementation and training costs. This makes their adoption particularly burdensome for small- and medium-sized enterprises. Therefore, in this study, we adopted a forward and inverse kinematics-based numerical analysis approach, considering the balance between technical expertise and computational load. The following section describes the application of this design method using a dishwashing system as an example.

3 Dishwashing system design preparation

3.1 Clarifying the task environment

The task environment in this study was constructed on the plane shown in Fig. 2. Assuming that the installation position of the robot arm is the origin O , it is composed of a circular area with a diameter of approximately 2.400 m. In this task environment, the task spaces in which the robot arm performs the Pick & Place task are set as $U_1 \sim U_4$, and the robot arm handles the dishes and racks. Each task space is arranged symmetrically around the coordinate origin O and has the same size in each direction along the x and y axes. In addition, the robot arm has rotational symmetry about the first axis near the base; thus, we can predict the behavior of other task spaces $U_2 \sim U_4$ by simply analyzing one task space, U_1 . Task space U_1 is defined relative to the

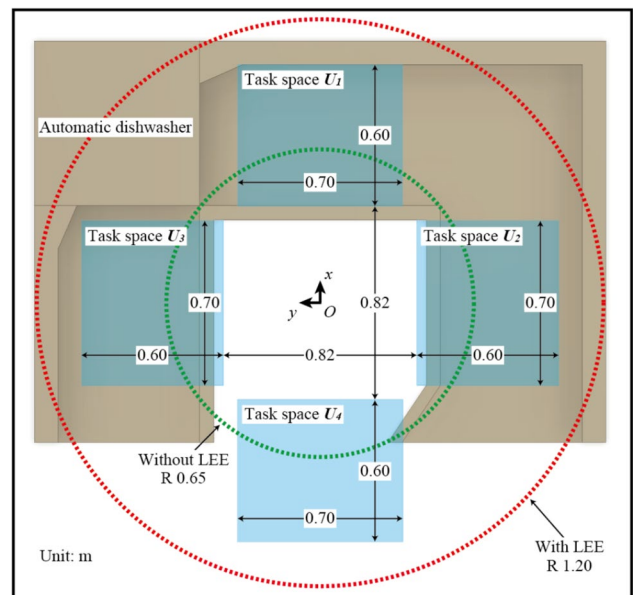


Fig. 2 Top view of the task environment for dishwashing tasks

coordinate origin O . The height direction z is set to 0.300 m, considering the height of the dishes when returning to the stacked state.

$$U_1 = \begin{cases} 0.410 \leq x \leq 1.010 \text{ m} \\ -0.350 \leq y \leq 0.350 \text{ m} \\ 0.000 \leq z \leq 0.300 \text{ m} \end{cases} \quad (1)$$

If it is difficult to shorten the analysis of task spaces by utilizing the characteristics of the robot arm as described above, it is necessary to describe and confirm all of $U_1 \sim U_4$. The target objects in this task are the dishes and rack, as shown in Fig. 3(a). The detailed parameters of each object are listed in Table 1.

3.2 Clarify handling conditions

In general, the constraints on the EE posture depend heavily on the task at hand, gripper shape, and object shape. Here, we limit ourselves to the Pick & Place task and assume an open-close gripper with an opening and closing range of approximately 10 cm. In this case, as shown in Fig. 3(b), there is a tolerance in each direction (roll, pitch, yaw) of the EE posture when grasping dishes. Therefore, based on the case where the EE posture is vertically downward, the EE posture constraint N_1 for workspace U_1 can be defined as follows:

$$N_1 = \begin{cases} 135.000^\circ \leq |\text{Roll}| \leq 180.000^\circ \\ 0.000^\circ \leq |\text{Pitch}| \leq 15.000^\circ \\ 170.000^\circ \leq |\text{Yaw}| \leq 180.000^\circ \end{cases} \quad (2)$$

3.3 Selection of existing robot arm

For the vibration problem discussed in Section 1, we assume a pneumatically driven open-close gripper made of a polymer material [16]. We can reduce the gripper weight, thereby bringing the total weight, including that of the long link, to approximately 1.500 kg. Therefore, a robot arm with a payload of approximately 4.000 kg is considered appropriate, along with the weight of the object to be grasped, as mentioned above. Among the robot arms with a payload of 4.000 kg, as shown in Fig. 1(a), RV-4FRL-D (Mitsubishi Electric Corporation, Japan), which has a maximum reach radius approximately at the midpoint, is selected to verify the usability of the LEE. Here, the green circle in Fig. 2 is the maximum reach radius of the selected robot arm. If the maximum reach radius is assumed to be 1.200 m to suit the task environment, the maximum reachable EE position is represented by a red circle. From this difference, the maximum link length of the LEE was predicted to be approximately 0.400 m.

Using the predicted maximum link length, we verify whether it can be achieved without exceeding the allowable joint torques. In general, the above must be considered for both the LEE and grasped object. However, the object weight (the dishes) is small compared to the LEE; thus, it is ignored. We also assume that the center of gravity of the LEE was half the maximum link length. In this case, the load torque is expressed as follows:

$$\tau = \frac{1}{2}wgL_{max} \quad (3)$$

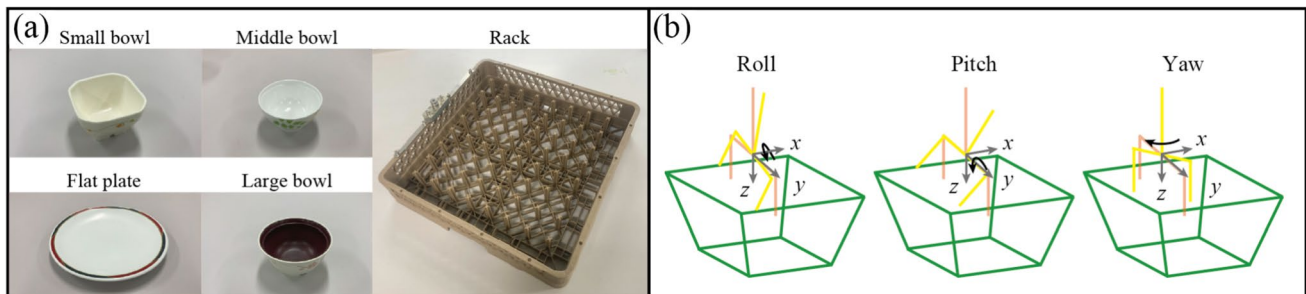


Fig. 3 Target objects: (a) represents the types of objects, and (b) shows the allowable EE posture range for dish during the handling

Table 1 Object parameters

Name	Side/Diameter[m]	Height[m]	Weight [kg]
Small bowl	0.105	0.060	0.105
Flat plate	0.220	0.020	0.201
Large bowl	0.130	0.060	0.098
Middle bowl	0.120	0.065	0.118
Rack	0.500	0.115	2.000

where τ is the load torque, $w = 1.500$ kg is the weight of the LEE, $L_{max} = 0.400$ m is the maximum link length, and $g = 9.806$ m/s² is the gravitational acceleration. For each assumed parameter, the load torque is 2.942 Nm. The minimum allowable torque of the selected robot arm is 3.900 Nm, which is considered usable.

Next, we evaluate whether structural deflection induced by the length of the LEE leads to a degradation of EE accuracy under the assumed task conditions, using a simplified model. To maintain consistency with the torque constraint analysis, the LEE link is approximated as a cantilever beam with uniformly distributed weight. Assuming a lateral acceleration of a , the inertial force acting on the LEE can be modeled as an equivalent uniformly distributed load. Under this assumption, the resulting tip deflection δ is given by the following expression.

$$\delta = \frac{waL_{max}^3}{8EI}, \quad (4)$$

where, E denotes Young's modulus of the LEE material, and I denotes the second moment of area of the LEE cross section about the weak axis. A hollow square pipe with outer dimensions of 0.400×0.400 m and a wall thickness of 0.002 m is assumed. From these dimensions, the second moment of area about the weak axis is calculated as $I = 8.406 \times 10^{-5}$ m⁴. Using this value together with $a = 0.500$ g m/s², $w = 1.500$ kg, $L_{max} = 0.400$ m, and the Young's modulus of aluminum, $E = 69.000$ GPa, the tip deflection estimated from Eq. 4 is $\delta = 1.162 \times 10^{-5}$ m. In this paper, the allowable positioning error is on the order of mm. Accordingly, the structural deflection evaluated above does not constitute a dominant source of positioning errors. From the perspective of structural deflection, the assumed link length of the LEE can therefore be regarded as acceptable in the initial design stage.

Finally, to preliminarily examine changes in vibration characteristics induced by the length of the LEE, the first natural frequency is evaluated. To maintain consistency with the torque and deflection analyses, the LEE link is approximated as a cantilever beam with uniformly distributed weight. Under this assumption, the first natural angular frequency ω_1 of a cantilever beam with uniformly distributed weight can be approximated.

$$\omega_1 \approx \beta_1^2 \sqrt{\frac{EI}{wL_{max}^3}} \quad (\beta_1 = 1.875), \quad (5)$$

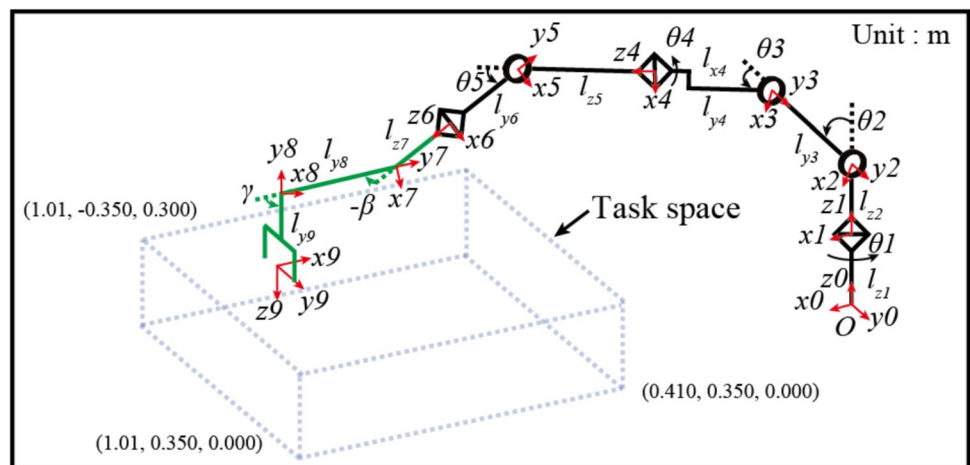
where β_1 is the modal constant corresponding to the first vibration mode of a cantilever beam. The first natural frequency is then obtained as $f_1 = \omega_1/(2\pi)$. By substituting the aforementioned parameters into Eq. 5, the first natural frequency is calculated to be approximately $f_1 \approx 128.486$ Hz. In typical pick & place operations of industrial robots, the dominant frequency components of motion are on the order of a few hertz and therefore do not reach the first natural frequency obtained in this evaluation. Consequently, under normal operating conditions, the primary resonance is unlikely to become a dominant issue. It should be noted that this study assumes the use of a lightweight gripper. If the EE weight becomes dominant relative to the link weight, both the structural deflection and natural frequency may change significantly. Such cases require separate consideration.

4 Analysis of the motion range with LEE

4.1 Selection of LEE design parameters

We perform a motion range analysis using the model shown in Fig. 4 in which the LEE is mounted on a 6 DoF robot arm. This model selects the following three main parameters for

Fig. 4 Robot arm model: task space, placement of the robot arm, installation of the LEE, and coordinate definitions for each joint when deriving the homogeneous transformation matrix



the LEE design: the length of the long link (L), installation angle between the long link and flange surface (β , pitch), and installation angle between the long link and gripper (γ , pitch). These parameters are selected based on the knowledge gained from the general Pick & Place task. For example, in a task environment, as shown in Fig. 2, the reference posture of the robot arm can be assumed to be vertically downward on the xz plane. Under these assumptions, the roll and yaw directions of the installation angles can disrupt the rotational symmetry of the robot arm. Then, we must analyze the behavior of other task spaces $U_2 \sim U_4$ individually. However, this places a heavy burden on the users. Therefore, such empirical parameter constraints allow us to predict the behavior in other task spaces by analyzing only U_1 . Theoretically, d_{z7} and d_{y9} can be considered as design parameters. However, they are often constrained by the commonly used grippers and tool changers. In contrast, in the environment shown in Fig. 2, it is often not possible to anchor the robot arm, and there is a possibility that there may be an error in the installation height (h) of the robot arm base. Therefore, the installation height (h) of the robot arm base is also added as a necessary design parameter, and an analysis is performed considering four parameters.

4.2 Setting of kinematics

In general, the reachable workspace of a robot arm can be evaluated by varying the joint angles and applying forward kinematics to verify whether the resulting EE positions and postures satisfy the task requirements [29]. For instance, as shown in Fig. 4, the homogeneous transformation from frame $i-1$ to frame i is defined based on the coordinate frames assigned to each joint. This transformation is expressed by Eq. 6 using the parameters listed in Table 2, which are specifically modeled after the RV-4FRL-D.

$${}^{i-1}T_i = \begin{bmatrix} R(\alpha_i, \theta_i) & t_i \\ 0 & 1 \end{bmatrix} \quad (6)$$

$$\begin{cases} R(\alpha_i, \theta_i) = \begin{bmatrix} \cos \theta_i & -\sin \theta_i & 0 \\ \cos \alpha_i \sin \theta_i & \cos \alpha_i \cos \theta_i & -\sin \alpha_i \\ \sin \alpha_i \sin \theta_i & \sin \alpha_i \cos \theta_i & \cos \alpha_i \end{bmatrix} \\ t_i = [l_{xi} \quad l_{yi} \quad l_{zi}]^T \end{cases}$$

where, $R(\alpha_i, \theta_i)$ represents the rotation matrix, while t_i denotes the translation vector. The forward kinematics of the 9 DoF robot arm, which incorporates the LEE parameters (L, α, β), is defined by the product of these successive homogeneous transformation matrices as follows:

$${}^0T_9 = {}^0T_1 \cdots {}^8T_9 \quad (7)$$

However, approaches relying solely on exhaustive exploration of the joint space through forward kinematics suffer from prohibitively high computational costs as the DoF increase. For the 9 DoF robot arm considered in this study, which includes an LEE, applying such brute-force methods at the initial design stage is highly inefficient.

Therefore, we decouple the 6 DoF of the robot arm from the 3 additional DoF introduced by the LEE. The extension provided by the LEE is defined by static design parameters, such as the link length and mounting angle, which are specified a priori. Consequently, these parameters do not serve as unknown variables in inverse kinematics calculations. Accordingly, the LEE can be represented as a fixed homogeneous transformation from the flange frame to the LEE frame, as formulated below.

$${}^6T_9 = {}^6T_7 \cdots {}^8T_9 \quad (8)$$

The homogeneous transformation matrix ${}^0T_9$, representing the target LEE position and posture within the task space U_1 , is treated as known. The required position and posture of the 6 DoF robot arm flange can be derived by decoupling the transformation introduced by the LEE using its inverse, as expressed below:

$${}^0T_6 = {}^0T_9 {}^6T_9^{-1} \quad (9)$$

Table 2 Parameters of the homogeneous transformation matrix

i	α_i [deg]	θ_i [deg]	l_{xi} [m]	l_{yi} [m]	l_{zi} [m]
1	0	$\theta_1(\pm 180.000)$	0	0	$l_{z1}[(0.190 + h)]$
2	-90.000	$\theta_2(\pm 120.000)$	0	0	$l_{z2}[(0.160)]$
3	0.000	$\theta_3(0.000 \sim 164.000)$	0	$-l_{y3}[(0.310)]$	0
4	90.000	$\theta_4(\pm 180.000)$	$-l_{x4}[(0.050)]$	$-l_{y4}[(0.060)]$	0
5	-90.000	$\theta_5(\pm 120.000)$	0	0	$l_{z5}[(0.275)]$
6	90.000	$\theta_6(\pm 180.000)$	0	$-l_{y6}[(0.085)]$	0
7	-90.000	β	0	0	$l_{z7}[(0.100)]$
8	0.000	γ	0	$-l_{y8}[(L)]$	0
9	90.000	0	0	$-l_{y9}[(0.150)]$	0

Consequently, the problem of determining whether the task space U_1 is satisfied for the 9 DoF robot arm can be reduced to solving the inverse kinematics of the 6 DoF robot arm for the derived flange position and posture from ${}^0T_6$ [30]. The feasibility is then confirmed by verifying whether valid joint angle solutions exist.

4.3 Analysis

The analysis was conducted on a system with 128 GB RAM, Intel Core i7-7820X CPU, NVIDIA GeForce GTX 1080 Ti GPU, running Ubuntu 22.04, and using Python (PyTorch). The computation took approximately 6 h, depending on the task space division, as shown in Table 3. The numerical calculation steps are as follows.

- (1) **Flange position/posture calculation** Combinations of LEE positions/postures are generated based on the ranges and step sizes in Table 3. For each combination, the flange position/posture is calculated using the selected LEE design parameters (h, L, β, γ).
- (2) **Joint angle calculation via inverse kinematics** The joint angles corresponding to each flange position/posture are obtained, constrained by the joint motion ranges

in Table 2. These angles are verified by recalculating the LEE position/posture using forward kinematics.

- (3) **Selection of LEE parameters** Verify whether joint angles exist that satisfy all LEE position/posture combinations. Record the valid LEE design parameters in a CSV file for those that meet the task space U_1 requirements.

Based on the numerical calculation steps, Fig. 5 visualizes the parameter combination space of the LEE that satisfies the reachability condition U_1 . This is intended to provide an intuitive understanding of how the installation conditions of the robot arm and the geometric parameters of the LEE influence the available design freedom. As shown in Fig. 5, the number of design parameter combinations that satisfy U_1 decreases monotonically as the installation height h of the robot arm increases. This trend indicates that a higher installation height restricts the available workspace adjustment enabled by the LEE, thereby reducing the overall design freedom. In contrast, increasing the link length L of the LEE tends to expand the allowable ranges of the mounting angles β and γ . This result suggests that adjusting the link length is an effective design variable for recovering design freedom that is otherwise lost due to restrictive installation conditions.

Table 3 Parameters of the numerical analysis

Parameters	Minimum value	Maximum value	Step width
h [m]	-0.050	0.050	0.050
l_{y8} [m]	0.300	0.400	0.020
β [deg]	-90.000	90.000	5.000
γ [deg]	-90.000	90.000	5.000
x [m]	0.410	1.010	0.200
y [m]	-0.350	0.350	0.100
z [m]	0.000	0.300	0.100
Roll [deg]	135.000	180.000	5.000
Pitch [deg]	0.000	15.000	5.000
Yaw [deg]	170.000	180.000	5.000

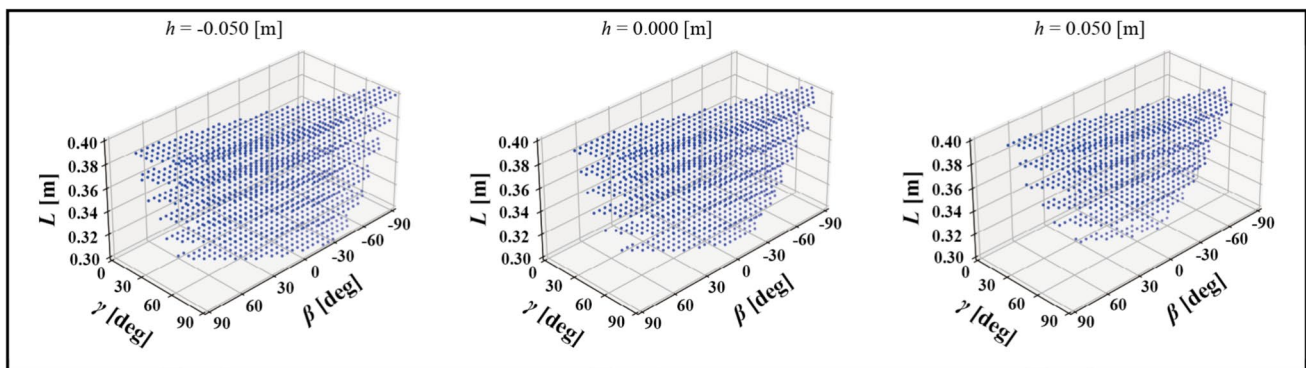


Fig. 5 Numerical analysis results: the range of LEE parameter combinations

Therefore, this result can be used as a guideline for design decision-making. For example, in environments where the installation height h of the robot arm cannot be significantly modified, the allowable ranges of the mounting angles β and γ can be preserved by adjusting the link length L , thereby maintaining a feasible design candidate region. Conversely, when a certain degree of flexibility is available in the installation conditions, the candidate region can be prevented from degenerating by adjusting the installation height h . Subsequently, finer adjustments can be made using the link length and angular parameters, enabling the system to satisfy the required task workspace without introducing excessive mechanical complexity. Through these adjustments, it is advantageous in the early design stage to retain a certain margin in the mounting angles β and γ , rather than fixing them rigidly. By reserving β and γ as final tuning degrees of freedom to be adjusted in the target environment, the proposed design approach avoids over-constraining the system at an early stage while maintaining flexibility to accommodate environment-specific constraints and installation uncertainties. These results indicate that the parameter combination space shown in Fig. 5 can be used to extract a feasible candidate region in the initial design stage, and can subsequently be refined in a stepwise manner by accounting for practical mechanical constraints and installation conditions.

5 Dishwashing system

5.1 System overview

The constructed system is shown in Fig. 6(a). The system comprises a 6 DoF robot arm (RV-4FRL-D, MELCO, Japan), two RGB-D cameras (RealSense D415, Intel Corporation, USA), and two LEEs. A rack end-effector (REE) is used to handle the rack. Furthermore, the robot arm is controlled using CREWBO (Chitose Robotics Inc., Japan). Additionally, the dishwasher used is the SD113EA6 (Nippon Senjoki K.K., Japan), and a lifter (Chitose Robotics Inc., Japan) is employed for dish storage. Each camera is installed above task spaces U_2 and U_3 . The features of this system are as follows.

- (1) **Movable installation** This task does not involve collaboration with humans. The system is installed without anchors, allowing it to be easily moved in the event of breakdown or inspection.
- (2) **Hygiene management** From the perspective of hygiene management, this system has a Dirty area for handling used dishes and a Clean area for handling washed dishes. The upper part of the dotted line in Fig. 6(a) is the Dirty area, and the lower part is the Clean area.
- (3) **Use of three EEs** For hygiene management, two LEEs are used to handle dishes, and a REE is used to handle

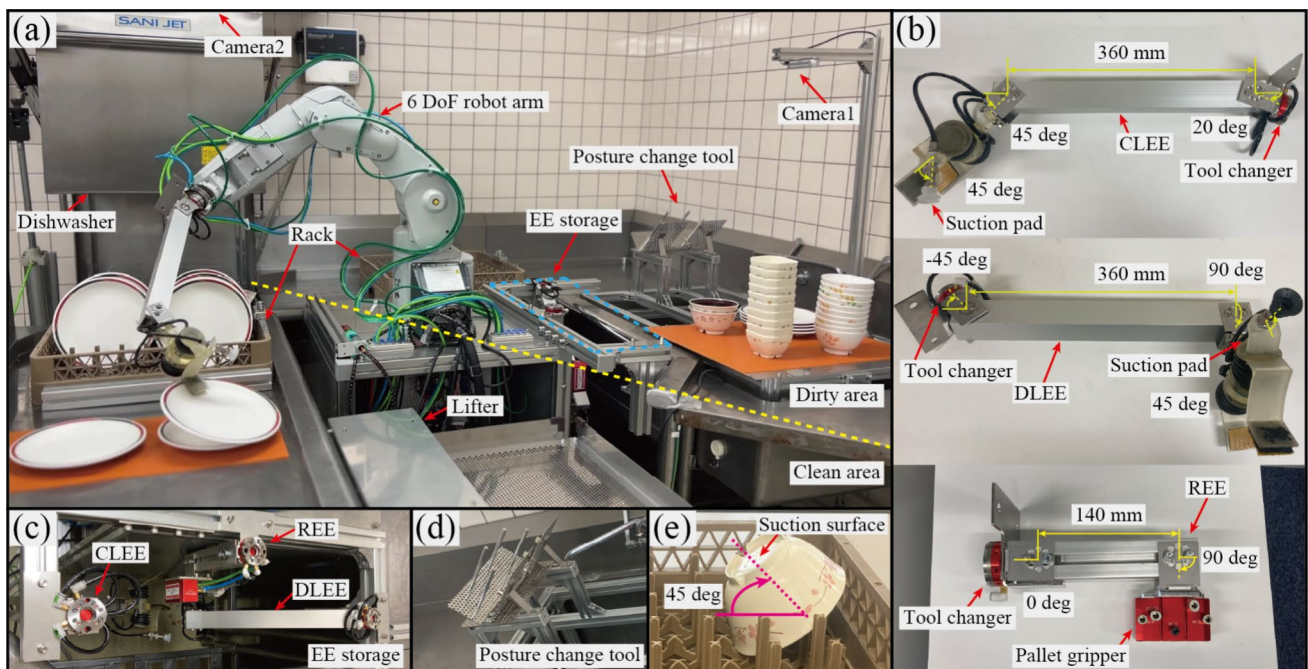


Fig. 6 Proposed system: (a) overview of the system configuration, (b) LEEs and REE manufactured for the proposed system, (c) EE storage, (d) posture change tool, and (e) dishes placed on the rack at an inclination of approximately 45°

racks (Fig. 6(b)). Each EE is placed in the EE storage shown in Fig. 6(c). We refer to each LEE as the Clean LEE (CLEE) and a Dirty LEE (DLEE).

- (4) **Changing the posture of dishes** The bowl-shaped dish is placed face down on the rack. However, because the dish is face up, it is necessary to change the posture of the dish. Therefore, we use the posture change tool shown in Fig. 6(d).

5.2 Manufacture of LEEs and REE

The combination of the LEE design parameters that can accommodate this task is shown in Fig. 5. Theoretically, any combination within these parameter ranges is acceptable for this system. However, in reality, it is preferable to select design parameters that minimize changes in the joint angles of the robot arm, considering the cycle time and energy consumption. In this study, we set the following parameters to reduce the joint angle changes: for the DLEE, $L = 0.360$ m, $\beta = -45.000^\circ$, $\gamma = 90.000^\circ$; and for the CLEE, $L = 0.360$ m, $\beta = 20.000^\circ$, $\gamma = 45.000^\circ$.

The two types of LEEs manufactured are illustrated in Fig. 6(b). Each LEE consists of a tool changer, link, and gripper sections. The tool changer used is SWR0070 (KOSMEK LTD., Japan). Additionally, as suction gripping is assumed to be the method for handling dishes after changing their posture, a suction pad is installed at the tip of each LEE. The dishes are placed at an angle of approximately 45.000° on the rack as shown in Fig. 6(e). Therefore, the suction pad at the tip of each LEE is offset by 45.000° .

The manufactured REE is shown in Fig. 6(b). The REE also consists of tool changer, link, and gripper sections. The REE uses a pallet gripper (KOSMEK LTD., Japan) in the gripper section. Additionally, handling racks is different from handling dishes because it involves repeating a set motion. Therefore, the REE design parameters can be easily determined without the need for motion range analysis. The following parameters were used: $L = 0.140$ m, $\beta = 0.000^\circ$ deg, $\gamma = 90.000^\circ$.

5.3 Feasibility demonstration

This part presents a demonstration to verify whether the proposed LEE design methodology is practically feasible under the assumed task workspace and task conditions. The primary objective of this demonstration is to show that a sequence of task motions can be successfully executed using a small robot arm by appropriately designing the workspace with the LEE. Accordingly, this demonstration is not intended to provide a quantitative evaluation of performance metrics, such as motion speed or task success rate. Such performance metrics are strongly influenced by

factors peripheral to the LEE design methodology, including the grasping strategy and installation conditions of the robot base. Therefore, these aspects are treated separately from the evaluation of the feasibility of the proposed LEE design approach.

As shown in Section 3.3, within the range of LEE mass and link length considered in this study, no dominant mechanical factors that would restrict motion—such as joint torque limits, payload overload, structural deflection, or degradation of the first natural frequency—are expected to arise in advance. Based on this observation, and in order to suppress the influence of disturbances and vibrations particularly associated with anchorless installation, the joint velocities are limited to 20% of their rated values during the demonstration.

Figure 7 and the accompanying supplementary video present the demonstration results of the dishwashing task performed using the proposed system. The overall process consists of three steps: (i) loading used dishes onto a rack, (ii) loading the rack into the dishwasher and retrieving it after washing, and (iii) unloading the washed dishes from the rack after washing. The details of each step are described below.

- (i) The robot arm attaches the DLEE from the EE storage. Then, Camera 1 (Fig. 6(a)) recognizes the edge of the topmost used dish stacked in task space U_2 [12]. The robot arm moves the fingertips of the gripper near the edge of the recognized dish and grips it by opening and closing the gripper. The gripped dish is then loaded onto the rack installed in the task space U_1 . If the gripped dish is bowl-shaped, the posture change tool is used to switch from open-close gripping to suction gripping before loading it onto the rack. This process is repeated until the rack is filled with dishes. In this basic motion check experiment, it took approximately 20–30 s to process a single dish. In addition, 16 dishes were loaded onto the rack. Therefore, the total time required for the loading process was approximately 7 min.
- (ii) The robot arm detaches the DLEE and attaches the REE. It grips the rack installed in task space U_1 with the REE and moves the rack into the dishwasher. While the dishwasher is washing the dishes (approximately 90 s), the empty rack installed in task space U_4 is moved to task space U_1 to prepare for step (i). Step (i) was performed until the dishwashing process (approximately 90 s) was completed. After washing, the rack is gripped with the REE and moved to the task space U_4 . The entire process of moving the rack took approximately 90 s.
- (iii) The robot arm detaches the REE and attaches the CLEE. The Camera 2 (Fig. 6(a)) recognizes the position/posture of dishes in the rack installed in the task space U_4 [13].



Fig. 7 Demonstration results: (i) loading used dishes onto a rack, (ii) loading the rack into the dishwasher and retrieving it after washing, (iii) unloading the washed dishes from the rack after washing, and (iv) handling dishes with leftovers

The flat plate is then gripped using open-close gripping, and the bowl-shaped dish is gripped using suction gripping. The flat plates were stacked face-up on an orange sheet installed in the task space U_4 . The bowl-shaped dish is stacked face down on the lifter installed in task space U_3 . We repeat the above steps for all the dishes on the rack. Finally, the robot arm detaches the CLEE using the EE storage to complete the task. In this basic motion check experiment, it took approximately 10 s to process a single dish. In addition, 16 dishes were loaded onto the rack. Therefore, the total time required for the removal process was approximately 3 min.

In this demonstration, a sequence of task motions was executed under the condition that the joint velocities were limited to 20% of their rated values, resulting in a total task execution time of approximately 15 minutes. Even under this execution time, no issues attributable to the proposed LEE design methodology—such as insufficient workspace or mechanical interference—were observed, demonstrating that the proposed approach remains stable and feasible under the assumed task conditions. On the other hand, improvements

in cycle time through increased motion speed, as well as the reproducibility and success rate of tasks involving diverse objects—including contaminated dishes, as shown in Fig. 7(iv) and the supplementary video—are expected to depend more strongly on peripheral factors than on the LEE design methodology itself. These factors include the grasping characteristics of the gripper, surface conditions of the target objects, and installation conditions of the robot base. Therefore, when considering deployment as a practical dishwashing system, systematically evaluating motion speed, task success rate, and reproducibility while accounting for these factors remains an important direction for future work.

6 Conclusion and discussion

In this study, we propose a method for designing the motion range of a small 6 DoF robot arm by combining it with a long end-effector (LEE) and adjusting its length and installation angle to match the task space. Our design method is summarized as follows, highlighting the key elements of each step.

(1) Clarifying the task environment

- Task environment size is checked, and the robot arm location and primary task space are determined.
- A list of object types and their basic parameters, such as weight and shape, is clarified.

(2) Clarify the handling conditions

- The gripper shape is determined based on object parameters, prioritizing a lightweight design.
- EE posture constraints are defined by object parameters in terms of roll, pitch, and yaw.

(3) Selection of the existing robot arm

- Determine the robot arm's payload based on the mass of the object, gripper, and long link.
- Within these constraints, the smallest feasible class of robot arm is selected, and simplified models are used to verify in advance that the allowable joint torque limits are satisfied and that structural deflection and vibration characteristics—specifically the first natural frequency—remain within acceptable ranges for the assumed task, considering the link length and mass of the LEE.

(4) Selection of the LEE design parameters

- Select the LEE design parameters, including long link length and installation angles.
- Constrain parameters based on typical robot arm motion and knowledge from SIs and other organizations.

(5) Analysis of the motion range

- Use both forward and inverse kinematics to verify that the EE positions and orientations satisfy the task-space and posture conditions.
- Obtain a range of LEE parameter combinations that satisfy the constraints.

The proposed long end-effector (LEE) uses fixed joints instead of active joints, allowing a cost-effective adjustment of the robot arm's motion range. Through the demonstration conducted, it was confirmed that even with such a configuration, a small-sized robot arm is capable of executing a sequence of task motions under the assumed task workspace and task conditions. From this, we identified the LEE design parameter ranges that meet the task space requirements, simplifying the design and manufacture.

However, this numerical analysis was limited to the LEE position/posture and did not minimize joint angle changes in the robot arm (affecting the cycle time and energy consumption). To satisfy the constraints of the EE posture, significant adjustments in the swivel-joint angle are necessary, and the motion of the swivel joint is crucial. An analysis that includes all of these factors will be a future topic. It is expected that the numerical calculation costs will be significant; therefore, we should also consider whether this will truly help reduce the burden of system integration work.

As the application range of industrial robot arms extends beyond factory automation and continues to expand, the development of systems tailored to specific task environments is becoming increasingly important. To address this issue, robot SIs are making aggressive efforts. However, there are a wide variety of challenges in actual system integration, and the motion range design explored in this study is one of the most critical. The proposed design method offers solutions to these challenges and aims to provide a practical approach for robot SIs. This method is expected to ease the burden of system integration in environments where new and diverse robots are employed, thereby promoting the broader use of robots across various fields.

7 Supplementary information

The video demonstrates the following tasks: (i) loading used dishes onto a rack, (ii) placing the rack into the dishwasher and retrieving it after washing, (iii) unloading the washed dishes from the rack, and (iv) handling contaminated dishes.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00170-026-17785-4>.

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Declarations

Conflicts of Interest/Competing Interests The authors declare that they have no conflict of interest or competing interests.

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication All authors consent to the publication of this work.

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