Task-based Method for Designing Underactuated Elastic Mechanisms

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Abstract: In this paper, we introduce a task-based method for designing underactuated mechanisms which actuators are linked with the joints via elastic elements. We consider multi-joint mechanisms that contain fewer independent actuators than the joints. The elastic elements work as convertors from the displacement of the actuators to the joint torques of the mechanisms. In our method, we analyze the joint motions of the mechanisms during the completion of each task and the level of participation of each joint for few specific tasks. The results of this study can be used for the synthesis of dedicated underactuated mechanisms that can operate in a low task coordinate space and for the systematic design of underactuated mechanisms.

1 INTRODUCTION

The design of robot mechanisms has often been inspired by the structure and functioning of the human body. Such an approach in designing robot hands leads to the synthesis of mechanisms that can handle the objects more dexterously; however, the designing of robot hands with a large number of joints by mimicking the human structure often becomes very complicated because of the necessity of many actuators. While human muscles can generate very high energy per unit weight, electrical motors do not have high power-to-weight ratio. This leads to serious design difficulties and the designed robot hands becoming large, heavy and less powerful.

Various studies show that specific human movement tasks can be expressed by only a small number of variables. Kim et al. (2011) confirmed that only four to five principal components are sufficient for achieving human walking patterns on a smooth surface. A study of human hand motions proved that a relatively small number of principal components are engaged during the completion of specific motions (Santello et al., 1998).

It is often suggested that hand prostheses and robot grippers must possess a kinematic structure that is similar to those of the natural human hand that allows grasping or pinching of various objects of different sizes and forms. Anthropomorphic hands with a large number of joints are highly dexterous, but the independent joint control requires a large number of actuators. As a solution to the problem, many design concepts of robotic hands have been introduced with fewer actuators than degree-of-freedom (DoF) in the hand mechanisms. For an example in such concepts, one actuator is connected with several joints and operates them simultaneously. In this research field such mechanisms are often called “underactuated” mechanisms. In our previous research we already proposed a task-based method for underactuated mechanisms in a systematic way (Kamada et al., 2012). The method was based on the analysis of the set of predefined tasks that should be performed by the new robot hand, which the analysis leads to the approximated motion trajectories with fewer independent variables than the variables for the exact achievement of the tasks. If such approximation is allowed, we can design a robot hand for the predefined tasks with a specific type of device which is called linear dependent drive (LDD). The approach allowed the synthesis of hands with a simple structure that include fewer actuators than joints and that possess high functionality and precise motions for the named set of tasks. Generally, the synthesized underactuated mechanisms can achieve only the approximated motions to the exact ones of mechanisms with the same kinematic structure and independently controlled joints. To cope with such deterioration on the accuracy of the motion trajectories, Birglen et al. (2004) and Dollar et al. (2007) introduced an approach that uses elastic

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elements for connecting the output of actuator to the joints in a simple robot hand. Such solution solves the problem on motion trajectories; moreover, the feature of self-adaptability to the object different shapes can be also expected because of the characteristics of the elastic elements. However, this robot hand is single purpose; only hard gripping the object is possible but other types of tasks, for examples pinching and twisting, are impossible.

To extend the good feature of such elastic robot hands for multi-purpose, we apply the task-based design method suggested by Kamada et al. in 2012 to design dextrous robot hands which possess more than one actuator with several elastic elements. We propose an index to analyze the level of participation of each joint for the named set of the given tasks. The kinematic and elastic parameters of the designed underactuated mechanism are determined by minimizing the criterion. We have verified the proposed method with few numerical design examples and provide here some of the key results that demonstrate its effectiveness.

2 SYSTEM STRUCTURE

In the present study we consider gripper mechanisms that consist of three components as represented in Figure 1. The fingers of a multi-joint robot hand are connected to a small set of actuators via Linear Dependent Drives (LDDs).

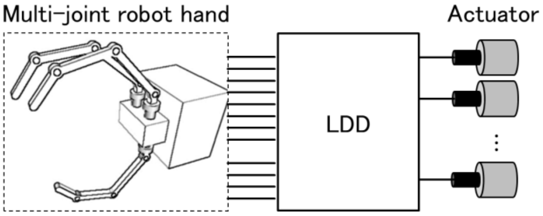

Figure 1: Components of designed mechanisms.

The structure of the joint between the i th link and the (i-1) th link is represented in Figure 2. Here, $\theta_{ai}(t)$ is the i th active joint angle, $\theta_{pi}(t)$ is the i th passive joint angle, $\theta_i(t)$ is the i th actual joint angle of the robot hand. Active joint angles are determined by LDDs and displacements of actuators. LDDs are mechanisms that transmit the displacements of the actuators to the joints as follows:

$$\boldsymbol{\theta_a}(t) = A\boldsymbol{\varphi}(t) + \boldsymbol{c} \tag{1}$$

Here, $\boldsymbol{\theta_a}(t)=\{\theta_{ai}(t)\}\in R^n$ is a vector of active joint angles, $A\in R^{n\times r}$ is a constant matrix, $\boldsymbol{\varphi}(t)\in R^r$ is a vector of displacements of actuators ($n>r$), $\boldsymbol{c}\in R^n$ is a constant vector. The number of actuator r is smaller than the number of the joints n. Passive joint angles $\boldsymbol{\theta_p}(t)=\{\theta_{pi}(t)\}\in R^n$ are determined by the torques which act on joints. The relation between passive joint torques $\boldsymbol{\tau_p}(t)\in R^n$ and passive joint angles is given as follows:

$$\boldsymbol{\tau_p}(t) = -K\boldsymbol{\theta_p}(t) \tag{2}$$

Here, K=diag(k_1, k_2, … , k_n) is a matrix of spring constants. k_i (i=1, … , n) are positive values. If there is no external force, the actual joint angles of the hand $\boldsymbol{\theta}(t)=\{\theta_i(t)\}\in R^n$ equal to the active joint angles. With some external forces, the actual joint angles of the hand $\boldsymbol{\theta}(t)$ are the sum of the active joint angles $\boldsymbol{\theta_a}(t)$ and the passive joint angles $\boldsymbol{\theta_p}(t)$.

$$\boldsymbol{\theta}(t) = \boldsymbol{\theta_a}(t) + \boldsymbol{\theta_p}(t) \tag{3}$$

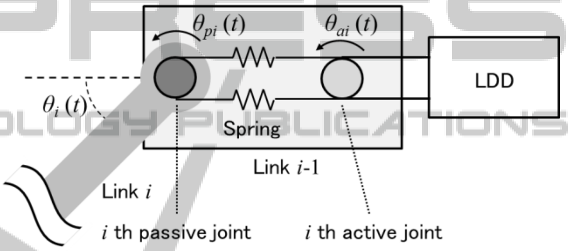

Figure 2: Connection between joints and LDD.

3 MECHANISM DESIGN

3.1 Principal Component Analysis

In this section we introduce a method for design of a LDD. Initially, it is assumed that the mechanism is fully actuated. Each joint of the mechanism is connected with an independent actuator via a pair of linear springs. From (2) and (3), joint angles of active joints $\boldsymbol{\theta_a}(t)$ are represented as follows:

$$\boldsymbol{\theta_a}(t) = \boldsymbol{\theta}(t) + K^{-1}\boldsymbol{\tau_p}(t) \tag{4}$$

In our study, the joints of the hand and the actuators are connected linearly via springs. The torques of the active joints $\boldsymbol{\tau_a}(t)\in R^n$ equal to the torques of the passive joints $\boldsymbol{\tau_p}(t)$.

$$\boldsymbol{\tau_a}(t) = \boldsymbol{\tau_p}(t) \tag{5}$$

From (4) and (5), the joint angles of the active joints $\boldsymbol{\theta_a}(t)$ can be represented as follows:

$$\boldsymbol{\theta_a}(t) = \boldsymbol{\theta}(t) + K^{-1}\boldsymbol{\tau_a}(t) \tag{6}$$

In equation (6), the active joint angles $\boldsymbol{\theta_a}(t)$ are the sum of the actual joint angles of the hand $\boldsymbol{\theta}(t)$ and the weighted active joint torques $\boldsymbol{\tau_a}(t)$. The joint angles $\boldsymbol{\theta}(t)$ determine the positions/orientations of the links of the hand. The active joint torques $\boldsymbol{\tau_a}(t)$ determine expressing forces of the hand. If we generate appropriate $\boldsymbol{\theta_a}(t)$ for the tasks, the hand accomplish them. In our approach, the active joint angles $\boldsymbol{\theta_a}(t)$ are analyzed and the information is used for design of a LDD.

In the paper (Kamada et al. 2012), the design method of a LDD based on Principal Component Analysis (PCA) have been introduced. We follow the method. PCA is a method which converts a multivariable data set into a set of uncorrelated variables called principal components by orthonormal transformation. We apply PCA to the joint angles data sets of the active joints for the executed task motions. The relation between the principal components $\boldsymbol{p}(t) \in R^n$ and the active joint angles $\boldsymbol{\theta_a}(t)$ is represented by the following equation:

$$\boldsymbol{p}(t) = W\{\boldsymbol{\theta_a}(t) - \boldsymbol{\theta_{a0}}\} \tag{7}$$

Here, $\boldsymbol{\theta_{a0}} \in R^n$ is the average of $\boldsymbol{\theta_a}(t)$, $W \in R^{n\times n}$ is the translation matrix of PCA. We can calculate a contribution rate for each principal component. Each contribution rate indicates the proportion of the variance of the principal component to the total variance of the joint angles of the active joints $\boldsymbol{\theta_a}(t)$. If we group all principal components into two groups depending on their contribution rates, (7) can be presented as follows:

$$\boldsymbol{p}(t) = \begin{bmatrix} \boldsymbol{p_h}(t) \\ \boldsymbol{p_l}(t) \end{bmatrix} = \begin{bmatrix} W_h \\ W_l \end{bmatrix} = W\{\boldsymbol{\theta_a}(t) - \boldsymbol{\theta_{a0}}\} \tag{8}$$

where $\boldsymbol{p_h}(t) \in R^r$ is the r principal components with higher contribution rates, $\boldsymbol{p_l}(t) \in R^{n-r}$ is the n-r principal components with lower contribution rates, $W_h \in R^{r\times n}$, $W_l \in R^{(n-r)\times n}$ are the submatrices of W. The reconstructed joint angles from $\boldsymbol{p_h}(t)$ are given as follows:

$$\hat{\boldsymbol{\theta}}_{\boldsymbol{a}}(t) = W_h^T \boldsymbol{p}_1(t) + \boldsymbol{\theta_{a0}} \tag{9}$$

where $\hat{\boldsymbol{\theta}}_{\boldsymbol{a}}(t) \in R^n$ is the reconstructed active joint angles. Since the relationship (9) corresponds to (1), it can be used for calculation the matrix A and the vector $\boldsymbol{c}$. In this approach, the number of the actuators equals to the dimension of $\boldsymbol{p}_1(t)$.

Without external force, the fingers of the robot hand generate approximated motion for the selected tasks. If the contact points of the finger is similar to the given task motions, the passive joint angles $\boldsymbol{\theta_p}(t)$ take similar values to the given ones.

3.2 Design Method

In Section 3.1, the group of the principal components with low contribution rates is excluded. Therefore there is the reduction errors $\boldsymbol{\Delta}(t)$ between the original joint angles $\boldsymbol{\theta_a}(t)$ and the reconstructed joint angles $\hat{\boldsymbol{\theta}}_{\boldsymbol{a}}(t)$. The reduction errors $\boldsymbol{\Delta}(t)$ can be defined as follows:

$$\boldsymbol{\Delta}(t) = \hat{\boldsymbol{\theta}}_{\boldsymbol{a}}(t) - \boldsymbol{\theta_a}(t) = (W_h^T W_h - I_n)\boldsymbol{\theta_a}(t) \tag{10}$$

If we change the link lengths or the spring constants, the errors $\boldsymbol{\Delta}(t)$ also change. We define the index J to select the parameters. In this paper, ‖·‖ means the Euclidean norm.

$$J = \int_0^{t_f} \|\boldsymbol{\Delta}(t)\|^2 dt \tag{11}$$

Here, tasks are executed from t=0 to t=t_f. Minimizing J yields the optimal parameters for the design.

4 DESIGN EXAMPLE

4.1 Structure of the Robot Hand

In this example, we consider a robot hand with two fingers and six links (Figure 3). Here, θ_{ai} are the joint angles of the active joints, θ_{pi} are the joint angels of the passive joints (i = 1, …, 6). The spring constants at each joint are given as

$$\begin{aligned} k_1 &= 80, k_2 = 80, k_3 = 80 \\ k_4 &= 90, k_5 = 90, k_6 = 90 \end{aligned} \tag{12}$$

The units above are mN·m/rad. The hand has an asymmetrical shape.

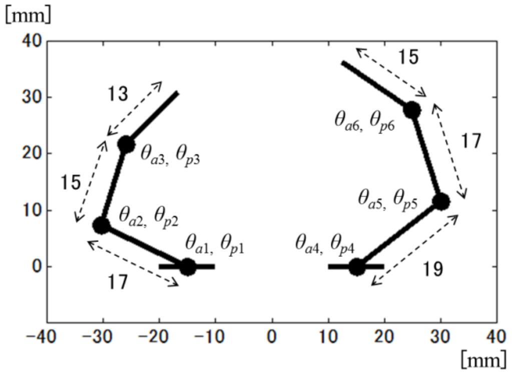

Figure 3: Shape of robot hand.

4.2 Given Tasks

We consider two tasks and design one robot hand which can accomplish the given two tasks. The dashed lines are applied forces. The motions for the tasks are shown in Figure 4 and 5. Task 1 is to pinch the target object with two fingers. The forces are applied vertically to the both sides of the object by the finger tips. The magnitudes of the forces are 0.5 N. Task 2 is to wrap the fingers around the target object. The forces are applied to the object as represented by Figure 5. The magnitudes of the applied forces are 0.447 N. It is assumed that the object is fastened on the floor plane. We analyzed the motion for tasks as indicated in Figure 4 and 5. We apply PCA to the joint angles of the active joints while the gripper in Figure 3 executes the both tasks in Figure 4 and 5. In Table 1, the contribution rates of the principal components are shown. The accumulate contribution rate of 2 major principal components is 97.7%. If the size of the object changes, the contribution rates also change. However, the change of the accumulated contribution rate of the two major principal components is relatively small. In this chapter, we design the mechanism with 2 actuators.

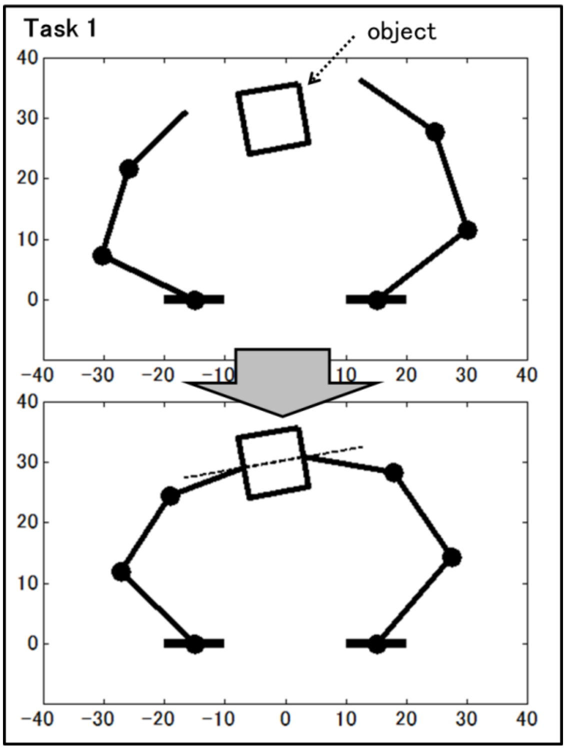

Figure 4: Motion for task 1.

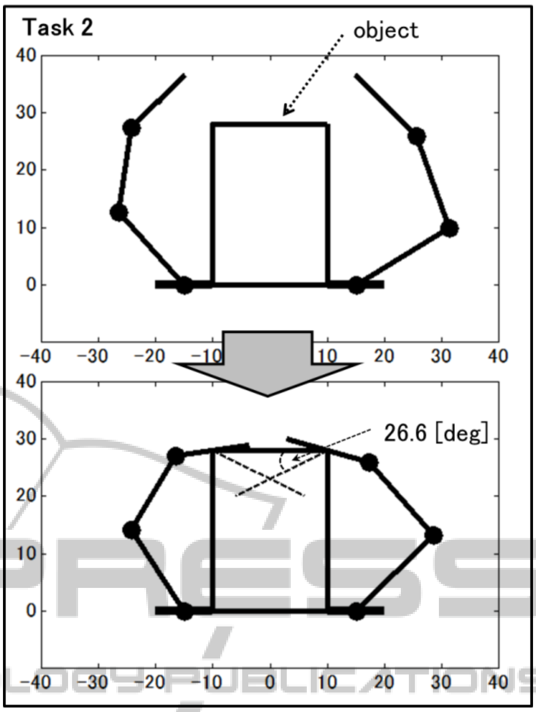

Figure 5: Motion for task 2.

Table 1: Contribution rates.

Principal component	Contribution rate [%]
1	69.2
2	28.5
3	1.84
4	3.56×10^{-1}
5	5.67×10^{-2}
6	5.63×10^{-3}

4.3 Motions of Designed Hand

The designed hand can apply forces to the target objects as shown in Figure 6. We use the index of (13) to evaluate the error between the force given as the task motion and the force applied to the object by the underactuated robot hand.

$$E_l = \frac{\left\| \boldsymbol{f_{gl}} - \boldsymbol{f_{al}} \right\|}{\left\| \boldsymbol{f_{gl}} \right\|} \times 100 \ [\%]$$
$$E_r = \frac{\left\| \boldsymbol{f_{gr}} - \boldsymbol{f_{ar}} \right\|}{\left\| \boldsymbol{f_{gr}} \right\|} \times 100 \ [\%] \tag{13}$$

Here, $\boldsymbol{f_{gl}}$ is the given force of the left finger, $\boldsymbol{f_{al}}$ is the actual force of the left finger, $\boldsymbol{f_{gr}}$ is the given force of the right finger, $\boldsymbol{f_{ar}}$ is the actual force of the right finger. In Table 2 and Table 3, we show the values of E_l and E_r for each task. The results show that in this simulation design example the forces to the object are similar to the given ones and the difference between them does not exceed 20 %.

Table 2: Error of force (Task1).

E_l [%]	E_r [%]
10.9	16.3

Table 3: Error of force (Task2).

E_l [%]	E_r [%]
19.7	18.9

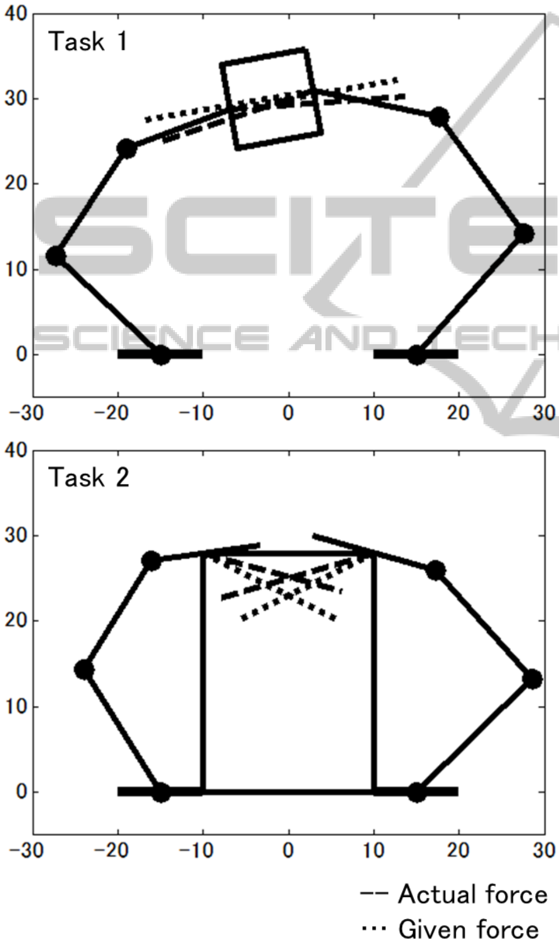

Figure 6: Motions of designed hand.

5 CONCLUSIONS

We introduced a task-based method for design of underactuated mechanisms attached elastic elements between joints and actuators. The given tasks are defined by the trajectories and the contact forces of the links in the task coordinate space. At the beginning, it is assumed that the given tasks are performed by fully actuated mechanisms. We analyze the joint motions of the mechanisms during the completion of each task and synthesize dedicated underactuated mechanisms. The proposed approach allows the synthesis of underactuated mechanisms that have fewer actuators than joints. Without external force, the joint angles of the synthesized mechanism are linearly dependent on the displacements of the actuators. We presented an example that shows promising results and potential of the proposed method in various practical applications.

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REFERENCES

Hirai, K., Hirose, M., Haikawa, Y., and Takenaka, T. 1998. The Development of Honda Humanoid Robot, In *Proc. 1998 IEEE International Conference on Robotics & Automation*, pp. 1321-1326.

Kawasaki, H., Komatsu, T., and Uchiyama, K. 2002. Dexterous Anthropomorphic Robot Hand With Distributed Tactile Sensor: Gifu Hand II, *IEEE/ASME Trans. on Mechatronics*, Vol. 7, No. 3, pp. 296-303.

Kim, Y., Tagawa, Y., Obinata, G., and Hase, K. 2011. Robust control of CPG-based 3D neuromusculo-skeletal walking model, *Biological Cybernetics*, Vol. 105, Issue 3, pp. 269-282.

Santello, M., Flanders, M., and Soechting, J. F. 1998. Postural Hand Synergies for Tool Use, *The Journal of Neuroscience*, Vol. 18, No. 23, pp. 10105-10115.

Birglen, L., and Gosselin, C. M. 2004. Kinetostatic Analysis of Underactuated Fingers, *IEEE Trans. on Robotics and Automation*, Vol. 20, No. 2, pp. 211-221.

Dollar, A. M., and Howe, R. D. 2007. The SDM Hand as a Prosthetic Terminal Device: A Feasibility Study, In *Proc. 2007 IEEE 10th International Conference on Rehabilitation Robotics*, pp. 978-983.

Kamada, S., Kim, Y., Obinata, G., and Stefanov, D., 2012. Task-Based Method for Designing Underactuated Mechanisms, *International Journal of Advanced Robotic Systems*, Vol. 9, pp. 1-12.