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# A Grasping Component Mapping Approach for Soft Robotic End-Effector Control

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***Abstract*—Soft robotic end-effectors with inherent compliance have excellent grasping adaptability and ensure safe human-robot interaction. The inherent compliance also limits structural dexterity in soft robotic systems and makes mathematical modeling difficult, therefore resulting in control challenges for existing soft robotic hands. To tackle these problems, we propose a general and intuitive control approach for various soft end-effectors with different kinematic structures. A grasping component based mapping approach is presented. This approach maps the essential human hand grasping components to robotic hand grasping components, without requiring a specific kinematic model per end-effector. A LMC-based human hand motion capturing system and multi-channel pneumatic actuation platform are accompanied to realize the intuitive control. The proposed intuitive control strategy does not require the human operator to wear any equipment or modify their natural hand behavior to match different end-effector structures. We demonstrate the efficacy of our control strategy with two, three, and four-fingered soft end-effectors. All static performances are depicted by photos in the experimental section and dynamic processes are in our accompanying video. The proposed approach provides an efficient solution to control various soft robotic hands and enhances the performance dexterity of soft robotic end-effectors.**

***Index Terms- Soft Robotics, End effectors, Intuitive grasping control.***

## I. Introduction

Recently soft robotic end-effectors have gained attention for their unique property of inherent compliance [1]. Inherent compliance allows soft robotic end-effectors to maneuver and adapt in an unstructured and unknown environment. These soft hands are a promising candidate for safe applications in human-centered environment due to their robust and compliant grasping ability [2-6]. The inherent compliance also alleviates the strict requirement of complex and precise kinematic model and high-resolution sensor feedback in soft robotic hands. Simply tuning the input pressure can provide an adequate control of the hand performance [7, 8].

However, inherent compliance has some drawbacks, which impose challenge for the control of the soft hands [9-11]. The difficulties arise from mainly two aspects. One is the nature of soft actuation. While it provides compliance, soft actuator undergoes continuum deformation, which makes precise mathematical kinematic modeling challenging for soft robots. For traditional rigid pin jointed robot, the motion can be described and planned in 6 degree of freedoms (DOF): one rotation and one translation in each x, y, and z-axes. But the continuum deformation of soft robot hinders straightforward quantification in planar motions. The second aspect is the low level of dexterity in soft robotic mechanism. Most soft hands contain one soft actuator as one robotic finger, the motion of which follows a predefined curvature without discrete angles [1]. With only one DOF in each finger, the soft hand's structural dexterity itself does not match other multi-DOF rigid robotic hand's dexterity. The kinematic modeling difficulty and limited structural dexterity are the main reasons that the control of soft robotic hand remains at low-level control, such as on/off control that only allows simple tasks (i.e. picking up and placing objects).

With the recent advancements, dexterity of soft robotic hands on the structural level has improved dramatically. Our previous attempts presented a 4-DOF hybrid gripper with four grasping modes [4], a 6-DOF robust soft gripper with excellent adaptability [5], and a 13-DOF soft robotic hand capable of dexterous in-hand manipulation [6]. However, the existing control strategy limited the performance capacity of those dexterous soft robotic end-effectors in present studies [10-13]. Although these soft hands can realize much dexterous motion or gesture mechanically, it is hard to identify and control the required actuation command for each DOF at the same time. Besides, for soft robotic end-effectors with different kinematics and structure, the control and actuation system requires specific adjustment or a development of an entirely new one if necessary. As such, a versatile control strategy that can accommodate various types of soft robotic end-effectors is needed to enhance the dexterous performance and ease of control.

In this paper, we propose a mapping synergy based on grasping components to bridge the kinematic gap between the human hand and soft robotic end-effectors. This mapping method gets rid of the accurate robotic hand kinematic model requirement and allows natural and intuitive control for the human operator without needing to modify their behavior to match the end-effector structure. The real-time motion of the human hand can be the master system to provide abundant actuation information up to 23 independent DOFs. With a human hand motion capturing device, the Leap Motion Controller, the real-time human hand motion can be obtained to provide intuitive control signal for a soft robotic hand [14, 15]. A general pneumatic actuation system capable of

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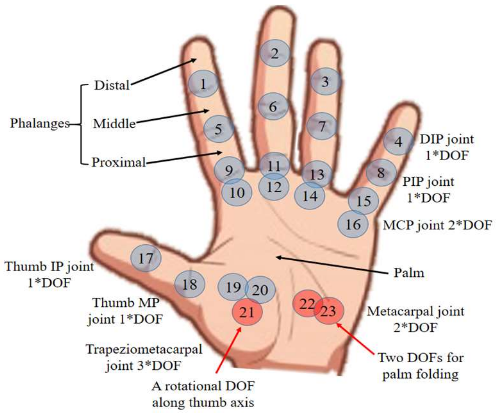

Figure 1. A commonly accepted 23-DOF human hand kinematic model. The blue DOFs are the joints captured by LEAP motion capture device. The red DOFs were unable to be identified by the device.

supporting up to 38 pneumatic channels simultaneously is provided to realize our soft end-effector actuation.

Detailed discussion of the human hand model reduction, proposed mapping synergy, and the multi-DOF actuation platform design is presented in Section III. Following the experiments to validate the proposed control and actuation system in Section IV, we apply our general and intuitive control and actuation system to most commonly used end-effector types: two, three and four-fingered soft end-effectors.

## II. Related Works

Two perspectives of previous hand control works are reviewed. The first is the control of previous multi-DOF rigid robotic hand. The control is an especially demanding task for rigid robotic hands because of the high number of DOFs required to be actuated. One of the most effective control approaches is the human hand mapping synergy, which provides complex control command to a robotic hand [16]. Four main categories of mapping approaches are Joint-to-Joint mapping, Workspace mapping, Pose mapping, and Projection mapping [17]. Joint-to-joint mapping provides a direct mapping from human hand joints to artificial hand joints [18]. This method is efficient and intuitive for the human to control an anthropomorphic hand with similar kinematic structure of human hand, but it is difficult to be applied to non-anthropomorphic rigid hand and gripper. Workspace mapping is focused on the workspace relationship between human hand and robotic hand, which usually focuses on the position of the finger-tip [19]. This approach works for non-anthropomorphic grippers, but different mathematical model is needed each time for a different artificial gripper. Pose mapping is a particular method for indirect joint angle mapping, which works well for dedicated grasping gestures [20]. However, pose mapping has limited capacity to process complex gestures. Its application is largely restricted to situations that employ simple grasp postures. Projection mapping translates the human hand into 2D or 3D workspace, which is based on delicate model providing a general human hand mapping synergy within certain modeled manipulating objects [17].

Secondly, we turn to the existing control approaches for the soft robotic hand. There are mainly two types of control approaches. The first is kinematic modeling based approach, and the second approach is without modeling. Modeling approaches attempt to construct a kinematic model for continuum deformation actuator [21], following the traditional rigid robots' precise modeling approach. Approaches without modeling are much simpler with low-level control strategy and sufficient enough for the main function of existing soft hands (e.g. adaptable picking and placing).

For our control strategy, we merge the merits of existing control methods and the merits of inherent compliance of soft robotics. We adopt the mapping approach from rigid robotic hand control and the approach without modeling from the existing soft robotic hand control.

## III. Intuitive Control and Actuation System Design

### A. Human hand study and motion capture

As a proven dexterous system, the human hand was chosen as the data source for the mapping approach to control the robotic hand. We study the structure and kinematics of the human hand first. A commonly accepted 23-DOF human hand model is illustrated in Figure 2. The thumb has 5 DOFs and each finger has 4 DOFs. Two DOFs for palm folding are located at the base of 4$^{th}$ and 5$^{th}$ finger. The motion of these 23 DOFs provides the original data source for joint-to-joint mapping synergy [22].

In the mapping synergy, the human hand motion is obtained by human hand motion capture devices. In our study Leap Motion Controller (LMC) was used. LMC has no motion limitation for the human hand. Up to 21 DOFs of the human hand can be captured by LMC (shown as the blue DOFs in Figure 2), except for the red DOFs (one rotational DOF in trapeziometacarpal joint and two DOFs for palm folding). These captured 21 DOFs are the available data source for the mapping synergy.

### B. Grasping component based mapping

With the obtained 21 DOFs as the original mapping source, we can study how the DOFs of the human hand can be mapped into soft robotic end-effector. From the existing mapping strategies that do not require a model, we adopt the joint-to-joint mapping method. Previous limitation of joint-to-joint mapping was that the method cannot be applied to robotic hands with dissimilar kinematic structure compared to human hand. To tackle this problem, we propose a grasping component approach to bridge the disparity between the human hand and soft robotic end-effectors with different kinematic structures. Soft robotic's inherent compliance and its leniency regarding control and actuation system make it possible to translate human hand's kinematics to various soft end-effectors. We change the mapping unit from a kinematically accurate component (i.e. the joint) to a grasping component. We identified 3 factors essential to grasping (thumb, fingers, and palm) from which we extracted 6 human grasping components (HGC): thumb, index, middle, ring, pinky, palm. The HGC list and the related DOF of each HGC are presented in Figure 2. These 6 HGC are the key units for human hand to achieve successful grasping. We map these 6

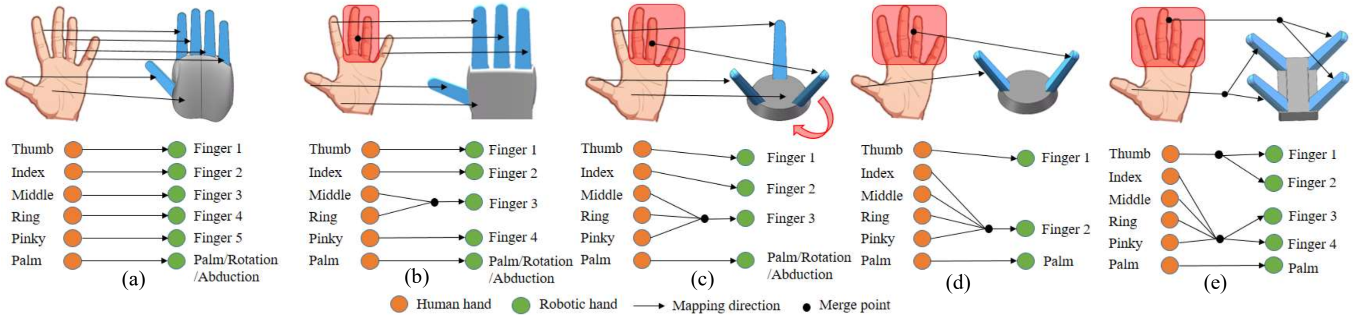


Figure 3. Examples of grasping component mapping with common soft end-effector types. (a) 5-fingered anthropomorphic hand. (b) 4-fingered anthropomorphic hand. (c) 3-fingered gripper. (d) 2-fingered gripper. (e) 4-fingered gripper.

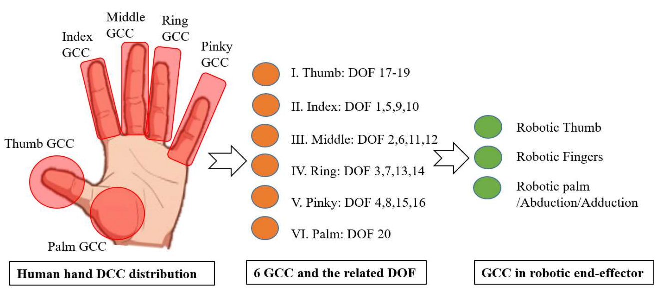


Figure 2. Grasping component mapping schematic. 6 human grasping components (HGC) map to 3 types of robotic grasping components (RGC).

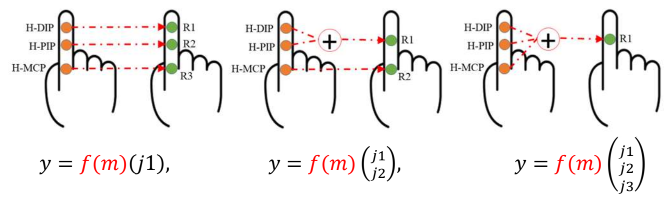


Figure 4. Reconfigured Joint-to-Joint mapping algorithm and data processing. *f(m)* is the mapping function. *j1* to *j3* are the human finger joint motion.

HGC to the related robotic grasping components (RGC). The principle of RGC is to achieve enough fingers/contact points to realize a force closure region for grasping. At least two fingers are needed to realize a stable force closure region [42]. We listed three kinds of RGC that are essential for grasping.

- Robotic thumb: Any one finger or a combination of fingers that is placed opposing the rest of the fingers.
- Robotic fingers: Individual fingers (one to four) or combinations of fingers.
- Robotic palm: Anthropomorphic robotic palm that aids thumb opposability [6, 10]; or a programmable palm that enables the rotation of fingers (i.e. abduction/adduction palm) [30]; or a fixed platform with fingers in a fixed position.

The details of the grasping component mapping schematic are illustrated in Figure 2. This mapping approach primarily focuses on the functional parts of the end-effectors. When the mapping target is an anthropomorphic soft hand, the mapping is easy to achieve with all related components directly translated as shown in Figure 3(a). As for non-anthropomorphic hands and grippers, the mapping approach reconfigures HGC arrangments.

In mechanism level, the HGC reconfiguration can be randomly chosen. However, there are natural inter-digit coordination preference in the human hand. In order to reflect the natural and intuitive control of the human hand, the HGC reconfiguration should reflect the natural motion. One optimum human finger reconfiguration approach for four, three, and two-fingered end-effectors are illustrated in Figure 3(b-d). Previous mapping reduction approaches of the human hand kinematics for an anthropomorphic hand have omitted the 5th finger [23-25]. In our approach, we utilize the 5th finger and combine the 3th and 4th finger together (Figure 3(b)). As for the 3-fingered gripper, it was important to distinguish the index finger and middle finger as separate RGC because people tend to use a three-fingered grasp and the position and control of those fingers change with object size [43]. Thus, we combined the middle finger with the ring finger and the pinky (Figure 3(c)). As for the two-fingered gripper and four-fingered gripper, the thumb opposability was prioritized. The rest of the fingers were combined with the index finger, as the thumb-index grasp is the most commonly used motion in grasping and manipulation [28-30].

For the grippers with rotational palm (Figure 3(c)), such RGC can be mapped from the human palm. Two-fingered gripper's fixed platform can also be mapped from the human palm. For some grippers with simple function, the grasping component mapping can be treated as a mapping reduction. A four-fingered parallel gripper can be regarded as a two-fingered gripper with the same mapping approach.

The grasping component mapping approach can improve the control dexterity of various soft robotic end-effectors because each robotic finger has one independent HGC to control. The component mapping solution we present here is based on the natural human hand motion consideration. For other considerations, the mapping solution can be adjusted with specific consideration.

### C. Mapping data acquisition and reconfigured joint-to-joint algorithm

In this section, we discuss how we process the data acquired from the LMC and transmit the data to the robotic end-effector. Our previous work of soft robotic hand employed a direct joint-to-joint mapping for control method as illustrated in Figure 4(a) [7]. Such mapping without significant transformation of the data was possible due to the soft robotic hand's kinematic structure matching the human hand. However, the direct joint-to-joint mapping cannot be

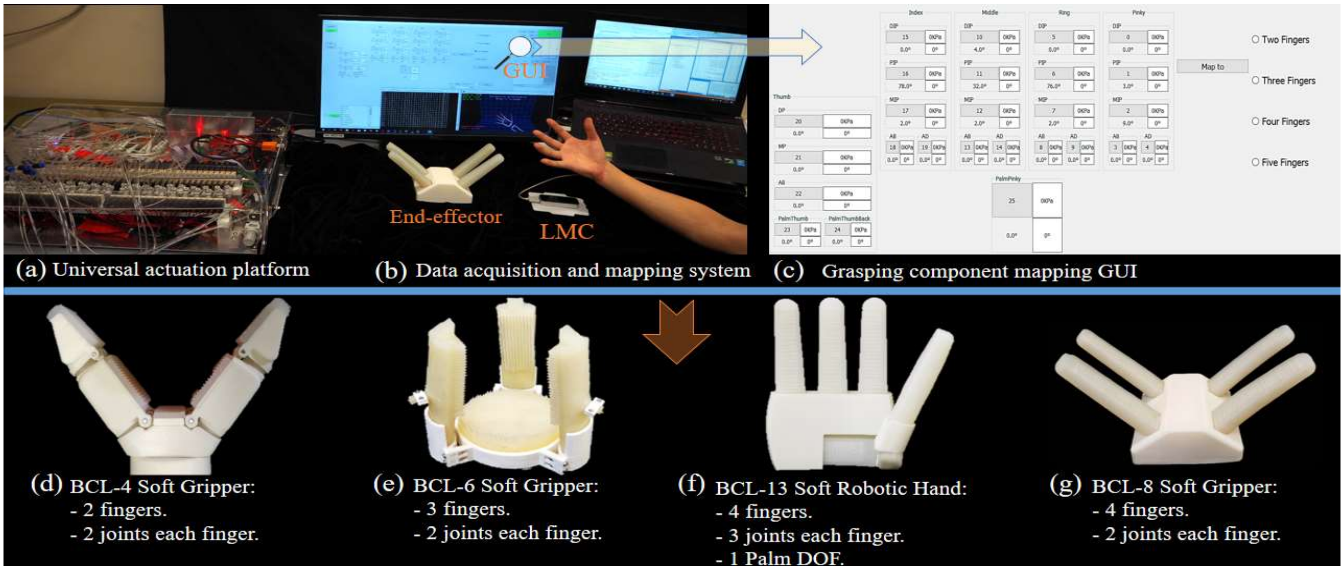


Figure 6. (a-c) Three steps for general and intuitive grasping system. (a) Data acquisition of the human hand motion data with LMC and the raw data processing. (b) The mapping realization based on grasping components. (c) Multi-DOF pneumatic actuation platform prototype. (d-g) Four soft robotic end-effector types to validate the performance of the proposed intuitive control.

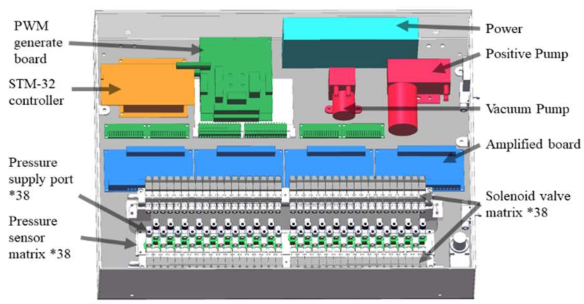


Figure 5. Multi-DOF pneumatic actuation platform.

applied to other soft robotic end-effectors that are not highly anthropomorphic. Hence, we present a generally applicable mapping method based on grasping components that can encompass end-effectors with dissimilar joint kinematics. The mapping between HGC joints and RGC joints can be a direct, one-to-one relationship, as well as a combination of several HGC joints corresponding to one RGC joint (i.e. multi-to-one), as depicted in Figure 4(b-c). The multi-to-one mapping problem can be solved by a mapping function $f(m)$. The ratio of the input combined joints to the output joint, decided by $f(m)$, determines the performance of the multi-to-one joint mapping performance. A preliminary attempt with the $f(m)$ is a linear combination will be processed in Section IV-A.

### D. Universal pneumatic actuation platform design

We present a universal pneumatic actuation platform. Developed from our previous single joint pressure based controller (PBC) and high frequency solenoid valves matrix [6, 7], the new platform is capable of actuating up to 38 DOF pneumatic robotic hand. For a high number of solenoid valves actuation, the multi-pulse width modulation (PWM) commands are created by the PWM generation board. The STM-32 board simultaneously processes different commands. The structure of the proposed pneumatic actuation platform is presented in Figure 5. This platform is efficient and affordable for various pneumatic actuation.

## IV. System Realization and Validation

### A. System realization

The intuitive grasping control system is achieved in three steps. The first step is data acquisition and mapping as depicted in Figure 6(b), the details of data acquisition and processing has been discussed in our previous work.

The second step is the grasping component mapping. A block GUI is designed to process the mapping (Figure 6(c)). The left side is the acquired human hand kinematic information. The right side is the mapping candidate soft robotic end-effector models. A list of four end-effector model presets is prepared: two-fingered, three-fingered, four-fingered, and five-fingered models. The user can select a model that matches the kinematics from the list. Then the system will direct the user to a kinematic model to define the number of joints for each finger and the bending range of each joint of the output robotic hand. After defining the relevant information of the output robotic hand, the user can link the related joints to the robotic hand model. Two kinds of mapping, joint-to-joint and multi-to-one, are selectable. As for the multi-to-one joint mapping, the user can modify the parameters in mapping function $f(x)$ as discussed above. The computer will process the mapped joint information onto the robotic joint actuation information as pressure data.

The third step is transferring the joint actuation data result to the Multi-DOF actuation platform as shown in Figure 6(a). The actuation system will process the provided position data to the related pressure actuation command.

As shown in Figure 6(d-g), four candidate soft robotic end-effectors, ranging from two fingers to four fingers, are prepared for the intuitive grasping control realization. Using the intuitive control system, we apply the mapping strategy

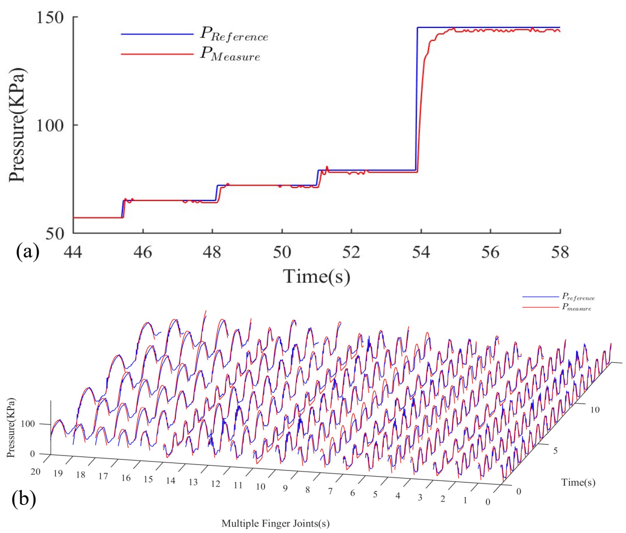


Figure 7. Performance of the proposed multi-channel actuation platform. (a) Step signal tracking performance of one channel. (b) 21 channels actuated simultaneously.

depicted in Figure 3 on these four kinds of soft end-effectors to validate the intuitive control performance.

## B. Actuation platform performance

Two tests were conducted on the proposed multi-channel pneumatic actuation platform. One is the individual channel tracking result as presented in Figure 7(a). The PBC-based control strategy performs well on the single joint step signal tracking with minor discrepancy. The accuracy is 2 kPa for a 30 $mm^3$ pneumatic actuator. The second test illustrated in Figure 7(b) presents the pneumatic platform simultaneously actuating 21 channels, the maximum number of the data can be captured by LMC. Each channel's pressure state can be identified in real-time. These two tests demonstrate the multi-channel actuation platform's excellent accuracy for pneumatic joint control and actuation. Multi-channel soft robots can be actuated by this platform simultaneously with dexterous performance.

## C. Intuitive grasping performance

Our mapping strategy bridges the gap between a complex 23-DOF human hand and various end-effectors with dissimilar kinematics. We demonstrate our general and intuitive whole hand control strategy based on grasping component mapping, as depicted in Figure 3, by executing intuitive control with four different types of soft end-effectors: two-fingered, three-fingered, four-fingered gripper, and four-fingered anthropomorphic hand. All dynamic processes are presented in our accompanying video.

As shown in Figure 8(a-d), the parallel 4-fingered BCL-8 gripper can be controlled by the human hand with four grasping modes: the gripper open mode, two single finger bending modes, and the power-grasping mode. The 4-fingered anthropomorphic BCL-13 hand can be controlled by human hand with each finger actuated independently (Figure 8(e-j)) [6, 7]. We use human hand with five fingers control the 3-fingered BCL-6 gripper (Figure 8(k-n)). Each of the

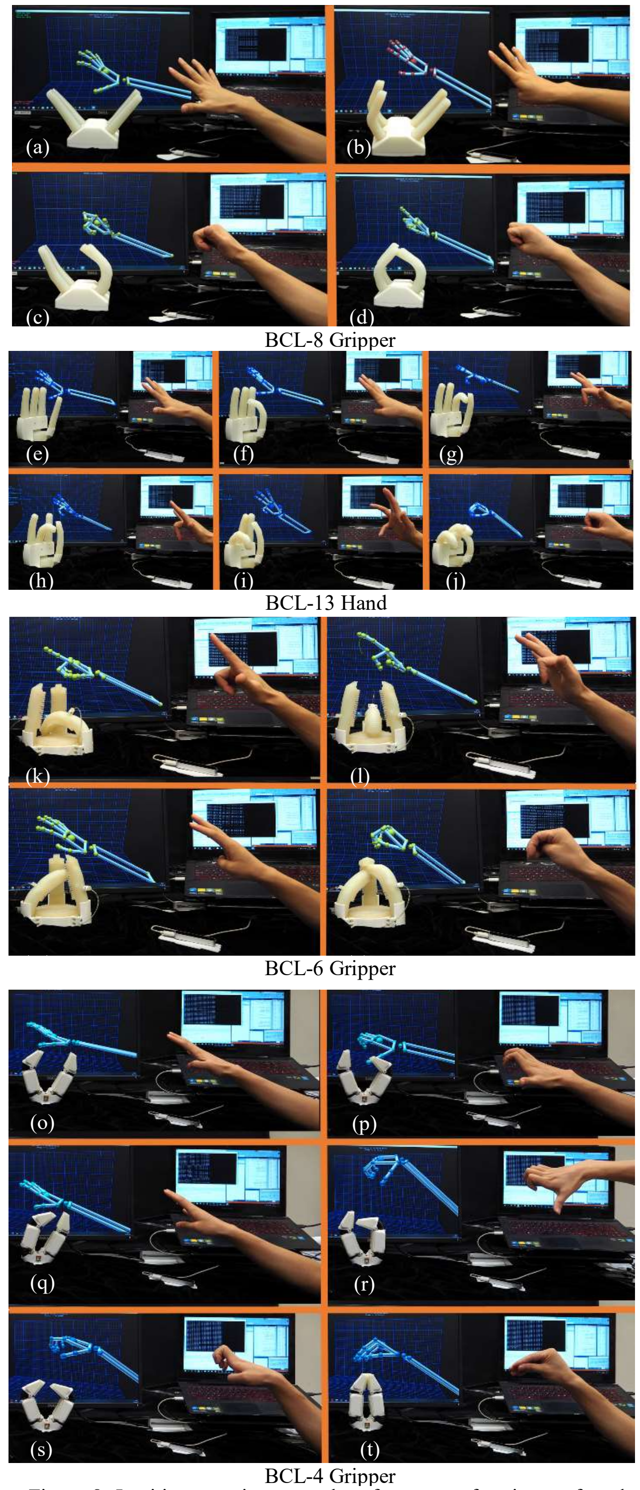


Figure 8. Intuitive grasping control performance of various soft end-effectors. (a-d) BCL-8, a 4-fingered gripper. (e-j) BCL-13 soft hand, a 4-fingered anthropomorphic hand. (k-n) BCL-6, a 3-fingered gripper. (o-t) BCL-4, a 2-fingered gripper.

three fingers of the gripper can be independently controlled by human hand independently.

In addition to individual digit control, our reconfigured joint-to-joint mapping enables the operator to actuate specific DOFs within the robotic finger as demonstrated on BCL-4 gripper shown in Figure 8(o-t). Dexterous grasping gestures can be controlled by human hand: parallel grasping, power grasping, and finger-tip pinch.

Our grasping component based mapping strategy allows the human operator to easily control and actuate each digit of the soft end-effector. Such individual control of the soft end-effector digits increases the diversity of potential grasping postures, which allows more flexibility to accommodate for different size and shape of the object.

## V. Conclusion and Future Work

In this paper, we presented a general and intuitive control approach based on grasping component mapping that can apply to a diverse range of soft robotic end effectors with dissimilar kinematics. We identified the functional components essential to grasping performance in the human hand, such as the thumb, fingers, and the palm, labeled as "Human Grasping Component" (HGC). These components are mapped to related components onto the robotic counterpart, "Robotic Grasping Component" (RGC). The mapping involves reconfiguration of the number of digits and number of joints, enabling intuitive whole hand control for the human operator of non-anthropomorphic end-effectors. A Leap Motion Controller based human hand motion capturing system is used to capture the human hand's real-time motion. A pneumatic actuation platform capable of simultaneously actuating up to 38 individual channels is used to realize the intuitive control. The proposed intuitive control strategy does not require the human operator to wear any equipment or modify their natural hand behavior to suit different end-effector structures. Our general and intuitive control approach provides a promising solution to control various soft robotic end-effectors and improves performance dexterity of soft robotic hands.

Future works include: Quantifying the grasping component mapping with simulation and experimental result; Studying the influence of the parameters in the mapping function; Including a generally applicable force feedback for robotic hands and tactile feedback for human operators.

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