Repetitive grasping with anthropomorphic skin-covered hand enables robust haptic recognition

Shinya Takamuku, Atsushi Fukuda and Koh Hosoda

***Abstract*— Skin is an essential component of artificial hands. It enables the use of object affordance for recognition and control, but due to its intrinsic locality and low density of current tactile sensors, stable and proper manual contacts with the objects are indispensable. Recently, design of hand structure have shown to be effective for adaptive grasping. However, such adaptive design are only introduced to the fingers in existing works of haptics and their role in recognition remains unclear. This paper introduces the design of the Bionic Hand; an anthropomorphic hand with adaptive design introduced to the whole hand and fully covered with sensitive skin. The experiment shows that anthropomorphic design of hand structure enables robust haptic recognition by convergence of object contact conditions into stable representative states through repetitive grasping. The structure of the human hand is found to solve the issue of narrowing down the sensor space for haptic object recognition by morphological computation.**

I. INTRODUCTION

Development of an artificial hand with the capability of the human hand is one of the grand challenges of robotics. Anthropomorphic hands suit the needs of humanoid hands and prostheses since most products found in our environment are made for the human hand. It is also likely to be easier to adapt for the amputees. While various dexterous hands have been unveiled till today [1] [2], issues on the skin still remain as a bottleneck [3]. Cutaneous sense provides rich information about manipulation states [4], affordances to lead tool use such as mobility [5],as well as unique information for object recognition; object properties such as stiffness [6] and heat characteristics [7]. Furthermore, its deformation and friction properties play essential roles in manipulation [8]. Development of the skin and a method for haptic sensing are prerequisites for the next generation of artificial hands.

An intrinsic difficulty of haptic sensing is due to its locality. Tactile sensors are local compared to vision, and its recognition depends heavily on the contact conditions[1]. The low resolution of current tactile sensors makes the problem even more critical since slight change in contact conditions can dramatically change the sensory output. It is then an important issue how to obtain proper and stable manual contact with the objects. Visual feedback is not always available for this purpose due to occlusions. Even if rich sensory feedback is provided, calculation of the proper manual contact is still a nontrivial problem.

Recently, the design of hand structure have shown to be helpful for this issue. As Pfeifer et al. [9] states, careful design of hand morphology enables passive movements of the digits leading to ideal contact with the objects through interaction. Several studies have shown the suitability of anthropomorphic design for obtaining such adaptive grasps[2]. Underactuation, actuation of the hand with number of actuators smaller than the degrees-of-freedom, is now a popular design to benefit from their passive adaptation to object shape [10] [11] [1]. Compliant joints [12] [13] and soft finger tips [8] are also found to improve the adaptability and stability of the grasps respectively. However, such adaptive design are only applied to the fingers in existing works on tactual recognition [10] [14]. Consequently, they are in essence a gripper instead of a hand, and their adaptations to objects are limited to two dimension space. Furthermore, previous works lack comparative experiments to show the effect of adaptive design for robust haptic recognition. In order to investigate the role of hand adaptability for realistic haptic recognition, these limitations need to be overcome.

This paper introduces the design of the Bionic Hand; an anthropomorphic hand with adaptive design introduced to the whole hand and fully covered with sensitive, deformable skin. The hand is developed by covering the Yokoi hand [15] with a soft anthropomorphic skin developed by Tada et al [16], and actuated with antagonistic pneumatic actuators. The Yokoi hand [15] in its own equip high adaptability by underactuated fingers coming together when bent. We further improve the adaptability by covering the hand with deformable skins having anthropomorphic arch structure known to be essential for stable grasps [17], and actuating it with antagonistic pneumatic actuators to obtain large range of compliance in the joints. Experimental results are given showing that anthropomorphic design of hand structure enables robust haptic recognition by convergence of object contact conditions into stable representative states through repetitive grasping. Since products found in our environments are designed for the human hand, it is likely that proper grasps on the objects are found as stable states. The repetitive grasps on the object is found to help contact condition convergence into optimal states avoiding suboptimal ones.

The paper is organized as follows. First, hand design is described. Then, experimental results showing the ability of adaptive grasp and robust haptic recognition follows. Finally, discussions, conclusions and future works are given.

All authors are from Department of Adaptive Machine Systems,Graduate School of Enginnering, Osaka University, located at 2-1 Yamadaoka, Suita, Osaka, 565-0871, JAPAN. Shinya Takamuku and Koh Hosoda are also members of the JST ERATO Asada Project {shinya.takamuku,hosoda}@ams.eng.osaka-u.ac.jp

[1]The term contact condition refers to the posture of the hand and its positional relation with the object in touch.

[2]The term adaptive refers to the ability of adjusting the grasping posture to obtain proper manual contact with the objects.

II. The Design of Bionic Hand

The Bionic Hand, shown in Fig. 1, has an endo-skeletal structure similar to that of UB Hand [18]. The hand obtains cutaneous sense from a modified version of the artificial sensitive skin introduced in [16]. Anthropomorphic structure and antagonistic pneumatic actuation are introduced to enable adaptive grasps.

Fig. 1. **Photograph of Bionic Hand**. The hand is covered with sensitive skins and actuated with antagonistic pneumatic actuators to make the hand strong and compliant.

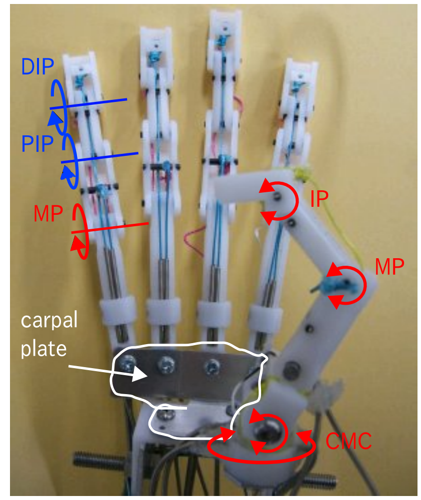


Fig. 2. **Skeletal structure** [15]. The distal interphalangeal (DIP) joint and the proximal interphalangeal (PIP) joints are underactuated; acted with the same set of actuators. The carpal plate mounting the fingers together is bent between the digits to have the fingers come together when the hand is closed.

TABLE I

Number of sensing devices in the skin.

finger/palm	part	# of PVDF	# of strain gauge
finger	distal	2	1
	proximal	1	1
	middle/metacarpal	1	1
palm		6	6

A. Musculoskeletal Structure

The prosthetic hand developed by Yokoi et al. [15] is utilized as the skeletal structure of the hand. The overview is shown in Fig. 2. The hand has 16 degrees of freedom (DOF) with the DIP (distal interphalangeal) and PIP (proximal interphalangeal) joints actuated with the same actuators. The underactuated digits, also found in the human hand, adapt to object shape by bending the joints from the proximal until the phalanges hit the object. The digits are aligned with the corpus plate so that the fingertips will come together when the hand is closed. This design, also inspired from human morphology [17], enables the digits to move the objects into stable condition on the palm. The hand is driven by 22 air cylinders attached antagonistically. Although pneumatic actuators have drawback that the response speed is slow, it also has the advantage of high power-to-weight ratio and large range of compliance at the joints. Joint compliance can be obtained by lowering the pressure of the antagonistic actuators.

B. Skin Structure

The anthropomorphic skin previously developed by our group is composed of multiple layers with sensing devices detecting strain and its velocity [16] as in the case of human skins [19]. The anthropomorphic skin shows high sensitivity such as detecting textures [16] and slippage [4]. Our challenge for developing the hand was to improve our anthropomorphic skin so that it could be extended to the whole hand. In order to obtain ideal deformation properties for stable grasp and manipulation, we chose the skin structure shown in Fig. 3. The construction process is as follows. First you attach a glove on the musculoskeletal structure described in the previous section to keep the skin and the bones apart. Then, finger sacks and palm sheets composed of relatively stiff polyurethane materials with strain gauges and PVDF (polyvinylidene fluoride) films inside are attached. PVDF films are capable of detecting the velocities of strain to obtain high sensitivity. A photograph of the hand at this development step is shown in Fig. 4. Wiring for the sensor devices runs through the center of the fingers so that there are not so much stretches nor compressions. Finally, the hand is covered with another glove and relatively soft polyurethane material is poured in between the two gloves. Lines of the skin on the joints and on the palm, shown in Fig.1, are produced by binding the gloves with the bones during the last process. The last process also produces an artificial thenar eminence which forms arch structure on the palm considered to be essential for adaptive grasping [17]. Numbers of sensing devices in the skin is described in Table I. Sensors in the palm are distributed equally, and multiple sensors are mounted in different depth in the fingers. The multi-layer structure of polyurethane material with different stiffness provides high sensing abilities [16], and improves stability of manipulation; i.e., fingers would be too soft to grasp objects properly without the finger sacks.

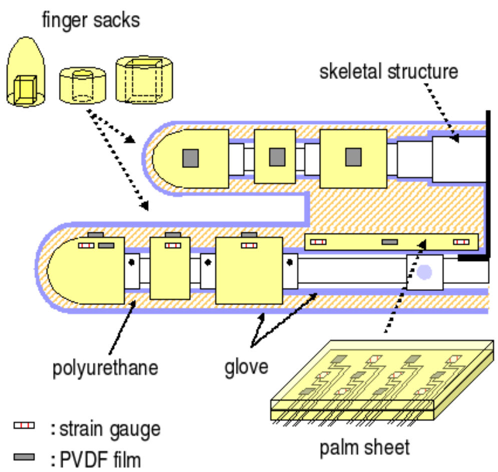


Fig. 3. **Skin structure**. First, the skeletal structure is covered with a glove. Then, finger sacks and palm sheets with strain gauges and PVDF films mounted in relatively stiff polyurethane material are attached. Finally, another glove is put on the hand and soft polyurethane material is poured in between.

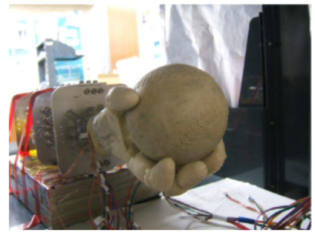
Fig. 4. **Structuring of the inside skin**. The photograph shows the inside structure of the skin. The wires for the sensing devices are winded down to avoid breaking by tension.

C. Control System

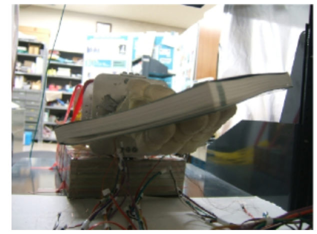
Digital outputs from the computer through DIO cards control on/off valves to supply/stop/exhaust air into/from the air cylinders by 250Hz. The pressured air from a compressor is controlled into stable pressure with a regulator to be transmitted to the actuators through the valves. Sensor signals from the strain gauges, PVDF films, and pressure sensors are amplified and fed to the host computer via ADC cards at a rate of 250Hz. The computer runs RTAI realtime Linux.

III. Adaptive Grasp

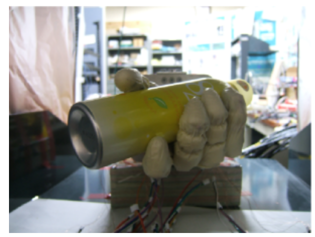
First we conducted a preliminary experiment observing the ability of grasping various objects. We gave objects with various shape to the Bionic Hand controlled with constant grasping actuation. Fig. 5 shows the hand producing stable grasping posture through interaction even though there are no changes in the actuation. Rough control is enough to have proper grasps for various objects, and the skin is at least not disturbing the grasps.



(a) ball



(b) book



(c) bottle

(d) prism

Fig. 5. **Adaptive grasping of various objects**. Spherical, cylindrical, and flat grasping postures are generated through interaction with the objects even though the actuation is the same for all the objects.

IV. Haptic Object Recognition

In order to show that adaptation by hand morphology enables robust haptic recognition, we investigate the transition of haptic sensory values during repetitive grasping. We expect that the contact condition for the same object will converge to few stable conditions after the repetitive grasps and the converging condition will differ when the objects are different, thus easing the recognition.

A. Setup

The repetitive grasp motion is shown in Fig. 6. First comes a large grasp ending after 9s (a-c). Then, grasps of 4.4s cycle with relatively smaller opening follows (d,e). The hand is placed so that the palm faces the gravity to avoid the object falling down. The hand was given the objects shown in Fig. 7 varying the initial contact condition. The sizes of the objects are described in Table II. The length of the finger from the MP joint is approx. 80 mm. The objects were grasped with five different initial contact conditions each. The initial contact condition of the prism, cylinder, and bottle was varied by rotating the object on the palm plane within the range of approx. 45 degrees. The ball was put on different positions.

TABLE II

Size of the Objects

	diameter / length of each side (mm)	height (mm)
prism	38	151
cylinder	50	140
bottle	42.5 (upper part) / 55.5 (bottom part)	124.5
ball	70	70

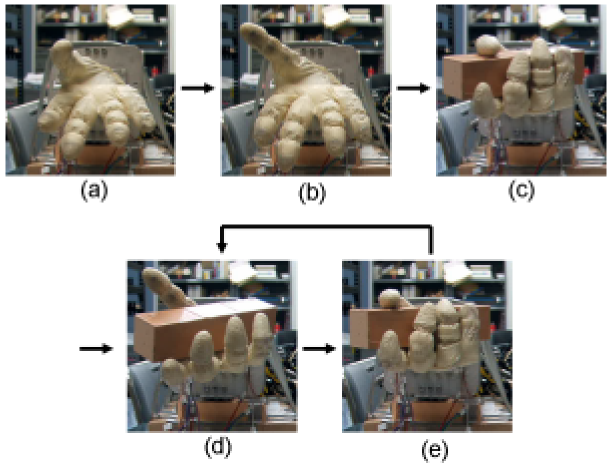
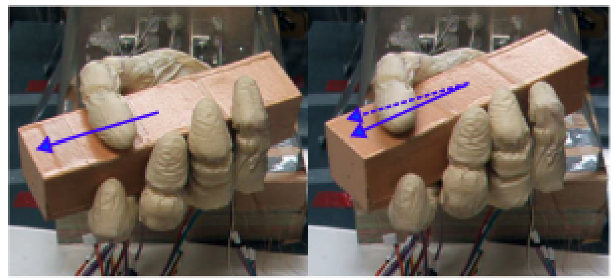


Fig. 6. **Motion of repetitive grasps**.

Fig. 7. **Photograph of the objects used in the experiment**.

(a) case1



(b) case2

Fig. 8. **Adaptation through repetitive grasping by hand morphology**. The left figure shows the contact condition in the first grasp, while the right figure shows the contact condition in the 10th grasp. In the left figure, the blue dotted allow shows the initial angle, whereas the blue solid allow shows the converged angle. Even though the two cases differ in initial conditions, they both converge to common contact condition through repetitive grasps.

B. Transitions of cutaneous sensory values

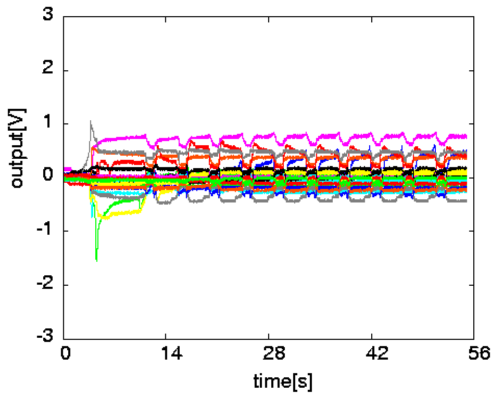
The contact condition converged into discriminative conditions through repetitive grasps. An example of which is shown in Fig. 8. Even though the initial contact condition differs between the two trials, they both converge into similar ones. The sensory outputs from the strain gauges and the PVDF films for the two trials are shown in Fig. 9 and Fig. 10 respectively. The sensory values are also converging into a common attractor through the grasping. Although the outputs of the PVDF films are found to detect the contact and release of the objects, it did not include so much data for this particular experiment and will not be used in the present work.

C. Analysis of Variance

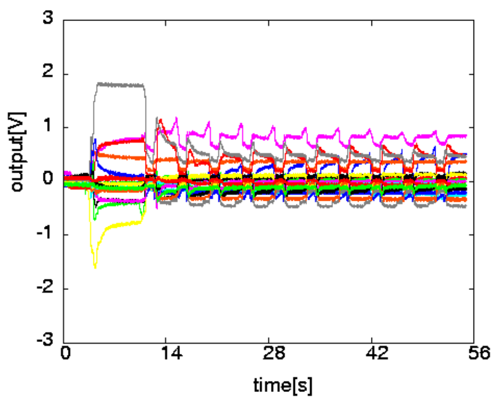
In order to investigate if the cutaneous signals during the grasps are efficient for object recognition, analysis of variances for the strain gauge outputs during each grasp is given. Fig. 11 shows the transitions of mean variance within the trials of the same object (within class variance), the variance between the mean values of different objects (between class variance), and the ratio of the two (variance ratio). Note that only the strain gauge output at the grasping posture is used and the variance within the class is due to variations in initial contact conditions. The distance measure is Euclidean. The figure shows that as the hand repeat the grasp on the object, within class variance decreases and the variance ratio rises. This shows that the cutaneous signals are converging into representative values for the objects to become features appropriate for object recognition.

D. Analysis with a self-organizing map

A self-organizing map (SOM) is an artificial neural network that is trained using unsupervised learning to produce a low-dimensional , discretized representation of the input space of the training samples. Since the output of the network, called the map, preserves the topological properties of the input space, it is used for the visualization of the distances of the cutaneous signals during grasps within/between the objects. We used the software package SOM-pak version 3.1 [20], where the size of the map was 32×32, topology was a hexagonal lattice and neighboring function type used was bubble. Fig. 12 shows the clustering of the self-organizing map with strain gauge values from the first and 10th grasps respectively. While data plots for the same object are mixed in the clustering with the first grasp signals, the objects are separated in the clustering with the 10th grasp.

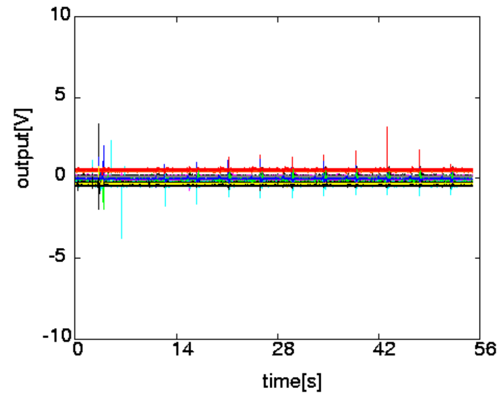


(a) case1

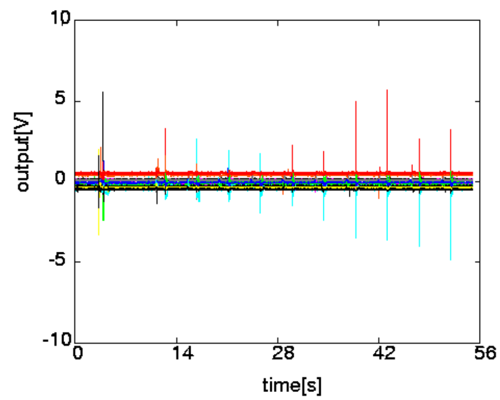


(b) case2

Fig. 9. **Strain gauge values during repetitive grasping**. Outputs from the strain gauges are converging into a common attractor.



(a) case1



(b) case2

Fig. 10. **PVDF film values during repetitive grasping**. The PVDF film is detecting the contact and releasing of the objects.

V. Discussion, Conclusion and Future Work

The analysis of variances and visualization with the self-organizing map both show that the cutaneous sensory values obtained during grasping converges into values representative of each object. Since the actuation for the repetitive grasps is constant during the experiment, the convergence should be due to the morphological adaptability of the hand. Thus, the idea of robust haptic recognition by virtue of adaptability of anthropomorphic morphology of the hand is supported. Reduction of sensory space is essential for object recognition [21] [22]. Flies [23] and human infants [24] are found to actively reduce the space by moving themselves or the objects to constant relative position. The result of the present paper shows that the structure found in the human hand solves the same issue of narrowing down the sensor space for object recognition by morphological computation. Note that once the relative position of the object is limited, any modality can be utilized for recognition. The effect is not only for tactile recognition.

Several questions remain to be investigated as future work. We combined several ideas for improving the adaptability of the hand. However, the role of each idea is not clear; i.e., what role does each design have in the overall adaptability of the hand? Only the role of repetitive grasping to help the convergence was investigated in the current paper. Another question is the conditions that should be fulfilled to obtain proper grasps with our method. Clearly, the hand should have roughly correct hand shapes for obtaining proper grasps. The shaping of the hand before grasping, often refered to as preshaping, should be considered. Finally, the issue of affordance remains. Since the hand has humanlike morphology and most products found in our environment are designed for the human hand, it is likely that the proper grasps for those products can be found as stable states by our method. Once such grasp is be obtained, stable, reproducible sensory feedback could be obtained to lead tool use. The possibility would be explored in the near future.

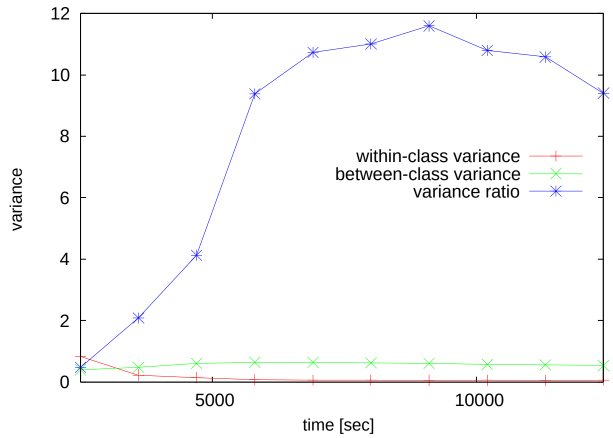
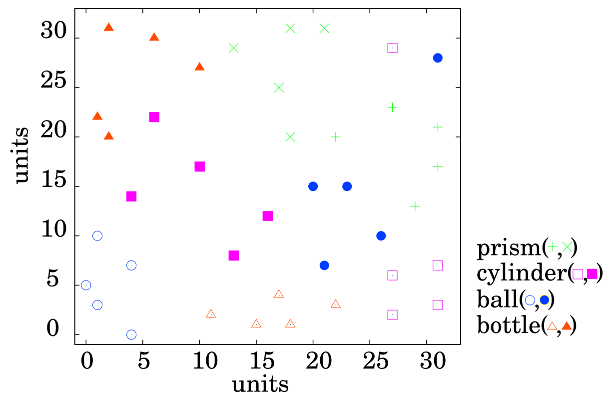
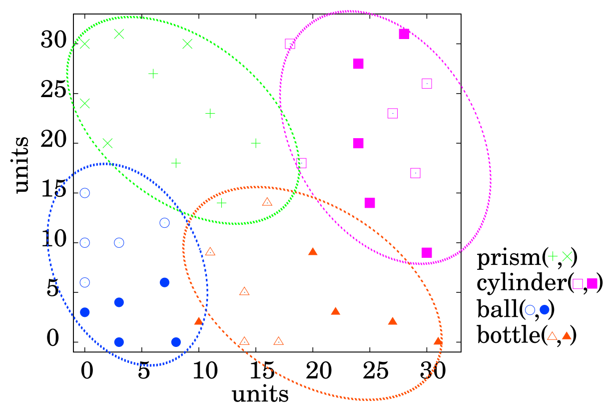


Fig. 11. **Variance analysis**. The within class variance reduces and the variance ratio rises through the repetitive grasps.



(a) first grasp



(b) 10th grasp

Fig. 12. **Som clustering**. Clustering of the self-organizing map is given where units most active for each object trial data is plotted. The graph shows the distance of sensory data between/within each object. Points with line crossings represent prisms, squares represent cylinders, circles represent balls and triangles represent bottles. While data plots for the same object are mixed in the clustering with the first grasp signals, the objects are separated in the clustering with the 10th grasp.

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