Robust Haptic Recognition by Anthropomorphic Robot Hand

Koh Hosoda, Osaka University

1. Introduction

We humans easily manipulate a variety of objects by our hands. During exploring the object, we gather rich information on it by haptics together with vision. The object image including both haptic and visual information obtained through such exploration is, in turn, the key for realizing dexterous manipulation. Reproducing such co-development of sensing and adaptive/dexterous manipulation by a robotic hand is one of ultimate goals of robotics, and further, it would be essential for understanding human's object recognition and manipulation.

Although many robotic hands have been developed, their performance is by far less than that of human hands. One of reasons is supposed to be difference in grasping strategies. Historically speaking, researches on robotic hands mainly focused on pinching manipulation (e.g. [Nagai93]) because the analysis was easy with point-contact conditions. Based on the analysis, they applied control schemes using force/touch sensors at the fingertips [Kaneko07, Liu08]. Since the contact points are restricted on fingertips, it is easy for the robot to calculate how it grasps the object (a holding polygon) and how large it should exert force based on friction corn analysis. Meanwhile, resultant grasping is very brittle since slip of one contacting fingertip leads to dropping the object.

The hand structure that only has sensors at fingertips also restricts the ability of sensing. A human hand is, in contrast, covered with soft skin and distributed receptors of several kinds in different depth. These receptors are not only for manipulating the object (sense for acting). But, the structure of our hands allows exploring the object to cumulate information on it (act for sensing) [Pfeifer 06]. During such a process, we would not only touch/grasp it statically but also act on it by some ways such as lateral motion, pressure, static contact, unsupported holding, enclosure, which is called exploratory procedures [Lederman87]. Soft skin with many receptors enables stable grasping by multi-faced contact and gathering rich information on the object.

To achieve human-like stable manipulation and robust recognition, we have built an anthropomorphic robot hand, a Bionic Hand, covered with soft silicon skin and equipped with distributed tactile receptors. It can realize stable grasping with the object and gather rich information on the object. It has ability to reproduce exploratory procedures of humans, and eventually, can be a very good tool for understanding human's object manipulation/recognition by hands. So far, we have demonstrated the sensing ability of soft skin with distributed receptors on lateral motion and pressure [Hosoda06]. In this chapter, we discuss on enclosure, one of exploratory procedures on the object, which obviously needs hand morphology.

If the hand has so many receptors, small change in position and orientation of a manipulated object leads to large change of the haptic pattern, and as a result, object recognition tends to be unstable. This could be the case with human haptic recognition. The goal of this chapter is to realize robust human-like haptic recognition by an anthropomorphic robotic hand. For stabilizing recognition, we propose to utilize physical interaction between the hand and the object: repetitive grasping. Thanks to several physical features of the hand, Bionic Hand can recognize object class by the repetitive grasping scheme, which is demonstrated by experiments.

2. Design of Bionic Hand

Bionic Hand is designed for realizing human-like adaptive and robust haptics. It has an endo-skeletal structure covered with soft skin in which many tactile receptors are embedded. It is driven by pneumatic actuators for realizing joint compliance. A photograph of a developed hand is show in Figure 1.

2.1 Why Human-like Structure?

Dexterous manipulation and categorization are typical intelligent behaviors of humans. Therefore, to understand the human intelligence, it is inevitable to study manipulation and categorization by hands. However, we still do not know much about the ability/function of our hands. To understand the manipulation/categorization skill in the daily life, we suppose that we have to reproduce the human-like structure and move it in daily life situations.

Especially, what we like to discuss is how the robotic hand can be used for generating sensor stimulus on the object by exploring. This aspect is not really well-studied so far while on another aspect, sensors are used for control, is intensively studied [Pfeifer 06]. Therefore, to handle the daily object, the hand is designed scalable to the human one: length and degrees of freedom. As a result, the developed Bionic Hand can grasp variety of objects without sophisticated feedback control.

2.2 Musculoskeletal Structure

A prosthetic hand developed by Yokoi et al. [Yokoi04] is utilized as the skeletal structure of the hand (show in Figure 2). The hand has 16 joints: the thumb has 4 joints, and index, middle, ring, and little fingers have 3 joints for each. The DIP (distal interphalangeal) and PIP (proximal interphalangeal) joints are actuated with the same actuators via underactuated tendon system. Underactuation, also found in the human hand, enables the fingers to adapt to the object shape (similar structure is used in [Fukaya00, Lee03, Biagiotti05, Saliba07, Dalley09]). In total, 11 joints can be controlled independently. The fingers are aligned with the corpus plate so that the fingertips will come together when the hand is closed [Takamuku07]. The design, which is inspired from human morphology [Kapandji82], lets the manipulated object move into stable condition in the palm.

The hand is driven by 22 air cylinders antagonistically so that we can realize joint compliance (see Figure 3). Each cylinder is controlled by an ON/OFF valve. The valve is operated by a host computer via DI/O connection by 250 Hz. Pressured air from a compressor is fed into the actuators through valves. Sensing signals from the receptors are also sampled by 250 Hz.

2.2 Skin structure

Hosoda et al. developed anthropomorphic artificial skin consisting of multiple layers with two types of receptors [Hosoda06]: one for sensing local strain and the other for sensing strain velocity as the case in human skin. It shows high sensitivity such as detecting textures [Hosoda06] and slippage [Tada07]. Bionic Hand inherits the same structure not only in the fingers but also in the palm (Figure 4). It has two layers: inner one is relatively hard (finger sacks in Figure 4, see Figure 5) and outer soft layer (hatched area in Figure 4). We adopt strain gauges and PVDF films as receptors that sense strain and strain velocity, respectively. Every finger has 3 strain gauges and 4 PVDF films and the palm has 6 strain gauges and 6 PVDF films.

2.3 Adaptive Grasping

First we conducted a preliminary experiment observing the grasping ability of the hand for various objects. We gave objects with varying shape to the hand controlled with constant grasping actuation. It adaptively changes grasping posture through interaction even though the actuation does not change (several examples are shown in Figure 6). This demonstrates that rough control is enough to have proper grasps for various objects.

3 Stable Recognition through Repetitive Grasping

Bionic hand has many receptors distributed in the skin like a human hand. Since each receptor gets only local information, and therefore, such morphology induces another difficulty: Small change in position and orientation of the manipulated object causes large change of sensation. We adopt repetitive grasping strategy by which the hand grasps and releases the object repetitively. If the hand has suitable compliance and morphology, the object will move to the most stable position and orientation in the hand.

3.1 Repetitive Grasping strategy

The repetitive grasping sequence is shown in Figure 7. Through (a) to (c), the hand grasps the object (in this case, a cuboid) in 9sec. Once it grasps the object, it releases the object a little bit (d) so that it does not release the object completely, and grasps it again (e) in 4.4sec. The hand repeats releasing and grasping through (d) to (e) several times. We applied a fixed valve sequence (an ON/OFF pattern) to realize the motion. Because of the morphology and compliance of the hand, the manipulated object moves to a certain stable position/orientation without falling down through the process. In Figure 8, we show two pairs of initial and resultant final postures. Even though the initial postures are different (left), the object will moves to almost the same posture after repetitive grasping (right).

Transition of strain gauge outputs and that of PVDF films are shown in Figure 9 and 10, respectively. The peaks of PVDF films tell us when a part of hand contacts with the object, but they do not supply us any information on the geometry of the object. At the beginning of the sequence, the strain gauge outputs are different between two different initial conditions. After a whole, the outputs become similar as a result of the repetitive grasping. This intuitively demonstrates that the hand can detect the object by a pattern of strain gauge outputs after certain times of grasping.

3.2 Classify Objects based on Haptic Sensory Information

We investigated the ability to classify the shape of the object based on patterns of strain gauges. At the beginning of the repetitive grasping sequence, the sensed pattern is not stable since the initial postures are different among trials. After several times of grasping, the object may become around a certain stable posture thanks to the morphology and compliance of the hand, and the pattern is expected to be stable.

The objects used for the grasping experiments are shown in Figure 11. We gave 4 different objects to the hand varying their initial postures: a cuboid, a cylinder, a bottle, and a ball. They are hard and not deformable. One trial consisted of 10 times of grasping. We conducted 10 trials for each object, 5 of them started from roughly the same initial posture. Therefore, we pursued 40 trials totally.

First, we investigated within-class variance, between-class variance (Figure 12), and variance ratio (Figure 13). Data from all 20 strain gauges were used for calculating variances. The with-in class variance decreases while between-class variance does not change so much over times of grasping. As a result, variance ratio increases, which means that after several times of grasping, the hand can differentiate these object.

For visualizing the result and understanding it intuitively, we apply self-organizing-map technique to decrease the 20-dimensional strain vector. The size of SOM was 32x32. The result is shown in Figure 14. Because we roughly started the trials from two initial postures, we can see that there are 2 clusters for each object at the first grasp. For example, solid and hollow triangles form two clusters, but they are distant at the first grasp, which means that the hand grasped the bottle roughly from two different initial postures. In this stage, the hand cannot distinguish the objects. At 10th grasp, these two clusters gather and form a large one for each object. This means that after 10 times of repetitive grasping, the hand can distinguish the objects even from different initial postures.

These experimental results demonstrate that the hand can distinguish the objects after several times of repetitive grasping even if the initial postures are different.

4 Discussion and Future work

The analysis of variance and visualization by self-organizing-map both show that the sensed pattern of strain gauges obtained during grasping converges into discriminative clusters representative of each object. Since the actuation pattern for the repetitive grasping does not change through experiments, the differences in the clusters should be due to the morphology and compliance of the hand. Therefore, we can conclude that the idea of robust haptic recognition through repetitive grasping by virtue of morphology of the anthropomorphic hand is supported.

The objects used in the experiments are rigid but the robot hand can manipulate soft objects as well because of its compliance. In such a case, however, the interaction between the hand and the object becomes more complicated. We could use proprioceptive sensors such as joint angle sensors and apply proprioceptive feedback for controlling the hand to modulate the interaction. We should investigate such interaction as well, and show that the hand and proposed strategy can be applied for soft object.

We did not use PVDF films directly for distinguishing the objects in this paper. In another paper, we have shown that these receptors can be utilized to sense materials by two types of exploratory procedures: lateral motion and pressure[Hosoda06]. We suppose that combination of these receptors and exploratory procedures would lead to more sophisticated sensing of the object. Moreover, combination with other sensations such as vision would enable the robot to build concept of objects. It can gather rich information on the object in different modalities and construct association. Such association is supposed to be the key to build the concept of objects [Pfeifer06]. Eventually, we could shed a light to understand how the human construct the concept of the objects in a constructivist approach.

References

[Nagai93] K. Nagai and T. Yoshikawa, “Dynamic manipulation/grasping control of multifingered robot hands,” in Proc. IEEE Int. Conf. Robotics and Automation, 1993, pp. 1027–1032.

[Kaneko07] K. Kaneko, K. Harada, and F. Kanehiro, “Development of multi-fingered hand for life-size humanoid robots,” Proceedings of 2007 IEEE International Conference on Robotics & Automation, pp. 913-920.

[Liu08] H. Liu et al., “The modular multisensory DLR-HIT-Hand,” IEEE/ASME Transaction on Mechatronics, Vol. 13, No. 4, 2008.

[Lederman87] S. Lederman and R. Klatzky, "Hand movements: A wind into haptic object recognition," Cognitive Psychology, Vol.19, pp.342-368, 1987.

[Hosoda06] K. Hosoda, Y. Tada, and M. Asada, "Anthropomorphic robotic soft fingertip with randomly distributed receptors", Robotics and Autonomous Systems, Vol.54, No.2, pp.104-109, 2006.

[Yokoi04] H. Yokoi et al., “Mutual Adaptation in a Prosthetics Application Embodied Artificial Intelligence”, Fumiya Iida et al. Eds., Springer-Verlag, pp. 146-159, 2004.

[Biagiotti05] L. Biagiotti et al., “Development of UB Hand 3: Early Results”, Proceedings of IEEE International Conference on Robotics and Automation, pp. 4488-4493, 2005.

[Saliba07] M. A. Saliba and M. Axiak, “Design of a compact, dexterous robot hand with remotely located actuators and sensors”, 15th Mediterranean Conference on Control and Automation, pp. 1-6, 2007.

[Dalley09] S. A. Dalley et al., “Design of a Multifunctional Anthropomorphic Prosthetic Hand With Extrinsic Actuation”, IEEE/ASME Transaction on Mechatronics, pp.1-8, 2009.

[Takamuku07] S. Takamuku et al., “Haptic discrimination of material properties by a robotic hand”, 6th International Conference on Development and Learning, 2007.
[Lee03] Y. K. Lee and I. Shimoyama, “A Skeletal Framework Artificial Hand Actuated by Pneumatic Artificial Muscles”, Morpho-functional Machines: The New Species, Fumio Hara and Rolf Pfeifer eds., Springer, pp.131-143, 2003.
[Fukaya00] N. Fukaya et al., “Design of the TUAU/Karlsruhe Humanoid Hand”, Proceedings of the 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2000.
[Kapandji82] A. I. Kapandji, “The Physiology of the Joints, 5th edition, Upper Limb”, Churchill Livingstone, 1982.
[Tada07] Y. Tada and K. Hosoda, “Acquisition of Multi-Modal Expression of Slip through Pick-up Experiences”, Advanced Robotics, Vol.21, No.5, pp.601-617, 2007.
[Pfeifer06] R. Pfeifer and J. Bongard, "How the body shapes the way we think", The MIT Press, 2006.

Figure 1: Photograph of Bionic Hand: The hand has anthropomorphic structure with sensitive skin, and actuated with antagonistic pneumatic actuators.

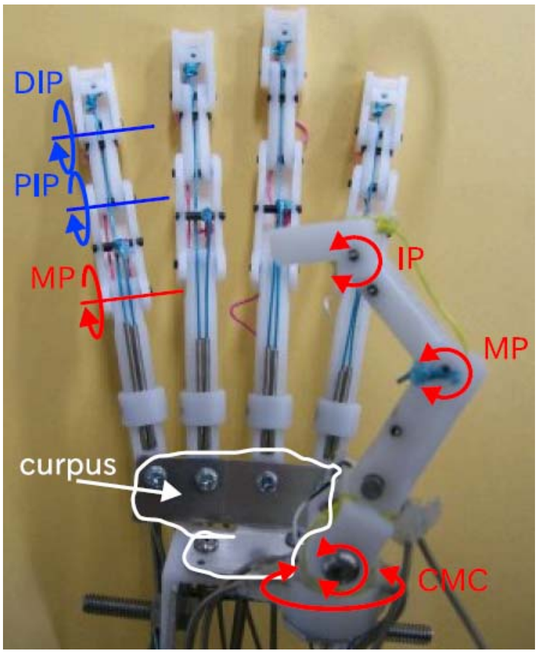


Figure 2: Skeletal structure [Yokoi04]. Distal interphalangeal (DIP) and Proximal interphalangeal (PIP) joints are underactuated; actuated by the same set of actuators. The curpus plate mounting the fingers together is bent between the fingers to have the fingers come together when the hand is closed.

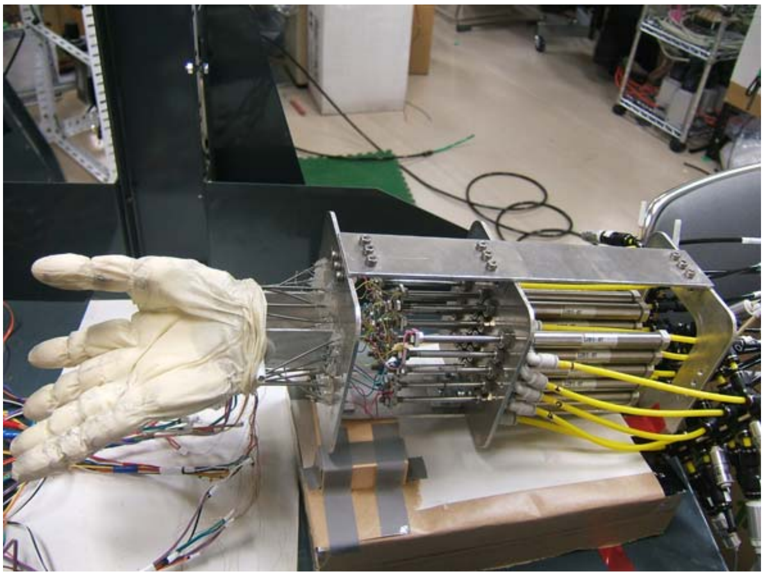


Figure 3: Bionic Hand is driven antagonistically by air cylinders. It has 11 independent joints and 22 pneumatic cylinders. The pressure of each cylinder can be observed to estimate the grasping force.

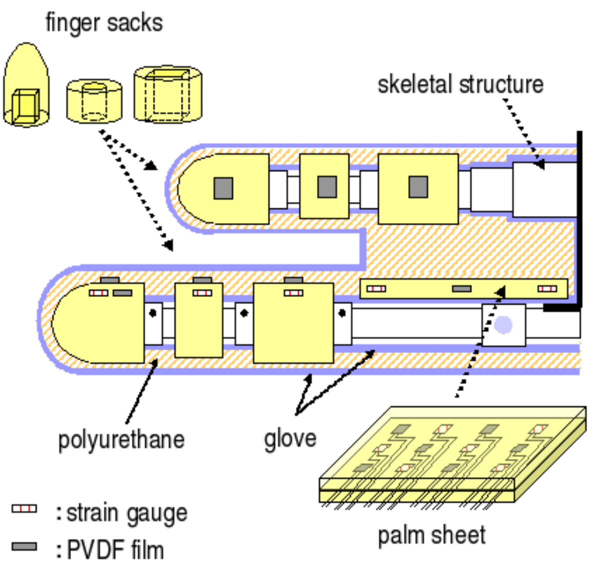


Figure 4: Skin structure: First, the skeletal structure is covered with a glove. Then, finger sacks and palm sheets with strain gauges and PVDF films mounted in relatively stiff polyurethane material are attached. Finally, another grove is put on the hand and soft polyurethane material is poured in between.

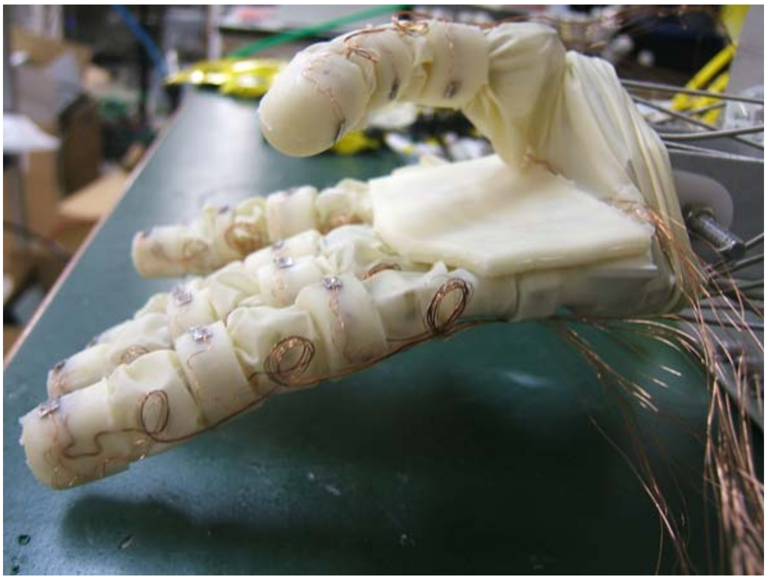
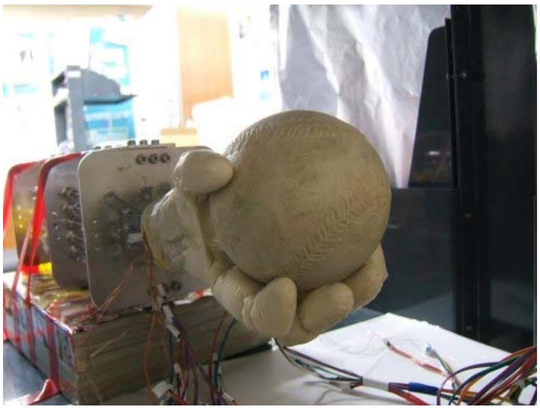


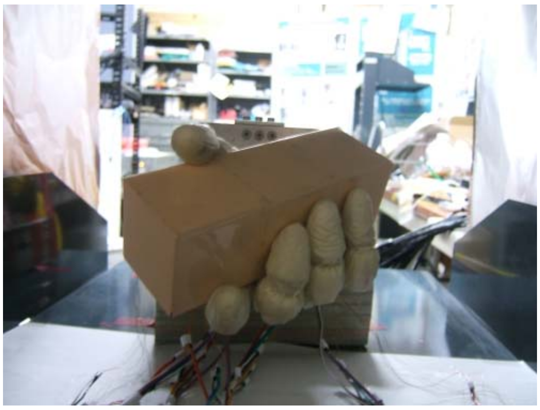
Figure 5: Structuring of the inside skin: The photograph shows the inside structure of the skin. This layer is made from relatively hard polyurethane. Several receptors are pasted on this structure, and will be covered with another glove stuffed with softer polyurethane. The wires for the sensing devices are winded down to avoid breaking by tension.



(a) a ball

(b) a book

(c) a bottle



(d) a cuboid

Figure 6: Adaptive grasping of various objects: We gave objects with varying shape to the hand controlled with constant grasping actuation. Spherical, cylindrical, and flat grasping postures are generated through interaction with the objects even though the actuation is the same for all the objects.

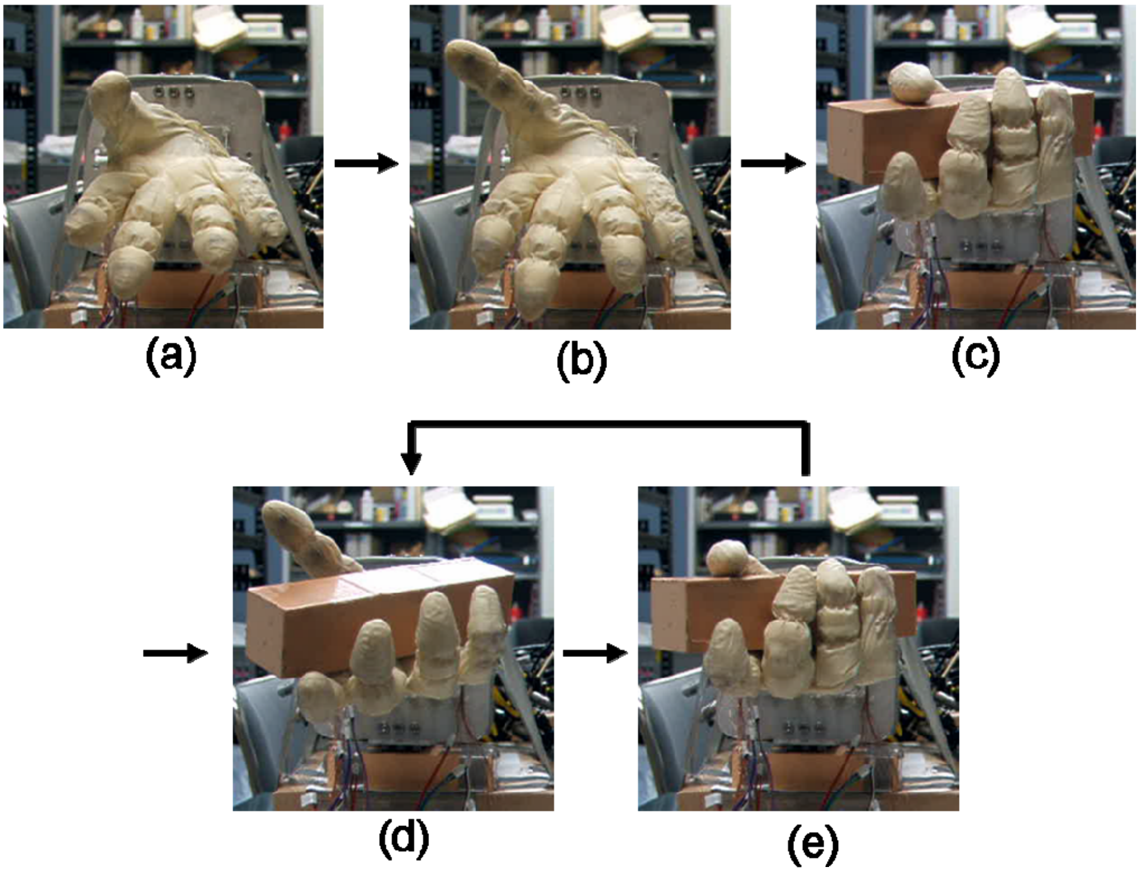
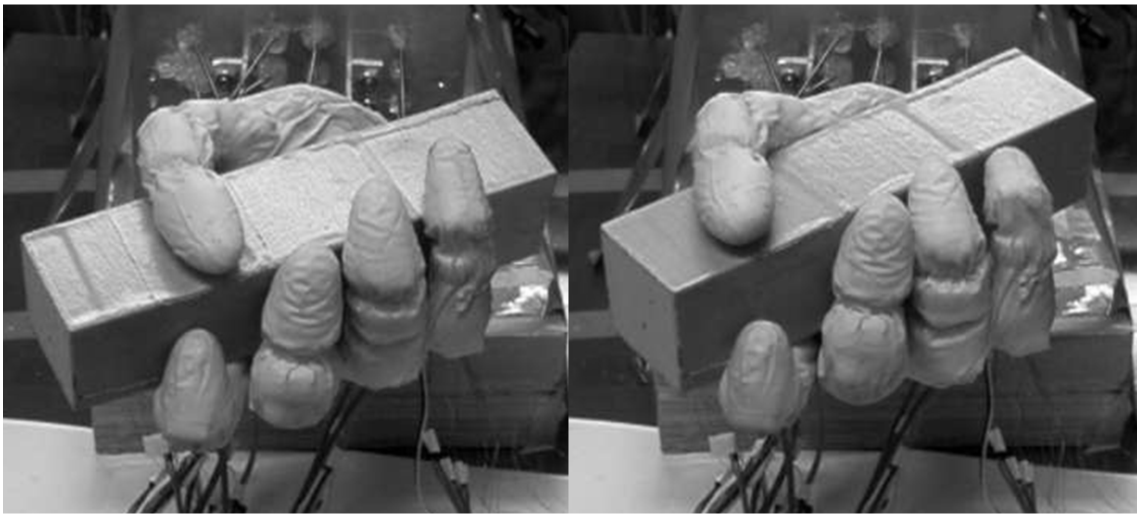
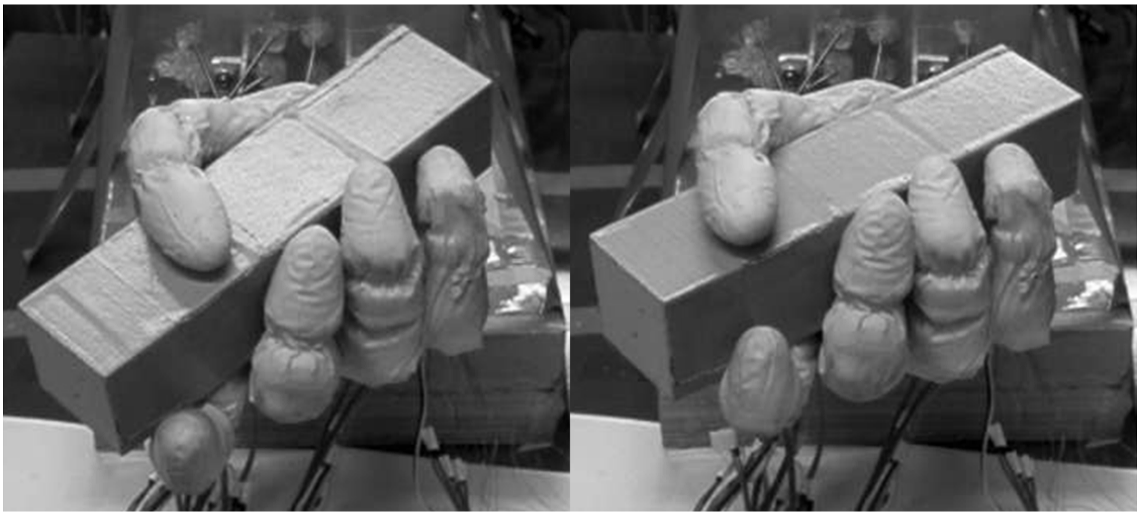


Figure 7: A repetitive grasping sequence: Through (a) to (c), the hand grasps a cuboid in 9sec. Once it grasps the object, it releases the object (d) in which it does not release the object completely, and grasps it again (e) in 4.4sec.

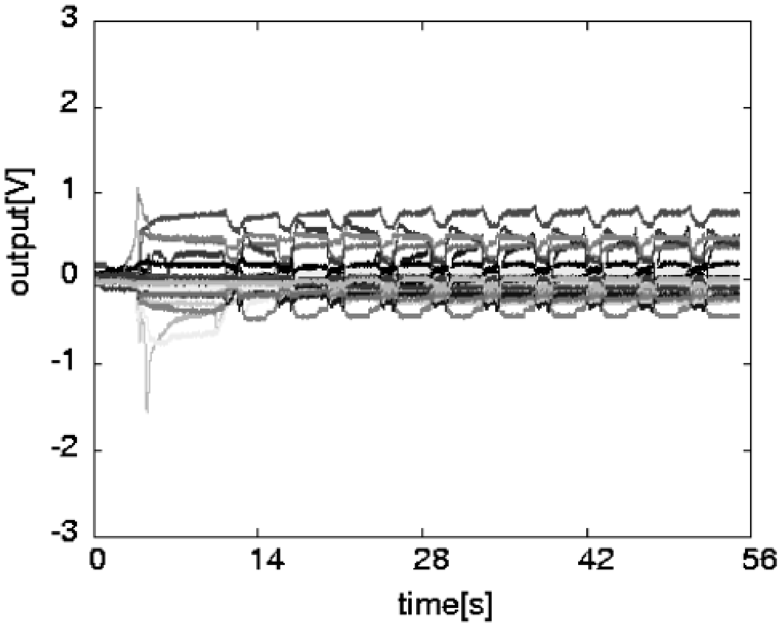


(a) case 1

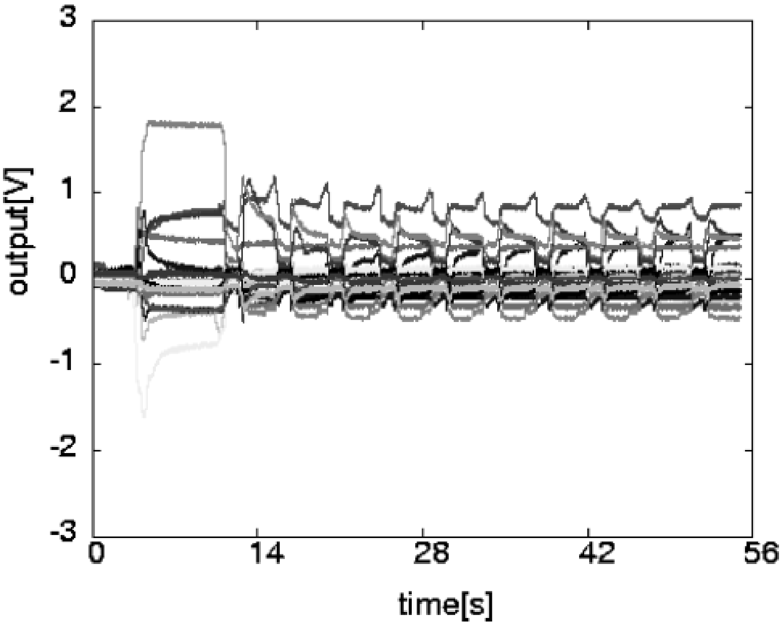


(b) case 2

Figure 8: Two pairs of initial and resultant final posture: The left figures show the object posture at the first grasp, while the right figures show the posture in the 10th grasp. Even though the two cases differ in initial conditions, the object moves to almost the same posture after repetitive grasping.

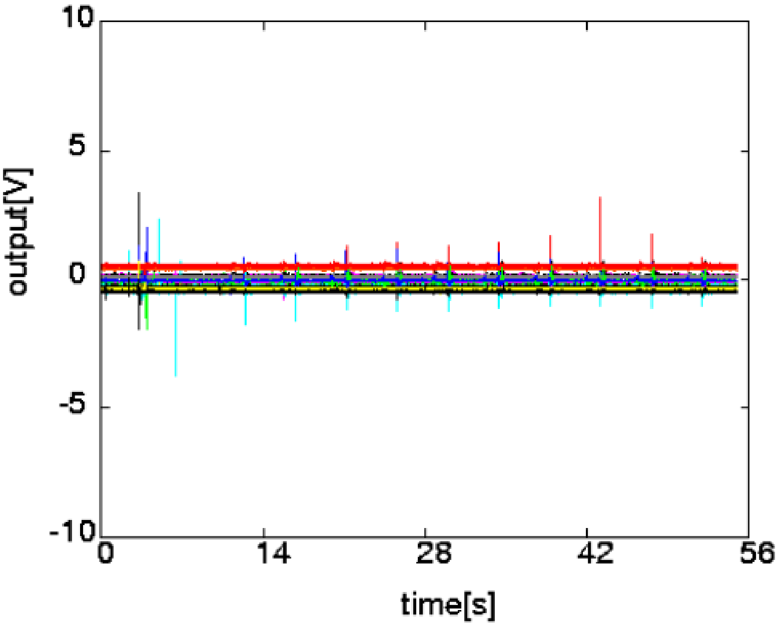


(a) case 1

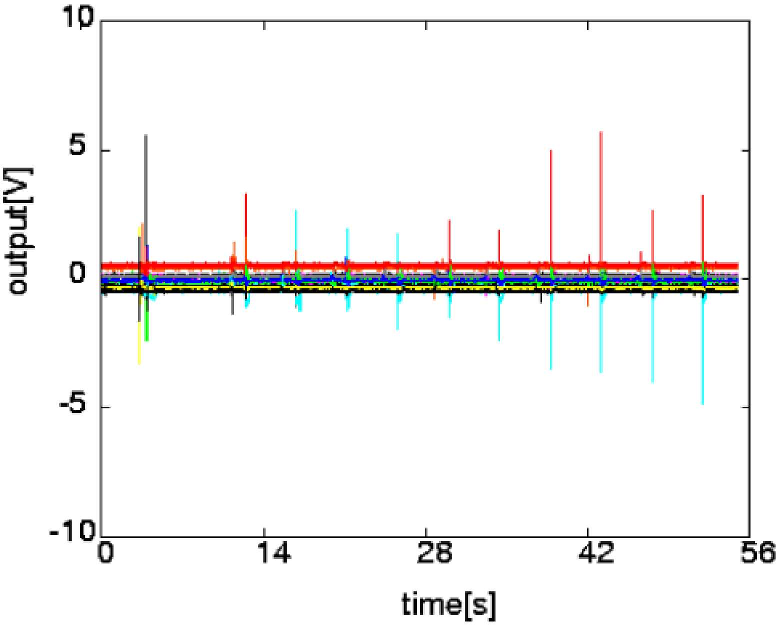


(b) case 2

Figure 9: Strain gauge values during repetitive grasping. At the beginning of the sequence, the strain gauge outputs are different between two different initial conditions. However, after a whole, the outputs become similar as a result of the repetitive grasping.



(a) case 1



(b) case 2

Figure 10: PVDF film values during repetitive grasping. The PVDF film is detecting the contact.

Figure 11: Photograph of the objects used in the experiment: a cuboid, a cylinder, a ball, and a bottle.

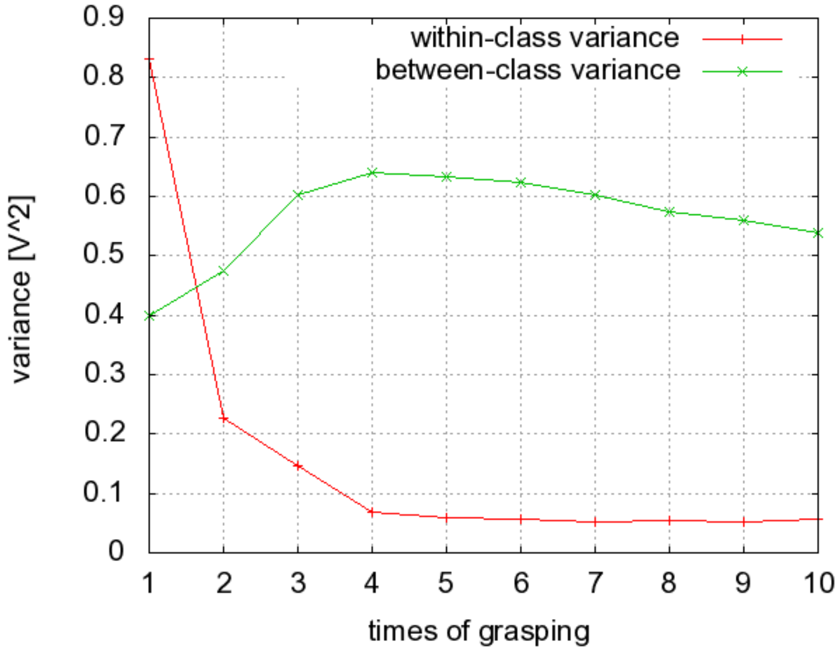


Figure 12: with-class variance and between-class variance.

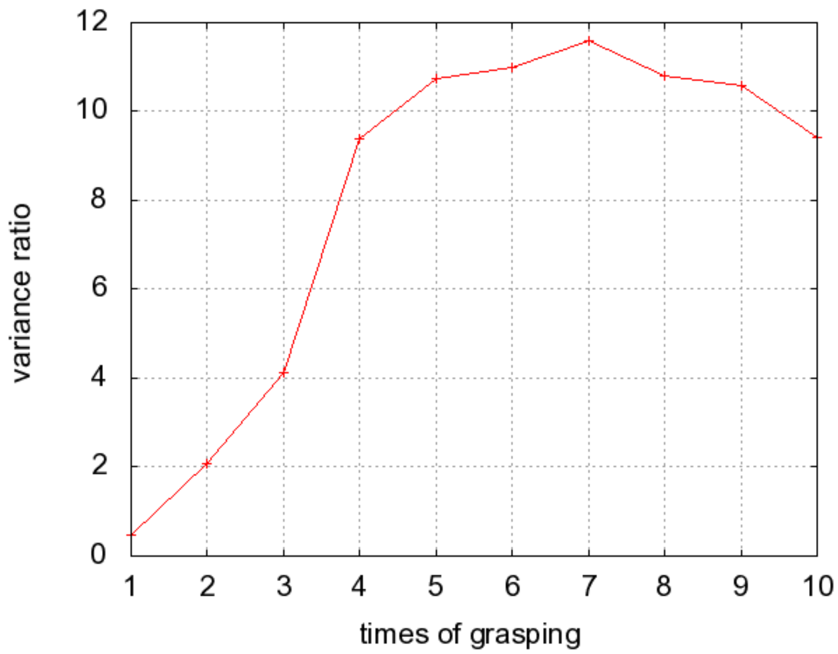
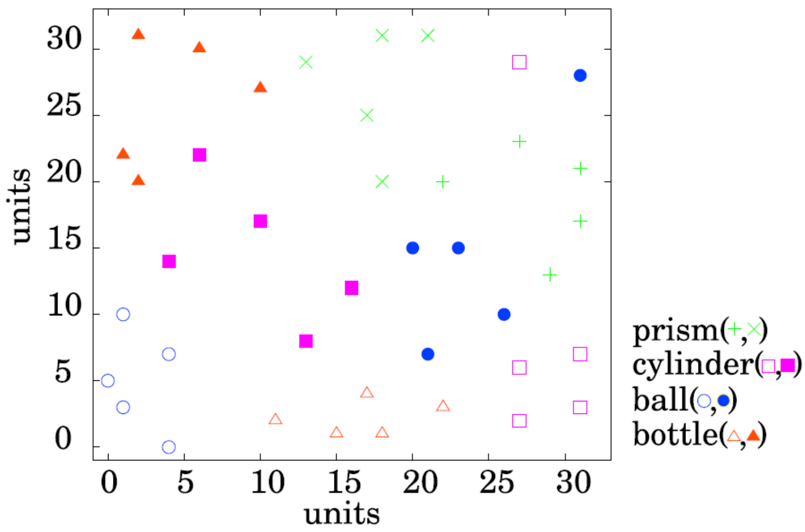
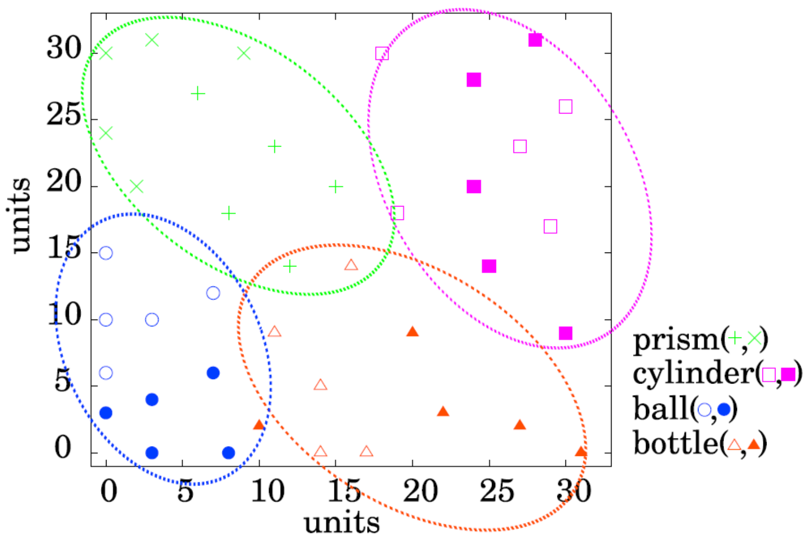


Figure 13: variance ratio.



(a) first grasp



(b) 10^{th} grasp

Figure 14: 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 cuboids, 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 10