Robot Finger Design for Developmental Tactile Interaction

Anthropomorphic Robotic Soft Fingertip with Randomly Distributed Receptors

Koh Hosoda[1][2]

[1] Graduate School of Engineering, Osaka University
[2] Handai Frontier Research Center
`hosoda@ams.eng.osaka-u.ac.jp`

Abstract. The developmental approach enables us to build adaptive robots, and furthermore, to understand the essence of intelligence from the constructivist viewpoint. In this paper, a new design principle for tactile sensors is proposed to investigate and to utilize developmental processes of robots. Based on the design principle, an anthropomorphic fingertip is developed. The fingertip is made of soft material with randomly distributed receptors inside. The robot learns to acquire meaningful information such as the slip and the object texture from the outputs of receptors through interaction with the environment like a human does. Several experimental results are shown to demonstrate its sensing ability and applicability for the developmental approach.

1 Introduction

Robots are going out of the laboratories, and therefore, have to deal with an uncertain real-world environment in which environmental change is more than the designer can predict. Looking at biological systems, they might utilize the "developmental process" to deal with such a real environment. Applying the developmental process for designing robots provides us the comprehensive understanding of intelligence from the constructivist viewpoint [1], which makes it possible to construct adaptive robots.

It is very difficult to implement physical development on a robot as far as we do not use biological material. Instead, by implementing as many actuators and sensors as possible, we can study how the robot develops the connection between them through interaction with the environment. Although they have designed and developed robots that have many degrees of freedom such as humanoids, the variety and the number of sensors are still not sufficient.

A camera is the only sensor that has been utilized for the developmental research so far: it has basically so many pixels that can be used for image processing. By changing the image processing in a coarse–to–fine manner, for example, we can simulate the developmental changes and investigate its effect in the process of learning [2, 3]. For the other kinds of sensing modalities, however, there is no developmental study to the best of the author's knowledge.

In this paper, a new design principle for tactile sensors is proposed to enable us to investigate and to utilize developmental processes of robots: embedding as many receptors as possible in soft material randomly. Based on the design principle, an anthropomorphic fingertip is developed. The word *anthropomorphic* has two meanings: one is that the fingertip is made of soft material with randomly distributed receptors inside and like a human does, the robot learns to acquire meaningful information such as the slip and the object texture from the outputs of receptors through interaction with the environment. The other is that the structure of the fingertip is similar to that of a human's; it consists of a bone, a body, a skin layer, and randomly distributed receptors.

The remainder of this paper is organized as follows. First, an overview of the existing design of tactile sensors is explained. Then, we introduce the design of an anthropomorphic fingertip based on a new design principle that relies on learning ability of the robot. Following that, several experimental results are shown to demonstrate its sensing ability and applicability for the developmental approach.

2 Toward adaptive manipulation: Overview

A human being can manipulate various objects by fingers dextrously and adaptively. Although there has been an enormous number of studies on robot hands trying to reproduce such adaptive and dextrous manipulation [4], so far the performance is not satisfactory. One of the reasons is that these existing hands are basically designed and controlled so that the designers can understand the manipulation. Although it is easy for them to implement their knowledge to the robot, it gives certain constraints on design and control of the robot hand, and as a result, it prevents manipulation from being adaptive. If the robot would have an ability to develop manipulation by itself, it would be freed by such constraints and the resultant manipulation would be adaptive.

In order for a robot to learn and/or develop its own representation of manipulation in its own sensor spaces, it should have several different sensing modalities. Among such modalities, tactile sensing plays a great role to gather information about the object and contact conditions. Many kinds of tactile sensors are proposed (we can find a comprehensive survey in [5] until 1999). Sensors with distributed receptors are especially effective to observe detailed contact conditions for adaptive manipulation. Many attempts have been made to construct such sensors with pressure-conductive rubber [6], an optical position sensitive detector [7], capacitor arrays [8–10], a LC network [11], ultrasonic sensors [12], force sensing resistance [13], conductive fabric [14], and conductive gel [15].

Almost all robotic fingertips that have been developed so far have their sensing receptors only on their surfaces. One of the reasons is that the fingers are basically made of rigid materials such as metals, and the receptors cannot be embedded in a deeper part of the finger. Rigid fingertips make the control easy since the position of the manipulated object is easily calculated by configurations of the fingers. However, the fact that the receptors are only embedded on the surface limits the sensing ability of existing robotic fingers. We humans have many receptors (corpuscles) of several kinds broadly distributed in the finger. The receptors embedded in a deep part of the finger are able to acquire the information filtered by its material property whereas the ones in a shallow part are sensitive to high frequency transient phenomena. Therefore, it would be possible to obtain more useful information about the object by combining the sensory information at many different locations in the finger rather than just using receptors on the surface.

Several studies mentioned that receptors embedded in soft material could provide useful information about dynamic characteristics such as the slip and the friction coefficient [16–20]. Although it is promising to get more information about them by increasing the number of receptors at various depths, there have been very few studies on it. It is difficult for the designer to derive the translation from the raw signals to meaningful information if the positions of the receptors are not controlled and the property of material between them are not known. Only Shinoda and his colleagues discussed on randomly distributed receptors in a soft material [21, 22] to the best of the author's knowledge. However, they only showed the characteristics of one receptor, and did not study the influence of the depth nor on the interplay of receptors.

3 Design of an anthropomorphic fingertip

3.1 Sensor design that relies on the learning ability

In order to translate raw signals into the meaningful information, the underlying structure provided by bodily, environmental, and task constraints is essential. For example, the electrical resistance of a strain gauge of a force sensor itself does not make any sense. If the robot knows the resistance-to-strain translation that is determined by the gauge material and structure and knows the strain-to-force translation determined by the sensor physical structure, it can translate the measured resistance into force.

A human designer usually calibrates the translation from the raw signals to meaningful information. He or she understands the constraints and implements knowledge about them as a *sensing model* for a robot. Then, the robot can behave properly even with a few receptors by compensating for a missing information with the model. Receptors of existing sensors are, therefore, placed regularly on relatively hard surface so that the designer can easily analyze the structure. As long as the task of the robot is simple, such a sensing model is functional. Recently, however, the task has become more complicated such as handling of the objects with various properties (e.g. material, size, mass, etc.), and the physical interaction between the finger and an object has also become complicated (e.g. grasping with slippage, finger gait, etc). Consequently, the realized behavior based on the human-designed sensing model is no longer robust against modelling errors and disturbances.

Owing to the recent development, the learning function of a robot is now ready to be used for many applications. If the robot can acquire the sensing model through experience, the receptors can be distributed randomly in or on soft material. The softness of a tactile sensor provides not only stability of grasping and protection against strong impact forces, but also more sensing abilities than hard sensors. It would even be possible for the robot to have a sensing ability that is excluded by the human designed sensors whose receptors are placed regularly. In this sense, the learning ability will change the design principle for tactile sensors. This paper describes a new design principle for tactile sensors that relies on the learning ability: **embedding as many receptors as possible randomly in soft material**. The word "many" means not only the number but also the variations of receptors.

It is obvious that the variety of receptors provides more sensing abilities. Even with receptors of the same kind, the robot can get different information from them in different depths since material existing between receptors play a role of a low-pass filter. In this sense, embedding many receptors provides not only redundancy, but also variety of sensing abilities. Another important point is randomness: non-uniform and anisotropic sensor structure potentially provides information that is excluded by the human design bias, that is, the uniformity of the sensor structure.

3.2 Structure of the finger

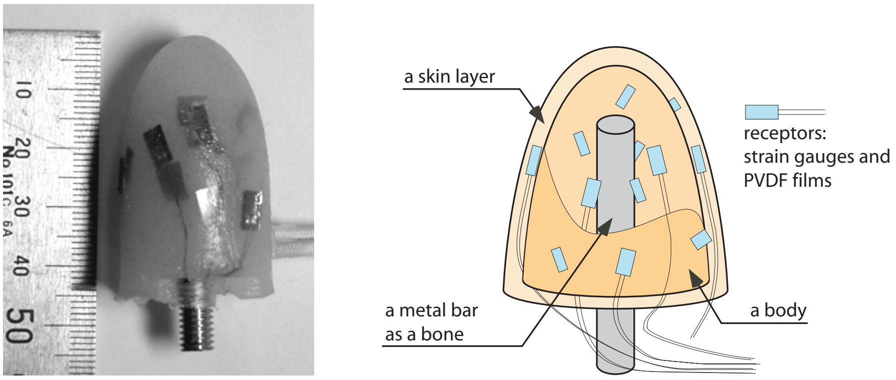

Fig. 1. A developed fingertip(left) and its cross sectional sketch(right): The fingertip consists of a metal bar, a body, and a skin layer inspired by the structure of the human finger. The body and the skin layer are made of different kinds of silicon rubber. Strain gauges and PVDF films are embedded randomly in the body and the skin layer as receptors.

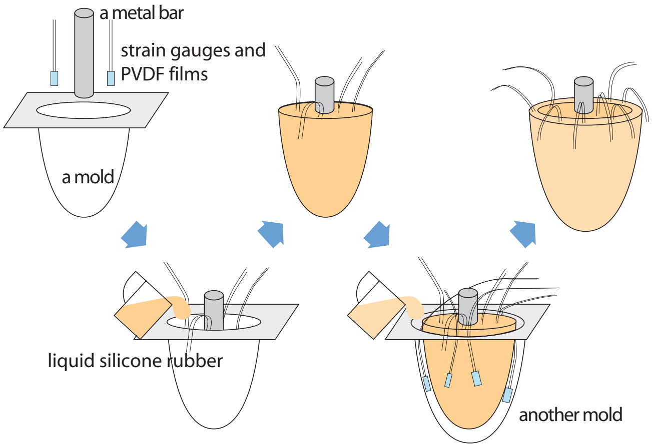

Fig. 2. A procedure to build a soft fingertip:a metal bar and several receptors, strain gauges and PVDF films are inserted into a mold, and silicon rubber is cast into it. This mold is then inserted into another mold that is slightly bigger. The additional receptors are implemented in this layer, then silicon rubber is again cast.

By following the design principle explained above, an anthropomorphic fingertip is developed (Figure 1). The fingertip consists of a metal bar that plays a role of a bone, a body, and a skin layer inspired by the structure of the human finger. The silicon used for the skin layer is slightly harder than that for the body. Strain gauges and PVDF (polyvinylidene fluoride) films are embedded randomly both in the body and in the skin layer as receptors. A PVDF film is sensitive to the strain velocity by using the piezo effect, whereas a strain gauge measures the static strain. In the human skin, there are also several corpuscles that are sensitive to the change of the strain (Meissner's corpuscle and Vater-Pacini corpuscle), and to the static strain (Merkel's disk and Ruffini ending). Since these receptors are embedded randomly, the robot has to learn to acquire meaningful information such as the slip and the object texture from the outputs of receptors through the interaction with the environment like a human does.

Figure 1 (left) shows a complete soft fingertip. Its diameter and length are 2[cm] and 9[cm], respectively. This finger has 6 strain gauges and 6 PVDF films both in the body and the skin layer, which results in totally 24 receptors. As mentioned above, the positions and the orientations of these receptors are not determined, i.e. the designer or the robot cannot know the geometries of the receptors beforehand.

We expect that the receptors of the same kind embedded in different positions would be able to measure different physical properties. A strain gauge embedded near the skin surface is expected to sense the local static strain between the skin and the object surface whereas a gauge embedded near the bone is expected to sense the total force exerted to the finger and is expected to be insensitive to the local texture of the object. A PVDF film senses the strain velocity, which means that it is more sensitive to the transient and the rapid strain changes (or stick-slip motions) than the strain gauges whereas it cannot sense the static strain. The silicon existing between two PVDF films is expected to function as a low-pass filter, therefore the difference between the signals is expected to represent the local stick-slip interaction.

3.3 Procedure to make a fingertip

Figure 2 shows the procedure to make the fingertip. First, a metal bar and several receptors, strain gauges and PVDF films are inserted into a mold, and silicon rubber is cast into it. The mold is put into the vacuum to remove bubbles, and is baked in the oven to be solid. It is then inserted into another mold that is slightly bigger. The additional receptors are implemented in this layer. Another kind of liquid silicon rubber that is harder than the previous one is cast, and the mold is put into the vacuum and is baked in the oven again.

4 Sensing ability of the fingertip

To investigate sensing ability of the anthropomorphic fingertip, it is mounted on a robotic finger (Figure 3), and rubbed on four different materials: wood, paper, cork, and vinyl. The finger is not force-controlled but position-controlled along a pre-determined trajectory.

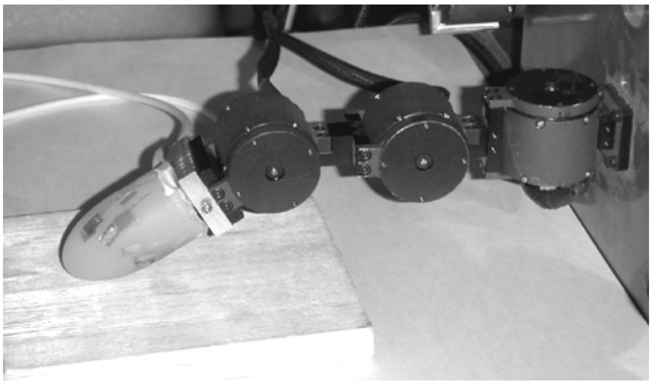

Fig. 3. The robot finger used for experiments: An anthropomorphic fingertip is attached at the tip of a robot finger.

The data from the PVDF films are obtained from the rubbing experiments. Figure 4 shows variance of signals originating from a PVDF film in the skin layer and that from another PVDF film in the body layer. In the figure, stars, crosses, oblique crosses, and squares represent the data obtained during rubbing vinyl, cork, paper, and wood, respectively. Since variance ellipsoids depicted in this figure do not overlap each other, we can conclude that these four materials are distinguishable by combining the outputs of these two receptors. It is important to note that, as illustrated in this figure, the paper, the cork, and the vinyl cannot be identified only from the film in the skin layer. The same holds for the wood, the vinyl, and the cork measured by the film in the body.

Since the finger is not force-controlled and the height of the surface is also not precisely controlled, the contact force is not constant through the rubbing process. This could be the main reason of the relatively large variance in the data points obtained from the same material. We expect that, if the finger is precisely controlled, the variance should be smaller so that one receptor is sufficient to identify the material. However, even without such a precise control, it is shown that the distributed receptors are able to distinguish the different materials. From the viewpoint of the developmental process of the robot, this characteristics would be particularly important since the robot would not be able to perform the precise position and force control from the beginning.

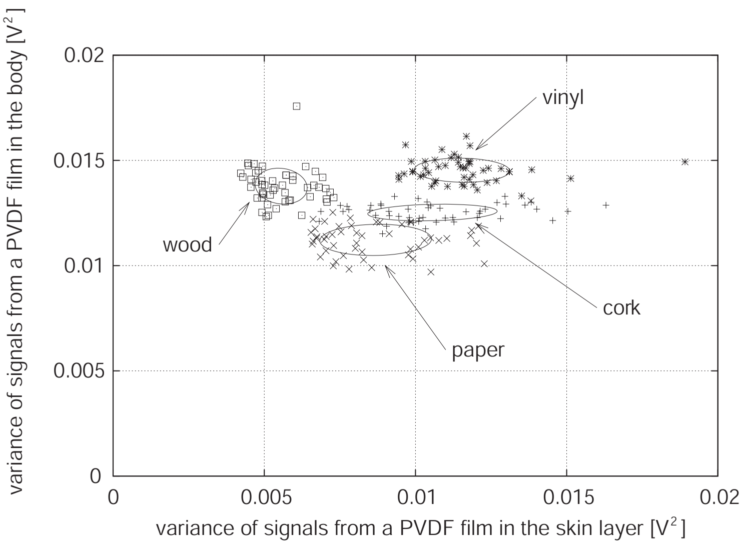

Fig. 4. The results from rubbing experiments: variance of signals of a PVDF film in the skin layer and that in the body layer are plotted. In the figure, stars, crosses, oblique crosses, and squares represent obtained data during rubbing vinyl, cork, paper, and wood, respectively. A ellipsoid represents the variance ellipsoid for each material. The paper, the cork, and the vinyl cannot be identified only from the film in the skin layer. The same holds for the wood, the vinyl, and the cork measured by the film in the body.

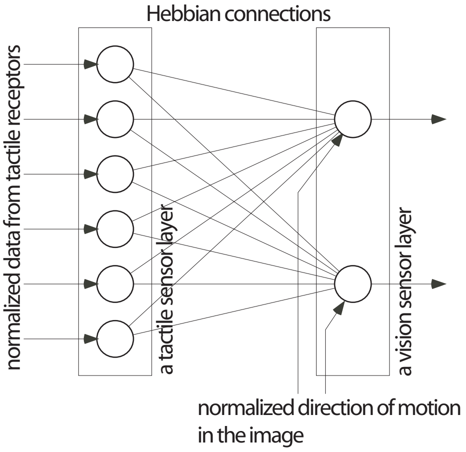

Fig. 5. A Hebbian network to find correlation between tactile and vision

5 Toward Development: Representation of the slip

Situatedness is one of the most essential properties for a robot to be truly autonomous [1]: an autonomous robot should have the perspective based on its own sensory system. It is very difficult, however, to transfer the knowledge of a designer into the control system of a situated robot. Therefore, the robot should be able to “develop” itself by using the sensory data from its own receptors.

At the beginning of developmental process, the robot get the sensory data flows but cannot see any correlation among them. If they come from the same physical interaction with the environment, the flows should have a certain relation between them because of the underlying dynamics, and the robot would be able to find it as a correlation after learning. The correlation should be robot’s own representation of the interaction acquired through the developmental process.

From this perspective, in this section, we investigate a case study of slippage. The problem addressed here is how the robot can identify the correlation between the data from the anthropomorphic finger and the visual sensory information during the slippery interaction.

5.1 Network to acquire representation of the slip

A simple Hebbian network is used to find correlation (Figure 5). There are two layers: a tactile receptor layer and a vision sensor layer. Two neurons in the vision layer are activated by the displacement of the image target in the image plane along x and y–axes, respectively. The 6 strain gauges in the skin layer are used, which are connected to the 6 neurons in the tactile receptor layer (PVDF films are not used in this experiment).

Since the relation between the vision sensor and the tactile receptors is not calibrated before learning, the weights between the neurons are initially 0. While the finger is touching an object and rubbing on it, the vision sensor can observe both the object and the fingertip. Therefore, when the tip slips, it is observed by the vision sensor as the difference of displacements of the object and the finger tip in the image plane. Simultaneously, the strain information can be obtained by the tactile receptors. If the direction of one tactile receptor happens to be along the slip direction in the image plane, the connection between the neurons is strengthened according to the Hebbian rule. Over time, the connection between a vision neuron and a tactile neuron in a corresponding direction has certain amount.

After some learning trials, the direction of a slip can be sensed by the tactile receptors as well as the vision sensor. This provides the system redundancy [1]. That is, even if the vision sensor cannot catch the slip information, for example, because of occlusion, the slip can be detected from the network and vice versa. An interesting aspect of this approach is the complementary nature of vision and tactile sensors concerning the sensitivity. Since the vision sensor is a non-contact sensor, the sensitivity (the minimum observable amount of a slip) changes according to the distance between the eye and the object whereas that of a tactile receptor does not change so much since the distance between the object and the receptor does not change. Therefore, at the beginning of learning when the vision sensor is mainly used, the sense of the slip is strongly affected by the position and orientation of the object. After learning, tactile receptors provide complemental information, and therefore, the sense will be insensitive to the object position and orientation. This process is supposed to be finding invariance in the observation.

In Figures 6 and 7, a broken line and a solid line represent normalized movement in the image plane along x axis (-1, 0, and 1 mean moving to $-x$ direction, stopping, and moving to $+x$ direction, respectively) and the sum of the outputs from the tactile sensor layer to the corresponding vision neuron, respectively. The continuous movement of the object is observed as pulses in the vision not as continuous signal because of the quantization of pixels.

Figure 6 shows the result from the first learning trial. The tactile output is 0 at the beginning since the the weights between the neurons are initially 0. There is almost no correlation between the outputs of the vision sensor and the tactile layer since the learning is not enough.

After 260 learning trials, the network obtains the correlation between them (Figure 7). The output of the tactile layer predicts the movement in vision, that is, at first the activation of the tactile sensors becomes larger, and then that of the vision is activated since the visual image is quantized.

6 Discussion

This paper has described a new design principle for the tactile sensor to investigate and to utilize the developmental processes of robots. The ability of the

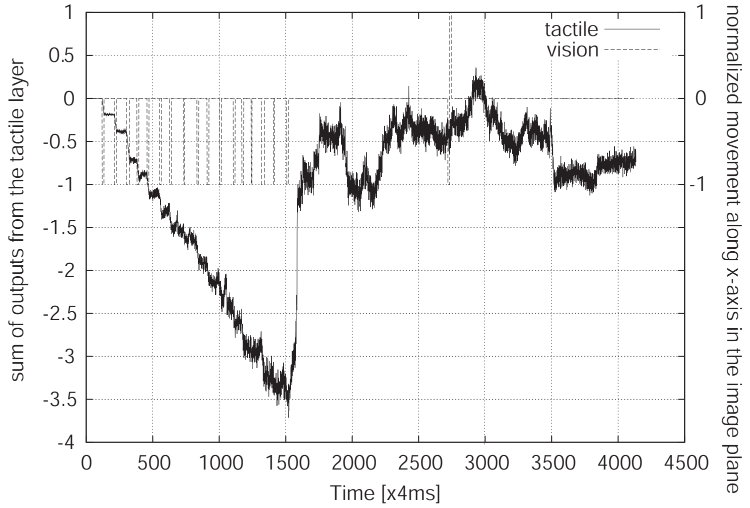

Fig. 6. The outputs of the vision neuron of x-direction and sum of corresponding tactile neurons of the first learning trial : the tactile output is 0 at the beginning since the weights between the neurons are initially 0. There is almost no correlation between the outputs of the vision sensor and the tactile layer since the learning is not sufficient.

anthropomorphic fingertip that can discriminate vinyl, cork, paper, and wood is provided by its softness and placement of receptors. The slippery interaction is also mapped onto the multi-modal sensory space consisting of vision and tactile as a set of distributed weights through robot's interaction with the environment.

Since the receptors are randomly distributed in the soft fingertip, the designer cannot map the physical phenomenon with the receptor outputs explicitly. Therefore, the robot has to learn the mapping through its own experience, and to organize the outputs of receptors. The learning and organizing process is one of most important developmental aspects of an autonomous robot. In this sense, this design principle will shed a light on the developmental study of robots.

In the first experiment of the object discrimination, the category is given by the designer. However, the category should be obtained by the robot itself based on its behavioral result. It does not have to discriminate the objects as far as the probability of achieving a given task (e.g. manipulating or grasping an object) does not change. This is very important point since the developmental process of the robot must be triggered by the internal motivation of the agent.

We expect that the study of an anthropomorphic fingertip could also provide an additional insight to the developmental process of human manipulation. Although it is still under a developing stage, the representation of the slip discussed in this paper pointed out some interesting issues toward future. Particularly, some interesting issues include (a) what kind of mechanism is effective

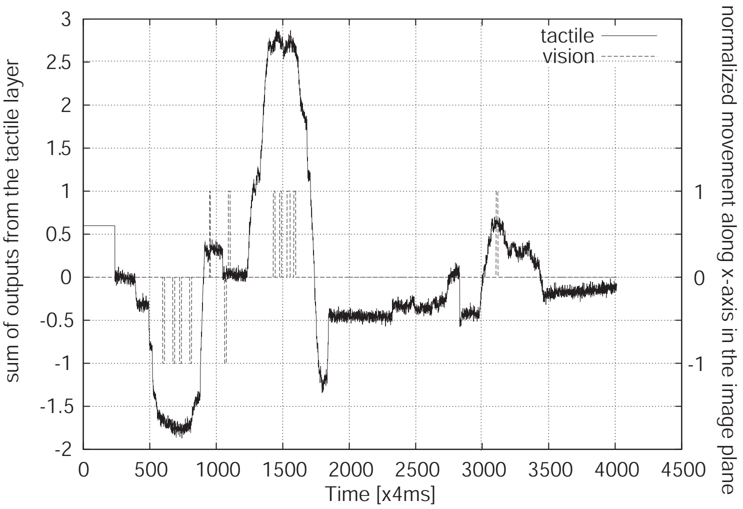

Fig. 7. The outputs of the vision neuron of x-direction and sum of corresponding tactile neurons of the 260th learning trial : the output of the tactile layer predicts the movement in vision, that is, at first the activation of the tactile sensor becomes larger, and then that of the vision is activated.

to acquire such distributed representation and (b) how we can utilize such a representation for the adaptive behaviors.

Acknowledgement

I would like to thank Mr. Yasunori Tada for his effort to produce the anthropomorphic fingertip and to perform an enormous number of experiments. I would also like to thank my colleague Minoru Asada for valuable discussions. Finally, I would also like to express my gratitude to the anonymous reviewers and Fumiya Iida for their valuable comments.

References

1. Pfeifer, R., Scheier, C.: Understanding Intelligence. The MIT Press (1999)
2. Nagai, Y., Asada, M., Hosoda, K.: Developmental learning model for joint attention. In: Proc. of the RSJ/IEEE Int. Conf. on Intelligent Robots and Systems. (2002) 932–937
3. Dominguez, M., Jacobs, R.A.: Developmental constaints aid the acquisition of binocular disparity sensitivities. Neural Computation **15** (2003) 161–182
4. Bicchi, A., Kumar, V.: Robotic grasping and contact: A review. In: Proc. of the IEEE Int. Conf. on Robotics and Automation. (2000) 348–353
5. Lee, M.H., Nicholls, H.R.: Tactile sensing for mechatronics — a state of the art survey. Mechatronics **9** (1999) 1–31

6. Shimojo, M., Ishikawa, M., Kanayama, K.: A flexible high resolution tactile imager with video signal output. In: Proc. of the IEEE Int. Conf. on Robotics and Automation. (1991) 384–391
7. Maekawa, H., Tanie, K., Komoriya, K., Kaneko, M., Horiguchi, C., Sugawara, T.: Development of a finger-shaped tactile sensor and its evaluation by active touch. In: Proc. of the IEEE Int. Conf. on Robotics and Automation. (1992) 1327–1334
8. Fearing, R.S.: Tactile sensing mechanisms. The International Journal of Robotics Research **9** (1990) 3–23
9. Johnston, D., Zhang, P., Hollerbach, J., Jacobsen, S.: A full tactile sensing suite for dextrous robot hands and use in contact force control. In: Proc. of the IEEE Int. Conf. on Robotics and Automation. (1996) 3222–3227
10. Hakozaki, M., Shinoda, H.: Digital tactile sensing elements communicating through conductive skin layers. In: Proc. of the IEEE Int. Conf. on Robotics and Automation. (2002) 3813–3817
11. Nilsson, M.: Tactile sensors and other distributed sensors with minimal wiring complexity. IEEE/ASME Trans. on Mechatronics **5** (2000) 253–257
12. Hutchings, B.L., Grahn, A.R., Petersen, R.J.: Multiple-layer corss-field ultrasonic tactile sensor. In: Proc. of the IEEE Int. Conf. on Robotics and Automation. (1994) 2522–2528
13. Lazzarini, R., Magni, R., Dario, P.: A tactile array sensor layered in an artificial skin. In: Proc. of the RSJ/IEEE Int. Conf. on Intelligent Robots and Systems. (1995) 114–119
14. Inaba, M., Hoshino, Y., Nagasaka, K., Ninomiya, T., Kagami, S., Inoue, H.: A full-body tactile sensor suit using electrically conductive fabric and strings. In: Proc. of the RSJ/IEEE Int. Conf. on Intelligent Robots and Systems. (1996) 450–457
15. Tajima, R., Kagami, S., Inaba, M., Inoue, H.: Development of soft and distributed tactile sensors and the application to a humanoid robot. Advanced Robotics **16** (2002) 381–397
16. Shinoda, H., Uehara, M., Ando, S.: A tacile sensor using three-dimensional structure. In: Proc. of the IEEE Int. Conf. on Robotics and Automation. (1993) 435–441
17. Yamada, D., Maeno, T., Yamada, Y.: Artificial finger skin having ridges and distributed tactile sensors used for grasp force control. In: Proc. of the RSJ/IEEE Int. Conf. on Intelligent Robots and Systems. (2001) 686–691
18. Yamada, Y., Maeno, T., Fujimoto, I., Morizono, T., Umetani, Y.: Identification of incipient slip phenomena based on the circuit output signals of pvdf film strips embedded in artificial finger ridges. In: Proc. of SICE 2002. (2002) 3272–3277
19. Nakamura, K., Shinoda, H.: A tactile sensor instantaneously evaluating friction coefficients. In: Proc. of the 11th Int. Conf. on Solid-State Sensors and Actuators. (2001) 1430–1433
20. Yamada, K., Goto, K., Nakajima, Y., Koshida, N., Shinoda, H.: Wire-free tactile sensing element based on optical connection. In: Proc. of the 19th Sensor Symposium. (2002) 433–436
21. Hakozaki, M., Nakamura, K., Shinoda, H.: Telemetric artificial skin for soft robot. In: Proceedings of TRANSDUCERS '99. (1999) 844–847
22. Shinoda, H., Oasa, H.: Passive wireless sensing element for sensitive skin. In: Proc. of the RSJ/IEEE Int. Conf. on Intelligent Robots and Systems. (2000) 1516–1521