Development of soft and distributed tactile sensors and the application to a humanoid robot

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Abstract—This paper describes a comprehensive tactile sensor system which can cover wide areas of full-body robots. Based on design criteria which are introduced from requirements, we develop two types of tactile sensor elements. One is a multi-valued touch sensor which has multi-level pressure thresholds. It is capable of covering wide areas of robot surfaces. The other is made of soft, conductive gel, which has the advantage of compliance compared with other sheet-type tactile sensors. With these two types sensors, we develop the tactile sensor system on the full-body robot ‘H4’. Details of the sensor system on the robot and some experiments using tactile information are described.

Keywords: Tactile sensor; sensor skin; humanoid robot; sensor system; conductive gel.

1. INTRODUCTION

Tactile sensors for robots have been studied for quite some time. Tactile sensing is essential for human beings and very useful for robot motion control. The tactile organs in the hands and fingers of humans have high precision and high resolution, and contribute to dextrous motion of the human hand. Thus many researchers are interested in tactile sensors for robot hands. Raibert [1] used VLSI technology to realize a small pressure sensor array which has high resolution. Fearing [2] and Maekawa [3] consider tactile sensors for the finger-tip. The criteria for these tactile sensors are precision, high resolution and the ability to cover narrow surfaces. Lee [4] and Nicholls [5] include enormous information about previous tactile sensor developments.

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For humans, the hands and fingers are not the only parts which have tactile sensors. In fact, they cover the entire body surface. It is considered that whole-body tactile sensing does very important work. For example, when we are tapped on our shoulder or arm, we can sense the contact, avoid the contact or notice the person who tapped us. Such contacts can also happen anywhere on the body of a robot. Today, a lot of robot tasks require the whole body, instead of just the end-effectors. In this paper, we propose a tactile sensing system for full-body robots.

There are some studies on tactile transducers or sensor systems for parts other than robot hands and fingers. Shimojo [6] produced a transducer which can cover relatively wide areas and has a sampling rate which is in the video range. Yamada [7] shows a method to attach the tactile sensors to joint parts, which is often problematic when equipping robot arms with tactile sensors. Inaba [8] proposes ‘a sensor suit’, which is a touch switch array produced by conductive clothes, and soft enough to allow the robot to wear the suit. Such a tactile sensor system was realized on a small full-body robot. Iwata [9] designed a tactile sensor device for the human interaction robot using force plates.

However, a more comprehensive tactile sensor system is required for robot motion generation. This paper describes the design criteria for a tactile sensor system and some experiments using a humanoid robot. It includes: (i) the design of transducers suitable for each part of the robot, (ii) the design of a system to cover wide areas and (iii) a method to generate motions using tactile sensor information.

Two kinds of tactile sensor elements are proposed and prototyped in this paper. These sensors were made based on the design criteria (the softness of surfaces, covering wide areas, etc.). The sensors were attached to the mobile humanoid robot ‘H4’, evaluated and used to generate simple robot motions.

2. DESIGN CRITERIA

The functions of a tactile sensor system which covers the entire robot body depend on the task. However, the general requirements of the system can be considered. Jacobsen [10] estimates the requirements of the tactile sensor system for the MIT/Utah dexterous hand. For the whole robot body, we consider the tactile sensor system as requiring the following characteristics.

(a) Covering wide areas. Since all robot surfaces may possibly make contact with the environment, the tactile sensor should cover the robot surfaces as much as possible. Therefore, the number of sensing points must be increased. Ease of producing a number of sensor elements is required. A few previous reports [7, 8, 11] aimed to develop tactile sensors which cover wide areas of robots. Sensors which can cover a wide area and have moderate resolution and sensitivity are needed. We can estimate the required resolution of the sensing points according to the capability of human beings. The distance between two contact points which a human can distinguish is about 3–8 mm on the
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finger tips, 2–3 cm on the back of the hands, and 6–7 cm on the hips and arms. Thus, high resolution sensors are not needed for all areas of the robot body.

(b) **Softness.** It is very important that the tactile sensors themselves or their covering has softness. If the sensors are rigid, we must move the robot slowly and carefully in order to avoid damaging the robot or its environment. Compliant skin weakens the shock of any impact and allows time for the tactile information to feedback to the robot motion. Compliant skin also has the advantage of increasing the contact area and its friction. The elastic surfaces is needed in robot hands for grasping, thus many tactile sensors for robot fingers have elasticity and soft surfaces [2]. Osada [12] developed a tactile sensing device from hydrogel which utilizes the piezoelectric effect.

(c) **Wiring.** The increase in the amount of wiring is a problem for the design of tactile sensor systems. Keeping wiring to a minimum is important for robots which have large areas to cover. Sensors based on filtering the electric signal by sensor devices [7, 13] are one solution for this problem.

(d) **Sampling rate and latency.** The increase in the number of sensing points increases the amount of sensor data, which can increase the latency and lower the sampling rate. Encoding and decoding data is one solution [14] to decrease the amount of data. The required sampling rate depends on the task, so we consider an adjustable sampling rate and latency as required.

Items (a) and (b) are requirements for each transducer, while items (c) and (d) are requirements for the tactile sensor system as a whole. In this paper, we present two new types of sensors which satisfy requirements (a) and (b). One is a ‘multi-valued touch switch’, which has a low capacity for sensing pressure but is suitable for covering large surfaces. The other is a tactile transducer made by conductive gels which have high compliance. The details of these sensor elements are described in Sections 3 and 4, respectively.

Based on requirements (c) and (d), we propose a tactile sensor system design. Figure 1 shows the outline of the system. Various types of transducers can be placed on a robot, so each transducer is driven by an MPU and uses a serial bus to unify the access method. Each MPU scans and filters based on the principle of each transducer. In addition, we can make simple tactile sensors by ICs (A/D converter, digital I/O, thermo-sensor, etc.) which can connect to the serial bus directly.

The computer which generates the robot motions can read the processed data asynchronously. The host polls the data from the MPUs, or reads the data when it receives a message indicating meaningful contact from the MPUs.

Some advantages of this design are given below.

- **Variety of sensors.** Using local sensor processors, it is possible to use different types of sensors in a uniform way. The differences between tactile sensors such as their addressing method or transducing principle are absorbed by the local processor. Moreover, it is easy to add new tactile sensors.
3. MULTI-VALUED TOUCH SENSOR

Binary switch-type tactile sensors are generally used in robotic applications because of their simplicity and robustness. However, it is impossible for such types of sensors to sense the magnitude of the contact force, since a binary switch sensor has only one pressure threshold.

We propose a switch array which has multi-level thresholds of pressure. Figure 2 shows a prototype of the multi-valued touch sensor. It consists of a flexible circuit board as lower electrodes, a conductive fabric as upper electrodes, and a rubber sheet as a cover. Pressure against the surface causes elastic deformation of the cover and
the upper electrodes make contact with the lower electrodes. The lower electrodes are multi-level layered (two layers in Fig. 2), so that the pressure threshold can be divided. This sensor principle is very simple and its structure can be designed by etching, therefore it is easy to make small and numerous switch elements.

It is possible to estimate the first threshold pressure by measuring the relationship between \((d, l)\) and the load. Figure 3 (left) shows the parameter and conditions of this experiment. A rubber sheet of 5 mm thickness is used as the top cover. The relationship between \((l, d)\) and the first threshold pressure is shown in Fig. 3 (right). The threshold pressure is in inverse proportion to the parameter \(d\) (the size of electrodes) and the parameter \(l\) (the width of electrodes).
Considering the applications for robots, the first threshold pressure is expected to be as small as possible. However, augmenting $d$ and $l$ causes this switch to turn ON with no load. Therefore, we set $d = 8$ mm and $l = 2$ mm. The first threshold pressure is estimated as 25 gf/cm$^2$ from Fig. 3. This parameter is used for the sensor covering the chest of the humanoid robot, H4 (see Section 5).

Figure 4 is a visualization of the tactile sensor output when a circular plate presses against it. The rough shape of the plate is recognized and the magnitude of the pressure can be estimated.

This sensor can be easily driven by a circuit forming a matrix using diodes similar to a keyboard. We made this circuit as a module with a one-chip microprocessor (Hitachi H8/3334YF). Figure 5 shows the layer structure of the matrix switch and the circuit of the module. This module scans 128 two-layered switch points within 1 ms. Figure 6 shows the electrode pattern of the sensor (left) and the driving circuit board (right).

**Figure 4.** Output of the multi-valued touch sensor when a circular plate is pressed upon it.

**Figure 5.** Structure of the multi-valued touch sensor module.

**Figure 6.** Photograph of the multi-valued touch sensor and its drive module.
4. TACTILE SENSOR MADE OF CONDUCTIVE GEL

4.1. The sensing principle

Many thin sheet-type tactile sensors have been developed so far [5]. As we mentioned in Section 2, tactile sensors are required to be compliant, but it is known that there is a trade-off between sensitivity and thickness of the cover. If the sensor has a thick elastic cover in order to make its surface softer, its sensitivity is sacrificed [15].

In this section, we propose a novel sensor made of conductive gel. This conductive gel is much softer than the conductive materials normally used. Thus it is possible to realize surface softness without using a thick compliant cover. The sensor itself is flexible, so we can equip robots with this sensor on geometrically complicated surfaces.

The underlying principle of this tactile sensor is similar to that of conductive rubber [6, 16]. The sensor measures the electrical resistance between electrodes mounted on both sides of a gel sheet. When touched, the deformation of the gel reduces the distance between the electrodes, thus lowering the resistance. Both the location of the contact and the intensity of the contact force can be obtained.

Figure 7 shows an experiment used to measure the impedance of the conductive gel. Flexible, conductive cloth and strings coated by Ni and Cu were used as electrodes, since they are flexible enough not to effect the gel’s deformation. The voltage, \( V_{cc} \), which is used to measure the impedance of the gel should be AC or pulse, because DC electrolyzes the gel and damages the electrodes.

The relationship between the applied pressure and impedance is shown in Fig. 8. The impedance changes approximately 20% from 0 to 400 gf/cm\(^2\) pressure. It is sensitive enough to satisfy the required properties if we amplify this impedance variation.

Figure 9 shows a simple way to make a 3 x 3 tactile sensor array. The sensor array consists of 5-mm square electrodes with a 10-mm distance between them. Since the stiffness of the electrode affects the deformation of the gel sheet, i.e. the sensitivity

![Image of tactile sensor array](image-url)
of this sensor, we used electrodes made of flexible conductive cloth and string. All of the impedances of this array were measured at 10 Hz. Since each portion has its own impedance value different from other areas, it is necessary to calibrate all of the output values initially.

Figure 10 shows the sensor output when a long, narrow shaped object is pressed against the surface of this sensor. The three bright squares express the reduction of the impedance in the areas 0, 4 and 8.

**Figure 8.** The relationship between the pressure and the impedance of the conductive gel.

**Figure 9.** 3×3 tactile sensor array.

**Figure 10.** The object pressed against the sensor (photo) and the tactile information (right side window, the bright squares indicate higher pressure).
4.2. Matrix-type tactile sensor

This sensor is driven by an electric matrix circuit using analog multiplexors. A number of row and column electrodes are mounted on both sides of a gel sheet, and the circuit scans the impedance at an intersection point between a row and a column electrode.

When driving a tactile sensor by a matrix circuit, undesirable current passes between a specified row electrode and an unspecified column electrode which does not face the row electrode at the specified intersection where the impedance is measured. This has been a problem of this type of sensor and a few methods to solve such problems have been presented [6]. However, we did not adopt such methods to reduce undesirable current because the size of this circuit is relatively small and such current is negligible in our case.

To recognize which part of its body is making contact, the robot needs to process information coming from several sensor modules, as well as integrate such information. As the sensor modules are distributed, processors for the sensor modules are also distributed. Each sensor module has a one-chip microprocessor (Hitachi H8/3334YF), two analog multiplexors (CMOS 4051) and an operational amplifier (MAXIM MAX 4322) so that information coming from each sensor module is processed locally. Processed information from sensor modules is transmitted to the main processor of the robot, which is the brain that integrates all information. In other words, the robot has both distributed sensing and processing systems. The processor on this sensor module has a high-speed 3-wired I^2C serial bus, so that it is possible to use many modules distributed across the robot body without increasing the number of wires.

Figure 11 shows the circuit diagram of the sensor module. The sensing part consists of a gel sheet and strips of electrodes. The processor scans all the intersection points one by one. The voltage, $V_d$ (V), from the processor’s DAC makes current flow through a selected intersection. The processor generates a 10-μs width pulse and all the intersections are scanned in 30 ms.

The voltage divided by reference resistor, $V R_0$, comes into a differential amplifier whose gain is $G$. The voltage, $V_{in}$, into the processor’s ADC (whose resolution is

![Figure 11. Diagram of the circuit of a gel-type tactile sensor module.](image-url)
Figure 12. Change in the electric impedance of conductive gel over time.

10 bit) is given as:

$$V_{in} = G \times \left( V_{ref} - V_d \times \frac{R_g}{R_g + VR_0} \right).$$

Adjusting the reference voltage, $V_{ref}$, the initial voltage from the multiplexor is cancelled out in the calibration mode.

It is necessary to cancel out the initial voltage because the impedance of the gel at the intersection point is different from others and the impedance value is unknown initially.

4.3. Problems of this sensor

There are two problems which one should be aware of when using this type of sensor. One is the vaporization of water over the long term. This makes the impedance of the gel increase and stiffens the gel. Figure 12 shows the variation of electric impedance of the gels over time. The impedance increases 20–30 times over 50 days. This problem can be solved by regulating the reference resistor ($VR_0$) and reference voltage ($V_{ref}$) in Fig. 11 each time the sensor is used. However, the water content of the gels should be recharged when the impedance becomes too large to calibrate.

The other problem is erosion of the electrodes. The Cu on the conductive cloth electrodes easily rusts when in contact with wet gels. Using other materials such as Au or other noble metals is one possible solution to this problem, but for now the lifetime of this sensor remains relatively short.

5. THE HUMANOID H4 AND THE TACTILE SENSOR SYSTEM

5.1. Humanoid robot H4

We developed a robot named H4 [17, 18] to investigate our tactile sensor system. This robot is designed for indoor environments, such as an office.
H4 has a total of 21 d.o.f.: 4 d.o.f. in the head, 6 d.o.f. in each arm, 3 d.o.f. in the waist and 2 d.o.f. in the wheels. Each joint is actuated by 4.5–90 W DC motors. It has two cameras mounted on the head for stereo vision processing. It has a battery and a PC-AT mounted on the wheeled base. The PC-AT is connected to an external LAN by a radio Ethernet device, so H4 is a completely wireless system. All of the joints are controlled by RT-Linux on the PC-AT within the robot, but its higher-level motions and behaviors can be programmed in Euslisp, a lisp-like language on the external powerful EWS. The solid model of H4 is also available in Euslisp.

5.2. Sensor system

H4 has tactile sensors on five areas of its body (Fig. 13). The chest is covered by a multi-valued touch sensor with 96 two-layered sensing points and one mounted driving MPU board. Each upper arm link is covered by a conductive gel sensor which has 64 sensing points each forearm link has 36 sensing points and sensor MPU boards are used for each sensor. It takes about 80 ms if the main processor sensing routine obtains all of the tactile sensor information for every sensor board. It takes less time if the routine communicates with only one board (about 10 ms for the body sensor and 50 ms for the arm sensors).

The elements of the tactile sensors correspond to points on the surface of the robot model. The value of the tactile sensor is normalized from 0 to 255. A visualization of the output of the tactile sensors on the chest is shown in Fig. 14. Figure 15 (left) shows the left upper arm link grabbed by a human hand. The touched elements are displayed in red on the robot model.

In this system, behaviors of the humanoid are programmed by parallel threads. A few basic threads are always running:

- **Tactile sensor thread.** This receives the tactile sensor information and sends it to the robot model. It updates the model display, and changes the color and its intensity of the touched sensing point.
- **Joint angle thread.** This receives the joint angle data and updates the robot model, and sends the target joint angle to the robot controller.
6. ROBOT MOTION EXPERIMENT

In order to show an example of the use of this tactile sensor system, some experiments with programmed behaviors and motions for H4 were conducted as follows:

6.1. Avoiding contact forces

This thread program calculates the contact force and torque on H4’s body using a weighted sum derived from the tactile sensor array. It uses the information from the multi-valued touch switch on the body front surface. When a man pushes the robot on its chest [Fig. 16(2)], H4 moves with compliance in response to an external force applied to its body surface using its wheels [Fig. 16(3) and (4)].
6.2. **Holding a box**

This thread program monitors the body surface’s tactile sensors. When an object such as a box is placed against the body surface [Fig. 17(1)], H4 moves its arm to embrace and hold the object [Fig. 17(2) and (3)]. When the arm’s tactile sensor value overcomes the threshold, it stops moving the arm and maintains its hold on the object [Fig. 17(4)].

6.3. **Locating a red box**

This thread program searches for a red box using the output of the stereo cameras. When it obtains the red box location, H4 faces the red box twisting its waist d.o.f. and embraces it with both arms [Fig. 18 (left)]. It repeatedly embraces the box and memorizes the positions where contacts happened. Finally, it displays the object’s edge information obtained entirely by touching in the robot model coordinates [Fig. 18 (right)].
7. CONCLUSION

We have proposed a comprehensive tactile sensor system for full-body robots. This system was designed based on the following four criteria: covering wide areas, compliant surfaces, reduced wiring and asynchronous sampling.

Based on these criteria, we develop two types of tactile sensors: one is a ‘multi-valued touch switch’ and the other is the one made of conductive gels.

The multi-valued touch switch is patterned on a flexible circuit board and consists of a matrix switch, thus it has the advantage of covering a wide area. The size of the sensing point is 5 × 5 mm and the first threshold pressure is 25 gf/cm². This sensor is developed to cover the wide area of robot surface which does not require accurate touch pressure values, like the front and back surface of body.

The conductive gel tactile sensor has more flexibility and softness than the one made of conductive rubber. Its electrodes consist of a matrix circuit to acquire the pressure data, thus it is capable of covering a wide area. The size of the sensing point is 6 × 6 mm and the sensitivity is 0–400 gf/cm² pressure in 10-bit resolution.

We implemented a tactile sensor system for the robot H4 based on the proposed criteria. It covers large areas of the robot and complies to the surface of the skin. Experiments using behaviors based on tactile information were conducted which show some of the advantages of this system.

For future work, tactile sensors which can cover larger and complicated areas such as the robot’s joints are needed. In addition, the development of motion planning strategies which include tactile sensor information is required.

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