Proceedings of the 2006 IEEE International Conference on Robotics and Automation
Orlando, Florida - May 2006

Conformable and Scalable Tactile Sensor Skin for Curved Surfaces

Yoshiyuki Ohmura, Yasuo Kuniyoshi
Depertment of Mechano-Informatics,
The University of Tokyo,
Tokyo, Japan
Email: {ohmura,kuniyosh}@isi.imi.i.u-tokyo.ac.jp

Akihiko Nagakubo
Intelligent System Research Institute
National Institute of Advanced Industrial Science
and Technology, Ibaraki,Japan
Email: nagakubo.a@aist.go.jp

***Abstract*— We present the design and realization of a conformable tactile sensor skin(patent pending). The skin is organized as a network of self-contained modules consisting of tiny pressure-sensitive elements which communicate through a serial bus. By adding or removing modules it is possible to adjust the area covered by the skin as well as the number (and density) of tactile elements. The skin is therefore highly modular and thus intrinsically scalable. Moreover, because the substrate on which the modules are mounted is sufficiently pliable to be folded and stiff enough to be cut, it is possible to freely distribute the individual tactile elements. A tactile skin composed of multiple modules can also be installed on curved surfaces. Due to their easy configurability we call our sensors "cut-and-paste tactile sensors." We describe a prototype implementation of the skin on a humanoid robot.**

I. Introduction

Intelligent behavior and interaction with the real world strictly depend on the availability of some form of tactile feedback. In this sense, distributed tactile sensor systems are an important requirement for humanoid robots not only as a means for providing better human-robot interaction but also to realize dynamic whole-body motion control (e.g. "roll-and-rise movement" [1]). Most humanoid projects, however, do without tactile sensor skin and their interaction with the real world is strongly restricted. In principle these humanoids can not do natural motion because applied force on the parts without tactile sensor can change body posture without controllability. (Most humanoid motions are limited to the posture of the end-effectors landing.) Although much previous work on tactile sensors exists the big bulk of it is devoted to feature detection and basic tactile sensing (for a review, see [2], [3]).

One important goal of our research is to cover the entire surface of a humanoid robot with tactile sensors and exploit them for dynamic whole-body motion control and human-robot interaction. None of the existing tactile sensors, however, do serve this purpose. There is only little work on full-body tactile sensors. Particularly relevant in the context of this paper is the construction of a full-body tactile sensing suit composed of an electrically conductive fabric [4]. The sensor suit is flexible and enables full-body perception through 192 sensing regions realized as binary switches, but has at least two significant drawbacks: its manufacturing is not trivial, and electrical contact among the strings composing the fabric is difficult to avoid.

One of the hardest problems in the realization of a distributed tactile sensor system is the wiring topology. Loosely speaking, the larger the number of sensing elements, the thicker the wire bundle becomes. For reducing the wiring problem, a two-wire tactile sensing element consisting of a capacitor and coil has been proposed (called LC-resonance traps) [5]. Despite the appealing nature of this solution, it has not been used in the context of an actual robot.

Here, we propose a practical method for manufacturing and installing a distributed tactile sensor system on an arbitrarily curved surface. In the following section, we give the specifications of a small-sized tactile sensor element. Next, we describe a tactile sensing module consisting of tactile sensor elements and a serial bus used to reduce the number of wires. These modules can be combined to form a tactile skin. Due to their easy configurability, we call our sensors "cut-and-paste tactile sensors." Before concluding we show how the skin can be implemented on a humanoid robot.

II. Performance Specifications

The basic requirements of a "usable" tactile sensor system or skin are:

1) Conformability: The skin should be applicable to arbitrarily curved surfaces (without specifically fabricating different sensor units for each curved part – which is overwhelmingly costly).
2) Compliance: The sensor should have a soft surface (some tactile sensors are rigid and not appropriate for whole-body contact motions).
3) Dynamic range and sensitivity: The sensors should be able to detect contact between light touch and total body-weight.
4) Installation space: Should be kept to a minimum because the inside of the robot's shell is full of mechanisms and circuits.
5) Area coverage: Should be as large as possible (keep the wiring to a minimum and taking into account ease of implementation).
6) Weight: The skin should be light-weight because it potentially has to cover the entire body surface which is a large area (i.e. sensor weight can be a big problem).

7) Power consumption: The power consumed by the individual tactile elements should be low (an increase of the number of sensors makes it large).
8) Size: The individual sensing elements should be of small size (implementation is easier and sensing resolution is higher).
9) Toughness: The skin should be tough, and robust against impact and shear forces.
10) Manufacturability: The skin should be easy to manufacture.

In the following sections, we describe a distributed tactile sensor system that meets these specifications.

III. Sensors and Sensor Network

The tactile sensing element consists of a photo-reflector covered by urethane foam (Fig.1). The foam not only guarantees mechanical compliance but provides also protective covering (against impactive forces) for the sensing elements and for the associated circuitry.

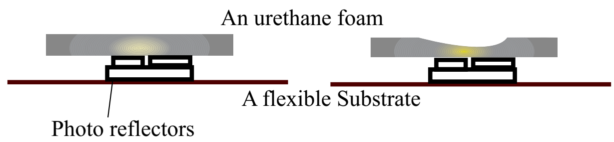

Fig. 1. Tactile sensor element.

The mechano-electrical transduction mechanism of the sensor works by measuring the light scattered by the urethane foam upon deformation. The scattered light is concentrated by the deformation. Our tactile sensing mechanism is a variant of the one used in KINOTEX^{TM} sensors [6] which consists of a light emitting diode, a photo detector, urethane foam, and fiber-optic cables. The cables are used to irradiate the foam with a thin beam of light, and to collect the light scattered by the foam. The working principle of KINOTEX sensors is to measure through a photo-detector changes of light intensity at end of the fiber-optic cable. An important feature of these sensors is their interpolation ability, in the sense, that the force between two sensor elements can be calculated as the ratio between the two sensor outputs. This characteristic is important for eliminating insensible zones, and for reducing the quantity of required elements. KINOTEX sensors, however, are also affected by two problems: (1) the manufacturing and installation on the robot are difficult; and (2) the opto-electronic interface of this sensor requires a large space because of the concentration of the fiber-optic cables at a LED and a photo detector.

A way to solve both problems is by not using fiber-optic cables. The sensors are constructed by bonding a photo-reflector directly onto the urethane foam. Realization of our small-size tactile sensor element ows much to the down-sizing of photo-reflectors. For example, the photo-reflector used by us has a size of $3.2\,mm\times$ $1.7\,mm\times$ $1.1\,mm$ (GP2S60 from SHARP).

Our sensor has some differences from KINOTEX sensor: (1)distance between the scattered light and the collector is longer; (2) attenuation through the fiber-optic cables does not exist; (3) the photo-reflector has height. Therefore, we need to examine the characteristics of the sensor.

Our tactile sensor element has a few notable characteristics:

- manufacturing is easy (automatic installation is possible);
- sensing element is small-sized and light-weight;
- dynamic range and sensitivity can be controlled, e.g. by changing the thickness of the urethane foam;
- the interface electronics is small.

A weak point of this tactile sensor is the large consumption of current. One LED consumes about $50\,mA$. For 1000 tactile sensing elements, the total current amounts to $50\,A$, which is obviously too large. A rather straightforward way to circumvent this problem is to restrict the number of powered-on LEDs through time-sharing control. By exploiting this control it is possible to reduce the number of analog-digital converters and signal wires. We call this strategy "scanning control." Figure 2 shows the circuit schematic used for the scanning control. When all LEDs are powered off, the photo-currents of the photo-detectors are vanishingly small. When one LED is powered on, a photo-current flows through a resistor to ground and the induced voltage drop can be measured to estimate the applied pressure. As the control is time-shared, the analog-digital converters and the analog signal wires can also be shared. Such scanning control enables to simplify the wiring topology and to reduce the amount of dissipated power. Note also that by controlling the current in each LED by pulse width modulation it is possible to tune the sensitivity of the tactile sensing elements.

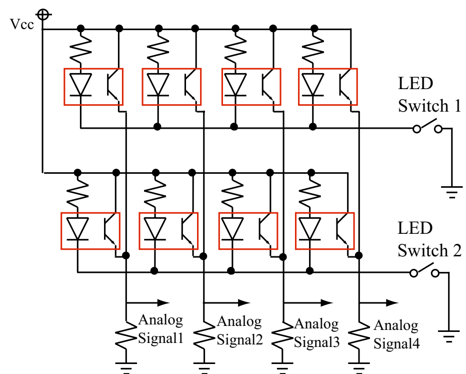

Fig. 2. Scanning control.

A. Cut-and-Paste Tactile Sensors

In order to realize a distributed tactile sensor on a curved surface, it is important to take into account the following requirements:

1) the area covered by the tactile sensors should be large and adjustable;
2) for conformability to curved surfaces additional tuning is necessary;

3) the density of tactile sensing elements should be adjustable.

We propose a module consisting of tactile sensor elements mounted on a bendable substrate which meets the aforementioned requirements. In order to adjust the area covered by the tactile sensors, cutting of the module and serial communication are useful. If some tactile sensor elements are removed from the module, the area with tactile sensors becomes smaller. If the tactile sensor modules can be connected through a serial communication bus, it is possible to cover larger area.

In order to conform to a curved surface, it should be possible to place each tactile sensor element freely. A side benefit is that the density of the tactile sensor elements can also be adjusted. In conventional tactile sensors mounted on flexible substrate the distance between the sensors (and hence the resolution of the sensor module) is typically fixed. Each module has to be manufactured specifically for a particular curved surface. Not surprisingly, this method is more expensive.

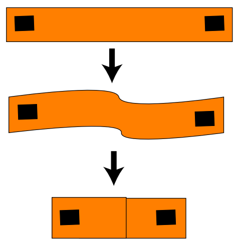

Fig. 3. Folding of a tactile sensor module.

In order to adjust a distance between each tactile sensor element, we use a band-like bendable substrate which can be easily folded. Two tactile sensor elements are mounted on the opposite ends of the flexible substrate. Figure 3 shows one possible folding-strategy for changing the distance between two tactile sensor elements. This strategy allows to freely change the location of each tactile sensor element. In addition, because the values sampled by the elements can be interpolated, then the adjustable range becomes even larger.

Figure 4 depicts the concept of "cut-and-paste tactile sensors." The first step is to define a tactile sensor sheet consisting of modules with tactile sensor elements and a serial bus. The sheet can be connected to other sheets and hence cover a large area. The term "cut-and-paste tactile sensors" refers to the installation of the sheets by literally cutting and pasting them on a surface. Moreover, because these sheets are flexible enough to be folded and cut, it is possible to select the location of each tactile sensor element rather freely. An important merit is that only one type of tactile sensor sheet is required for covering a whole system.

B. Flexible Sensor Network

One way of transferring sufficient sensory data but circumventing an explosion of wires, a sensor network is necessary. The network has to be fast enough to handle data gathered in real time. In addition, a special network topology is required for the cut-and-paste tactile sensors.

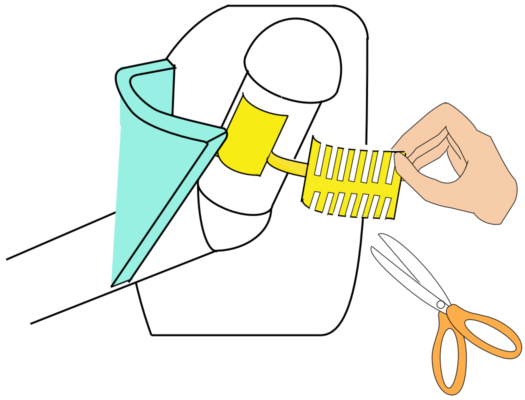

Fig. 4. Application example of cut-and-paste tactile sensors.

The sensor network has to satisfy the two following specifications: (1) flexible network topology; and (2) redundant wirings.

In order to paste the sheets in different directions, flexibility of the network topology and redundancy of the wiring is required. An additional advantage of having a redundant wiring is that the network becomes robust against a faulty wires. To realize these characteristics, a serial bus is a suitable choice. Because a serial-bus consists of electrically identical wires, this network meets the characteristics mentioned above. Moreover, a serial bus requires less wires. Another solution is a fast serial communication without constraints of a topology such as the Responsible Link [7]. This network, however, requires too much space. Not to mention that serial-bus is, nowadays, a common peripheral interface available on many small-sized micro-controller.

However, a solution based on a serial-bus has at least one problem: an increase of the bus capacitance makes it impossible to communicate at high speed. Therefore, a serial-bus covering a wide surface is difficult. Thus, the serial-bus has to be combined with another network. A ring-type network proves to be useful for real-time communication while reducing the wiring for a wide area. Therefore all serial-buses are connected with slave nodes of a custom-designed ring-type network – each node having a small-sized micro controller as a serial-bus-master.

The communication flowchart is shown in Figure 5:

1) The host computer sends a packet with the address of a slave node of a ring-type network and the address of some tactile sensor elements.
2) Each slave node has a serial-bus-master. An identified serial-bus-master controls each serial bus. At the same time, the slave node sends one-step previous data so as not to block the network.
3) The serial-bus returns the identified sensor data.
4) The serial-bus-master receives the sensor data, and transmits the data to the host computer during the next communication.

The sensor network has to be real-time. If a serial-bus-

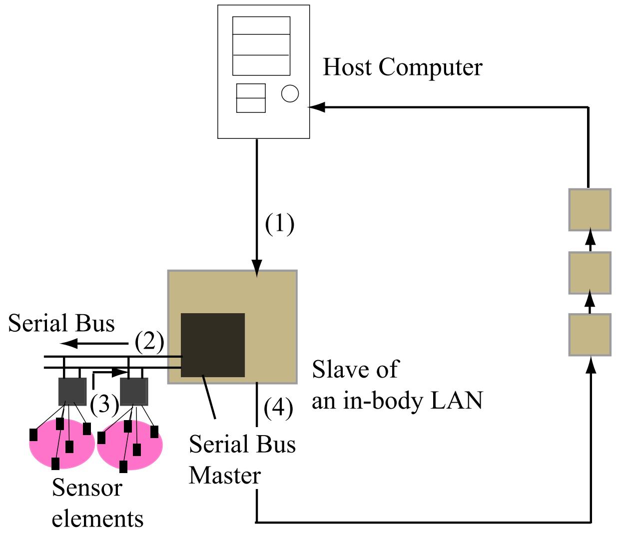

Fig. 5. Network configuration.

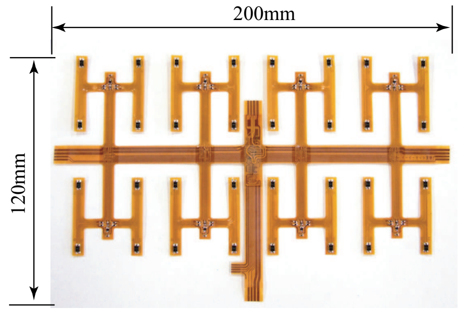

Fig. 6. Tactile sensor sheet.

master is alone in the serial bus, the worst time of communication can be estimated because of no packet collision; the serial bus can communicate in real-time. For this reason, each tactile sensor sheet works as serial-bus slave, and only one serial-bus-master controls them.

The ring-type network consists of a host computer (as a master) and some slave nodes, and all of them are connected in a circular pattern. Each slave node receives a packet from an upstream, and sends the reply downstream. In short, the network is one-way. The packet has no priority, and can not overtake. Therefore, this network is real-time. To communicate faster, a delay of each slave node should be smaller and a communication speed should be faster.

We examined the time to sample one tactile sensor element. This value is defined as the time until the receiving sensor data after the host computer sends the address packet; the time of our system is $0.2\,ms$(see section V-.2). As the speed of a serial bus is often slower than other networks, the serial bus speed becomes the bottleneck. If a serial-bus-master blocks the in-body LAN until it receives data, the worst time to sample is longer. Therefore, the serial-bus-master should not block the network; the serial-bus-master sends one-step previous data before it receives sensor data from the serial bus.

IV. System Design

Our tactile sensor sheet consists of 32 tactile sensor elements, one micro-controller (C8051F330 from Silicon Laboratories) and four serial bus terminators (Fig.6). These components are mounted on a flexible substrate. Eight tactile sensor elements share one analog-digital converter. Each set of eight tactile sensor elements is simultaneously controlled by the micro-controller. The task of the micro-controller is to switch on and off the LEDs corresponding to the individual tactile elements. As a serial-bus, we use the System Management Bus (SMBus).

The size of the sheet was $120\,mm \times 200\,mm$ and its weight is $1.7\,gr$. Each sensor element can be removed by cutting the flexible substrate. A four-direction wiring substrate from the center consists of the SMBus wires and power supply wires. Figure 7 depicts the installation flowchart. At first, the tactile sensor sheet are connected to each other. Then, the location of all tactile sensor elements is changed by folding the sheet so as to adapt to curved surface. The last step consists in covering the sensors with urethane foam.

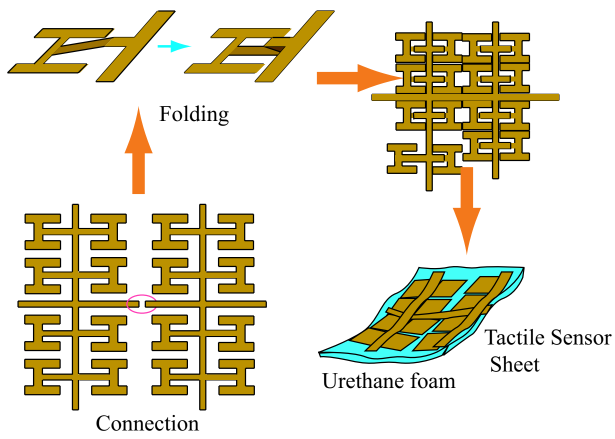

Fig. 7. Implementation.

A. Network Specification

Each tactile sensor sheet is an SMBus-slave with a 5-bit address. The maximum number of tactile sensor sheet on an SMBus is therefore 32. Each sensor sheet has eight LED switches: four tactile sensor data can be sampled by each channel. The LED switches are thus identified by a 3-bit address and 32 (8×4) tactile sensor data can be sampled from each tactile sensor sheet. If an SMBus master specifies an 8-bit address (a 5-bit SMBus slave address and a 3-bit LED switch address), four tactile sensor data can be collected. These data are 8-bit digital data converted by an analog-digital converter. The maximum number of tactile sensor elements that can be served by one SMBus is 1024 (32×32).

Each SMBus master is connected to a slave node of in-body LAN and communicates with a host computer in the real-time. As each slave node has a 6-bit address, the maximum number of the slaves in one network is 64. The whole network combined with these two networks can have maximum of 65536 (32×32×64) tactile sensor elements. Despite this large number, if the number of switched-on LED set in the network is one, the whole current consumption is limited to approximately 200 milliampere.

B. Slave node of in-body LAN

Figure 8 shows a slave node of in-body LAN. The slave consists of an FPGA, an SMBus master, circuitry for communication and power. Its size is $20\,mm \times 20\,mm \times 5\,mm$. The communication speed of the in-body LAN is $20\,MHz$.

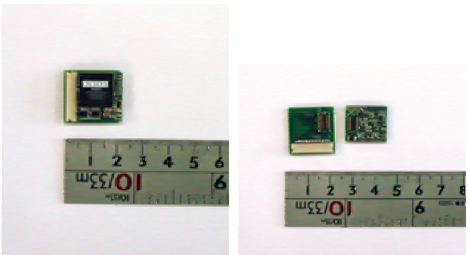

Fig. 8. Slave node of in-body LAN.

V. Experiments

First, we examined the characteristics of the individual tactile elements. We then tested the communication properties of SMBus. Finally, we implemented a cut-and-paste tactile sensors.

1) Characteristics of the proposed tactile sensor element:

a) Dynamic range and sensitivity: As a photo-reflector, we used GP2S60 (from SHARP). The urethane foam was "POLYOLEFIN FOAM PE-LITE A-8" (from INOAC). Figure 9 displays the output of the photo-reflector as a function of the pressure applied on the urethane foam. In absence of load, the output of the photo-reflector saturates. For increasing loads, the change of the voltage is negative and large. For increasingly larger pressures, the change of voltage decreases and eventually flattens out. In short, the characteristics of this sensor is nonlinear, and both higher dynamic range and higher sensitivity are realized at the same time. These characteristics can be controlled by changing the variety of urethane (or its thickness).

b) Interpolation ability: We also tested the interpolation ability of our sensor. We arranged two photo-reflectors and covered them with urethane. The distance between the two photo-reflectors was $20\,mm$. We applied the same load at a space between two tactile sensor elements. Figure 10 shows the result of this experiment. The two tactile sensor elements responded to the load not only right above these elements but at the points between two elements. And each change of output is smaller at farther points from each element. Therefore, a position of load is calculated using ratio between these two outputs. In short, this sensor has interpolation ability.

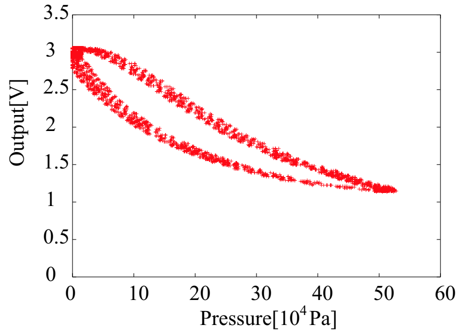

Fig. 9. Characteristic of tactile sensor element. The vertical axis is the output voltage of each tactile sensor element. The horizontal axis is the applied pressure.

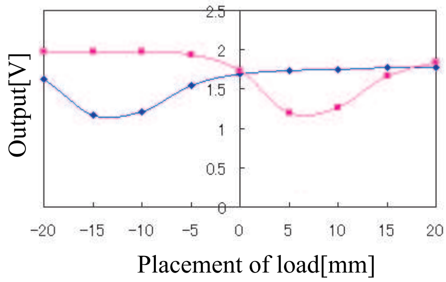

Fig. 10. Interpolation ability. The vertical axis is the output voltage of each tactile sensor element. The horizontal axis is the location where the load is applied.

2) SMBus communication tests: First, we made test-substrates which could only communicate. We connected the 32 test-substrates to one SMBus. The communication at high speed proved to be difficult because of the large bus capacitance which slows down the rise time of the clock. In order to make the rise time shorter, we used SMBus accelerators which are small-sized integrated circuits (IC) for improving the communication. Communication via SMBus with this IC was compared to SMBus without one. Totally, we used 32 SMBus accelerators in the SMBus.

Figure 11 shows SMBus signal in the two conditions. The same signal was used as an input. In the case with SMBus accelerators, the maximum communication speed was $1\,MHz$. Without SMBus accelerators such high speed is not possible.

We then measured the sampling time. The sampling time is defined as the sum of the time required for communication and of the time of transition duration of a tactile sensor after switching the LED on. The time required for sampling four sensors was approximately $0.2\,ms$. Therefore the sampling is independent from other SMBus, the number of tactile sensor elements sampled in $0.2\,ms$ is the number of SMBus $\times$ 4. In the case of the maximum of 1024 tactile sensor elements, all

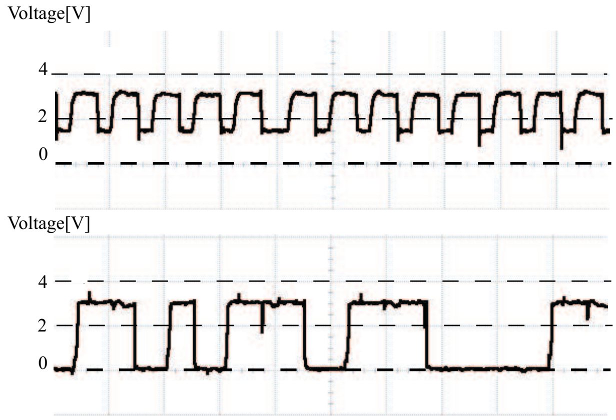

Fig. 11. SMBus communication test. Top: without SMBus accelerator. Bottom: With SMBus accelerators.

sensors can be sampled in approximately $51.2\,ms$.

3) Installation: Figure 12 shows that an installation example. First, we connected a couple of tactile sensor sheets. Then, we folded the individual tactile sensor modules by taking care of appropriately distributing the sensors. Finally, we mounted the resulting "skin" on the arm of our humanoid. The connected tactile sensor sheet had 120 tactile sensor elements(eight elements were removed by cutting) and weighed only $25\,gr$.

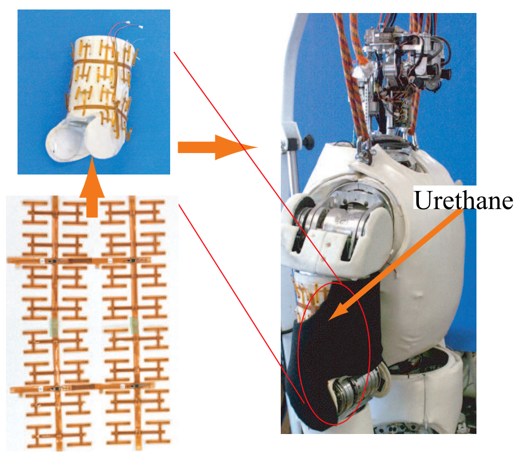

Fig. 12. Installed tactile sensor sheet consisting of 120 sensing elements.

VI. Conclusion

In this paper, we proposed a novel small-sized tactile sensing element composed of a photo-reflector covered by urethane foam. This sensor has a few notable characteristics:

1) It is easy to manufacture;
2) The sensing element is small-sized and light weight;
3) The dynamic range and sensitivity of the sensor can be controlled;
4) Interpolation between neighboring tactile elements is possible;
5) The interface electronics is small.

A weak point of this tactile sensor is large consumption of current. We solved this problem, by restricting the number of powered light-emitting devices through time-sharing control. A further advantage of using such control is that it is possible to reduce the quantity of analog-digital converters and signal lines.

We also introduced the concept of "cut-and-paste tactile sensors", and showed how such sensors can be realized. We defined a tactile sensor sheet consisting of modules of tactile sensor elements interconnected by a serial bus. The sheet can be connected to other sheets and hence potentially cover a large area. Moreover, because the individual sheet are bendable enough to be folded and sufficiently rigid to be cut, it is possible to select the location of each tactile sensor element rather freely. An important merit is that only one type of tactile sensor sheet is required for covering a whole system.

Finally we also proposed a bus-based communication network to be used in conjunction with the realized skin. The network is a real-time network and can deal with a large number of tactile sensor elements.

The complete tactile sensor system meets all criteria exposed in Section II and is therefore suitable for realizing dynamic whole-body movements in a humanoid. To our knowledge, our sensor is the first instance of a tactile skin applicable to dynamic whole-body movements. Our future work will be oriented towards installing the tactile skin such as to cover the entire humanoid body and to use it for the control of dynamic whole-body movements.

Acknowledgment

The authors would like to thank Max Lungrarella Phd. for his help of writing this paper and Naoko Seta for her help of experiment. And we would like to thank Japan Society for the Promotion of Science and Grant-in-Aid for Scientific Research Basic Research A.

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