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Development of a Humanoid with Distributed Multi-axis Deformation Sense with Full-Body Soft Plastic Foam Cover as Flesh of a Robot

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1. Introduction

In order for humanoid robots to work around human, it is important to enable them to be touched by humans, and to sense its contact states throughout the body. Almost all of full-body tactile sensors of robots ever developed were sensors which detect distribution of vertical pushing force on its thin "skin". Existing whole-body tactile sensors were called "skin" (V. J. Lumelsky, 2001), "cover"(H. Iwata, 2002), "suit"(M. Inaba et.al., 1996).
About sixty percent of human body is made of soft organs such as skin and muscles. Human can sense multi-dimensional deformation on its thick deformable "flesh". As a machine modeled after human and working automatically around us, it can be considered effective to have human-like thick soft deformable exterior with multi-axis tactile sensors.
In this research, we aim to obtain a method to construct both a robot skeleton and a whole-body soft sensor exterior as "flesh" . We are developing a robot named "macra" (Hayashi et.al., 2007;) with soft thick exterior, shown in Fig.1.

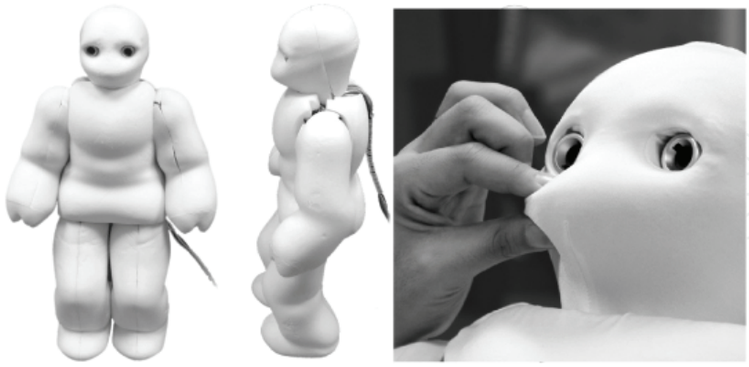


Fig. 1. A humanoid robot which has soft exterior parts with distributed force/torque sensors

2. Deformation sensing "Flesh"

Considering implementation of multi dimensional sensors, spatial limitation of soft cover is a problem. Thin tactile sensors often come up important theme. Through the "flesh" approach, it is possible to locate relatively thick sensors which sense distribution of multi-

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axis force vectors, because the spatial constraint can be eased by thick exterior. There are some sensors which sense multi-axis force vector. For example, three-axis force/torque sensor which is used as sole sensor, acoustic resonant tensor cell sensor which sense six-axis stress sensor (H. Shinoda et.al.), vision-based tactile sensor(K. Kamiyama et.al. 2004).
Adopting this kind of sensor composition, it can sense not only distribution of vertical pushing force (Fig.2-a), but also shearing force (Fig.2-b) and pulling force (Fig.2-c). When the robot is grabbed its arm like Fig.2-a/b, the robot can detect whether it is pulled forward or pushed backward. The soft cover enables us to emulate local deformation such as pinching.

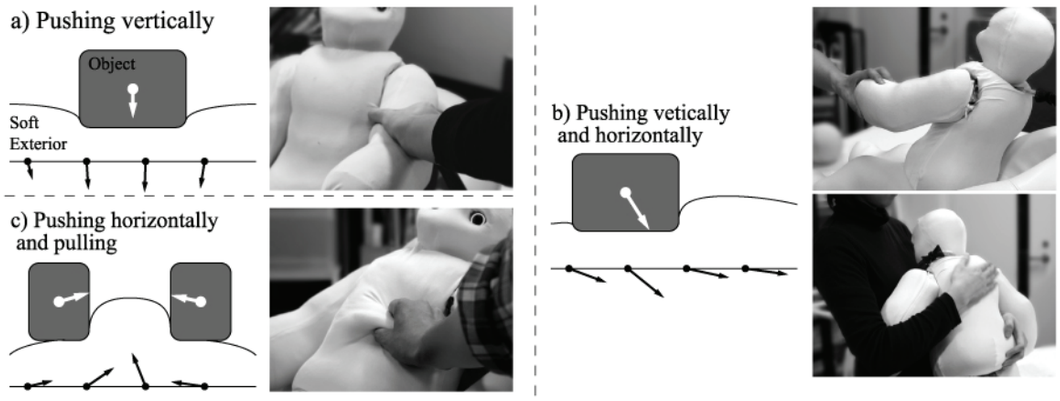


Fig. 2. If a robot has thick "flesh", it can predict its next contact state without actually changing the contact position.

3. Constitution method of full-body cover made of thick foam

3.1 Soft material which is light and possible to form its shape

Molded soft polyurethane foam is adopted for material of soft cover, because it is light and easy to fabricate. Its elastic characteristics can be customized by changing ratio of main component and curing agent. Molding method which enables precise production of exterior shape is adopted, because precise and reproducible production is important for sensing. Other representative examples of soft foam plastics are made of polyethylene, rubber. Polyethylene foam and rubber foam are produced by kneading base compound and bloating agent and then heating them, which are relatively difficult to produce experimentally. It is necessary to form films on the surface of it to avoid significant deterioration. In-mold coating and film laminating has fine texture and durability capacity. But these methods require precise temperature and pressure management, and expensive mold. Thus, we employed stretchable fabric cover to put on the molded foam.

3.2 Softness adjustment of soft plastic foam cover

Softness of thick whole-body cover including sensors affects the sensor characteristics. Movable ranges of joints are also affected. It is effective to design softness of soft cover locally around its joints. In order to adjust softness locally, there are several methods. One of these is to divide molds and mold plastic foam covers from different kinds of solution, and join them with adhesive. Other method is to control temperature or curative agent mixture locally and mold at one time. These methods are not effective for now. Adhesion plane becomes hard. Molds for local temperature control are too complex. For prototyping,

adjustment in shape and slits is adopted. Bases of limbs were divided, thickness around joints were designed to be thin.

4. Implementation of distributed multi-axis deformation sense

Inside the soft exterior parts (on the surface of internal mechanical frame), forty nine three-axis capacitance-type force/torque sensors (PD3-32-05-15/40/80, NITTA Corp.) are embedded (Fig.3). Disk-shaped parts are screwed to force-sensitive sticks. When the soft exterior parts are pushed, stress is applied to the disk-shaped parts, then the sensors output voltages associated with z-axis force and x/y-axis torque(Fig.4). This sensor is not so small (diameter 18[mm], thickness 15.6[mm]), but it is possible to embed this sensor inside the thick cover. If the external force includes shearing components, stress on the disk slants, then x-axis torque and y-axis torque applied to the disk are detected. Soft exterior parts as tactile sensors have spatially interpolating characteristics, therefore there is availability that force detecting disks need not necessarily large enough to cover the entire area of robot's surface.

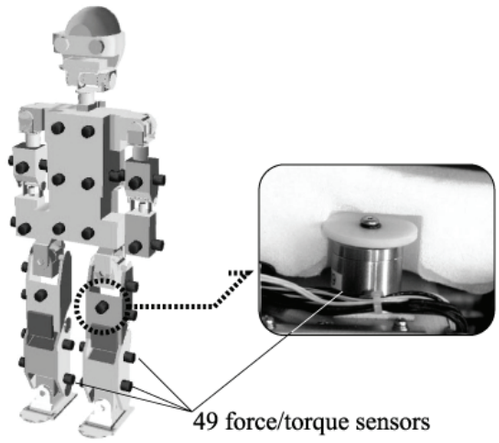


Fig. 3. Forty-nine three-axis force/torque sensors embedded inside the flesh.

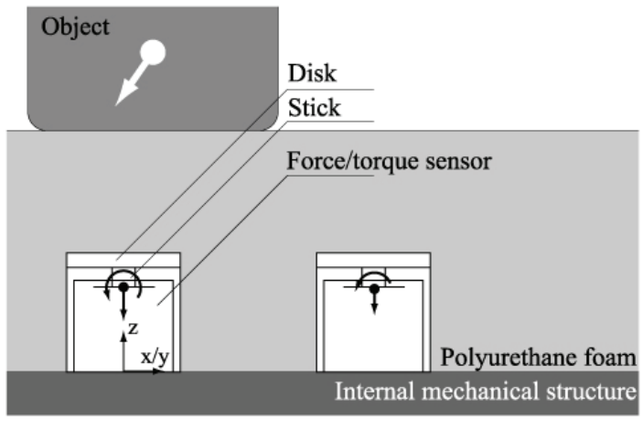


Fig. 4. Sensors are embedded in the polyurethane foam. Thicknesses of polyurethane foam varies from about 2[mm] to 60[mm]. The bottom face of the sensor is screwed shut to shell of robot skeleton.

5. Implementation to a humanoid robot

We have designed internal mechanical structure of the robot so that it has enough space to wear thick cover and joint movability. Its actuators and the sensors except tactile sensors are reused from a commercially available humanoid robot (HOAP-1, Fujitsu automation Corp.). Its height is about 700[mm], weight is about 7.5[kg]. Average thickness of soft cover is approximately 25[mm]. Specifications of the robot are shown in Table.1.

Num of Total DOF	22
Height [mm]	about 700
Weight [kg]	about 7.5
Motor Units	Smart Actuator Module, Type-I,Type-III (Fujitsu Automation)
Sensors	Incremental encoder, Accelerometer, Angular rate sensor, Force Sensing Resistor (Interlink Corp.), USB camera, Microphone,3-axis force/torque sensors (Nitta Corp.)

Table 1. Specifications of humanoid body.

5.1 Mobility of joints

Movability of Joint: Characteristics of compression and extension of polyurethane foam is not linear. Customized polyurethane foam in softness is used for the cover material. It is difficult to predict load torque from exterior to actuator at joint. Therefore load torque and maximum exterior thickness which is calculated using 25% compression hardness and breaking extension and breaking force of soft polyurethane foam were checked at first. This calculation method for design was investigated by Aono et.al.(2005). Then, for modifying its mobility of joints, slits and hollows were added. Stretchable cover envelops slits, not to expose the internal skeleton.

Currently, the robot can do several motions such as crawl, roll-over, and stepping (Fig.6). The movable range of knee joint is about 80 degrees, the maximum torque of the actuator is 45[kgf-cm].

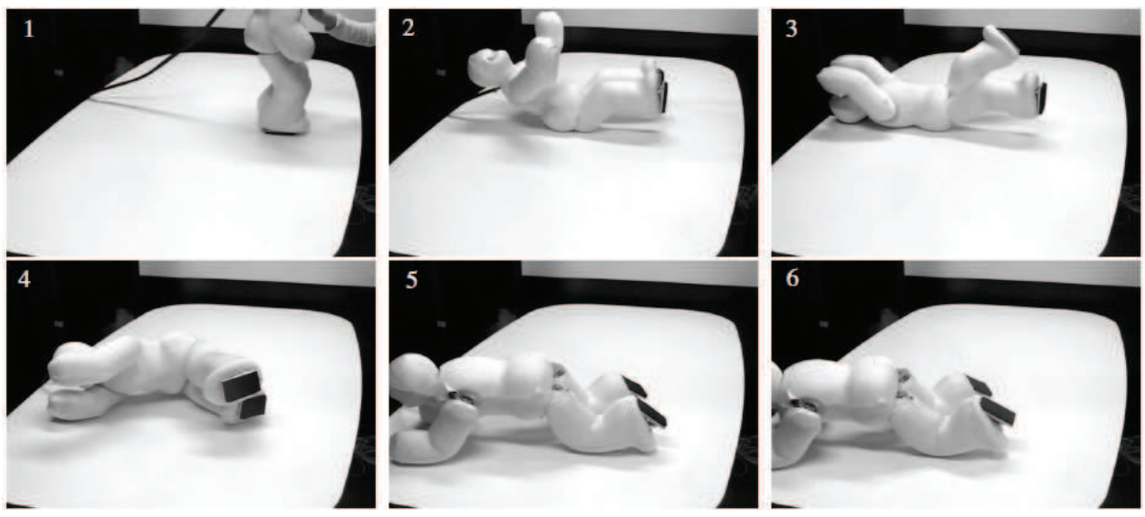


Fig. 6. Soft exterior enables a robot to fall down and roll-over more easily.

5.2 Heat exhaustion

Degree of heat conductivity of foam plastic is very low (about 0.02-0.07[W/mK]). One of solutions for heat exhaustion problem is forced cooling.

To test heat exhaustion effect of fans, two exhaust fans (1204KL-01W-B50 Minebea Corp.) and ventilation lines (width ~50[mm], thickness ~15[mm]) were embedded inside the exterior at toe and ankle. Exhaust outlet was made at crotch joints of limbs, considering occlusion caused by change in posture and contact with flat plane such as floor. Then the robot was hung and was made to bend the knee joint 40 degrees and stretch it back with a period of six seconds. Without fans, temperature on the surface of mechanical frame increased 12.5[oC] in 26 minutes. Heat elevation was reduced to 2[oC] with the two fans under the same conditions. Therefore, thick foam plastic cover was found not to be unrealistic.

5.3 Ability of distributed multi-axis deformation sense

Fig.7 shows an output of a sensor on the chest. When the robot is stroked or pushed in several ways. The output voltages were calibrated to zero. Sensitivity of x-/y-axis is 3.3-6.0[V/Nm], z-axis is 26.7-46.7[mV/N]. When the robot was pushed, z-axis output became high. When it was stroked downward, x-/y-axis output became high.

Black lines on the models of the robot in Fig.8 indicate output voltages of each actual situation. On the left of Fig.8, a person is holding and then pushing and pulling the arm of the robot. Even if the contact position does not change, the direction (pushing or pulling) can be detected.

Thick soft exterior enables to emulate various contact states including local deformation such as pinching. On the right of Fig.8, a person is pinching the robot. It can be seen that two sensors on the side of the robot react to the pinching in each direction.

7. Conclusion

In this research, a humanoid robot with thick polyurethane foam exterior and embedded distributed three-axis force/torque sensors was developed. This developed full-body tactile system can sense direction and distribution of force, so that this sense different contact states such as holding or pulling or pushing. Tactile sensor information processing using this multi dimensional distributed data is the topic of our further study.

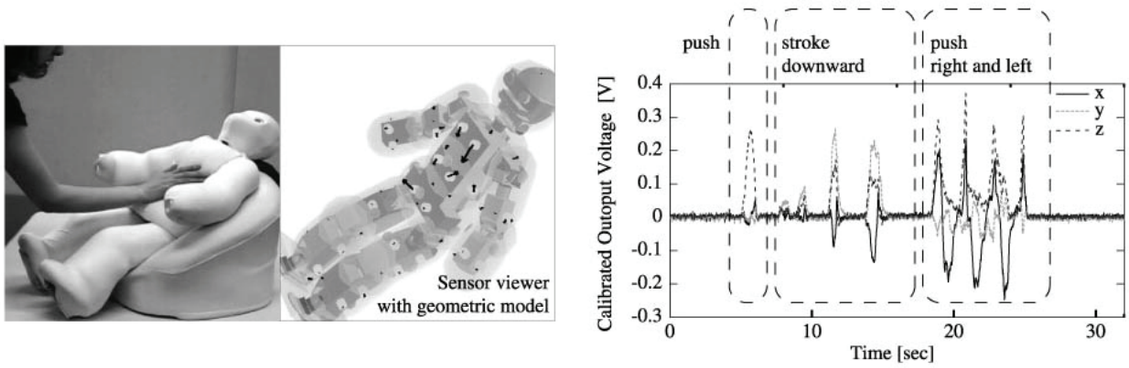


Fig. 7. The output of a three-axis force/torque type sensor which is located on front body of the robot. The sensor system is able to discriminate different states of touch from a person.

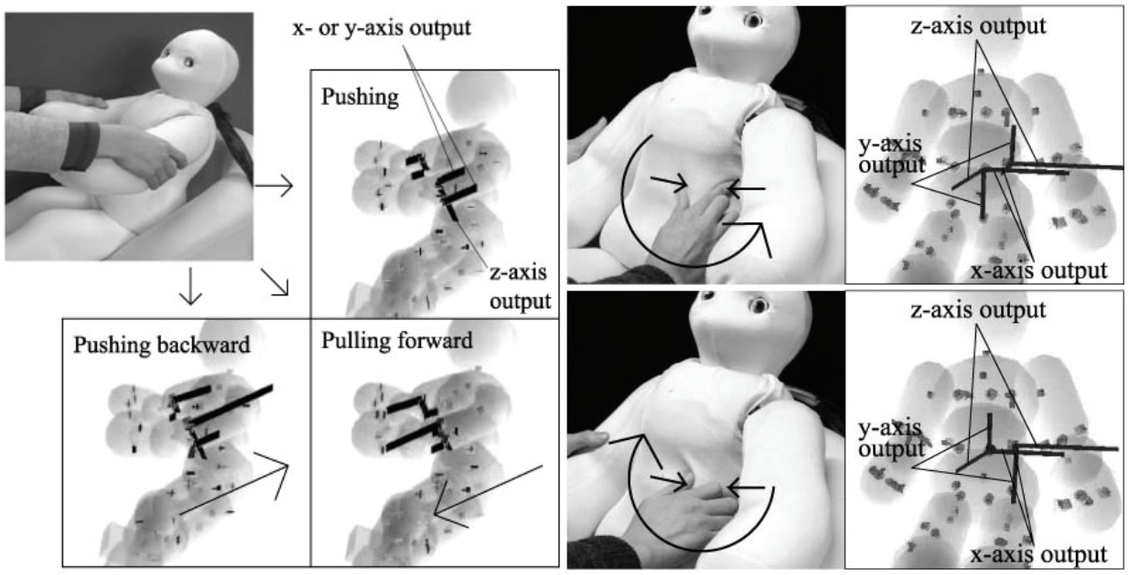


Fig. 8. Sensor output differs from its shearing force in the same contact state. Thick soft exterior enables local deformation state such as pinching. The distributed three dimensional sensors react to the direction of pinching.

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Sensors: Focus on Tactile Force and Stress Sensors

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This book describes some devices that are commonly identified as tactile or force sensors. This is achieved with different degrees of detail, in a unique and actual resource, through the description of different approaches to this type of sensors. Understanding the design and the working principles of the sensors described here requires a multidisciplinary background of electrical engineering, mechanical engineering, physics, biology, etc. An attempt has been made to place side by side the most pertinent information in order to reach a more productive reading not only for professionals dedicated to the design of tactile sensors, but also for all other sensor users, as for example, in the field of robotics. The latest technologies presented in this book are more focused on information readout and processing: as new materials, micro and sub-micro sensors are available, wireless transmission and processing of the sensorial information, as well as some innovative methodologies for obtaining and interpreting tactile information are also strongly evolving.

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