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Design and Development of a Humanoid with Soft 3D-Deformable Sensor Flesh and Automatic Recoverable Mechanical Overload Protection Mechanism

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Abstract— In order for robots to be able to assist humans at a very close distance, robots should allow contacts occurred at many places and deal with them. For realizing such functions, robots should have whole-body soft sensor exterior for preparing contacts against almost every body parts since it is difficult to limit where to be touched from humans.

Although several groups have developed humanoid type robots which have soft tactile sensors, most of them detects distributed 1-axis forces and that is not sufficient when the robot and a human have contacts very closely. In addition to that, there is no consideration in the previous studies about humans' movement during close contact with the robots.

In order to solve these problems, we have newly developed a humanoid with soft 3D-deformable sensor flesh and automatic recoverable mechanical overload protection mechanism. Soft 3D-deformable sensors are implemented by molding the infrared light receiving devices into the urethane cube and by detecting the changes of the output voltage of the devices during the deformation. On the other hand, automatic recoverable mechanical overload protection mechanism is implemented by small mechanical torque limiters and monitoring system for embedded potentiometers in the torque limiters. Also detail implementation of the embedded electric system and the overall software structure is described in this paper.

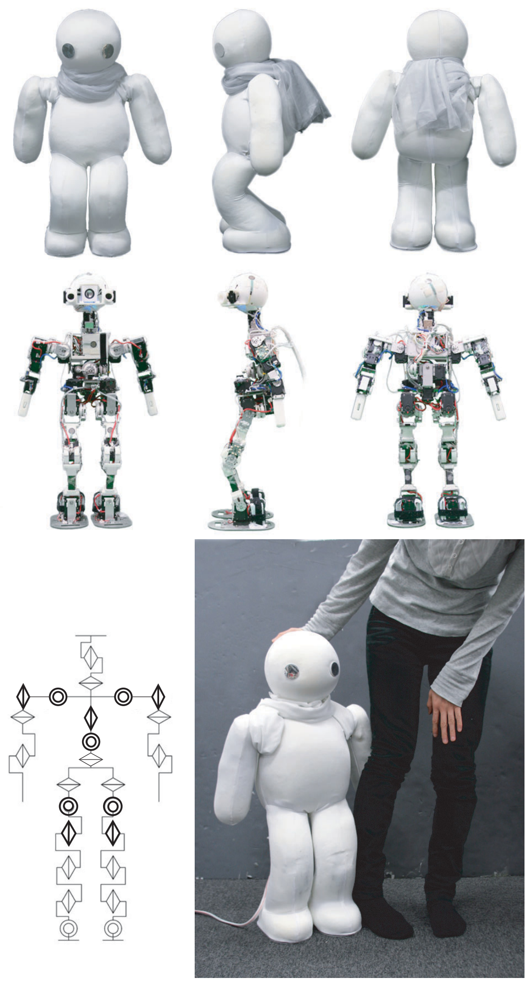

Fig. 1. Appearance & D.O.F arrangement of the developed robot 'macket'

I. Introduction

In order for robots to be able to assist humans in daily life, situations where robots and humans are working at a very close distance should be considered. In such situations, not only safe contacts with humans should be achieved, but also robots should allow contacts occurred at many places and deal with them. For realizing such functions, it is necessary for robots to be able to have contacts with human softly and to react to the contacts detecting contact forces.

Those functions enable humanoid robots to do many essential tasks for assisting our lives, such as close communication with humans, or caring humans by holding them, etc. Since it is difficult to limit where to be touched from humans in those cases, robots should have whole-body soft sensor exterior for preparing contacts against almost every body parts.

These days, several research groups have interests for developing such humanoid robots with whole-body tactile sensing exterior. Ishiguro et al developed several communication robots which have distributed soft skin sensors. For example, Robovie-IV[1] , Repliee Q2[2], and CB^2[3] have distributed soft pressure sensors using piezo films and those sensors are used for detecting human touches during communications. Kuniyoshi et al have developed tactile skin sensor which can fit to curved surfaces[4]. Their tactile sensor consists of a photo-reflector covered by urethane foam and the applied force is transformed into the strength of the received light. They implemented it to an adult-size humanoid robot and the robot can lift 30[kg] box by whole body contact and tactile feedback[5]. Also, Mukai et al have developed soft tactile sensing exterior by embedding FPC with small pressure sensors in an elastic body[6]. They implemented it to Humanoid robot RI-MAN, and the robot can speculate the movement of the held-up 16[kg] dummy human from tactile sensing output. Although all of their exteriors are made of soft material and the embedded sensors can detect forces applied to each sensing elements, the problem is that detecting 1-axis forces is not sufficient when the robot and a human have contacts very closely. Multi-axis force detection is necessary not only for dextrous manipulation of the objects but also for simplifying the interpretation of the applied forces during close contacts conditions. For example, when human tries to hold up a robot with their hands on the robot's torso, the robot can detect which direction to be moved by the humans directly from the multi-axis sensor outputs. If the robot can detect only 1-axis forces, it has to process the temporary transition of the distributed 1-axis forces, and the distinguishable force directions depend on the sensor resolution of the place where human touched. If spatial resolution of the distributed sensors are reduced, 3D force detection ability is also decreased with 1-axis distributed tactile sensors. In addition to that, there is another problem with the previous studies. Although robots should deal with the increased internal forces caused by the sudden motion of the held-up objects or humans in close contact conditions, there is little consideration for that situations.

So far, we have developed 1-dimensional distributed tactile sensor suits made of electro-conductive strings and fabrics[7], and we improved the 'Sensor Suit' to 'Sensor Flesh' by adopting the method to embedded the 3-axis small force/torque sensors in the soft thick urethane foam[8]. Although this 'Sensor Flesh' can solve the first problem listed above to some extent, there is enough room to be improved. Also, there is no consideration for the second problem in our previous work.

In order to solve these two problems, we have newly developed a humanoid with soft 3D-deformable sensor flesh and automatic recoverable mechanical overload protection mechanism. In this paper, hardware and software system for the developed humanoid is reported, including descriptions for the mechanism of the developed soft deformable tactile sensing element and the mechanical overload protection function.

II. 'macket' : a Humanoid Robot Which Allows Close Contacts with Humans

For realizing a humanoid robot which can be held by humans softly and respond to humans based on how they are in contact with humans at a very close distance, following requirements should be met.

- Robots should have whole-body enclosing type soft exterior.
- Distributed multi-axis tactile information during close contact is needed.
- Robots allow sudden and rough motion of humans to some extent.

'macket' is our newly developed humanoid robot prototype for realizing a humanoid robot which meets above requirements. Fig.1 shows the appearance of macket with sensor flesh and bone structure. What we call 'sensor flesh' here is a soft thick exterior embedded with multi-axis tactile sensors. In the lower row of the Fig.1, arrangement of the degrees of freedom is shown. Also, specification of macket is shown in the Table.I, and the part of locomotion performance of the macket is shown in the Fig.2.

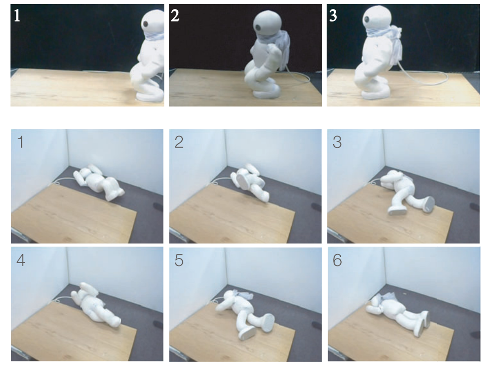

Fig. 2. Locomotion performance of macket (upper photos: dynamic walking, lower photos: rolling-over motion)

Soft thick exterior makes the robot physically safe for humans to hold it and also it works for forming friendly impression. However, there are demerits of such thick enclosing type exterior. Especially, a loss of movability and heat release problems should be considered. Although these demerits are trade-off with the better effects of soft thick exterior, we try to cope with those demerits.

First of all, following points are conducted for the loss of movability.

- Clearance gap is designed around each joints for preventing exterior from being clipped.
- By cutting some parts of urethane exterior and covering them with stretchable cloth material, stretchableness around each joints is improved.
- Internal mechanical frame is designed to be thin for ensuring wider movable range.

As a result, macket can bend its knee joint about 117.4[deg] while the maximum movable range without exterior is 150[deg]. Although movable range is decreased to about 78% of the original one, about 120[deg] bending of the knee joint is enough for doing some dynamic behavior shown in Fig.2.

Also, for heat release problem, following points are conducted.

- Exterior is divided for each limbs and there is some gap at the root of each limb. Those gaps can be used for heat releases.
- Fans are set at the soles of both legs and inside of the body for forced cooling.
- By monitoring the temperature of actuators, execution of the behavior is stopped and take a rest when the temperatures go beyond thresholds.

Compared with our previous prototype, 'macra'[8], a humanoid with soft sensor flesh, there are two big features for macket.

1) It has distributed soft 3D-deformable sensing elements.
2) It can tolerate human's relatively rough movements during close contacts.

The softness of the sensing elements themselves are very important property since it affects tactile impression that human receives during close contacts. In macra,

TABLE I

Specifications of macket's skeleton

Total DOF	26
Height	~800[mm]
Weight	5.6[kg] (not including soft cover)
Actuator	RX-64 (Maximum hold torque 64[kgf-cm]) (ROBOTIS Co.)
	RX-28 (Maximum hold torque 28[kgf-cm]) (ROBOTIS Co.)
Sensor	FSRs for tactile & ZMP sensor (Interlink Co.), potentiometers for dislocation sensor (ALPS Electric Co.), 3D Motion Sensor MDP-A-3U9S-DK (NEC/TOKIN Co.), two cameras, two microphones, 3D-deformation sensor (explained in Section III)
Electric interface	RS-485(actuators, sensors), USB(sensors)
Human interface	two cameras, two microphones, speaker

commercially available 3-axis force/torque sensors are adopted and human can detect where the sensing element is because of the rigid body of the sensor. For realizing natural contact behavior between humans and the robot, it is desirable that human cannot detect the location of the sensing elements. If human detects the location of the sensors, they can be conscious about the sensors during interaction and it can't be a natural situation. Therefore we have developed new soft deformable sensing elements[9] and mount them on this robot. The detail design and implementation for the sensor is explained in section III.

The second feature is important for tolerating humans' motion and also robot's motion during close contacts. In a natural situation, humans can move arbitrary even if a robot hold them, and the robot should tolerate such movements. For realizing such function, we developed small automatic recoverable mechanical overload protection mechanism and installed it to some of the important joints of the robot. The detail design and implementation for the mechanism is explained in section IV.

III. Soft Tactile Sensing Element Detecting Multi-axis Deformation

Even if the robot's exterior is softly made and exterior itself is suit to close contacts with humans, tactile impression can be ruined by the embedded rigid and hard tactile sensing devices. So far, there are many studies about developing soft tactile sensors[10] [11], [12]. However, these sensors are still in the developmental stage and it is not easy to introducing those elements into our robot system. Therefore, we have developed the soft 3D-deformable sensing device[9] for giving multi-axis distributed tactile sensation to our robot.

The developed sensor is shown in the left of the Fig.3. Detail information and evaluation experiments are written in another paper[9], which focuses on the sensing element itself. Therefore, detecting theory and basic properties are described in this paper.

The basic principle of deformation sensing for this sensor is as follows (the right of the Fig.3) : sensing part for infrared rays ('Light receiving box' in the figure) is molded in the soft urethane cube, and the 3D-deformation of the urethane body can be speculated from the changing value of the received infrared ray at the sensing part. In the figure, arrows from 'Light receiving box' indicate normal directions for each light receiving elements. By adopting the method to convert the deformation to the received light strength, the problem of the drift of the sensor output caused by heat, which is a big problem for capacitance-type force sensors that we use in our previous studies, is solved. The arrangement of the light receiving elements is very important for distinguishing multi-axis deformation. In some arrangements, received light patterns for different stimulations can become almost the same. In our sensor prototype, we assume that these sensor elements are covered by soft thick exterior. Under this assumption, local deformation is not large enough to have almost same value between two different stimulus when the light receiving elements are attached to the plane of some polygon which is referred to 'Light receiving box' in the figure[1].

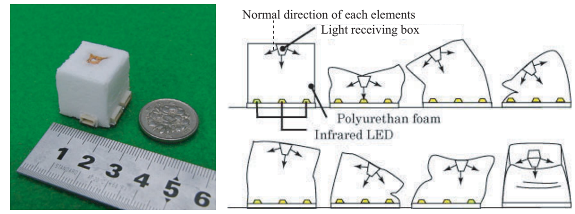

Fig. 3. Deformation of the developed sensor

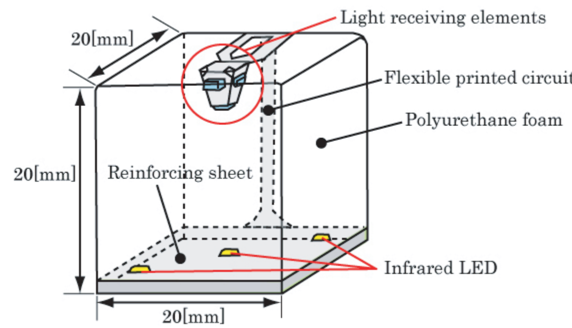

Fig. 4. Schematics of Soft Tactile Sensor for Multi-axis Deformation Sense

In Fig.4, schematics of the internal structure of the developed sensor is shown. Developed sensing element is molded to 20x20x20[mm] cubic shape. Here, cubic shape is adopted for preventing displacement between the urethane exterior and the attached sensor elements. The size of the sensor can be smaller by selecting the mechanically small light receiving device (in this implementation, photo-transistor). As shown in the figure, 3 infrared LEDs are placed at the bottom of the sensor for ensuring the enough amount of the received light. For speculating 3D deformation of the sensor unit, light receiving devices should be arranged as they are mounted on the surfaces facing each other. It is easy to make such

[1]It is an inclined cubic shape, actually in this case.

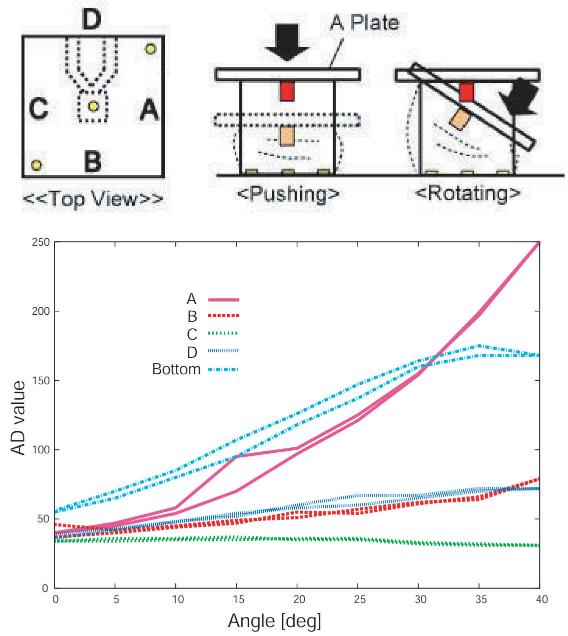

Fig. 5. Sensor output of the Developed sensor(when rotating toward direction 'A')

structure when those devices is arranged at the top of the sensing element. The circuit board including the light-receiving part is made by FPC. After the light-receiving part is glued to the small cubic-shaped plastic box and the circuit board is fixed to the mold, the urethane sensor cube is molded by integral molding method.

The example of this sensor output is shown in Fig.5. Here, this output is corresponding to the one when the plate put on the sensor is rotated from 0 to 40[deg] by 5[deg] interval toward direction 'A' in the Topview of the Fig.5. The horizontal axis of the graph expresses the rotated degree[deg], and the vertical axis expresses the output AD value[2]. In the graph, 5 lines corresponds to the sensor outputs for each light receiving devices (4 devices on the lateral face and 1 device on the bottom face). From the graph, output of the inclined side, that is the receiving device 'A', output the discriminable level compared with other 3 receiving devices that are located on the lateral face of the light receiving cube. Although the sensor output from bottom device is relatively high against the output of 'A', it is not the problem since the bottom output is usually used independently from other 4 devices for deciding the vertical displacement of the light receiving cube. We confirm similar results when rotating toward other directions. However, they are not shown here because of the space limitation.

Sensitivity and force ranges of this sensor unit can be adjusted to some extent by changing the property of the urethane foam. In our developed prototype, it can detect the applied force from 0 to about 1.4[kgf] linearly, and around 1.5[kgf] the sensor output reached almost the maximum value.

In Fig.6, a prototype of the sensor flesh is shown.

[2]ADC has 10bit value and FS is 1024.

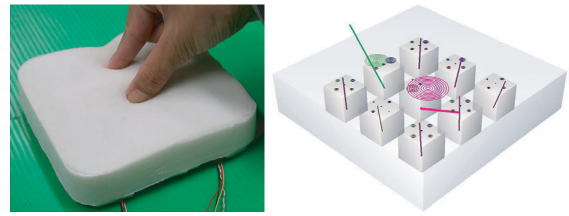

Fig. 6. Pinching a prototype of sensor flesh with Two Fingers

9 developed sensor cubes are embedded in the 30 [mm] thick urethane foam. In the right of the figure, sensor output is drawn on the geometrical model. 3D-Deformation is expressed as the incline of the bar arranged at each sensor cube model, and the magnitude for each light receiving device is expressed as the radius of the drawn circle. As you can see from the figure, pinching the sensor flesh prototype makes the 3D-deformation of the sensors. As it stands now, accuracy of this sensor is not so high, because assembling and molding process are totally hand-crafted. But the important thing is that discrimination of the natural human-like contact states, not only pushing, but also contacts with 3D-deformation, such as pinching or twisting, can be possible by this kind of simple structure. Also, easiness to realize the distributed tactile sensors for the actual robot is another key issue. Therefore, each 3D deformable sensor has a microprocessor for A/D conversion, and it can send a signal through SMBus Protocol.

Using this soft 3D-deformable sensor elements, sensor flesh for macket is developed. In Fig.7, an arrangement for the sensor elements and the actual situations of the human touch are shown. In the current setup, macket has 48 soft 3D-deformable sensor elements inside of the thick urethane foam exterior. In the left of the figure, small blue boxes indicate each sensor element. Those elements are mainly arranged at both arms, torso, and head. Sensors for legs are planed to be added in the future. In the right of the figure, lower images are corresponded to the upper photos. For each situation, 3D deformation is calculated by comparing facing pairs of light receiving devices in each sensor element, and the result is drawn on the robot's geometrical model as an arrow. For the robot with distributed tactile sensors, information processing which eliminates undesirable tactile signals generated by self interferences is very important. Those self interferences can be eliminated by constructing sensor signal output table relating to the robot's joint angles. This method is originally proposed by Hoshino et al for their sensor suit[7], and this method can be extended for multi-axis force distribution.

IV. Automatic Recoverable Mechanical Overload Protection Mechanism

When humans held up by a robot with close contacts moves unexpectedly, locally-concentrated force can be applied to the robot's joints, and it can be a cause of the actuator's breakdown. By adopting soft thick exterior, shock elimination and stress depression with cushioning medium can be expected to some extent. However, static mechanical overload to actuators cannot be loosened

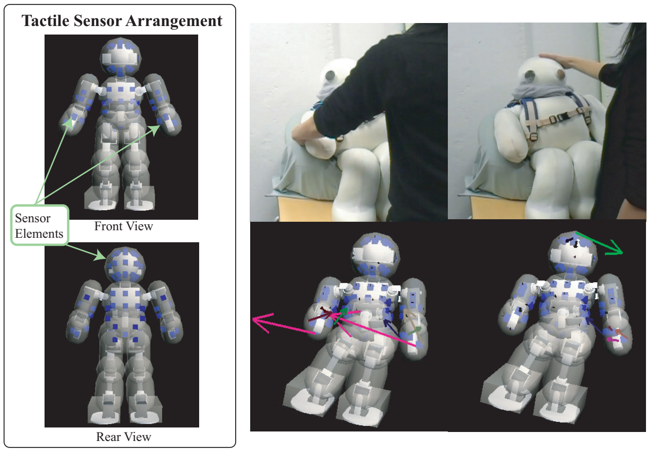

Fig. 7. Soft deformable sensor outputs of macket, drawn on the geometrical model

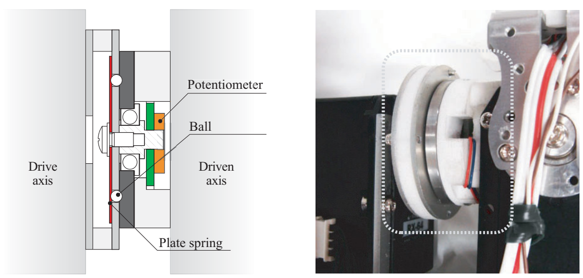

Fig. 8. Structure & photo of a developed mechanical torque limiter

with the soft exterior. Therefore, we implemented overload protection with mechanical torque limiter at some important joints for preventing joint's breakdown due to relatively rough contacts with humans.

So far, overload protection with mechanical torque limiter was mainly discussed about non-humanoid type robots[13]. In the case of humanoid robot, mechanically compliant assembly such as series elastic actuator [14] inside the limited part was studied. However, their structure is too large and complicated for implementing them to the joints of our small humanoid. Therefore, we developed the small and simple mechanical torque limiter with automatic recoverable function.

Fig.8 shows the structure of a developed torque limiter unit. A potentiometer is located inside the limiter for automatic restoration from dislocation. Ratchet type torque limiter is adopted, since slip torque of magnet type limiter is too small and friction type limiter is sensitive to temperature. Limit torque can be configurated by changing thickness or number of plate springs inside. It is desirable that limit torque is set a little bit larger than the maximum torque for the actuators. Limit torque for macket is adjusted by some preliminary experiments not to work during basic motions, such as dynamic walking, or rolling over. Torque limiters are located only at the bases of limbs (10 torque limiters are implemented for macket) considering possibility of increase of backlash, and also considering space of soft exterior. Joints with this torque limiter is drawn thick in the DOF arrangement of Fig.1.

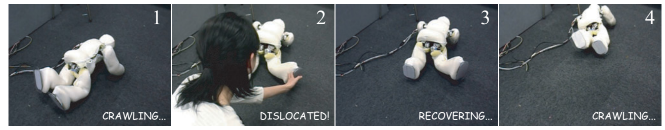

Fig. 9. The robot can crawl, dislocate its joints, and restart crawling

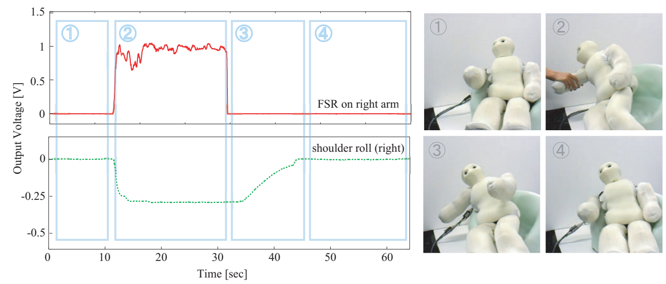

Fig. 10. When the FSR output voltage is high (2), the robot does nothing, and then(3), starts restoration

Fig.9 shows an example of rough contacts between a human and a robot. When a person touches the robot in a rough manner during its crawling motion, the robot can dislocate its joints and then restart crawling motion after recovering its original angle. In this case, the torque limiter and its automatic recovering system can protect the body from the unexpected rough contacts. Here, dislocation of the joint is monitored by the potentiometer inside of the torque limiter and the dislocated joint is driven to the normal position automatically after the dislocation of the joint is detected.

In the cases of contact behaviors shown in Fig.9, timing of automatic restoration is not important. However, adequate timing to start restoration is important when a human moves unexpectedly keeping contacts with a robot. If restoration started before removal of external force, the joint might repeat dislocation and restoration, or it encounters the limit of rotating angle. One approach to solve this problem is to use tactile information for hints of existence of external load. In Fig.10, transition of the FSR(Force Sensing Resistor) on the robot's right forearm (the left upper graph in the figure) and potentiometer output of the robot's shoulder roll-axis joint are shown. In this experiment, the robot waits for starting restoration watching FSR output on right forearm (period 2 in the graphs), and then it starts recovering the dislocated joint after the removal of human's hand (period 3 in the graphs).

Here, in Fig.9 and Fig.10, exterior of the robots is different from the Fig.1. But the internal frame is macket. In these experiments, the older version exterior was used.

V. System structure of macket

A. Embedded Electric System

In Fig.11, embedded electric system for macket is shown. Basically, system is constructed in a distributed manner since there are so many sensor elements inside the body. As shown in the figure, there are two main communication lines, one for actuators and the other

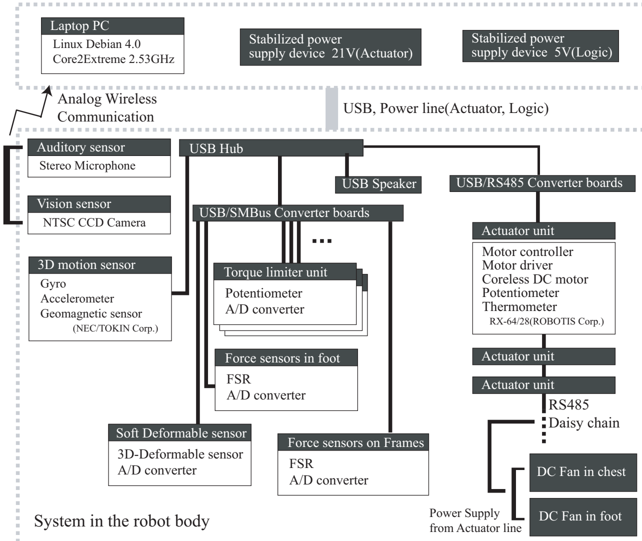

Fig. 11. Electronics system of macket

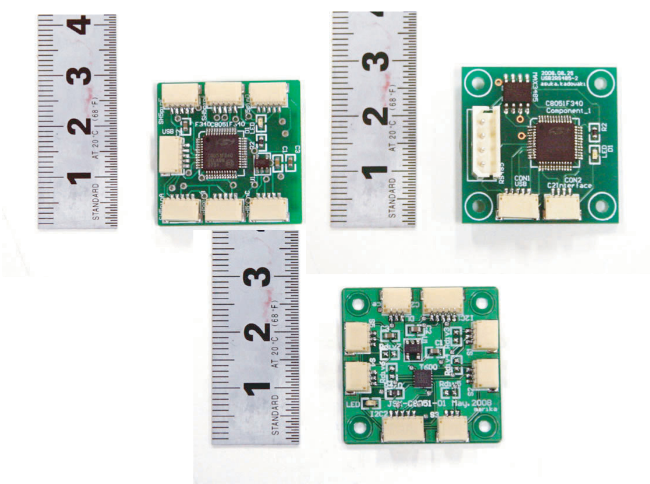

Fig. 12. Processor boards embedded inside of macket

for sensors. For actuators, Dynamixel Rx-28 and Rx-64 manufactured by ROBOTIS Co. is adopted and they are daisy-chained using RS485 protocols. Through USB/RS485 converter boards we have developed (right upper of the Fig.12), main computer('Laptop PC' in the figure) sends target joint angles in every 40 [ms]. Another output device is USB speaker arranged at the head, and it is controlled by main computer via USB hub board.

On the other hand, there are 3 systems for sensors. One is for visual and audio sensation. Their signal is sent to the main computer by 2.4[GHz] analog wireless communication. Signals from two 25 million pixels CCDs and two microphones are captured and processed at the main computer. Second system is for devices which can A/D convert the signals and sent it to the main computer. Here, 3D motion sensor arranged at the base of the robot's torso is in this category. It can detects angular speed and acceleration and geomagnetism, 3-axis for each, and the main computer can access the A/D converted value through device driver. Third system is daisy-chained less-wired sensor system using SMBus protocols. Using the developed sensor A/D boards (lower of Fig.12) and USB/SMBus converter boards (left upper of Fig.12), the collected sensor information is sent to the main computer and processed in every 40 [ms]. The 3D soft deformable sensor element explained in Section III is also connected to this USB/SMBus converter board.

B. Software Structure

Software system for macket is realized by the extended RT Middleware system. In our system, OpenRTM-aist[15], proposed and implemented by Ando et al is integrated with Lisp interactive programming environment. In this environment, each component can be written both in C++ and EusLisp[16] and the components are completely controlled in the interpreter of the EusLisp. By adopting such interactive component system, system construction and extension is easily realized. For example, sensor components using 3D deformable sensors are constructed and debugged in parallel to the macket actuator system. After we confirm the behavior of the sensor components, we integrate them to the macket system without recompilation.

In Fig.13, constructed perception-action system for macket is shown. In the figure, each box expresses RT component and arrow-shaped object on the component indicates data port. Also, square-shaped object on the component indicates the service port for the common message service. All components in this system are executed synchronously in 25[Hz]. In the figure, 'USB Dynamixel Component', 'USB Sensor Reader Component', and '3D Motion Sensor Reader Component' are device dependent component and communicating with each device. 'Converter Component' is a component for converting the sensor value from raw data to physical value, and vise versa. 'Multiplexer Component' is a component which gathers the outputs from multiple components and output the gathered information as one input. 'Sequencer Component' is a component for interpolating the target angles for each joints. Behavior program written in EusLisp ('Various Behavior Programs') gets sensor information from 'Multiplexer Component' and calculate the actuator outputs. Then it send the target command to 'Sequencer Component'.

VI. Conclusions

In this paper, we have reported the design and implementation of our newly developed humanoid for allowing close contacts with humans. In order to overcome the problem in our previous works, two features are the key issues. One is a soft 3D-deformable sensing device for distributed tactile sensation, and the other is automatic recoverable mechanical overload protection mechanism for tolerating rough contacts between a human and a robot. 3D-deformable sensors are implemented by molding the infrared light receiving devices into the urethane cube and by detecting the changes of the output voltage of the devices during the urethane foam deformation. On the other hand, automatic recoverable mechanical overload protection mechanism is implemented by small mechanical torque limiters and monitoring system for

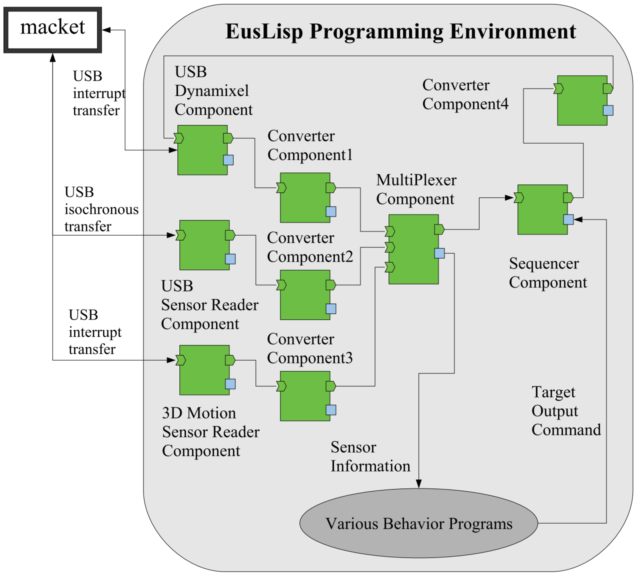

Fig. 13. Component structure for macket's perception-action system

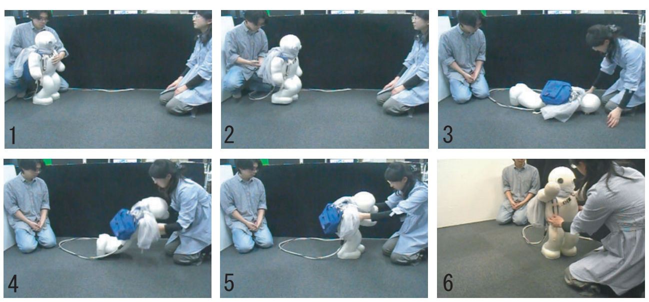

Fig. 14. An example of sensor-triggered close interaction behavior with humans

embedded potentiometers in the torque limiters. There are many future works, some of them include the issues such as improvement for the robustness of the soft deformable sensing network, organization of the tactile sensation during the behavior, whole-body tactile-feedback behavior during close contacts with humans and so on.

Using the developed system for close interaction behavior, now we are trying various situations where natural and close contacts are occurred. Fig.14 shows one example of such behavior. macket starts walking when it detects human's push against its torso by soft deformable sensors ('1' in the figure). When it falls down, it can know that it fell down using the 3D motion sensor, and tries to recover its posture ('3' in the figure). When it is grabbed, then it watched the grabbed parts and it makes the servo-control for leg actuators off expecting the human in front of it helps it to stand up ('4' in the figure). After it judges that its posture is recovered by the human's help using 3D motion sensor, it makes the servo-control of its leg actuators on again and tries to stand up with itself ('5' in the figure). And then, it expresses the joy with some dance ('6' in the figure). Although behavior transition is executed by monitoring various sensor changes, this is just an elaborated scenario example. However, robots that are working in close contacts with humans should deal with various kinds of contact situations. And from the concrete contact examples, robots with sensor flesh should be evaluated and improved from now on.

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