

## Sensor system of a small biped entertainment robot

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**Abstract**—SDR-4X II is the latest prototype model of a small biped entertainment robot. It is the improved model of SDR-4X. In this paper we report on the sensing system of this robot, which is important and essential for a small biped entertainment robot which will be used in the home environment. One technology is the design of the motion sensing system, i.e. the inclination sensor system and the force sensor system which obtains the inclination of the trunk and the foot with force. Another technology is the real-world sensing system. One aspect is the touch sensing system. The robot is used in a normal home environment, so we should strongly consider the safety aspects for human. Another is the vision sensor system. The configuration and the distance image acquisition are explained. Next is the audio sensor system which obtains the sound and the voice information. The hardware system and the direction recognition are explained. These sensing systems are the key to making the biped robot walking and dynamic motion highly stable, and understanding the real-world around the robot.

*Keywords:* Humanoid robot; biped robot; entertainment robot; sensors.

### 1. INTRODUCTION

When we develop a humanoid-type robot which is specifically an entertainment robot, the ability of whole-body stable motion control and effective sensing of the environment should be considered. Some important studies about whole-body cooperative motion control for humanoid robots have been undertaken [1–3]. Following these studies, we proposed a small biped entertainment robot SDR-3X (Sony Dream Robot, a prototype) in November 2000 [4]. That robot realized dynamic and elegant motion performance using the small high-performance robot actuator ISA (Intelligent Servo Actuator) and Whole Body Cooperative Dynamic Motion Control [5]. SDR-4X, which was developed in March 2002, is the advanced model and has the capability of Real-time Integrated Adaptive Motion Control using the enhanced ISA and many types of effective sensors [6, 7]. By using real-time

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adaptive control with effective sensors, SDR-4X can walk on uneven surfaces and perform adaptive motion control against external forces. Falling-over control of the robot is also realized by real-time adaptive control.

In March, 2003, we developed SDR-4X II, which is an improved model of SDR-4X. The difference of the new model is mostly improvement of reliability and performance of the mechanical system, sensor system and control software [8].

In this paper, in particular, the sensing system of SDR-4X II is proposed. First, we explain sensors for detecting inclination and forces from the outside for stable motion performance. As inclination sensors, we explain the micro accelerometer and the angular rate sensor. These should be small and light for fitting to our small biped robot. We use micro electro-mechanical system-type sensors which are improved to our specifications. As the force sensing system, we use four force sensors in each foot and process the output data to obtain the necessary data, e.g. Zero Moment Point position data. As the real-world sensing system, a touch sensor system is explained first. We assume that this robot exists close to humans, so that safe interaction with humans is indispensable. Many touch sensors are installed around the body. Next, the vision sensor system is explained. We use micro CCD cameras as the stereo vision system. The hardware system for processing the input image and how to obtain the distance data is explained, and the audio sensing system is also explained. As the audio input system, seven microphones are used. We explain the position of microphones, and how to obtain the direction of sound and clear sound with reduced noise. The hardware system and the accuracy of the input are also explained. We consider sensing technology to be one of the key technologies for humanoid robot development.

## 2. INCLINATION SENSOR SYSTEM

### 2.1. Accelerometer sensor system

The accelerometers installed in our robot should be a small and light as possible. The type of sensor which we use is the micro electro-mechanical system. The package size is  $5 \times 5 \times 2$  mm and the weight is 0.2 g. The principal specifications are shown in Table 1. It is a two-axis accelerometer and the type is an electrostatically driven capacitive accelerometer. The range is  $\pm 2$  G and the sensitivity is 300 mV/G. The resolution is 2 mG in 60 Hz bandwidth and the frequency response is 6 kHz in 3 dB bandwidth. The resolution of 2 mG satisfies the resolution of  $0.1^\circ$  of inclination angle which is required for stable motion performances. The output format is PWM. The processing circuit for PWM transformer is installed in the package.

The locations of accelerometers are shown in Fig. 2. Two accelerometers are located in the trunk and these measure the inclination of the trunk with three gyroscopes. When the trunk does not move, the output of the accelerometers shows the inclination of the trunk as it is. However, normally, the trunk is moving and the output of the sensors includes the inertia force. Thus, we are using the low pass



**Figure 1.** Overview of SDR-4X II.

**Table 1.**  
Specifications of the accelerometer

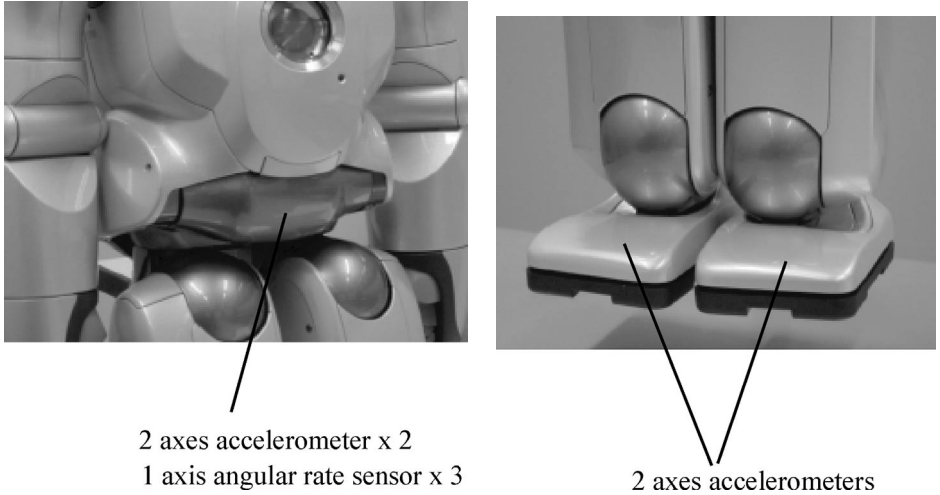
|                    |                                      |
|--------------------|--------------------------------------|
| Type               | 2 axis<br>(electrostatically driven) |
| Range              | $\pm 2$ G                            |
| Sensitivity        | 300 mV/G                             |
| Resolution         | 2 mG<br>(60 Hz bandwidth)            |
| Output format      | PWM                                  |
| Package            | $5 \times 5 \times 2$ mm             |
| Frequency response | 6 kHz<br>(3 dB bandwidth)            |

filter to cut-off the moving frequency efficiently. The cut-off frequency should be adjusted low enough to cut-off the moving frequency.

Accelerometers are also installed in both feet. This sensor detects the foot inclination angle when the foot is touching the walking surface and does not move. This sensor can detect the surface angle directly, so it is very effective.

## 2.2. Angular rate sensor system

The angular rate sensors which are installed should also be as small and light as possible. The sensor which we use is also of the micro electro-mechanical system



**Figure 2.** Location of accelerometers.

**Table 2.**  
Specification of the angular rate sensor

| Type               | z-axis<br>(electrostatically driven)                               |
|--------------------|--------------------------------------------------------------------|
| Dynamic range      | $\pm 150^\circ$                                                    |
| Stability (drift)  | $0.03^\circ/\text{s}$                                              |
| Output format      | analog                                                             |
| Package            | $7 \times 7 \times 3$ mm BGA                                       |
| Frequency response | 40 Hz<br>(3 dB bandwidth)<br>14 kHz<br>(sensor resonant frequency) |

type. The package size is  $7 \times 7 \times 3$  mm and the weight is 0.4 g. The principal specifications are shown in Table 2. It is a one-axis angular rate sensor and the type is an electrostatically driven capacitive sensor. The range is  $\pm 150^\circ$  and the stability is  $0.03^\circ/\text{s}$ . The frequency response is 40 Hz in the 3 dB bandwidth and the sensor resonant frequency is 14 kHz. The output format is analog.

The locations of the angular rate sensors are shown in Fig. 2. They are located in the trunk and measure the inclination of trunk. When we use the output of the angular rate sensors, we take the integration and use the output of the high pass filter. This output from the high pass filter is added to the output of the low pass filter of the accelerometer. The final added data is used as the inclination of the trunk:

$$D_1 + D_2 = D,$$

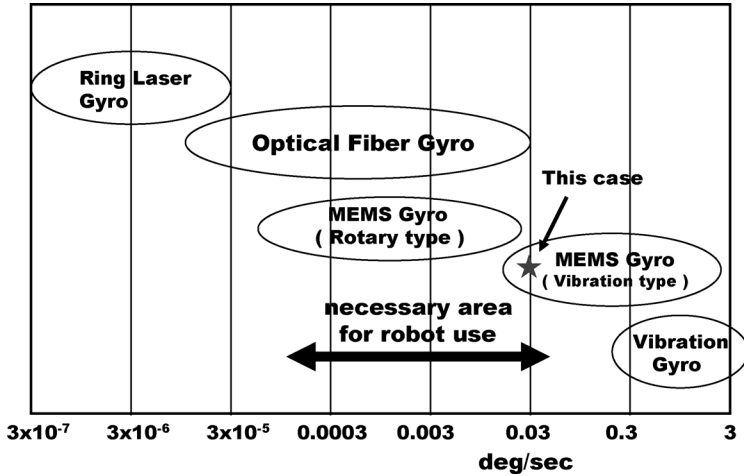


Figure 3. Accuracy of the angular rate sensor (gyro).

where  $D_1$  is the output of the low pass filter of the accelerometer,  $D_2$  is the output of the high pass filter of the angular rate sensor and  $D$  is the inclination of the trunk.

There are many types of angular rate sensors. Some of these are shown in Fig. 3. Currently, our sensor is the vibration-type MEMS gyro and has the high specification of that group. However, as with the ideal angular rate sensor, more stability is required for robot use, e.g. the optical fiber gyro or the more recent rotary-type MEMS gyro are assumed to be ideal.

### 3. FOOT SOLE SENSOR SYSTEM

The foot sole force sensor system is very important for stable motion control. In particular, when the surface for walking or standing is not horizontal or is uneven, the robot foot should follow the surface in real-time. In addition, obtaining the actual ZMP is indispensable for stable walking and motion performance.

There are four force sensors in the foot sole. The sensors are specially designed diafram-type sensors. The measurable range is 0–5 kg and the resolution is 10 g. The maximum bearable force is 20 kg. The locations of these sensors are shown in Fig. 4. A mechanical stopper for protecting the sensor is installed so that the force bearable from the outside of the foot sole is about 50 kg, which is sufficient to protect it.

The hardware configuration of these force sensors is shown in Fig. 5. The outputs of the four force sensors are input to an AD converter and the outputs of the converter are input to a satellite Digital Signal Processor (DSP). The satellite DSP calculates the position of the actual ZMP and sends the ZMP position data and the force data to the main CPU through the satellite CPU.

The positions of force sensors is shown in Fig. 6, where variables like the positions,  $X_1$ – $X_4$ , the forces,  $F_{z1}$ – $F_{z4}$ , are also shown.



Foot Sole Force Sensors

Figure 4. Location of the foot sole force sensors.

**Force sensor**

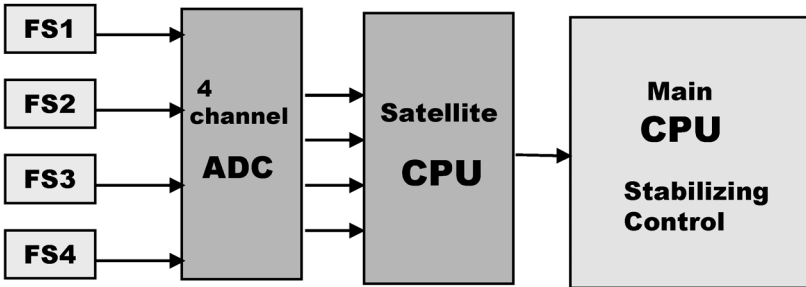


Figure 5. Hardware configuration of the force sensors.

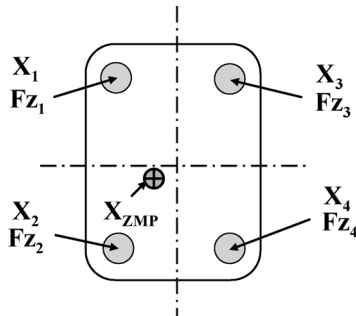
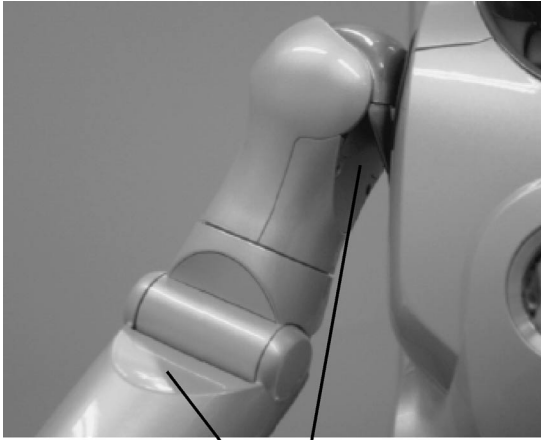


Figure 6. Position of the force sensors.  $X_n$ : position of force sensor  $n$ ;  $F_{z_n}$ : force applied to force sensor  $n$ ;  $X_{ZMP}$ : position of the ZMP.



Touch Sensors against the trap

**Figure 7.** Location of the touch sensors.

The position of the ZMP is obtained from the following equation. The accuracy of the position data of the ZMP calculated by using the force sensors is 0.5 mm, which gives satisfactory accuracy for stable motion performance and walking motion.

$$\sum_{n=1}^4 F z_n (X_n - X_{ZMP}) = 0,$$

$$\therefore X_{ZMP} = \frac{\sum_{n=1}^4 X_n F z_n}{\sum_{n=1}^4 F z_n}.$$

#### 4. TOUCH SENSOR SYSTEM

SDR-4X II has been designed not to injure humans because the purpose of this robot is to be used in a home environment where a human may touch it very often. Therefore, it has a safe design including a joint structure that does not trap hands and fingers in between joints. Touch sensors are installed everywhere (Fig. 7) to when hands and fingers become trapped, e.g. sensors are installed inside the shoulder, elbow, trunk, leg and foot joints. Currently the total number of sensors is 19. These sensors are sheet-type tactile sensors made of polyethylene printed by carbon. If these are activated, the main control system stops the motion of the actuators and changes the control to release the trapping force.

## 5. VISION SENSOR SYSTEM

We developed a micro stereo vision system with obstacle detection as the real-time and real-world vision sensor system. Figure 8 shows a head view with the stereo vision system. The hardware configuration of the stereo vision system is shown in Fig. 9. We use two color CCD cameras with about 110 000 pixels, whose baseline is about 5 cm. The disparity is computed by FPGAs, where a block-matching-based algorithm is implemented. The disparity image is further transferred to range data using the mechanical information of SDR-4X II. The range data and normal color image sequences are transferred to a main CPU via a high-speed bus named LVDS (Low Voltage Differential Signaling). The programs for the FPGAs can be downloaded from a main CPU via an OPEN-R BUS.

The method by which we obtained the distance by using two CCD camera is described as follows. Figure 10 shows the situation when the base camera and detection camera are observing the three-dimensional scene. If the point P is

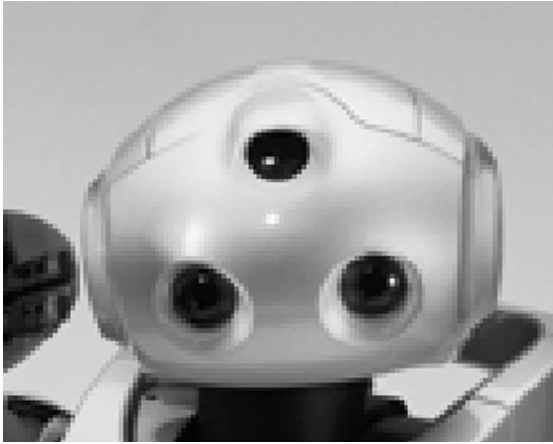


Figure 8. Vision sensor system inside the head.

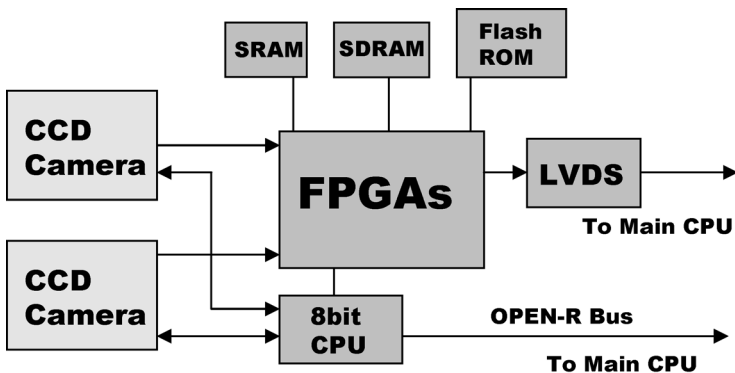


Figure 9. Hardware diagram of the micro stereo vision system.

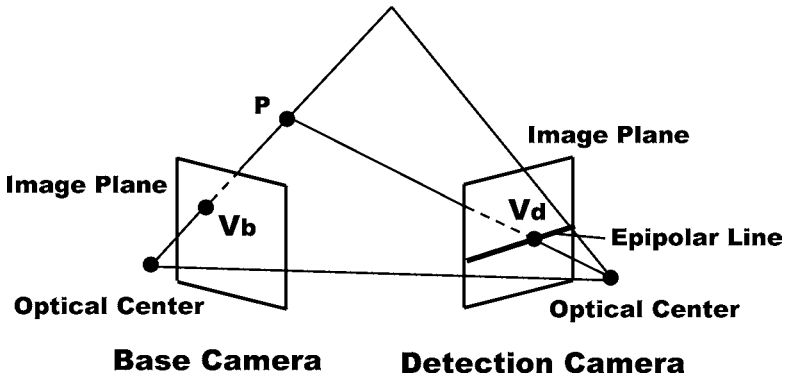


Figure 10. Corresponding points and the epipolar line.

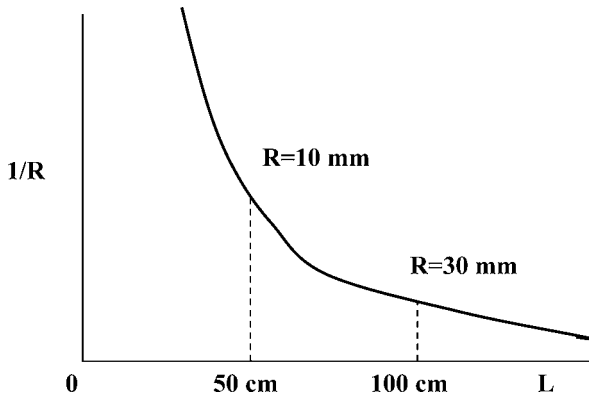


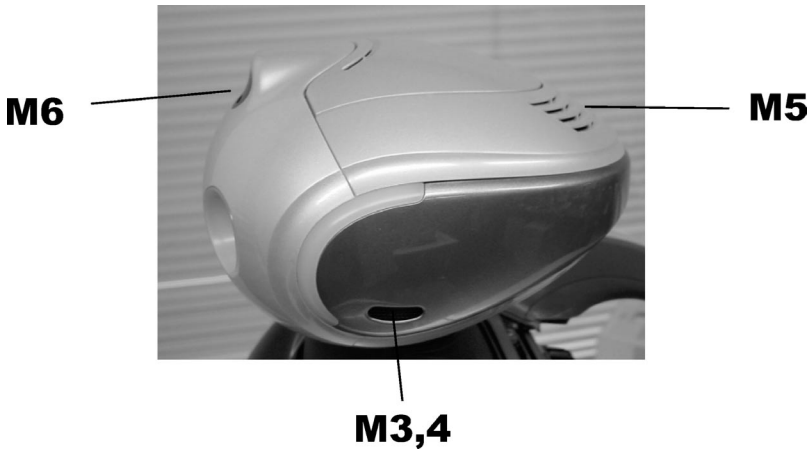
Figure 11. Resolution of the plane estimation.

observed as point  $V_b$  by the base camera and also as point  $V_d$  by the detection camera, the 3D position of point  $P$  is obtained.

It is not so easy to decide that the observed point  $V_b$  from the base camera is the same point as observed point  $V_d$  from the detection camera. As you see in Fig. 10, the point  $V_d$  exists on the line where the plane fixed by both the optical center and the observed point  $V_b$  from the base camera crosses the image plane of the detection camera. This line is called the epipolar line.

The corresponding point is found by searching on this line. We use the template-matching method to obtain the corresponding point. Some area on the epipolar line is compared with the image of  $V_b$  and the most similar image is obtained. After repeating this comparison, the corresponding point is obtained. If the whole part of the image plane of the base camera is repeated to obtain the distance data of each part, the depth image can be obtained.

We further implement a plane extractor using range data. As Fig. 11 shows, for a short distance like 50 mm, it is possible to estimate the plane with about  $\pm 10$  mm distribution, but for a the long distance like 100 mm, it is about  $\pm 30$  mm distance.



**Figure 12.** Audio sensor system.

From theoretical estimations, the resolution of the image sensors and the base-line distance result in about 80 mm resolution; however, the error distribution must be evaluated as the vertical distance error from the estimated plane, whose value must be multiplied by  $\sin(\theta)$ . Thus, the estimated error of the plane extractor is not so bad for 'plane estimation' purpose.

Currently, the range of the visible area of the CCD camera is  $50^\circ$ , which is not particularly wide. Thus, if the robot wants to find something, it has to rotate its head very often, which takes time to find the necessary object. We think a wider range camera will be more useful for the robot.

## 6. AUDIO SENSOR SYSTEM

We developed a multi-microphone system for the real-time audio sensor system. Figure 12 shows a head view with the multi-micro phone system. We use seven microphones and the locations of these microphones are shown in Fig. 13. Two microphones are located at right and left side of the head. The fifth microphone is located on the back and the sixth is located on the front. The last one is located inside the head.

The reason why two microphones are used on one side is to control the direction for gathering the sound. Currently, the direction is adjusted a little bit to the foreside. The backside and frontside microphones not only get the sound from those directions, but also distinguish the vertical direction of the sound. These microphones are shifted a little from the plane of the right and left side microphones. The microphone in the head is used to cancel the noise produced in the head by the motors.

From this alignment of seven microphones, the resolution of the sound direction is shown in Fig. 14. Horizontally, the accuracy of the observed direction of the sound

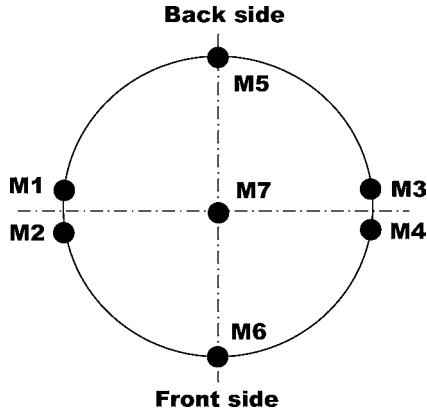


Figure 13. Location of the microphones.

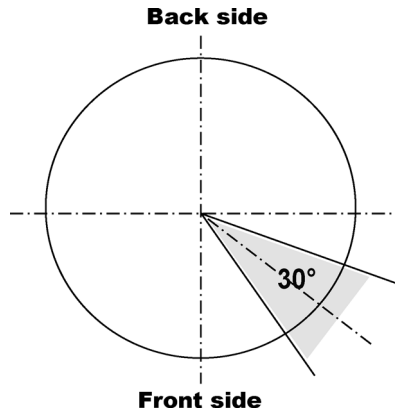


Figure 14. Accuracy of the detecting direction.

is  $\pm 15^\circ$ , i.e.  $30^\circ$  width. The front side is a little bit better than the back, but we assume the same resolution in the software. For vertical resolution, the accuracy of the direction is also  $\pm 15^\circ$ , i.e.  $30^\circ$  width. In this case, the accuracy in the upper half side is a little better than that in the lower side.

The hardware configuration of the audio sensor system is shown in Fig. 15. The analog outputs of the seven microphones are input to the eight-channel AD converter. The outputs of the AD converter are input to the satellite DSP. The roll of the DSP is to process the data from the seven microphones. There are many points of processing. For example, one is to adjust the direction of gathering the sound more from the front side using the output of microphones M1, M2 and M3, M4. Another is to obtain the direction of the sound source using all seven microphones. A further point is to cancel the noise from the outside as much as possible. Microphone M7's output is useful for canceling the noise which occurs inside the head by the motors. After processing the output of all the microphones, the clearer sound or voice data

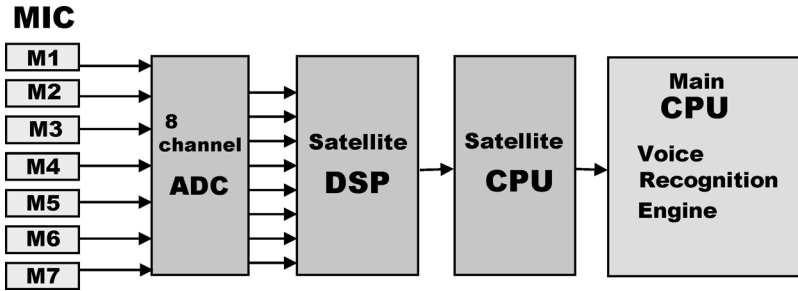


Figure 15. Hardware diagram of an audio sensor system.

and other data like the direction of the sound source are sent to the satellite CPU. The satellite CPU sends those data to the main CPU through a USB bus.

Then, the main CPU first distinguishes the sound data to speech data or non-speech data. The data which is distinguished as speech data is decoded. Then, the decoder finds out recognized words, speaker identification, etc. Those data are used for the next main speech recognition process.

Currently, the sampling rate of the sound is 16 kHz and so a sound of 8 kHz can be detected. That is normally sufficient for the speech recognition. The sensitivity of the sound input is automatically changed depending on the environment situation.

## 7. SUMMARY AND CONCLUSIONS

We described the essential technologies of the SDR-4X II sensing system. First, for stable motion performance, sensors for detecting inclination and forces from the outside are explained. As inclination sensors, we explain the micro accelerometer and the angular rate sensor. These should be small and light for fitting to our small biped robot. We use micro electro-mechanical system-type sensors which are improved to our particular specifications, which are also explained. For the angular rate sensor, the recent other types of sensors are described and our system level is shown. The force sensor is also explained. We use four force sensors in each foot and process the output data to obtain the necessary data, the ZMP position data. How we calculate the actual ZMP position data is also described. Next, the touch sensor system is explained. We assume that this robot exists close to humans, so that safe interaction with humans is a prerequisite. Nineteen sheet-type touch sensors are installed around the body. As a real-world sensing system, the vision sensor system is explained. We use two micro CCD cameras as the stereo vision system. The hardware configuration for processing the input image and how we obtain the distance data is explained. The resolution level of this system is also described. Next, the audio sensing system is explained. Seven microphones are used as the audio input system. We explain the positions of the microphones and how to obtain the direction of sound and clear sound or voice with less noise. The resolution of the direction detection is measured. The hardware system for processing the sound

input data is also explained. All these sensing systems give SDR-4X II a very high level of stable walking and dynamic motion performance. These also support SDR-4X II's high-level communication capabilities with a human. We consider sensing technology to be one of the most key technologies for humanoid robot development.

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