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Development of a Bioinstrumentation System in the Interaction between a Human and a Robot

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***Abstract* - Personal robots, which are expected to become popular in the future, are required to be active in joint work and community life with humans. Such robots must have no bad physical or psychical effect on humans. The psychical effect of a robot on humans has been subjectively measured using questionnaires. However, it has not been objectively measured yet. Human emotion and the consciousness direction can be measured by physiological parameters and body motion, respectively. Therefore, the bioinstrumentation system WB-1 was developed in order to objectively measure the psychical effect of a robot on a human. It can measure physiological parameters such as respiration, heart rate, perspiration and pulse wave, and arm motion. Analyzing human stress in the interaction with a robot from electrocardiogram, the robot could generate a motion for decreasing the stress.**

Index Terms – Interaction, Bioinstrumentation, Physiological Parameter, Motion Capture.

I. Introduction

Industrial robots have various functions, such as assembly and conveyance, within manufacturing factories. However, operators have to define the robot's behavior with complex processes or methods. On the contrary, personal robots, which are expected to become popular in the future, will have to be active in joint work and community life with humans. Active behavior and adaptation to partners or the environment are necessary for personal robots. Therefore, the objective of this study is to develop new mechanisms and functions in order to realize the natural bilateral interaction by expressing the emotions, behaviors and personality in a human-like manner.

There are several examples of humanoid robots in the world. Sony Corporation developed the entertainment humanoid QRIO, which is 50[cm] tall and has 50-DOFs. It can autonomously walk based on CCD camera information on its head and controls its behavior via a homeostasis regulation mechanism [1][2].

We have developed the Human-like Head Robot WE-3 (Waseda Eye No.3) series since 1995. So far, coordinated head-eye motion with V.O.R. (Vestibular-Ocular Reflex), depth perception using the angle of convergence between the two eyes, adjustment to the brightness of an object with the eyelids and four sensations (visual, auditory, cutaneous and olfactory sensations) have been achieved. In addition, emotional expressions using not only the face, but also the upper-half of the body and bilateral interaction between a human and a robot have been produced by the Emotion Expression Humanoid Robot WE-4RII (Waseda Eye No.4 Refined II) with 9-DOFs emotion expression humanoids arms and humanoid robot hands RCH-1 (RoboCasa Hand No.1) [3-5].

Also, the mental model for humanoid robots has been proposed from viewpoints of both robotics and psychology in order to realize human-like motion. A mental space with three independent parameters, mood vector, second order equations of emotion, robot personality, need model, consciousness model and behaviour model were introduced into the mental model [6][7].

Such humanoid and personal robots must have no bad physical or psychical effect on humans. In general, the motions of robots have been subjectively evaluated by questionnaires. It was evaluated how the WE-4RII's emotions are transmitted by its upper-half bodily expressions, by questionnaires. In the experimental evaluations, many subjects showed the movies of six basic emotional expressions exhibited by WE-4RII. Next, they chose an emotion that they thought the robot expressed. The correct recognition rate of each emotional expression was examined. The averaged recognition rate of all emotional expressions of WE-4RII was 93.5 [%]. WE-4RII can effectively convey its emotions using its upper-half bodily expressions.

(a) Back View (b) Front View (c) Chest and Hand Parts

Fig.1 Bioinstrumentation System WB-1 and Measurement Indexes.

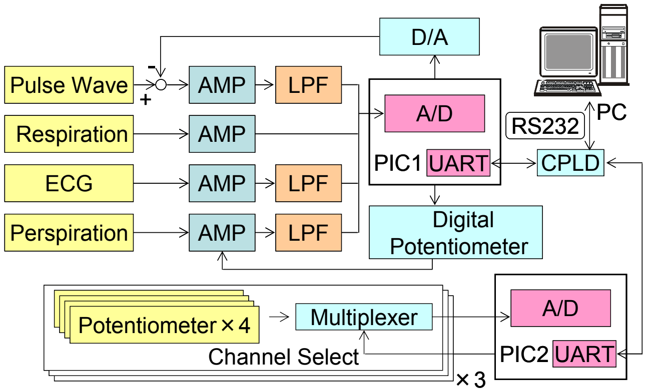

Fig.2 System Configuration of WB-1.

However, a method for objective evaluation of robots has not been proposed yet. It is very important to measure the psychical effect of robots on humans in real time and with high reliability by objectively evaluating robots. Change of human emotion appears in physiological parameters [8]. On the other hand, it is considered that human consciousness direction is measurable by upper half part body motion. Therefore, the objective of this paper is the development of a bioinstrumentation system that can measure physiological parameters and the arm motion of the upper half part body in order to objectively measure the psychical effect of robots on humans.

II. Bioinstrumentation System

Change of human emotion appears in physiological parameters such as brain waves, respiration, heart rate, muscle tension, perspiration, pulse wave and so on. For example, heart rate becomes faster when a human surprises. On the other hand, humans move their body with intent except for reflex motions in response to touching eyelashes and ammonia smell. For example, humans square their shoulders if they are angry, or humans reach out their hands to food if they are hungry. That is, human consciousness direction is found by head motion, eyes, arms motion, trunk motion, hand grasp and so on. There are many measuring instruments already. However, they are very expensive and have large system. Therefore, we developed the bioinstrumentation system WB-1 (Waseda Bioinstrumentation system No.1), which consists of sensors that measure physiological parameters and a motion capture system for measuring arm motion, as shown in Fig.1. In this paper, respiration, heart rate, perspiration, pulse wave and arms motion were selected to measure human emotion and consciousness direction, respectively. WB-1 can measure them at the same time. It weighs 2.2[kg] and is driven by dry cells. The total system configuration is shown in Fig.2.

III. Measurement of Physiological Parameters

A. *Heart Rate (Electrocardiograph)*

The heart produces tiny electric current, which spread through the heart muscle to make it contract. The graphic tracing of the electric current is recorded with an electrocardiograph (ECG). Electrocardiogram is made by applying electrodes to various parts of the body in order to lead the heart current to the recording instrument. The chest wall is the standard site for applying the electrodes. In this study, an electromyography was made as the electrocardiograph. Since noise is generated when a human moves, three electrodes were vertically put on the side of the greater pectoral muscle as shown in Fig.1. Electric potential between upper two electrodes was amplified 500-fold and processed by the 0.1[Hz] high-pass filter, level shifter and 30[Hz] low-pass filter. The Level Shifter shifted the signal into the region from 0[V] to 5[V], where A/D conversion is possible by PIC. A/D conversion of the signal was carried out with the 20[ms] sampling period and 10[bit] resolution. The lowest electrode is grounded and needs for the rejection of hum noise and the preventation of electronic shocks. The hum noise means 50[Hz] or 60[Hz] noise, which comes from the AC power supply. Fig.3 shows the measured electrocardiogram. The wave peak in this figure is called R wave. The heart rate can be obtained from R-R wave interval Δt_h as

$$\text{Heart Rate} = \frac{60}{\Delta t_h} \text{ [bmp]}. \quad (1)$$

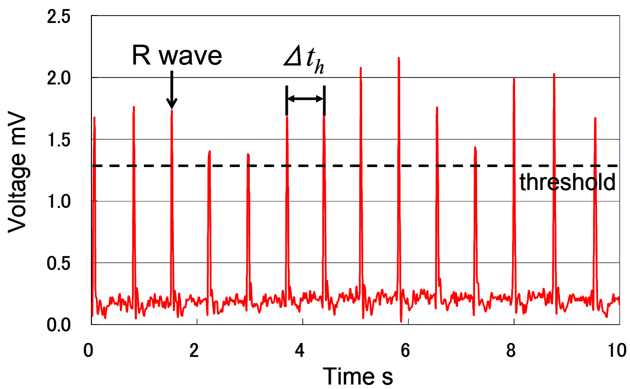

Fig.3 Electrocardiogram and Measurement Method of Heart Rate.

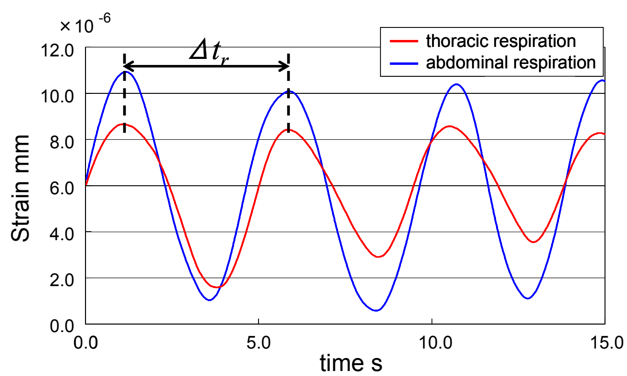

Fig.4 Thoracic and Abdominal Respirations.

Therefore, the heart rate was calculated by setting a threshold at which the R-wave is sensed. The heart rate becomes large, if we feel stress, anxiety, anger and agitation.

B. *Respiration (Respirometer)*

Respiration can be thoracic and abdominal. Thoracic respiration means the capability to breathe extending or shutting the ribs using the thoracic muscles, and abdominal respiration means breathing by raising or lowering the diaphragm using the abdominal muscles. In general, women and men breathe thoracically and abdominally, respectively. However, they do not always breathe according to the same method. Both thoracic and abdominal respirations were applied in order to obtain exact data. Rubber bands with stain gages were wound around the abdomen and the chest. KFG-20-120-C1-11 made for general stress measuring by Kyowa Electronic Instruments Co., Ltd., was used as a strain gage. In this study, the bridge circuit needs for reducing power consumption, since WB-1 is driven by a battery. The output of bridge circuit was amplified 10000-fold and processed by A/D converter with the 20[ms] sampling period and 10[bit] resolution. And then, 60 data were averaged by the moving average filter in a PC. The measured respiration data is shown in Fig.4. If the interval of stain peak is denoted by Δt_r, the respiration rate is provided by

$$\text{Respiration Rate} = \frac{60}{\Delta t_r}\ \text{[times/min]}. \qquad (2)$$

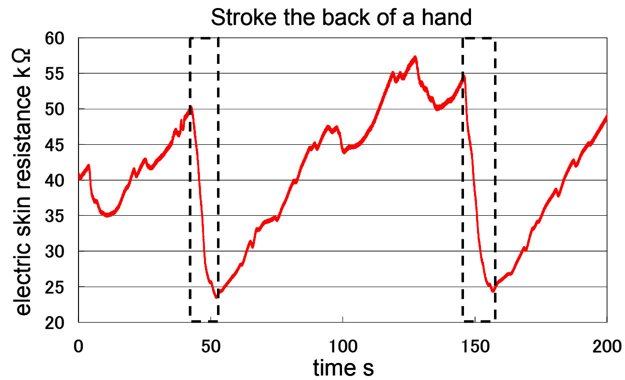

Fig.5 Perspiration measured on the fingertips.

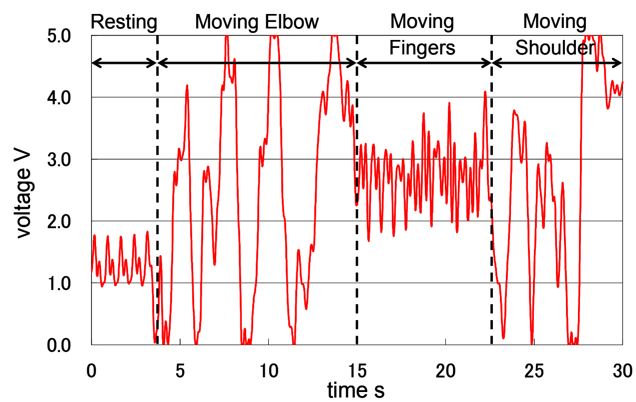

Fig.6 Pulse Wave Measured in Various Conditions.

C. *Perspiration (Sudorometer)*

The perspiration is divided into the mental sweating on the palm and soles and the thermal sweating on the other parts. Electrodermal activity (EDA) is a term that describes the electricity changes conducted by mental sweating. If we have strong emotion, the electrodermal activity increases. As the measurement method of electrodermal activity, there are the electrical method and the potential method. Using the former, the skin resistance change is obtained by passing a tiny electric current through the palm or fingertip. On the other hand, the potential difference is directly obtained without passing an electric current using the latter. In this study, the electrical method to pass the electric current through two electrodes put on the fingertips was adopted. 0.5[V] constant voltages were applied to one electrode and the output of another electrode was amplified 1000-fold. In addition, the signal was processed by 10[Hz] low-pass filter and A/D converter with the 20[ms] sampling period and 10[bit] resolution. Perspiration occurs if the back of the hand is stroked. Fig.5 shows that the electrodermal activity is decreased by stroking the back of the hand.

D. *Pulse Wave (Plethysmograph)*

The pulse wave is the expansion of an artery coursing through a blood vessel as a result of heart contraction. The hemoglobin in blood absorbs the light within a certain wavelength range (about 660[nm]). The transmitted light when 660[nm] light is irradiated to the body depends on the

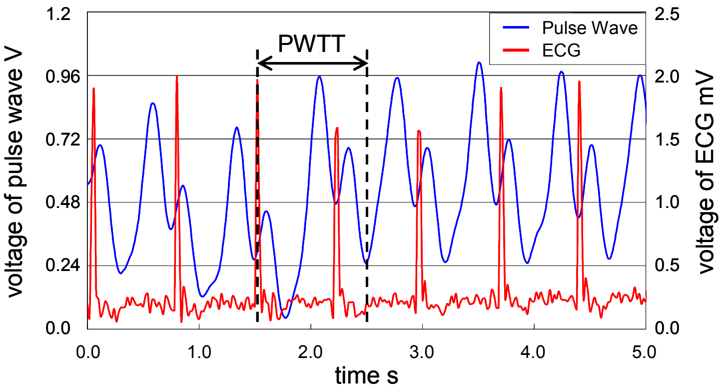

Fig.7 Measurement Method of PWTT.

quantity of the hemoglobins according to the capacity change of a blood vessel. It is possible to calculate the pulse wave from the transmitted light. In this study, the transmitted light was measured using a photodiode, when the light of LED was irradiated to the little finger. First, I/V conversion of the photodiode output were carried out. After that, the signal was amplified 100-fold and processed by 5[Hz] low-pass filter and A/D converter with the 20[ms] sampling period and 10[bit] resolution. The measurement result of the pulse wave is shown in Fig.6. As we can see in Fig.6, the correct pulse wave was obtained when resting. However, it fluctuated when moving fingers, an elbow and a shoulder, since a blood vessel was pressed. Therefore, the pulse wave was measured at an ear, which is seldom influenced by motion. Unfortunately, it was influenced by head motion in this case. In this study, the pulse wave was measured at the little finger and was used only when the body motion was not observed by the motion capture system of WB-1.

E. Blood Pressure

When the pulse wave was usable as a physiological parameter, PWTT (Pulse Wave Transit Time) was calculated to obtain the relative change of blood pressure. PWTT means the time when the pulse wave travels from the aorta to a peripheral artery, and it is the time from the top of R-wave to the point at which the pulse wave finishes propagating (Fig.7). A blood vessel becomes hard if blood pressure goes up, and conversely, soft if blood pressure goes down. PWTT becomes short since the pulse wave quickly propagates if a blood vessel becomes hard. On the hand, PWTT becomes long since the pulse wave slowly propagates if a blood vessel becomes soft. If we feel stressed, PWTT becomes short.

IV. Development Of Motion Capture System

The motion capture system is used to measure human motion. It is accomplished by any of three technologies: optical, magnetic and mechanical. In the first system, the motion of reflective makers attached to the joints of the body is tracked by several video cameras. This has high accuracy and does not prevent a subject from moving. However, it can be used only in a limited region and cannot be controlled in real time. In addition, it requires considerable time for setup and high cost. The second system uses sensors placed on the body in order to measure the low-frequency magnetic field generated by a transmitter. Using this system, the motion can be measured in real time and the subject is free to move. However, this requires high cost and cannot be used if there is metal around. Finally, a mechanical motion capture system measures human motion wearing a frame with joint angle sensors such as goniometer and potentiometer at each joint. In this system, the motion is measured everywhere, in real time and at low cost. In this study, the mechanical motion capture system was adopted in order to achieve low cost and not to depend on the environment.

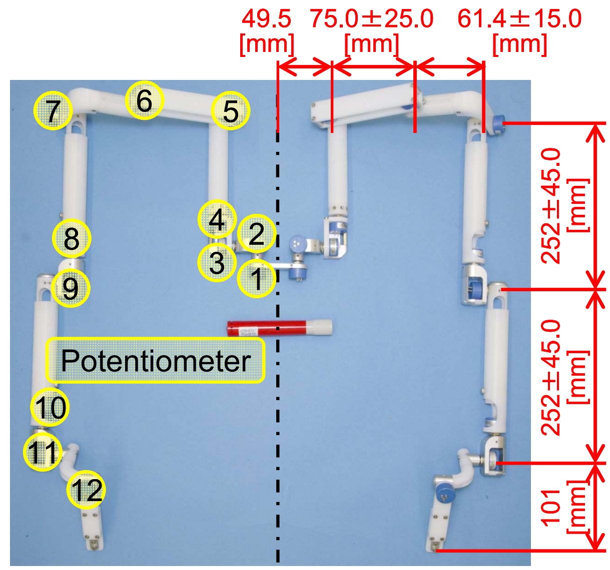

Fig.8 Mechanical Motion Capture System.

A. Mechanical Hardware

Fig.8 shows the new mechanical motion capture system for measuring arms motion. Humans generally have 7-DOFs arm: 3-DOFs shoulder, 1-DOF elbow and 3-DOFs wrist [9]. However, a rotation center of the shoulder moves when a human squares and shrugs shoulders. Therefore, the frame with 12-DOFs per arm, which consists of 6-DOFs from the back origin to the shoulder and 6-DOFs from the shoulder to the wrist, was developed in order to follow the movement of the rotation center. This has a serial link mechanism with a potentiometer at each joint. The length of links is changeable according to human size.

B. Conversion from Motion Capture Model to Human Model

In this study, it was defined that humans have a 9-DOFs arm that consists of a 2-DOFs base shoulder corresponding to a shoulder center rotation, 3-DOFs shoulder, 1-DOF elbow and 3-DOFs wrist. First, the motion capture model and human model were determined as shown in Fig.9 by the yugan vector method [10]. Human joint position was calculated from the joint position of the motion capture system using direct kinematics. And then, it derived the human joint angle using inverse kinematics. In Fig.10, we measured arms motion using WB-1 and displayed the converted human motion.

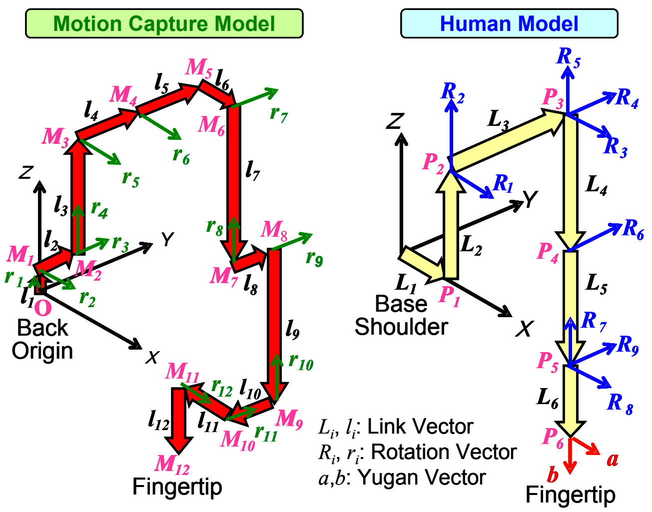

Fig.9 Conversion from Motion Capture Model to Human Model.

Fig.10 Measurement of Arms Motion.

V. Experimental Evaluation

A. Evaluation of Motion Capture System

Here, we describe experimental evaluation of the accuracy of the motion capture system. In this experiment, the 5*5 lattice points at 100[mm] intervals were a certain distance 638[mm] away from the fixed back origin as shown in Fig.11. Each lattice point was pointed using the motion capture system. We obtained the error between the calculated fingertip position and the actual pointed point position.

Table 1 shows the experimental results in X, Y and Z direction. Maximum error was 53.3[mm] and average error of X direction, Y direction and Z direction was 26.5[mm], 9.7[mm] and 16.9[mm], respectively. It was considered that the error occurred since the coordinate system of the lattice point did not conform to the absolute coordinate system. However, this error is sufficient tolerance just in order to measure the human consciousness direction in the interaction between a human and a robot.

B. Interaction Experiment between human and robot

Human stress is one of most important factor in the interaction with a robot. In this paper, how to analyze human stress was described. First, the time evolution of R-R wave interval Δt_h is obtained from electrocardiogram in Fig.3. Fig.12 shows the result of the frequency analysis of the R-R wave interval by using the fast Fourier transform. The peak

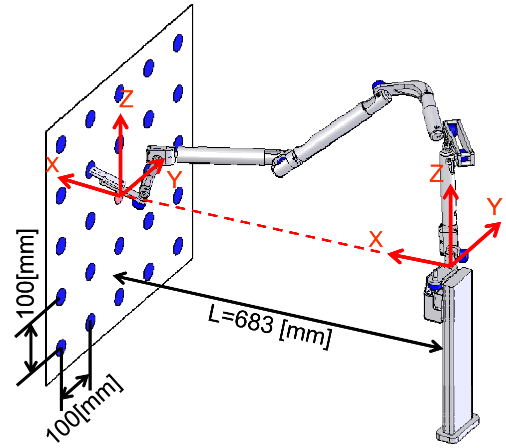

Fig.11 Experimental System of Motion Capture.

Table 1 Experimental Results of Motion Capture System.

	Maximum Error [mm]	Average Error [mm]
X	53.3	26.5
Y	42.0	9.7
Z	30.0	16.9

around 0.1[Hz] is called MWSA (Mayer Wave related Sinus Arrhythmia) which is affected by sympathetic and parasympathetic nerve. The peak around 0.3[Hz] is called RSA (Respiratory Sinus Arrhythmia) which is affected by parasympathetic nerve. MWSA and RSA increases and decreases if a human feels stress, respectively. That is, MWSA/RSA increases if a human feels stress. In this study, MWSA/RSA was used for measurement of human stress.

Next, human stress was measured in the interaction with the Emotion Expression Humanoid Robot WE-4RII developed in 2004. If human stress increases, a robot has to generate a motion for decreasing it. Humans ease tension by shaking hands when they first meet a person. Therefore, in this experiment, WE-4RII shook hands with a subject when his stress has become larger than a threshold as shown in Fig.13.

Fig. 14 shows the stress of a subject who interacted with WE-4RII. First, WE-4RII pursued the red ball which the subject was taking. And then, his stress became high since he

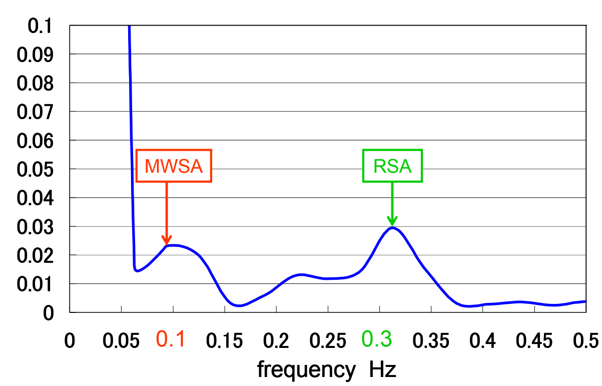

Fig.12 FFT Result of R-R Wave Interval.

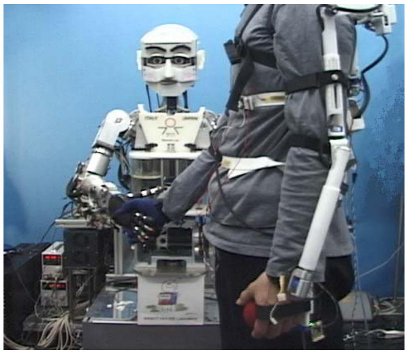

Fig.13 Experiment for Decreasing Human Stress.

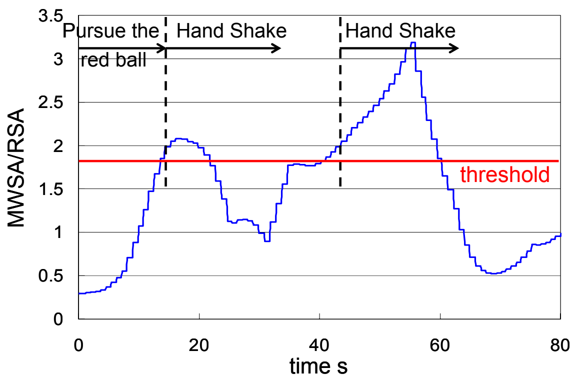

Fig.14 Experimental Result of Human Stress.

felt dullness. When the stress exceeded a threshold, WE-4RII shook hands with him. We found that his stress decreased by shaking hands with WE-4RII.

VI. Conclusion

The bioinstrumentation system WB-1 (Waseda Bioinstrumentation system No.1) was developed in order to objectively measure the psychical effect of robots on humans. Human emotion influences the physiological parameters. Human consciousness direction is measured by the upper half body motion. Therefore, the electrocardiograph, respirometer, sudorometer, plethysmograph and motion capture system was developed in order to measure the heart rate, respiration, perspiration, pulse wave, blood pressure and arms motion. The heart rate, respiration and perspiration could be measured even if the subjects moved their arms. However, since the pulse wave and blood pressure were influenced by the subject's arms motions, they were defined to be used only when the body motion was not observed by the motion capture system. On the other hand, the motion capture system had 12-DOFs per arm, since the rotation center of a shoulder moves if a human squares and shrugs shoulders.

It was confirmed that this system has sufficient accuracy in order to measure the human consciousness direction in interaction between a human and a robot. Moreover, analyzing human stress in the interaction with a robot from electrocardiogram, the robot could generate a motion for decreasing the stress. As a result, the subject's stress decreased by the robot's motion.

Since the weight of WB-1 is 2.2[kg], WB-1 does not impose so many burdens on a subject. However, we need to confirm whether humans feel unpleasantness by wearing WB-1 soon. We would like to develop new system which imposes no burden. Furthermore, the Emotion Expression Humanoid Robot WE-4RII will be evaluated by using other physiological parameters. The mental model, the emotional expression and the several behaviors of WE-4RII will be improved by experimental results.

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