On the development of the Bioinstrumentation System WB-1R for the evaluation of human-robot interaction
- Head and Hands Motion Capture Systems -

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Abstract— **Personal Robots and Robot Technology (RT)-based assistive devices are expected to play a major role in Japan’s elderly-dominated society, both for joint activities with their human partners and for participation in community life. These new devices should be capable of smooth and natural adaptation and interaction with their human partners and the environment, should be able to communicate naturally with humans, and should never have a negative effect on their human partners, neither physical nor emotional. To achieve this smooth and natural integration between humans and robots, we need first to investigate and clarify how these interactions are carried out.**

Therefore, we developed the portable Bioinstrumentation System WB-1R (Waseda Bioinstrumentation system no.1 Refined), which can measure the movements of the head, the arms, the hands (position, velocity, and acceleration), as well as several physiological parameters (electrocardiogram, respiration, perspiration, pulse wave, and so on), to objectively measure and understand the physical and physiological effects of the interaction between robots and humans.

In this paper we present our development of the head and hands motion capture systems as additional modules for the Waseda Bioinstrumentation system No.1 (WB-1). The preliminary experimental results, given the inexpensiveness of the systems, are good for our purposes.

Index Terms— **Bioinstrumentation, Human-machine interaction, sensor systems and smart sensors**

I. INTRODUCTION

The average age of the Japanese population is rising fast because of an increased life expectancy and a reduced birth rate. Today there are about 2.8 workers per retiree; in fact, this figure is estimated to fall to 1.4 by 2050, when more than 35% of the population is expected to be over 65 [1]. Therefore, there is considerable expectation for a growing need for home, medical, and nursing care services to assist this aging society, both from the physical and psychological points of view [2].

In this elderly-dominated society, Personal Robots and Robot Technology (RT)-based assistive devices are expected to play a major role, both for joint activities with their human partners and for participation in community life. These new devices should be capable of a smooth and natural adaptation and interaction with their human partners and the environment. They should also be able to communicate naturally with humans, especially in the case of home and personal assistance for elderly and/or handicapped persons. Moreover, these devices never should have a negative effect on their human partners, neither physical nor emotional.

A. *Personal and Humanoid Robots*

Based on this situation, several humanoid robots have been developed in recent years, for example the Honda ASIMO [3] and Kawada HRP-2 [4]. Some of them can even express emotions. For example, Sony Corporation developed the entertainment humanoid QRIO [5], which is 50[cm] tall and has 50-DOFs. QRIO can autonomously walk based on information from the CCD camera on its head and can control its behavior via a homeostasis regulation mechanism. Another example is Kismet [6], developed at MIT, the first

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autonomous robot explicitly designed to explore socio-emotive face-to-face interactions with people.

Our group has been developing the Human-like Head Robot WE-3 (Waseda Eye No.3) series since 1995. The latest version in the series, the Emotion Expression Humanoid Robot WE-4RII (Waseda Eye No.4 Refined II), can express emotions by using not only the face, but also the upper-half of the body (shoulders, arms, hands), and can carry on bilateral interactions with humans [7]. At the same time, WE-4RII is equipped with a mental model that takes into account both robotics and psychology to realize human-like motions and behaviors [8].

B. *Quantitative analysis of Human-Robot Interaction*

These kinds of humanoid and personal robots, unlike industrial robots, must have no bad physical or physiological effects on humans during normal activities and interactions. Until now, these effects have been mostly evaluated by questionnaires. In case of WE-4RII, for example, the recognition rate of all the emotional expressions was 93.5% [7]. This type of evaluation, however, is highly subjective.

Recently, research on emotional body language is rapidly emerging as a new field in cognitive and affective neuroscience [9]; this research focuses on analyzing the response of the Mirror Neuron System [10] to understand how whole-body signals are automatically perceived and understood and what role they play in emotional communication and decision-making. However, current studies rely either on fMRI, ECG, or cortical electrodes, which are not suitable for everyday use outside of the laboratory environment. So, it would be very important to measure and understand the physical and physiological effects of robots on humans in real time, with high reliability, in any place, and with not-so-expensive equipment.

The goal of our research, therefore, is to develop a portable bioinstrumentation system capable of measuring both the physical and physiological parameters of the user. By integrating the analysis of human motion (position, velocity, acceleration) with the analysis of several physiological indexes (electrocardiogram, perspiration, respiration, pulse wave), this system can be used as a core research tool to clarify how the human neuromusculoskeletal system works, and how its performance is related to emotional perception and expression.

In this paper, we present our development of system WB-1R, the motion capture system for the head and for the hands (as additional modules) of the Waseda Bioinstrumentation system No.1 WB-1 described in [11]; our experimental evaluation of the system is also presented.

II. BIOINSTRUMENTATION SYSTEM WB-1R

Change of human emotion appears in physiological parameters such as brain waves, respiration, heart rate, muscle tension, perspiration, pulse waves, and so on [12]. For example, heart rate becomes faster when a human is surprised. On the other hand, except for reflex motions in response to jarring situations (such as having one’s eyelashes touched or smelling ammonia), humans usually move their bodies with particular intentions. For example, humans square their shoulders if they are angry, they reach out their hands to food if they are hungry, and so on. That is, the focus of human intentions can be found by analyzing the motion of the head, eyes, arms, trunk, and hands.

There already are many measuring instruments on the market. However, they are usually very expensive and bulky (see next sections for details). Moreover, they do not provide the degree of integration between physical and physiological parameters that we would require. Therefore, we developed the bioinstrumentation system WB-1R, which consists of sensors that measure physiological parameters (electrocardiogram, perspiration, respiration, pulse wave) and a motion capture system that measures head, arm, and hand motions, as shown in Fig. 1.

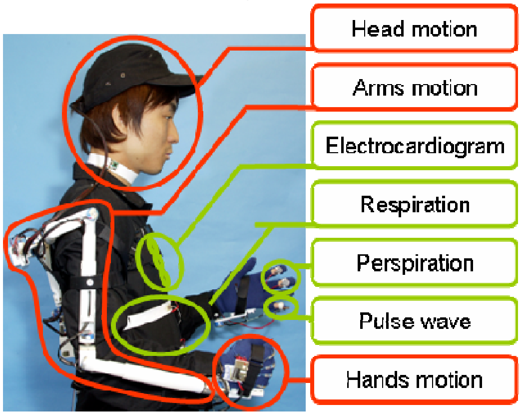


Fig. 1: System Configuration of WB-1R. The motion capture subsystem is shown in red, and the physiological parameters subsystem is shown in green.

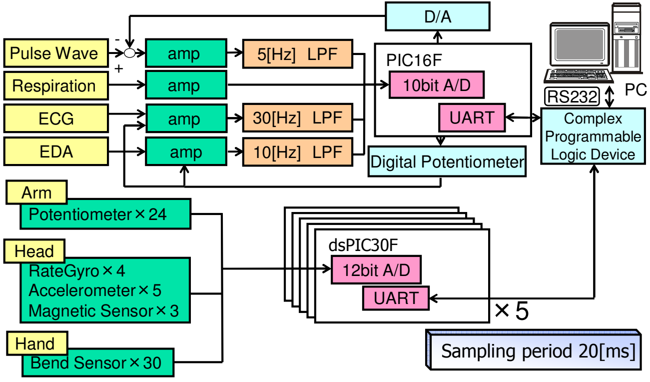


Fig. 2: System Configuration of WB-1R.

In this paper, we describe the development of the head posture angle sensor and the sensor glove. The complete system, WB-1R [11], weighs 2.2 kg including batteries (Sanyo Lithium Ion Battery UF103450). The total system configuration is shown in Fig. 2.

In the next sections, details of the head posture measurement system and of the hand measurement system are presented, together with some experimental results.

III. MEASUREMENT OF HEAD AND HANDS MOTION

A. Head Motion

A head posture measurement module should measure the four degrees of freedom shown in Fig. 3. As we are interested in the emotional expression of the movements, and as we aim at developing a module that would not interfere with the movements of the head, miniaturization and low price are more important than high precision.

Commercially available angle sensors cannot be used, because they are expensive and usually bulky (see Table 1); potentiometers are not suitable for this task, either, because they need bulky mechanical frameworks. Hence, we decided to create this module by using acceleration sensors, rate gyros, and a geomagnetic sensor.

Table 1: Other Inclinometers

Model	Maker	Size (mm)	Price (USD)
Inertia Cube2	InterSense	32×29×24	2'400
Inertia Cube3	InterSense	26×39×15	2'600
Wireless Inertia Cube3	InterSense	31×43×15	4'600
FAS-G	MicroStrain	64×90×25	-

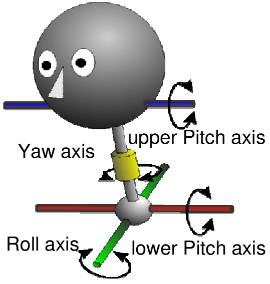


Fig. 3: DOFs Configuration of the Head.

We used 1 acceleration sensor (3-axis acceleration sensor H48C, Hitachi Metals, Ltd.) and 1 rate gyro (Piezoelectric gyroscopes ENC-03R, Murata Co., Ltd) for the head roll, pitch, and yaw axis. It should be noted that, when an acceleration sensor is used as an inclinometer during movements, it is affected by errors caused by inertia. So, acceleration sensors are more suitable for use in static cases than they are in dynamic cases. In addition, a rate gyro outputs an angular velocity, and the corresponding angle is calculated by integration. The error resulting from integration increases with time.

Therefore, we decided to create and implement an algorithm that could avoid the errors of the acceleration sensor and the rate gyro, while exploiting their merits (Fig. 4). In this algorithm, the integral calculus error of angular velocity of the rate gyro output is canceled by a double integration filter. The inclination angle is calculated from the acceleration sensor output, which is smoothed through a CIC (Cascaded Integrator-Comb) filter. Finally, posture angle is calculated by adding these two terms.

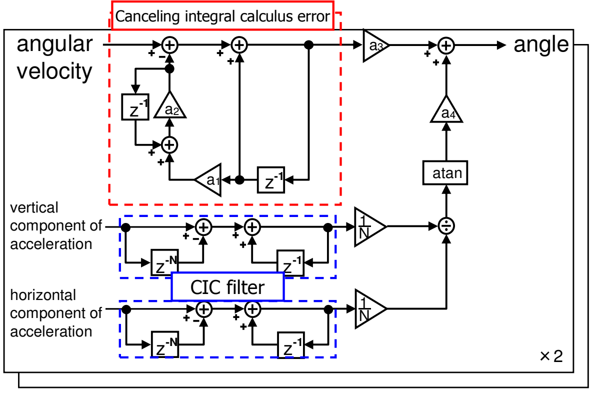


Fig. 4: Algorithm for the Calculation of Posture Angle (Roll, Pitch).

Acceleration sensors cannot be used to measure the rotation on an axis perpendicular to the head Yaw axis because it is the direction of gravity. In addition, integral calculus errors increase in a single application of a rate gyro. So, we decided to use a geomagnetic sensor. We used the 3-axis magnetic sensor AMI501 (Aichi Micro Intelligent Corp.), which uses the MI (Magneto-Impedance) effect. The azimuthal angle θ is calculated from a reverse tangent function of the magnetic field components, H_x and H_y (Fig. 5). When the geomagnetic sensor is in the horizontal plane, we have:

$$\theta = \tan^{-1}\left(\frac{H_y}{H_x}\right) \tag{1}$$

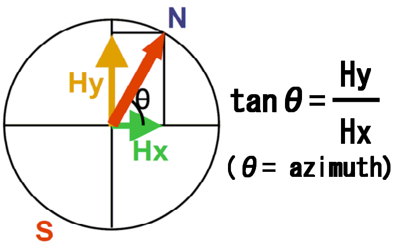


Fig. 5: Angle Calculation from Geomagnetic Sensor.

When a geomagnetic sensor is titled off the horizontal plane at an inclined angle (φ, ϕ), we have:

$$H_x = H_x'\cos\phi + H_y'\sin\varphi\sin\phi - H_z'\cos\varphi\sin\phi \tag{2}$$

$$H_y = H_y'\cos\varphi + H_z'\sin\varphi \tag{3}$$

where H_x, H_y, and H_z are the outputs of the geomagnetic sensor.

The head posture measurement module base is shown in Fig. 6. The overall dimensions of the module are 24x24x14mm, and it costs about 300 USD. Therefore, it is smaller and less expensive than the current commercial modules. Some examples of reconstruction using this module are presented in Fig. 7(a)-(c).

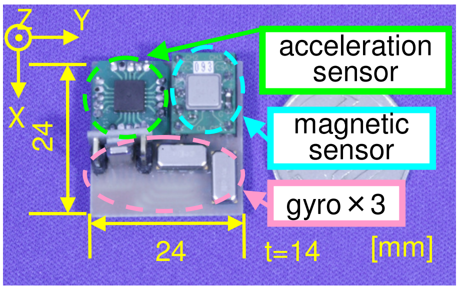


Fig. 6: Head Posture Measurement Module Base.

(a) Roll

(b) Pitch

(c) Yaw

Fig. 7: Reconstruction of Roll, Pitch and Yaw.

B. Hands Motion

The human hand has 22 degrees of freedom (DOFs) for flexion/extension or adduction/abduction of each finger [13]. Some commercially available sensor gloves can measure the movement of a human hand with high precision, but they are quite expensive; other gloves are cheap, but they do not have enough DOFs. Some examples are shown in Table 2. Therefore, we decided to develop our own sensorized glove that can measure the movement of the fingers with sufficient precision (without being bulky), while keeping the overall price down.

In this study, we implemented a 15-DOFs configuration (as shown in Fig. 8) by using the Abrams Gentile Entertainment Bend Sensors (Patent # 5,086,785). In particular:

- Flexion/extension for each finger (1 DOF for the thumb, 3 DOFs for the other fingers) = 13 DOFs;
- Adduction/abduction of the thumb = 2 DOFs

Although this configuration cannot replicate all the possible movements of the hand, it seems to be enough to understand the intention of the user (grasping, pointing, etc).

Table 2: Commercially Available Sensor Gloves.

Model	Maker	DOFs	Price (USD)
5DT Data Glove 5 Ultra	Fifth Dimension Technologies	5	~ 400
Cyber Glove	Virtual Technology	22	~1400

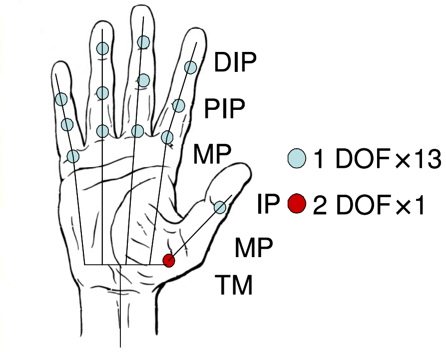


Fig. 8: DOF Configuration of WB-1R Sensor Glove.

A comparison of the bend sensors used in the glove with a potentiometer is shown in Fig. 9. The average error of the bend sensor is less than 2[deg] (for a flexion-extension movement, it is between 0[deg] and 90[deg]. The bend sensor, therefore, has enough precision for our purposes.

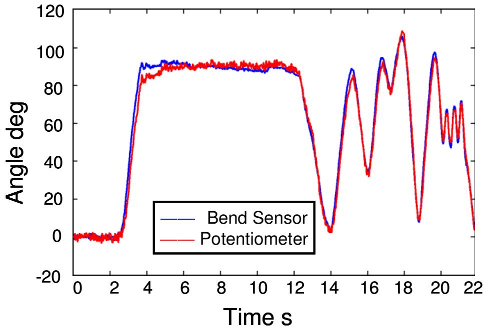


Fig. 9: Comparison of Bend Sensor with a Potentiometer

A photograph of the prototype sensor glove we developed is shown in Fig. 10. Some reconstructions of the posture of the hand are presented in Fig. 11. The overall cost of our sensorized glove is about 300 USD. Therefore, we achieved a high number of DOFs at a reasonably low price.

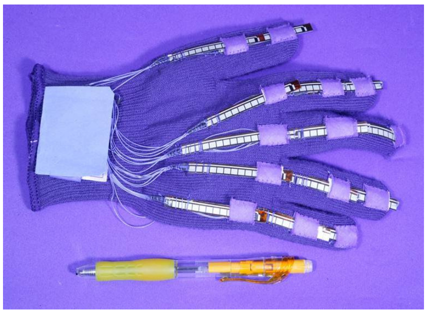
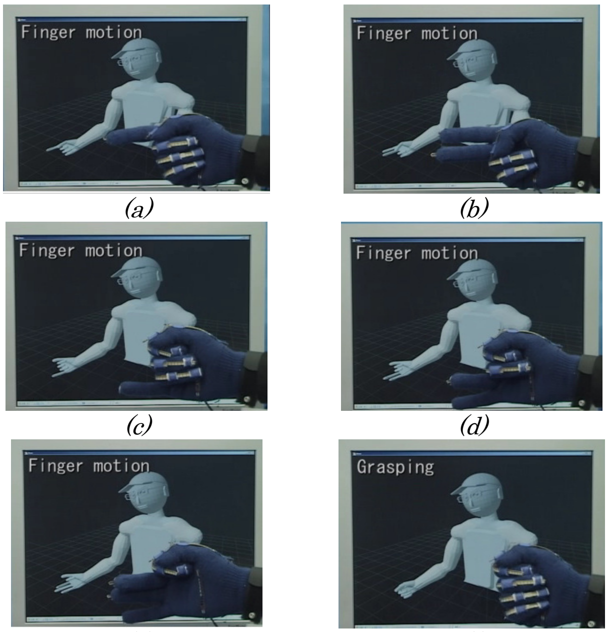


Fig. 10: WB-1R Sensor Glove.



(a) *(b)* *(c)* *(d)* *(e)* *(f)*

Fig. 11: Some examples of reconstruction of finger motion (a)-(e) and of grasping (f).

IV. EXPERIMENTAL EVALUATION OF THE TWO SUBSYSTEMS

We used the VICON motion capture system (Fig. 12) as a reference to evaluate the errors of the head and the hand motion measurement module. We put 4 markers in front of, to the right of, to the left of, and on top of the sensorized hat to measure the movements of the head; we put an additional 4 markers in front of the chest, on the back, and on both shoulders as a benchmark. The mounting location of the markers is shown in Fig. 13.

Fig. 12: Experimental Evaluation with VICON.

Fig. 13: Location of the markers.

With the subject seated, the perpendicular position is set as the initial state. The head is then turned on the Roll, Pitch, and Yaw axes, and the X, Y, and Z positions of the markers are measured.

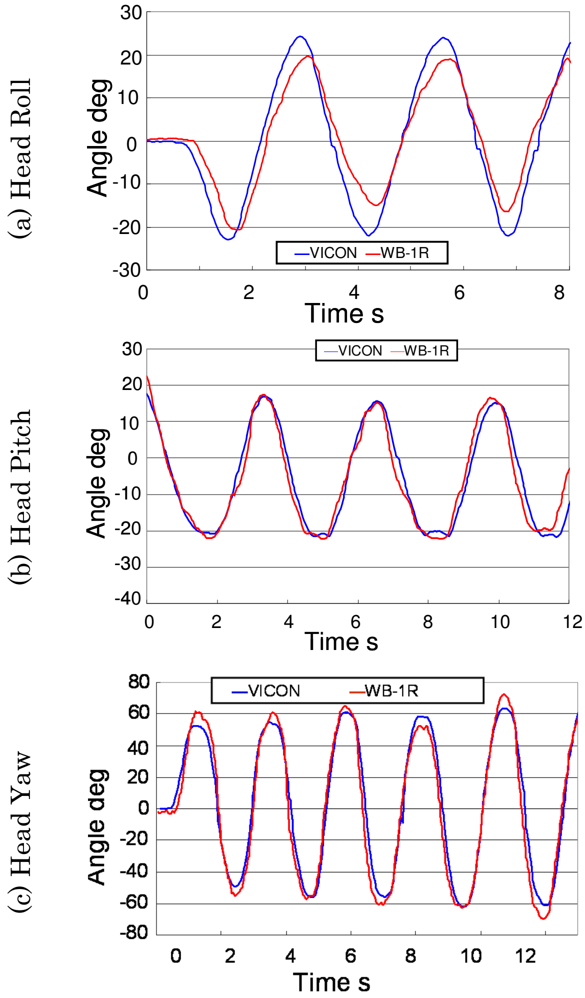


Fig. 14: Comparison of WB-1R with VICON – Head.

The comparison of the data obtained from the head posture measurement module with the data obtained from VICON (with a resolution of 0.2 mm within the calibrated area) is shown in Fig. 14(a-c) and Table 3. The resulting errors (in particular for the Yaw axis) sometimes are not very small: average error ranges from 4.1 to 7.1 [deg], while maximum error ranges from 9.3 to 27.3 [deg].; However, Fig. 14(a)-(c) clearly show that the patterns are very similar to VICON's data. These results seem sufficient for our purposes.

1) Evaluation of the Hand Subsystem

Regarding the hand module, we put a marker to all the finger-tips and measured the X, Y, and Z positions of each marker over time. The results of the experiment are shown in Fig. 15. Again, the error is not particularly small (average error 7.1 [deg], maximum error 27.3 [deg]), but the performance is good enough to understand the intention of the user.

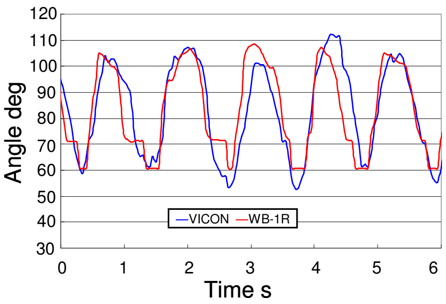


Fig. 15: Comparison of WB-1R with VICON – Hand Part

Table 3: Summary of the experimental Results.

Parameter	Maximum Error (deg)	Average Error (deg)	Correlation Coefficient
Roll	9.3	4.1	0.96
Pitch	10.6	2.5	0.97
Yaw	24.2	6.8	0.98
Finger	27.3	7.1	0.85

V. DISCUSSION AND CONCLUSIONS

In this elderly-dominated society, Personal Robots and Robot Technology (RT)-based assistive devices are expected to play a major role, both for joint activities with their human partners and for participation in community life. So far, several different personal robots have been developed. However, it is not clear how they affect the user's life and how interaction with them is perceived. It is therefore essential to measure and understand the physical and physiological effects of robots on humans in real time, with high reliability, and in any place, while keeping the overall cost of the system down.

In this paper, we presented our development of the Head motion capture system and the Hand motion capture system. Consciousness direction, in fact, is measured by motion of the upper half of the body. In particular, the human head generally shows the consciousness direction and plays an important role in communication. Therefore, we developed a posture angle sensor module that can measure the Roll, Pitch, and Yaw axes of the head (without disturbing its movement) by using a rate gyro, acceleration sensor, and geomagnetic sensor. The hands, meanwhile, are used for communications (gestures) and for interaction (grasping). Therefore, we developed a sensorized glove by using inexpensive bending sensors. This glove can measure 15 DOFs (flexion/extension of each finger plus adduction/abduction of the thumb). These two modules (head and hand) have been integrated into WB-1. The new system is named WB-1R (Waseda Bioinstrumentation system No.1 Refined).

Preliminary experimental results sometimes show errors that can be big, in particular for the reconstruction of the position of the fingertips and for the yaw axis of head movement. However, overall performance of the modules seems good enough to understand the direction of the user's attention and what he would like to do with his/her hands (gesture, grasping, etc). Therefore, we consider that the errors are in an acceptable range.

In the near future, we will extensively apply WB-1R for the analysis of human-robot interaction, in particular with the Emotion Expression Humanoid Robot We-4RII. The mental model, emotional expression and the several behaviors of WE-4RII will be improved by analyzing the experimental results. We will also use the current system as a tool to evaluate performance, for example the performance of surgeons in the operating room while executing laparoscopic surgery.

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