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Full paper

Motion capture-based wearable interaction system and its application to a humanoid robot, AMIO

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Abstract—In this paper, we present a wearable interaction system to enhance interaction between a human user and a humanoid robot. The wearable interaction system assists the user and enhances interaction with the robot by intuitively imitating the user motion while expressing multimodal commands to the robot and displaying multimodal sensory feedback. AMIO, the biped humanoid robot of the AIM Laboratory, was used in experiments to confirm the performance and effectiveness of the proposed system, including the overall performance of motion tracking. Through an experimental application of this system, we successfully demonstrated human and humanoid robot interactions.

Keywords: Human robot interaction; wearable system; motion capture; humanoid.

1. INTRODUCTION

Robots have been evolving into more advanced and anthropomorphic robots, such as humanoids and personal service robots, having multimodal sensing and expression capabilities. With this evolution, human–robot interaction (HRI) is becoming a more important research issue in the area of humanoid robot research. A humanoid robot should be capable of high-level interaction skills, i.e., it must be able to interact with humans through human-like skills such as gestures and dialogue with multimodality. In consideration of the human side in HRI, a wearable computer can be used to assist the user and enhance interaction with a humanoid robot.

HRI can be defined as an area of study including humans, robots and the ways they influence each other. In this regard, multimodality allows humans to move seamlessly between different interaction channels, from visual to voice to touch, according to changes in the context or user preference. A humanoid robot also should provide multimodal interfaces that integrate dialogue, gestures, eye or lip

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*To whom correspondence should be addressed. E-mail: yhseo@paradise.kaist.ac.kr movements and other forms of communication in order to better understand the human, and to interact more effectively and naturally [1].

In consideration of human robot cooperative situations, interaction between the human and a robot is very important to support necessary services efficiently and conveniently. For the human operator, the use of a wearable computer as an interface device for interacting with robots and also with agents is an attractive approach [2]. A wearable computer provides a convenient means of carrying and supporting a multimodal interface [3]. In addition, body signals can be conveyed by making use of sensors embedded in the wearable computer in order to recognize the person's movement and monitor their status.

From the telepresence or teleoperation in the robotics area, this method of operation might be regarded as a means of kinematic interaction between a human and robot. In addition, in previous teleoperation research, the issues of comfortableness and the wearability have often been ignored or regarded as minor concerns. These weaknesses of conventional teleoperation systems have restricted their usability in HRI as well as the range of teleoperation applications. As such, a more convenient and flexible method of tracking human motion is needed.

Several recent telerobotic system studies have shown the possibility of such an interaction system. The Robonaut Project seeks to develop and demonstrate a robotic system that can function as an extravehicular activity astronaut equivalent. This group's robot development work focuses on specific tasks essential for basic exploration mission operations. Furthermore, they aim to use this robotic system in 'partner-to-partner' interactions to share information and provide mutual support [4]. The research team of AIST recently demonstrated teleoperation tasks using the humanoid robot HRP-2. They successfully controlled a humanoid robot remotely to drive an industrial vehicle *in lieu* of a human operator. They also have focused on going to and retrieving an object by semi-autonomous teleoperation combining basic autonomy with human reasoning [5]. The wearable robot called 'Parasitic Humanoid', developed by the University of Tokyo, also provided inspiration for the present authors to develop a new type of teleoperation system [6]. These new kinds of wearable robotic systems can be applied not only for conventional teleoperation areas, but also to HRI, robot motion training systems and entertainment or simulation systems based on virtual reality or augmented reality technologies.

There has been some notable research on robotics considering the use of motion capture data. Zhao *et al.* generated robot motion by mapping motion capture data to a robot model and employing a similarity evaluation [7]. Naksuk *et al.* proposed a system to simulate the robot's motion using motion capture data [8]. Nakazawa *et al.* generated the robot's motion using motion primitives extracted from motion capture data [9]. Matsui *et al.* used motion capture devices on both the operator and the robot in order to build a system that minimizes the motion difference between the operator and the robot [10]. Inamura *et al.* used voice commands and motion capture data to control their robot [11]. Kanzaki *et al.* used a wearable system instead of using a motion capture system [12]. Although motion capture systems are effective in terms of generating robots motion, they are not suitable in terms of HRI in daily life because motion capture devices have many constraints. Therefore, we focused on enhancement of the interaction between a human user and a humanoid robot through a wearable interaction system.

The wearable interaction system proposed in this paper has the advantage of wearability and a flexible method of tracking human motion. A prototype of the system is also presented. Accordingly, we designed and implemented the aforementioned methods and successfully verified their feasibility through demonstrations of human and humanoid robot interactions with the AIM Laboratory's humanoid robot. This paper describes the development of a humanoid robot in the AIM Laboratory, an overview of the proposed system, detailed information about the prototype of the wearable interaction system, and interaction skills and the robot control model. Experimental results with a performance evaluation and conclusions are also presented.

2. DEVELOPMENT OF AMIO — A BIPED HUMANOID ROBOT

As a humanoid robot is expected to work within the home, a biped walking mechanism offers many advantages. Honda's P2, P3 and ASIMO, Sony's QRIO, AIST's HRP-2, and the robots of KAWADA industry are representative humanoid robots that utilize a biped walking mechanism [13–15]. Biped-walking robots, which have been developed in earnest since 1990, have greater potential mobility compared to wheeled mobile robots, despite the fact that they are relatively unstable and difficult to control in terms of posture and motion. Biped robots can move over stairs, irregular planes and discontinuous planes.

Since 1999, we have focused on building new humanoid robots with a self-contained physical body, perception to a degree that allows the robot to be autonomous and social interaction capabilities of an actual human symbiotic robot. This study builds on previous research conducted by the present authors related to social interaction and wearable telepresence using our humanoid robots. We have also been developing a software that performs intelligent tasks using a unified control architecture based on behavior architecture and emotional communication interfaces.

AMIO is a recently developed biped humanoid robot. It consists of a self-contained body, head and two arms, with a two-legged (biped) mechanism. Its control hardware includes vision and speech capabilities and various control boards such as motion controllers, with a signal processing board for several types of sensors. Using AMIO, biped locomotion study and social interaction research were concurrently carried out [16]. The appearance and mechanical structure of AMIO are shown in Fig. 1.

Structural balance is necessary for stable motion. This type of balance requires an appropriate length of each link, an interval between the two legs and weight distribution on each leg. Practical and technical issues of design and manufacturing

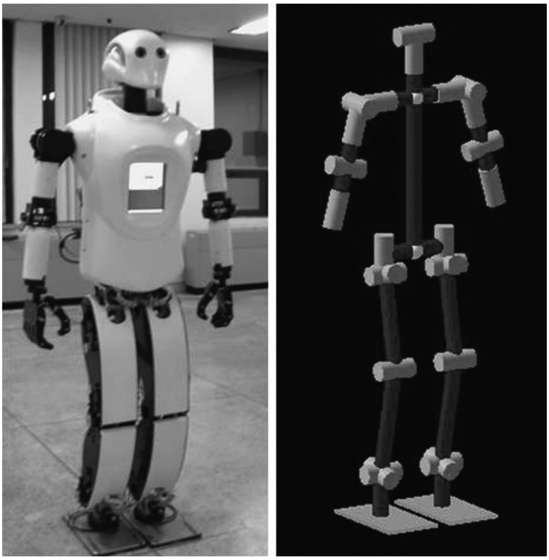


Figure 1. A biped humanoid, AMIO.

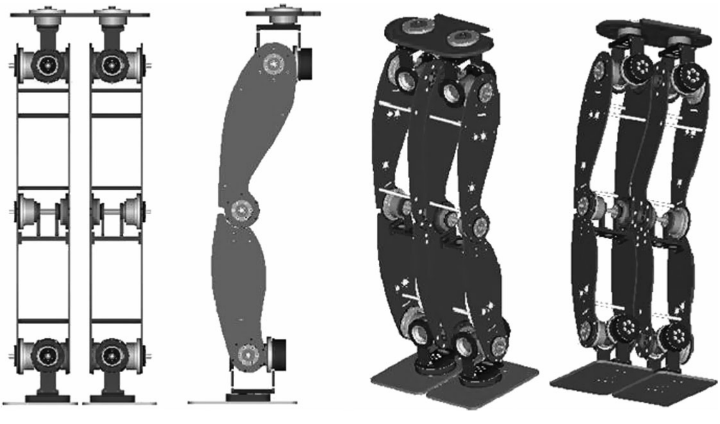


Figure 2. Mechanical drawings of the AMIO biped mechanism.

include mechanical deployments for effective and stable actuation, precise assembly of the linkage and actuators of the coaxial joints with 2 d.o.f., and damping and backlash of the servomotors for stable kinematical motion during continuous activity. Most importantly, a shock and vibration absorption plate made of rubber is attached to the sole of the foot. For the coaxial joints with 2 d.o.f., timing belts and pulleys with bearings are installed to transmit mechanical power. Mechanical drawings of the leg mechanism of AMIO are shown in Fig. 2. The specification and d.o.f. data for the developed robot are shown in Tables 1 and 2, respectively.

Table 1.
Specifications of AMIO

Dimensions	
height	1500 mm
breadth of shoulder	540 mm
chest	320 mm
Weight	45 kg
Total d.o.f.	36
Walking speed	1 km/h
Grasping force	0.5 kg/hand
Sensors	
motor	magnetic and optical encoder
vision	two CCD cameras
chest	one axis inclination sensor 2EA
leg	one axis inclination sensor 4EA × 2
foot	FSR sensor 4EA × 2
Actuators	DC servo motor 10–90–150 W with harmonic drive for arms, legs; RC servomotors for head, hands
Battery	Li-Pol battery DC 30 V, 11 Ah

Table 2.
Degrees of freedom of AMIO

Neck	2 d.o.f.	
Arms		
shoulder	3 d.o.f.	× 2
elbow	3 d.o.f.	× 2
wrist	3 d.o.f.	× 2
Hands	6 d.o.f.	× 2
Arms		
hip	3 d.o.f.	× 2
knee	3 d.o.f.	× 2
ankle	3 d.o.f.	× 2
Total	36 d.o.f.	

3. OVERVIEW OF WEARABLE INTERACTION SYSTEMS

There has been some remarkable research on HRI using motion capture data [7–11]. However, motion capture devices are very expensive and difficult to use. To obtain motion data, numerous markers should be attached to the human operator or the operator should wear an uncomfortable suit. In order to make HRI more natural, a more convenient interaction method is necessary. The wearable interaction system proposed in the present work is designed to meet this goal.

The goal in this study is to make a wearable interaction system that is lightweight enough to wear and easy to operate with multimodal channels for a humanoid robot application. Instead of using conventional motion capture devices, a simple wearable system with magnetic sensors, flex sensors and a head-mounted display (HMD) device is employed, thus providing greater ease of use than motion capture devices. In addition, by supporting operator-selective telerobotic modes of operation between the human master and slave robot, subtasks can be performed automatically, especially tasks that are repetitive, require high precision or involve extreme patience. These modes of operation have potential for increasing the efficiency of remote work systems [17].

A humanoid robot aims to be autonomous, with a self-contained anthropomorphic body; it has sufficient intelligence to have some degree of autonomy. Furthermore, it has the capability to sense its environment and express itself. However, the skills to satisfy the goal of a real autonomous robot cannot yet be realized using current technologies. Therefore, we focused on the aforementioned operator-selective telerobotic modes to overcome the current limitations regarding the level of robot intelligence.

A humanoid intelligent slave robot, having the capability of executing automatic subtasks including the ability to detect objects using a stereo camera system when approaching and grasping objects, is a good test-bed for realizing the operator-selective telerobotic modes *via* the proposed interaction system. It is also useful for examining the performance of teleoperative robotic systems.

A human operator wearing the wearable interaction system sends commands through a multimodal channel, e.g., through voice, arm and head motion. The commands are delivered to the target slave robot *via* wireless and wired networks. The intelligent slave robot can follow the human motion. The operator can make the slave robot perform various subtasks by simply voicing commands through a microphone attached to the wearable interaction system. Figure 3 shows the wearable interaction system and interaction with AMIO.

The proposed system has its own inverse kinematics solver, which calculates the joint angles of the robot arm from the position and orientation data of the human operator's wrist. The shape of the humanoid robot is similar to that of a

Figure 3. Wearable interaction system and humanoid robot, AMIO.

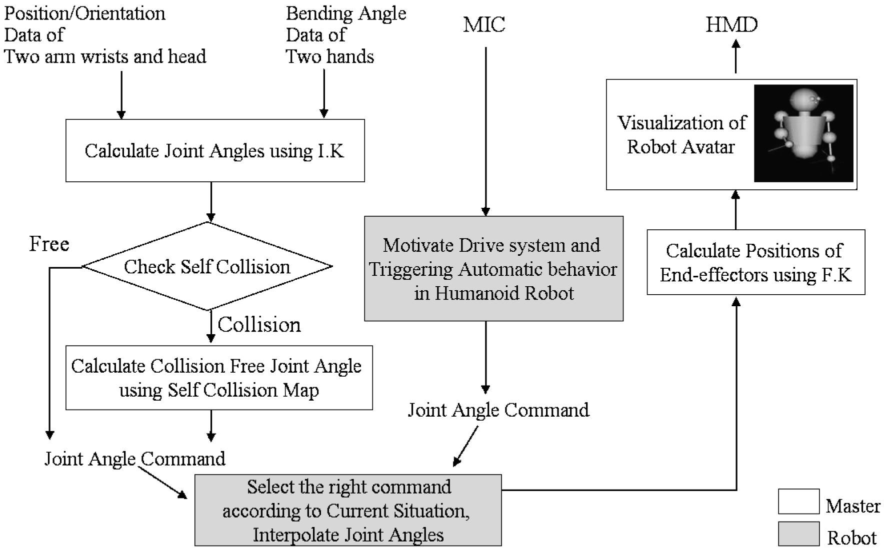


Figure 4. System flow and interaction with robot control model.

human. However, it is difficult for the operator to predict self-collisions between the arms and other parts of the humanoid robot. We therefore use a self-collision checking algorithm that calculates collision free joint angles of the arms using a predefined self-collision map. The self-collision map consists of joint limits and some heuristics on reducing collision pairs, similar but simpler to that of HRP2 [18]. Our self-collision map is designed for only two arms, not the whole body. Accordingly, our collision detection process is efficient enough to run in real-time. Through this sequence, the master system can avoid self-collisions successfully. Figure 4 presents the overall system flow of the wearable interaction system and its interaction with a robot control model, which activates automatic interaction skills in the robot.

4. PROTOTYPE OF THE WEARABLE INTERACTION SYSTEM

The developed wearable master system has a self-contained computer with a HMD, a microphone, a speaker, a wireless LAN and hardware for tracking arm and head motion. The motion-tracking hardware is comprised of magnetic-based position and orientation trackers and several types of small, light sensors, such as three-axis postural sensors and flex sensors. The control board and sensors for the master system are connected to a laptop through the USB interface. The wearable interaction system has two kinds of sensors for detecting the user's arms and head motion. The sensors are attached to the operator to obtain relevant data for the system's usage.

To measure the movements of the operator, we used a magnetic-based position and orientation tracker called Fastrak (Polhemus). Fastrak measures the position and orientation of applications and environments. It is suitable for head and hands

Figure 5. Prototype of the wearable interaction system.

points tracking. Tracking of head movement is accomplished by using a sensor attached to the HMD. The HMD is used for not only sharing the robot's view, but also tracking the direction of the user's head. We attached a microphone to the HMD to receive the operator's voice commands. Two other magnetic trackers are located on both wrists of the operator, while a single transmitter and control box are attached to the back of the wearable suit. With these magnetic trackers, two flex sensors are attached to each glove of the operator. Flex sensors (FLX-01; Abrams Gentile) measure the bending angles of each finger. Figure 5 shows the developed wearable interaction system prototype.

In order to interact with a humanoid robot using this system, we need to analyze the system's kinematics. First, we assumed different lengths of the master arm and the slave robot arm. We also assumed identical positions of the end pointers, which are located at the back of both wrists of the master and the robot. The kinematical process has two subprocesses. First, we apply the positions of the master arms' end points to that of the robot arms. Second, we apply the directions of the master's hands to that of the robot's hands. After applying the position and direction of the master arms' end points to the slave arm, we used a Denavit–Hartenberg matrix to describe the positions of the end points.

Inverse kinematics usually does not provide a unique solution. Therefore, we restricted the solutions to the three-dimensional (3-D) directions of the three-axis sensors located on the operator's wrists. We made the directions of the master's lower arms correspond with those of the slave's lower arms. To obtain the 3-D directions of the wrist locations, we used the Euler angles captured *via* the magnetic tracker system [19].

5. INTERACTION SKILLS AND ROBOT CONTROL MODEL

We also focused on the humanoid robot's automatic interaction skills. Our assumption is that the robot is intelligent enough to perform some limited subtasks. However, the user should model the behaviors and reactions for various tasks. Hence, we implemented a robot control model in which users can easily dictate tasks and behaviors [19, 20].

The robot control model manages two functions, i.e., tasks and behavior development. Although the robot is equipped with various states and user-defined tasks and behavior, there are limitations to what it can do. We, therefore, produced an interface that enables the user to use predefined types of behavior in a behavior database. For example, if the user wants the robot to bring a baseball, a 'baseball' task that consists of selecting, finding, approaching and grabbing behavior can be defined. The user then simply says 'baseball'.

For the second function, behavior development, the user teaches the robot to do something in a particular situation. For example, although performing repetitive tasks makes the user feel tired, the robot has to perform its tasks without being influenced by the user's fatigue. Hence, we are developing a new algorithm that can teach the robot performing behaviors automatically under the interaction system framework shown in Fig. 6.

We adopted the Creature–Kernel Framework proposed by Yoon and we reinforced that framework with advanced memory features [20, 21]. The motivation system in the robot control model is established such that the nature of the robot is to communicate with humans and ultimately to ingratiate itself with them. The motivation system consists of two related subsystems, i.e., one that implements drives and a second that implements emotions. Each subsystem serves as a regulatory function for the robot to maintain its 'well-being'.

In our previous research, three basic drives were defined for a robot's model to communicate with humans [20, 23]. In the new drive system in the robot control model for a humanoid robot operating and engaging in interactions with a human,

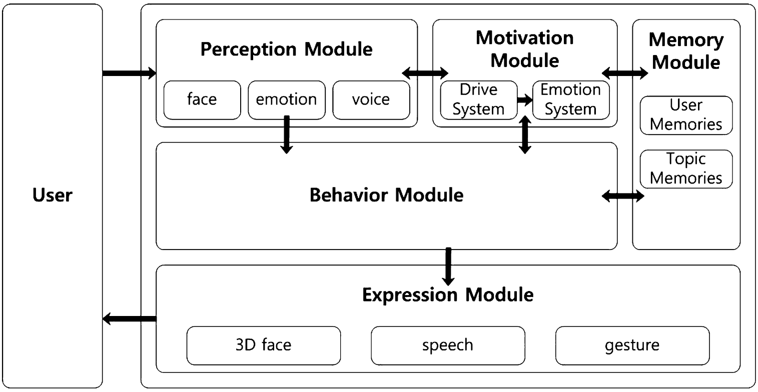


Figure 6. Interaction system framework.

four basic drives are defined for the robot's objectives as they relate to social interaction with a human: a drive to obey a human's commands, a drive to interact with a human, a drive to ingratiate itself with humans and a drive to maintain its own well-being. The first drive motivates the robot to perform a number of predefined services according to a human's commands including imitation of human movements and activation of interaction skills with autonomy.

6. EXPERIMENTAL RESULTS

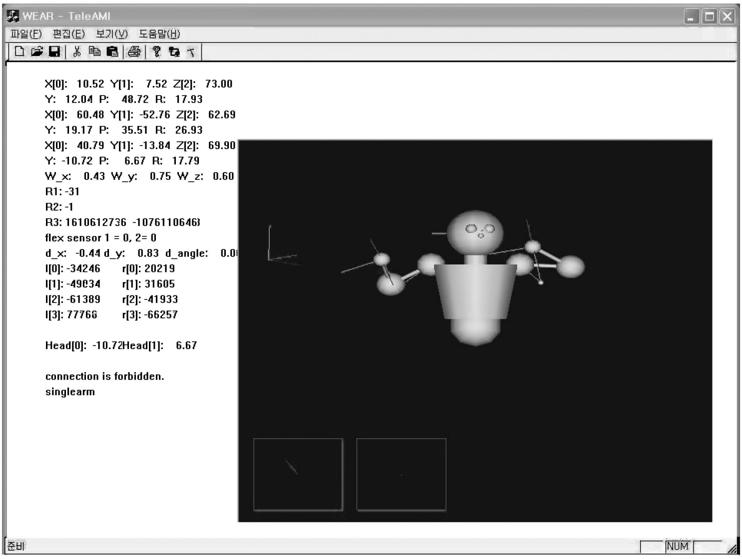
To test the performance of the wearable interaction system, we conducted motion tracking and object grasping solidus delivery experiments with a humanoid robot, AMIO. Before applying the robot control mechanism, we developed a simulator to test our method. We made a 3-D model of the robot's torso to assess whether a self-collision problem exists. Using this simulator, input values from various sensors can be checked. The simulator is shown in Fig. 7.

Interaction with a human using the developed system was examined through the object grasping and delivery experiment shown in Fig. 8. The overall motion tracking experiments are shown in Fig. 9.

To evaluate the motion tracking performance of the wearable interaction system, we captured sequential motion data of 3-D positions of both master and slave end-points simultaneously, during several motion tracking experiments focused on movement of the operator's arm and the humanoid robot following that movement. To test the motion tracking algorithm, we compared the original trajectory of the human operator's end-point and the trajectory of the humanoid robot's end-point. Through these experiments, we confirmed that the proposed system performs well.

Our tracking method is composed of calculating joint angles using inverse kinematics, self-collision checking and modification of joint angles. This process is not so time consuming. The following experiments were all performed in real-time. In this system, a human operator can see the remote scene and also the visualized robot avatar on a HMD screen. Thus human operator can easily control the slave arm.

In the first motion tracking experiment shown in Fig. 10, the trajectory of the humanoid robot's end point successfully followed the original trajectory of the human operator. However, the original trajectory of the human operator is larger than the trajectory of the humanoid robot. We concluded that this was caused by a latency problem with the motion tracking. This means that the human operator's movement is always prior to and faster than the robot's movement and, thus, there exists some time delay for the humanoid robot to follow the operator's movement. However, when the operator moves his or her arm slowly, the trajectories are very similar, as shown in Fig. 11. We concluded that there is a trade-off between the tracking speed and smooth and natural following. The trajectories of movement when the operator makes the shape of a triangle are shown in the 2-D and 3-D plane in Figs 12 and 13, respectively.



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X[0]:  10.52  Y[1]:   7.52  Z[2]:  73.00
Y:  12.04  P:   48.72  R:  17.93
X[0]:  60.48  Y[1]: -52.76  Z[2]:  62.69
Y:  19.17  P:   35.51  R:  26.93
X[0]:  40.79  Y[1]: -13.84  Z[2]:  69.90
Y: -10.72  P:    6.67  R:  17.79
W_x:   0.43  W_y:   0.75  W_z:  0.60
R1: -31
R2: -1
R3: 1610612736  -1076110646
flex sensor 1 = 0, 2= 0
d_x:  -0.44 d_y:   0.83  d_angle:   0.0
l[0]: -34246      r[0]: 20219
l[1]: -49834      r[1]: 31605
l[2]: -61389      r[2]: -41933
l[3]: 77766       r[3]: -66257

Head[0]: -10.72Head[1]:   6.67

connection is forbidden.
singlearm
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Figure 7. Torso motion simulator.

Figure 8. Object grasping and delivery experiment.

In this experiment the slave arm successfully followed the complex trajectory of the human operator. A motion tracking experiment was performed where the human operator could see robot movement and the robot's environment through a HMD screen. The human operator successfully conducted predefined remote tasks such as object grasping and delivery, handshaking, and other remote interactions.

However, the trajectory of the slave arm becomes more pronounced when the operator's movement is rapid and complex, and is due to a latency problem of the robot movement following, as discussed above. We are now trying to resolve this problem by applying a Kalman filter to the captured sensory data and by adapting other predictive methods over the kinematic analysis of the robot and wearable master system.

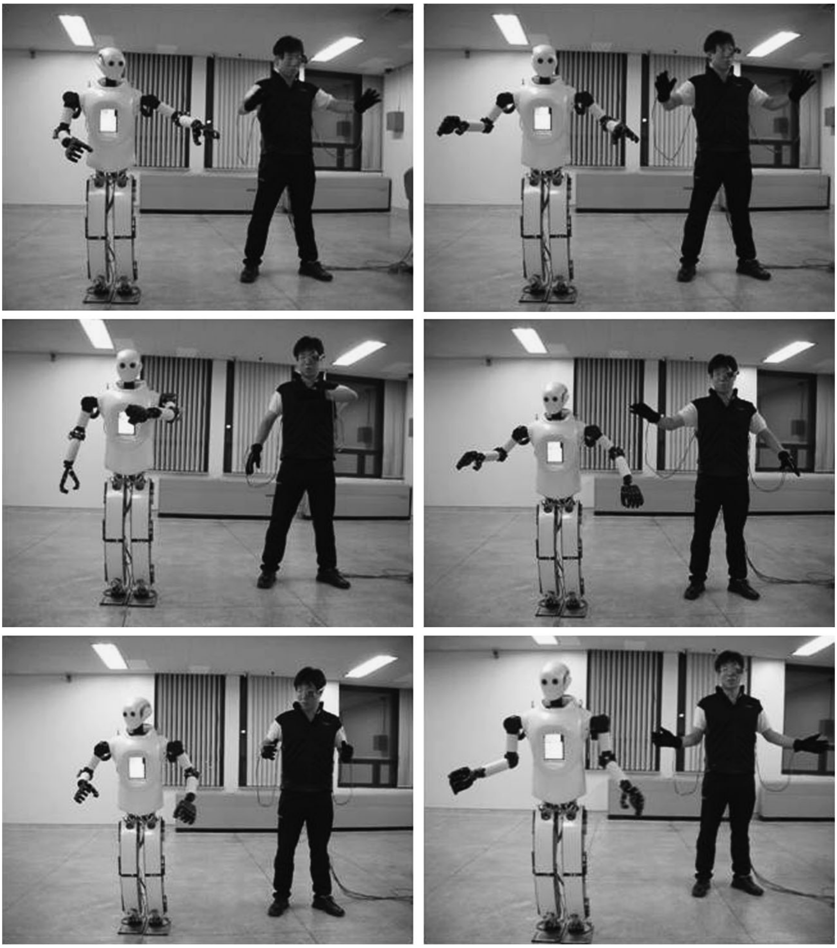

Figure 9. Motion tracking experiments with AMIO.

7. CONCLUSION AND FUTURE WORK

In this study, we proposed a wearable interaction system to enhance interactions between a human and a humanoid robot. Implementation of the system is described in detail and experiments to assess the system have been conducted. The proposed system consists of a lightweight wearable platform that has arms and head motion tracking mechanisms that detect the motion data of an operator. The system also supports intelligent self-sensory feedback to the human operator and interaction with a humanoid robot that has autonomous behaviors, such as automatic grasping and trained gestures, managed by the robot control model. The operator who wears this system can obtain information feedback from the robot through HRI using a multimodal communication channel.

AMIO, a humanoid robot, was used as a test bed in experiments conducted to confirm the performance and effectiveness of the proposed system. Through

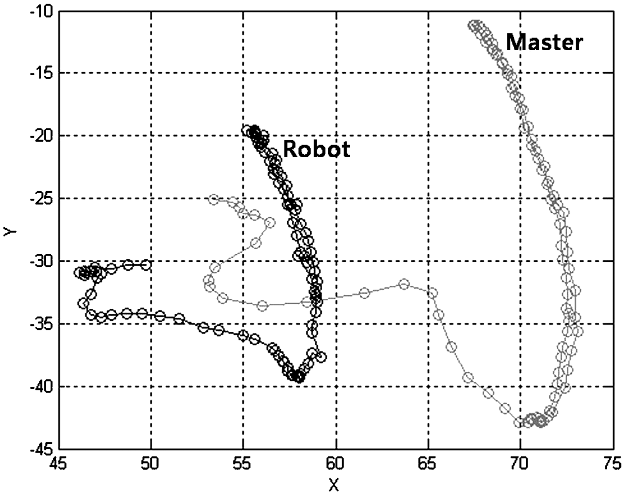

Figure 10. Comparison between master and robot trajectories.

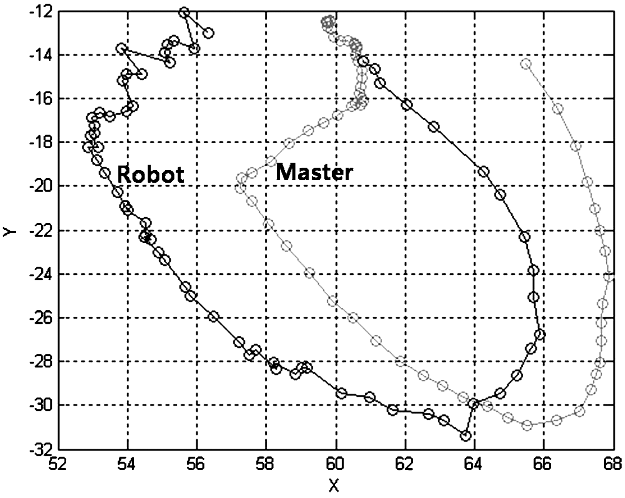

Figure 11. Comparison between master and robot trajectories in slow movement.

teleoperation and interaction experiments, we successfully demonstrated several teleoperative tasks, including motion tracking, multimodal control of the humanoid robot, object manipulation and gesticulant commands. We also showed the overall motion tracking performance of the proposed wearable interaction system.

In our previous research [22], we attempted to use some local sensors. For example, three-axis altitude sensors consisting of a gyroscope sensor and a 2-D accelerometer, a magnetic compass, and flex sensors are attached to each part of the arm joints. However, the experimental results of the previous system were somewhat disappointing due to its precision and limitations of global calibrations. Hence, we have shifted our focus to a magnetic-based global motion capture system.

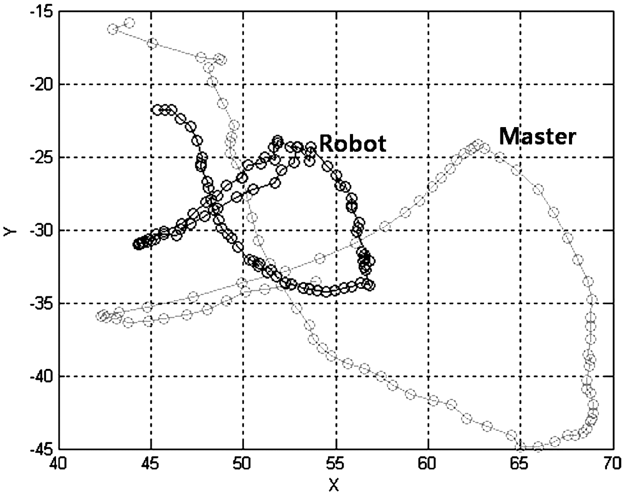

Figure 12. Comparison between master and robot trajectories to describe a triangle in the 2-D plane.

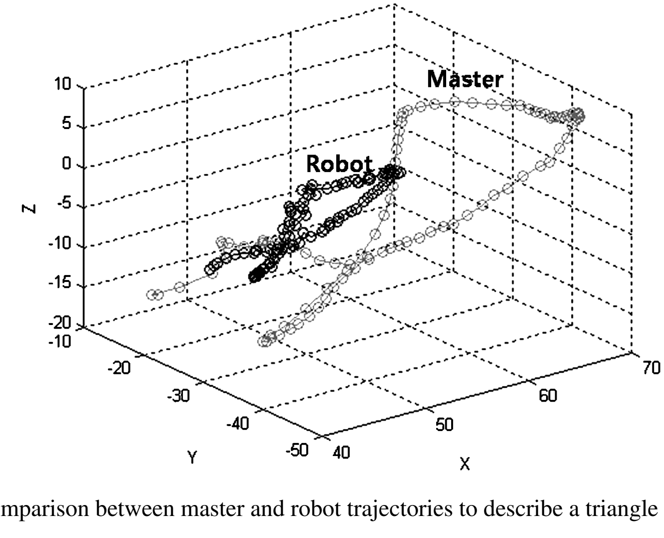

Figure 13. Comparison between master and robot trajectories to describe a triangle in the 3-D plane.

In this system, we integrate a motion capture system into a wearable master system. Thus, the user can interact with a humanoid robot by using the wearable master system which is comfortable and provides intuitive control methods.

We used magnetic sensors to measure the orientation and location of the wrist and head. In order to use magnetic sensors, a magnetic origin is required. The magnetic origin was located at the back of the wearable suit. As this imposes some limitations on the system we plan to develop a new measuring method for the human arm motion using accelerometers and inclinometers.

For a biped robot, maintaining balance is a very important factor while performing various whole-body motions. We implemented a basic balance controller for the humanoid robot using inclination sensors and force sensing resistors at each foot sole [16]. However, we did not precisely consider the dynamic constraint because we assumed that AMIO does not move its legs when its interaction mode is running. We are now developing a new control mechanism to deal with the dynamic balance problem.

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