Synchronous Imitation Control for Biped Robot Based on Wearable Human Motion Analysis System

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Abstract—To achieve accurate and efficient interaction with humans, robot training is indispensable to make robot cooperate with different host. We are focusing on development of a human motion analysis system to real-time measure body segment orientations. Imitation control was applied on a biped robot based on measurements of the developed wearable sensor system. Experimental study was implemented to verify the synchronous imitation control method proposed for the biped robot, and verification results proved the feasibility of the proposed control method. Through comparing results obtained from direct imitation control method and improved method based on training algorithm considering the personal motion pattern, we found that the imitation control accuracy was markedly improved, and the three-axial average errors of x-y- and z-moving displacements related to leg length were 12%, 8% and 4% respectively.

I. INTRODUCTION

HUMANOID robots are gradually appearing in daily life, when some key technology are being addressed and resolved, such as safely coexistence with humans, interactively communication with humans and efficient operating objects in human life space [1]-[3]. Recently, considerable research work has been concentrated on the development of humanoid biped robots [4]-[7]. However, in order for humanoid robots to assist human with home work in human-centered environments, it is no only important to equip them with manipulative, perceptive and communicative skills necessary for real-time interaction with the working environment, but also accurate and efficient interaction with humans for robot training is indispensable to make robot cooperate with different host. Recently, many researchers are becoming interesting in robot imitation about learning affordances [8]-[10]. A generic framework for solving the correspondence problem: ALICE (Action Learning via Imitation Corresponding Embodiments) was proposed in [11], in which the problem of embodiment differences between the learner and instructor for imitation control was addressed. We are focusing on human dynamics analysis to develop intelligent machines or robots, for example real-time measurements of human joint orientations and ground reaction forces for controlling a rehabilitation robot to support human walking [12]-[13]. The goal of our work can be divided into two parts. On the one hand a wearable sensor system is being developed to implement human motion analysis without environment restriction, and on the other hand the real-time control of a biped robot is implemented to imitate human motion based on measurements of the sensor system. Because of embodiment difference between robot and human, some complex 3D joint motions of human, for example knee joint, were measured using inertial sensor on body surface, then simplified to obtain 2D angle information for robot imitation control.

The paper is organized as follows. In Section 2, we describe the components of the wearable motion sensor system and its developed and implemented algorithm for estimating orientations of human lower limbs. Section 3 describes the developed biped robot architecture including its hardware and software modules. The experimental study on imitation control of the biped robot using the wearable motion sensor system is described in Section 4. In Section 5, the results of verification experiment using an optical motion analysis system are described.

II. WEARABLE MOTION SENSOR SYSTEM

A. Components of the Sensor System

As shown in Fig.1, a sensor module was designed for integrating gyroscope (Murata ENC-03J, size 15.5×8.0×4.3 mm, weight 10 g) and accelerometer-chip (ADXL202). The principle operation of the gyroscope is the measurement of the Coriolis acceleration, which is generated when a rotational angular velocity is applied to the oscillating piezoelectric bimorph. These inertial sensor can work under low energy consumption (4.6 mA at 5V), and are appropriate for ambulatory measurements. The signal from the gyroscopes and accelerometer are amplified and low-pass filtered (cutoff frequency: 25Hz) to remove electronic noise. The frequencies outside the pass-band were filtered out because they are invalid in the study of human kinetics.

Gyroscope was used to measure angular velocities of body segments of waist, thigh and shank. The sensing axis was vertical to the medial-lateral plane so that the angular velocity
in the sagittal plane could be detected. In local coordinates of three segments, sensing axis of the gyroscopes is along y-axis, and the z-axis is along leg-bone. A two-axial accelerometer was attached on based board plate of the sensor module to measure two-directional accelerations along tangent direction of x-axis and sagittal direction of z-axis. A two-axial accelerometer was attached on based board plate of the sensor module to measure two-directional accelerations along tangent direction of x-axis and sagittal direction of z-axis. In this data analysis system the data from accelerometer were fused with data collected from gyroscopes for cycle system calibration, through supplying initial angular displacement of the attached leg segments. As shown in Fig. 2, the wearable sensor system includes three sensor modules composed of a gyroscope and bio-axial accelerometer. Two sensor modules are attached on thigh and shank respectively, and a sensor module and a data sampling system are attached on the waist.

**B. Algorithm for Estimating Orientations of Human Lower Limbs**

As shown in Fig. 3, because the sensor module including a gyroscope and a two-axial accelerometer only perform measurements of angular velocity and acceleration in segment-fixed reference frame during human moving, three local coordinates were defined for each sensor module fixed on the human body. Considering the two-dimensional (2D) model of a segment motion, a sensor module including a biaxial accelerometer and a gyroscope was placed at point on the segment. The vector \([R_1, R_2, R_3, R_4, R_5]\) indicates the distance between sensor module and joint, and 2D local coordinate systems \(x^wz^w, x^tz^t\) and \(x^sz^s\) represent the orientations of the sensor modules with respect to body segments. We aligned z-direction along the connection line of the two joints, and let x-direction be anterior-posterior direction.

For the simplified model, human body segments were considered as rigid bodies. We analyzed the motion of the sensor module fixed on a body segment by dividing the motion into the linear motion of the segment’s rotation point, and the angular motion of the sensor module about the point. Therefore, to estimate joint angle, the first step was to calculate two-directional accelerations of joint on every local coordinate system using measurements of the sensor modules fixed on the body segments.

\[
\begin{align*}
\begin{bmatrix}
    a_x^h \quad a_z^h \\
    a_x^t \quad a_z^t \\
    a_x^k \quad a_z^k \\
    a_x^s \quad a_z^s
\end{bmatrix}
&= [a_x, a_z]^w - [R_1 \omega_1, R_1 \omega_2]^2 \quad (1) \\
[\begin{bmatrix}
    a_x^h \quad a_z^h \\
    a_x^t \quad a_z^t \end{bmatrix}]'
&= [a_x, a_z]^t - [R_2 \omega_2, R_2 \omega_2]^2 \quad (2) \\
[\begin{bmatrix}
    a_x^k \quad a_z^k \\
    a_x^s \quad a_z^s \end{bmatrix}]'
&= [a_x, a_z]^t + [R_3 \omega_3, R_3 \omega_3]^2 \quad (3) \\
[\begin{bmatrix}
    a_x^k \quad a_z^k \\
    a_x^s \quad a_z^s \end{bmatrix}]'
&= [a_x, a_z]^s - [R_4 \omega_4, R_4 \omega_4]^2 \quad (4) \\
[\begin{bmatrix}
    a_x^s \quad a_z^s \\
    a_x^s \quad a_z^s \end{bmatrix}]'
&= [a_x, a_z]^s - [R_5 \omega_5, R_5 \omega_5]^2 \quad (5)
\end{align*}
\]

where \([a_x, a_z]^w\), \([a_x, a_z]^t\) and \([a_x, a_z]^s\) are 2-D accelerometer outputs obtained from the three sensor modules fixed on body segments including waist, thigh and shank respectively; and \([a_x^h, a_z^h]\), \([a_x^k, a_z^k]\) and \([a_x^s, a_z^s]\) are hip, knee and ankle joints accelerometers which were calculated on two local coordinate systems of the connected segments.

The next step was to calculate joint angle between two segments using two sensor modules fixed on each segment. Since one point should physically have a unique acceleration, the two estimated accelerations on local coordinates at rotation joint should give equal accelerations.

\[
\begin{align*}
[\begin{bmatrix}
    a_x^h \quad a_z^h \\
    a_x^t \quad a_z^t \end{bmatrix}]'
&= R(q_1)[a_x, a_z]^w \quad (6) \\
[\begin{bmatrix}
    a_x^k \quad a_z^k \end{bmatrix}]'
&= R(q_2)[a_x, a_z]^t \quad (7)
\end{align*}
\]

where \(R(q_1)\) and \(R(q_2)\) are axis rotation matrices of the
calculated joint accelerations in relation to the two connected local coordinates by angles $q_1$ and $q_2$, respectively.

When subject is standing on the ground, the accelerations of ankle related to the coordinate system fixed on the foot could be given as:

$$[a_x^a, a_z^a]^T = [0, g]^T$$  \hspace{1cm} (8)

where $g$ is referred as gravity acceleration. Then we can calculate ankle joint angle $q_3$ using the ankle accelerations obtained from the local coordinates.

$$[a_x^a, a_z^a]^T = R(q_3)[a_x^a, a_z^a]^T$$  \hspace{1cm} (9)

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II. SYNCHRONOUS IMITATION CONTROL FOR BIPED ROBOT

Imitation control was implemented on a biped robot using the developed wearable sensor system and algorithm. We developed a robot integrated with angular position control for the real-time motion control by human inputs.

A. Developed Biped Robot

As shown in Fig.4, a small biped robot “R1” (height: 330mm and mass: 2kg) was developed for the experimental study. Each leg has six degrees. In this robot, 12 servo motors (Kondo Kagaku Co., LTD) were used to make actuators for all the robot joints, and the specification of the robot is given in Table I. A micro-computer controller (PIC 16F877A by Microchip Co) was inbuilt in the robot, which can output the 12-channel pulses for the drive motors and connect with a wireless module to communicate with a master computer.

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B. Inverse Kinematics

A simplified model of right leg of the biped robot is given in Fig.5. We calculated robot joint angles from inputs of subjective displacements of foot through inverse kinematics analysis. An algorithm was developed to produce the biped robot motion according to displacement vector $[rx \; ry \; rz]$. Geometric relations of the robot links are shown in Fig.6, and we can resolve joint angles for motor control. [14]

Firstly the robot pitch angle can be calculated as following:

$$Z^2 = A^2 + B^2 - 2 \cdot A \cdot B \cdot \cos(\pi - \theta_1)$$  \hspace{1cm} (10)

$$Z = \sqrt{rx^2 + ry^2 + rz^2}$$  \hspace{1cm} (11)

$$\theta_1 = \cos^{-1}\left(\frac{Z^2 - A^2 - B^2}{2 \cdot A \cdot B}\right)$$  \hspace{1cm} (12)

Secondly, we can use trigonometric functions and sine theorem to derive the robot ankle roll angle $\theta_2$ and ankle pitch angle $\theta_3$ by
\[
\alpha = \sin^{-1}\left(\frac{A}{C} \cdot \sin(\pi - \theta_1)\right) 
\]  
(13)

\[
\theta_2 = \tan^{-1}\left(\frac{ry}{rz}\right) 
\]  
(14)

\[
\theta_3 = \tan^{-1}\left(\frac{rx}{\sqrt{ry^2 + rz^2}}\right) + \alpha 
\]  
(15)

Finally, to keep standing balance of the robot, we constrained the other joint angles including hip roll angle \(\theta_4\) and hip pitch angle \(\theta_5\) by following equations:

\[
\theta_4 = -\theta_2 
\]  
(16)

\[
\theta_5 = \pi - \theta_4 + \theta_3 
\]  
(17)

C. Synchronous Imitation Control

As described in the above section, an inverse kinematics algorithm could be used to produce pre-designed motion trajectories such as walking, standing and rotation. We want to design cyclic joint angle trajectories which have to be synchronous with the output of the motion sensors mounted on human body segments. Fig. 7 gives the architecture of the synchronous imitation control system for the biped robot. A database of robot movement trajectories can be real-time added using measurement results obtained from the wearable motion analysis system.

This is a kind of imitation control method, which can be, for example, very useful in the case of controlling leg prosthesis or remotely operating a walking robot.

\[\text{Fig. 6. Geometric relations of the robot links.}\]

\[\text{Fig. 5. Simplified model of right leg of the biped robot.}\]

\[\text{Fig. 7. Architecture of the synchronous imitation control system.}\]

IV. EXPERIMENTAL STUDY

Experimental study was implemented to verify the synchronous imitation control method proposed for the biped
robot. As shown in Fig. 8, three-directional waist movements were sampled as inputs of the synchronous imitation control system which generated control trajectories to determine motor angular positions. Based on pre-designed motion trajectory of the biped robot in the case of no human motion inputs, we could control the robot motion from real-time orientation information of human lower limbs.

To quantitatively validate performance of the robot motion control based the measurements of the developed wearable sensor system and control method, we have compared the quantitative results of measurements of the motion sensor system, the robot motion responses and control outputs of the designed synchronous imitation control system, which were synchronously measured using a commercial optical motion analysis system Hi-DCam (NAC image technology, Japan). The motion analysis system (Hi-DCam) tracked and measured the three-dimensional (3-D) trajectories of retro-reflective markers placed on the subject’s body segments and robot joints, as shown in Figs. 9. The cameras with sampling frequency 100 Hz were used to track the marker positions with accuracy of 1 mm.

V. RESULTS AND DISCUSSION

In this paper, to exam proposed synchronous imitation control method, 3D motion of human was sampled and analyzed to control the biped robot. We have compared three-directional displacements of the human subject and the controlled robot with the sensor motion control system outputs in the first test motion for training experiment. As shown in Fig. 10, the responses of three-directional waist displacements were almost the same for human and the robot, but there were large differences about motion pattern between the robot and the human subject, because human segments length rates and joint freedoms are widely different, which may affect the measurement precision of the wearable motion sensor system for real-time robot control. It shows that there were large errors if the imitation control is just based on measurements of motion sensors, for example, the displacement error was larger than 150mm in the z-axis at a time point. The synchronous imitation control system was developed to address this problem by saving the first time human motion data to motion trajectories database as a reference input for robot imitation control. As shown in Fig. 11, after considering the personal motion pattern, we implemented the waist motion imitation control experiment on the same subject, and the verification results proved the feasibility of the synchronous imitation control system. Through comparing results obtained from direct imitation control method and improved method based on training algorithm considering the personal motion pattern, we found that the imitation control accuracy was markedly improved, and the three-axial average errors of x- y- and z- moving displacements related to leg length were 12%, 8% and 4% respectively.
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