Imitation Control for Biped Robot Using Wearable Motion Sensor

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In conventional imitation control, optical tracking devices have been widely adopted to capture human motion and control robots in a laboratory environment. Wearable sensors are attracting extensive interest in the development of a lower-cost human-robot control system without constraints from stationary motion analysis devices. We propose an ambulatory human motion analysis system based on small inertial sensors to measure body segment orientations in real time. A new imitation control method was developed and applied to a biped robot using data of human joint angles obtained from a wearable sensor system. An experimental study was carried out to verify the method of synchronous imitation control for a biped robot. By comparing the results obtained from direct imitation control with an improved method based on a training algorithm, which includes a personal motion pattern, we found that the accuracy of imitation control was markedly improved and the tri-axial average errors of x-y- and z-moving displacements related to leg length were 12%, 8% and 4%, respectively. Experimental results support the feasibility of the proposed control method. [DOI: 10.1115/1.4001097]

Keywords: imitation control, biped robot, wearable motion sensor, human motion analysis

1 Introduction

Humanoid robots are gradually appearing in daily life, with key technology being addressed and resolved for safe coexistence with humans, interactive communication with humans, and efficient operation of objects in human space [1–4]. Integrating human motion analysis and existing robot control technology to implement a friendly human-robot system will be an interesting research focus in biomedical, industrial, and aerospace fields. Recently, considerable research work has concentrated on the development of humanoid biped robots [5–8]. However, in order for humanoid robots to assist people with work in human-centered environments, it is not only important to equip them with the manipulative, perceptive, and communication skills necessary for real-time interactions in a working environment, but it is also indispensable to train robots to interact accurately and efficiently with humans so as to make robots cooperate with different hosts.

Recently, many researchers are becoming interested in robot imitation of learning [9–11]. A generic framework for solving the correspondence problem: action learning via imitation corresponding embodiments (ALICE) was proposed in Ref. [12], in which the problem of different embodiments between the learner and instructor for imitation control was addressed. Ferreira et al. [13] used acquired human gait data to control a biped robot, in which computer vision techniques were adapted to extract kinematic features of human motion and obtain gait signatures in the sagittal plane. Ude et al. [14] proposed a method for transforming human motion information captured by an optical tracking device into a high dimensional trajectory for a humanoid robot and used B-spline wavelets for noise reduction in offline analysis. These methods based on stationary motion capture devices are difficult to use in real-time control and are limited to laboratory environments because a method based on optical motion analysis requires considerable work space and high-speed graphical signal processing. The devices are expensive, and prefabrication experiments and offline analysis of recorded pictures are especially time consuming. We are focusing on human dynamics analysis to develop intelligent walk support machines or robots, for real-time measurements of human joint orientations and ground reaction forces for controlling a rehabilitation robot to support human walking [15,16]. In this paper, 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 environmental restrictions, and on the other hand, real-time control of a biped robot is implemented to imitate human motion based on measurements by the sensor system.

2 Materials and Methods

2.1 Wearable Sensor System for Estimating Segment Orientations. As shown in Fig. 1, a sensor module was designed by integrating a gyroscope (Murata ENC-033, size of 15.5 × 8.0 × 4.3 mm³, weight of 10 g) and an accelerometer chip (ADXL202). The principle of operation of the gyroscope is based on a measurement of the Coriolis acceleration, which is generated when a rotational angular velocity is applied to an oscillating piezoelectric bimorph. These inertial sensors can work with low energy consumption (4.6 mA at 5 V) and are suitable for ambulatory measurements. The signal from the gyroscopes and accelerometer are amplified and low-pass filtered (cutoff frequency of 25 Hz) to eliminate electronic noise. The frequencies outside the passband were filtered out because they are irrelevant in the study of human kinetics.

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 to the thigh and shank, respectively, and a sensor module and data sampling system are attached to the waist. Three local coordinates were defined for the sensor modules mounted on the thigh, shank, and waist. We aligned the y-direction along the line connecting the segment’s proximal and distal joints and let the x-direction be the anterior-posterior direction, and the z-axis was chosen such that the resulting global coordinate system would be right handed. The gyroscopes were used to measure the 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 the local coordinates of the three segments, the sensing axes of the gyroscopes are along the z-axis. The bio-axial accelerometer was attached to the base board plate of the sensor module to measure the two components of acceleration along the x-axis and y-axis. In our data analysis system, the data from the accelerometer were fused with data collected from gyroscopes for cycle system calibration, by supplying the initial angular displacement of the attached leg segments.

In a simplified human model, the human body segments were assumed to be rigid. We analyzed the motion of the sensor module fixed to 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 around the rotation point. Therefore, to esti-
mate the joint angle, we calculate the two components of acceleration of each joint in their local coordinate systems using measurements of the sensor modules fixed to the body segments and combine the measurements of gyroscopes in the sensor modules. The detailed calculation method to estimate segment orientations is given in Ref. [16]. In this study, the human leg model was simplified to a link with three degrees of freedom, in which the knee joint has one degree of freedom, and the hip joint and ankle joint have two degrees of freedom, respectively. We can measure the three joint angles in the sagittal plane (x-y plane) and the roll angles of the hip joint and ankle joint around the x-axis in the motion sensor system. The three-dimensional (3D) displacement vector pointing from the ankle joint to the hip joint can be used to control a biped robot moving in 3D space.

2.2 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 real-time motion control by human inputs. As shown in Fig. 3, a small biped robot “R1” (height of 330 mm, mass of 2 kg) was developed for the experimental study. Each leg has six degrees of freedom. 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 1. A microcomputer controller (PIC 16F877A by Microchip Co., Chandler, AZ) was built into the robot and can output the 12-channel pulses for the drive motors and connect with a wireless module to communicate with a master computer.

A simplified model of the right leg of the biped robot is given in Fig. 4. We calculated robot joint angles from inputs of subjective displacements of the foot through an inverse kinematics analysis. An algorithm was developed to produce the biped robot motion according to displacement vector \([r_x, r_y, r_z]\). Geometric relations for the robot links are shown in Fig. 5 and we can resolve joint angles for motor control [17].

First, the robot pitch angle can be calculated as follows:

\[
Z^2 = A^2 + B^2 - 2 \cdot A \cdot B \cdot \cos(\pi - \theta_1)
\]  

**Table 1 Specification of the robot**

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Height</th>
<th>300 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Width</td>
<td>150 mm</td>
</tr>
<tr>
<td>Foot size</td>
<td>130 x 70 mm²</td>
<td></td>
</tr>
<tr>
<td>DOF (single leg)</td>
<td>Yaw axis</td>
<td>1 deg</td>
</tr>
<tr>
<td></td>
<td>Pitch axis</td>
<td>3 deg</td>
</tr>
<tr>
<td></td>
<td>Roll axis</td>
<td>2 deg</td>
</tr>
<tr>
<td>Weight</td>
<td>1.8 kg (including battery)</td>
<td></td>
</tr>
</tbody>
</table>

First, the robot pitch angle can be calculated as follows:

\[
Z^2 = A^2 + B^2 - 2 \cdot A \cdot B \cdot \cos(\pi - \theta_1)
\]  

**Fig. 1 Motion sensor module**

**Fig. 2 Wearable motion sensor system. A strap system was designed to attach the sensor modules to the human body segments.**

**Fig. 3 Biped robot**

**Fig. 4 Simplified model of right leg of the biped robot**
Second, we can use trigonometric functions and the sine theorem to derive the robot ankle roll angle and ankle pitch angle according to

$$\alpha = \sin^{-1}\left(\frac{A \cdot \sin(\pi - \theta_1)}{C}\right)$$

$$\theta_2 = \tan^{-1}\left(\frac{r_y}{r_z}\right)$$

$$\theta_3 = \tan^{-1}\left(\frac{r_x}{\sqrt{r_y^2 + r_z^2}}\right) + \alpha$$

Finally, to maintain the standing balance of the robot, we constrained the other joint angles including hip roll angle $\theta_4$ and hip pitch angle $\theta_5$ with the following equations:

$$\theta_4 = -\theta_2$$

$$\theta_5 = \pi - \theta_1 + \theta_3$$

By using Eqs. (1)–(8), an inverse kinematics algorithm can be used to produce predesigned motion trajectories such as walking, standing, and rotation. We want to design cyclic joint angle trajectories, which are synchronous with the output of the motion sensors mounted on the human body segments. Figure 6 shows the architecture of the synchronous imitation control system for the biped robot. A database of robot movement trajectories can be added in real time using the results of measurements obtained from the wearable motion analysis system. The acceleration data for the two leg segments and the waist mounted with the sensor modules can be obtained and used to estimate the joint angles of human subjects, and the calculated displacement vectors pointing from the ankle joint to the hip joint were scaled to the saved displacement vectors of the robot. Therefore, the differences between the segment length rates and joint freedoms between the human being and the robot can be used to drive imitation control in a training process.

3 Results

An experimental study was carried out to verify the synchronous imitation control method proposed for the biped robot. As shown in Fig. 7, the three components of waist movement were sampled as inputs for the synchronous imitation control system used to generate control trajectories to determine motor angular positions. Based on a predesigned motion trajectory of the biped robot in a case with no human motion inputs, we could control the robot motion from real-time orientation information of human lower limbs.
To quantitatively validate the performance of the robot motion control system based on measurements of the wearable sensor system and control method, we compared the quantitative results of measurements of the motion sensor system, the robot motion responses, and the control outputs of the 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 3D trajectories of retroreflective markers placed on the subject’s body segments and robot joints. Cameras with a sampling frequency of 100 Hz were used to track the marker positions with an accuracy of 1 mm.

4 Discussion

In this paper, to examine the proposed synchronous imitation control method, the 3D motion of a human being was sampled and analyzed to control a biped robot. We have compared the three components of displacement of the human subject and of the controlled robot with sensor motion control system outputs in the first motion test of a training experiment. As shown in Fig. 8, the responses of the three components of waist displacement were almost the same for the human subject and the robot, but there were large differences in motion pattern between the robot and human subject because the human segment length rates and joint freedoms were significantly different, which may reflect the measurement precision of the wearable motion sensor system in real-time robot control. This shows that there are large errors if the imitation control is only based on measurements of motion sensors, for example, the displacement error was larger than 150 mm along the z-axis at one point in time. A synchronous imitation control system was developed to address this problem by saving the first series of human motion data to a motion trajectory database as reference input for robot imitation control. As shown in Fig. 9, after taking into account the personal pattern of motion, we implemented a waist motion imitation control experiment on the same subject and the results proved the feasibility of the synchronous imitation control system. By comparing the results obtained from the direct imitation control method and the improved method.
based on a training algorithm, which incorporates the personal pattern of motion, we found that the accuracy of imitation control was markedly improved and the tri-axial average errors of x-y- and z-displacements related to leg length were 12%, 8%, and 4% respectively.

References


