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Characteristic Studies on Imitation Control for Static Walking of Biped Robot

***Abstract**. The purpose of this paper is to present a new kind of imitation control architecture for a biped robot. A human operator can interact with the robot and control it to walk. The robot is built based on the skeletal structure of humans. Partial joints are controlled by the operator wearing motion sensors in the body and other joints controlled by the controller. This paper describes the difficulties of balance control due to the random trajectory data by the operator and gives a static walking control method to keep the posture of the robot stable in imitation walking.*

***Streszczenie.** W artykule opisano strukturę sterowania metodą naśladowczą dla robota dwunożnego, zbudowanego na podstawie struktury ludzkiego szkieletu. Algorytm umożliwia kontrolę robota, w tym ruchów związanych z chodzeniem i utrzymanie stabilnej pozycji. Przedstawiono problemy związane z balansem. (**Badania charakterystyki sterowania metodą naśladowczą dla dwunożnego, chodzącego robota**)*

Keywords: Imitation control architecture, Biped robot, Static walking
Słowa kluczowe: sterowanie metodą naśladowczą, robot dwunożny, chodzenie statyczne.

Introduction

At present, robot application fields are gradually increasing. Robots do simple, dangerous, and difficult jobs. For example, they are engaged in simple assembly processes in manufacturing plants, and work in nuclear power plants or on the ocean floor in the deep sea. Robots are also being developed for various fields such as industry, games, welfare for the disabled, and guide services. In addition, many recent studies for the development of biped humanoids are underway. Studies for robots closer to humans in appearance, face expression and gait, and for technology development are also up to date. Honda ASIMO is the most representative example.

For remote biped robot walking, there were some attempts. Remote controllers (RC) for flight vehicles were used as ones for biped robots, but it turned out that they are low in DOF with limited motion control. Keio University has presented that biped robots can be controlled by recognizing touch inputs of gestures similar to that used in touch-screen smart phones [1]. A. Senior and S. Tosunnoglu have presented how to control biped robots by transmitting commands from the computer with serial communication connection to biped robots [2]. J. H. Ahnn has tried to control robots by transmitting the data created in a desktop computer GUI to them in radio communication [3]. Additionally, remote control cases using Bluetooth are found.

Moreover, imitation control has become new research issues. It is a kind of control method for robots to copy the movements after obtaining operator's body movements. To measure body movements, gyroscope and acceleration sensors are attached to specific areas of the body. T. Liu, et al, especially have presented that gait was estimated to be accurate after applying a fuzzy inference engine to measurement data of angular speed and acceleration [4, 5]. Ude has also tried to move robot by attached magnetic marking systems to exoskeletons or joints for the measurement of joint angles to capture and use motions [6]. There was also an attempt to control, using a device with joint structure similar to actual robot's, which was a study where the operator moves the device and the robot copies the movement using a sensor like potentiometer attached to the joints of a "teach pendant" named Waldo [7].

However, actual robot walking was not realized. As for remote biped imitation control, R. Chalodhorn, et al, have said that direct use of motion capture data is more likely to be flexible and intuitive than programming control, though it is kinetically unstable [8].

We have been faced with the challenging task to get kinematic information from operator's body motions and reproduce them in the form of stable robot movements.

Imitation control architecture

Imitation control architecture is proposed as shown in Fig. 1. The robot control system consists of a biped robot, named CUSST-1 EX, a host computer as the controller, and one encoder-mounted operator. The robot is controlled so as to act the same motions as carried out by the operator. As for the first step of walking, the operator plans and executes motions sequentially after perceiving robot conditions and environment. Information about terrain or environment is perceived with the operator's eye and brain. Decision on how or where to move is made also by the operator. After then, motion and trajectory data are generated as the operator moves. The operator's gait and walking patterns are transmitted to the robot controller using communication between the operator and the robot. In the robot controller, these data for walking are transmitted to robot actuators after the motion balance algorithm is applied. When the robot starts to move, the robot joints angular data are transmitted to the controller, which are, in turn, communicated back to the operator.

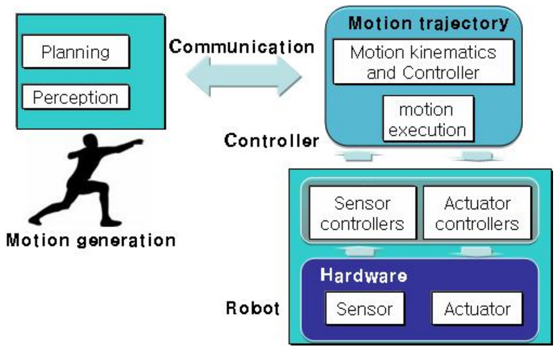

Fig. 1. Imitation control system for a biped robot

The difference of our biped robot from existing studies is in the real-time imitation control system. We use the ROBOTIS's Dynamixel AX-12A servomotors for the actuators of the robot and for the warable sensors of the operator at the same time. It simplifies the complexity of our control system for the reason of identical signal and command transmission between sensor/actuator and controller. Actuators just bring into correspondence with the wearable sensors.

The biped robot, shown in Fig. 2, is made by servomotors as the motion joints and rigid rods as the support bones. It has total of 17 servomotor joints in its whole body and the 17 DOFs (Degree of Freedom) including vertical vibration (pitch), rotation (yaw) and horizontal vibration (roll) DOFs [9].

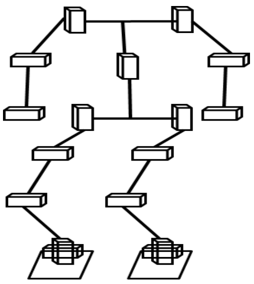

Fig.2. The structure of the robot

A teleoperated imitation control system serves the position angles of the operator's joints θ_{o1} ,…, θ_{om}, which represent the operator's arm, leg, and body postures, respectively, to correspond to their robot counterparts θ_{r1} ,…, θ_{rm}, as in the equation (1).

$$\theta_{o1} = \theta_{r1}, \theta_{o2} = \theta_{r2}, \dots, \theta_{om} = \theta_{rm} \qquad (1)$$

Theoretically speaking, imitation can be made easily from copying operator's joint angular values to the robot's corresponding joints. But, accomplishing a stable balance control in robot walking is not easy. To the top of that, joint angles between the operator and the robot cannot be made equal simultaneously because of time delay between them, and different characteristics of the sensor system. Some practical problems of this kind of late-model biped robot need us to think seriously about it.

Control style choosing

As described in Fig.1, the control system consists of operator's perception and reaction, motion generation, controller and robot block. In the first, operator's perception and reaction is to perceive about terrain and environment information, and to decide where or how to act. Motion generation is to generate next motions, to obtain the operator's motion data, and to transmit it to the controller. The controller as a main system understands operator's motions, communicates with between the operator and the robot, and does a key play to keep the balance up.

Control functions for robot's 17 joints are categorized into two groups of balance and posture. The robot's ankle joints are assigned to control the balance because it is the pivot point of an inverted pendulum. And the other joints ars assigned for determining the robot's direction and posture. So, we have decided to use 13 joints of the robot for the imitation control by the operator and others for the balance control by the controller, details please refer to Table 1.

Table 1. Actuator design in robot

Actuators	Joints	Control function
1,2	Ankel (horizontal)	Keep balance
3,4	Ankel (vertial)	Keep balance
5,6	Knee	Imitation control
7,8	Hip (vertial)	Imitation control
9,10	Hip (horizontal)	Imitation control
11	Waist	Imitation control
12,13	Shoulder (horizontal)	Imitation control
14,15	Shoulder (vertical)	Imitation control
16,17	Elbow	Imitation control

Control system theory can be broadly broken up into two major categories: open loop control (OLC) and closed loop control (CLC). Open loop control is by far simpler than closed loop control. In open loop control, there is some sort of input signal which passes through amplifiers to produce the proper output, and is then passed out of the system. In closed loop control, the system is adjusted by itself, data does not flow in one way, and it may pass back from a specific amplifier to the start of the control system, shown in Fig. 3, telling it to adjust itself accordingly.

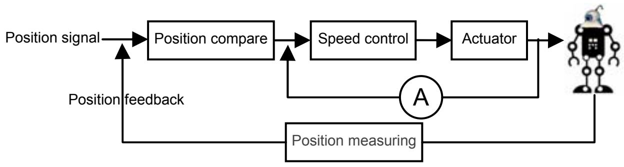

Fig.3. CLC control system

In our control system, a set of output signals such as angular position, angular velocity, load, temperature and voltage can be retrieved from the AX-12A actuators. For the reason why our servos have the feedback of angular position and speed information, we tend to the CLC method at each actuator.

Experiments on the robot's joint motion and walking performance following the operator's joint motion (e.g. angle or speed) are performed on a flat floor in a usual office environment.

Fig.4 is the expriment result of CLC angular position control of AX-12A actuator. It is observed that the robot(dotted line) follows the operator(solid line) well and there is a temporal delay between the operator and the actuator. The actuator tries to follow the desired time varying sinusoidal reference position by changing its load charge through time. Experiment shows how a joint angular position of the robot well follows as the operator moves his joint position randomly.

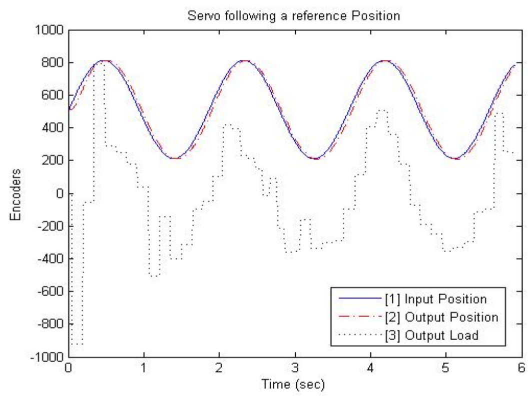

Fig.4. Servo imitating a reference Position in CLC system

Walking algorithm design

Existing autonomous robots walk as kinematically pre-designed. To generate a specific robot motion, a series of movements with pre-calulated postures are executed following the motion trajectory. However, for the imitation control, the joints's angles generated by the operator's motions are not predictive. Unseen trajectory inputs by the operator are not kinematically guaranted to make the stable robot's posture. Moreover, there is temporal delay between the operator and the robot. This also makes the robot's posture balance hard to control remotely in real time. In order to resolve these problems, it is required to develop a walking algorithm applied to the controller.

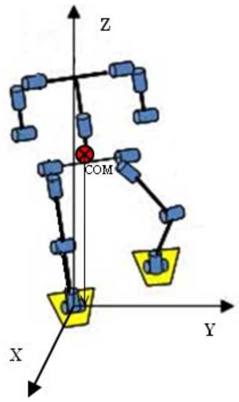

Fig. 5. Static walking standed on one foot

Consider the moment when the biped robot lifts its one foot to start walking from standing on two feet. it begins to fall down due to unstable posture. For robot imitation walking, a static walking process is designed. The two feet of the biped robot in static walking can be regarded as single support phase and swing phase. In Fig. 5, the right foot is the support phase and the left one is swing phase. Imitation robot walking, which is randomly generated by the operator, also forms the center of mass (COM) unforseen.

The walking algorithm for the robot in this paper is to control the robot's COM lacated in the stable region during static walking as in the equation (2). The yellow part also means the sole area of the support phase in Fig. 5, even though the joint angles entered into the robot is unforeseen,

Equation (2) describes the walking algorithm us the calculation method of COM, m_i is the weight of each joint, $\vec{r}$ is the vetor of the corresponding joint in the zero coordinate system which builds on the swing phase, and M is the total weight of all joints. Here we ignore the rigid weight for it's light material of aluminium alloy.

(2) $$COM = \sum_{i=1}^{N} \frac{m_i \vec{r}_i}{M} \leq \text{ Stable Region}$$

The stable region for left-right side, as shown in Fig.6, is experimentally measured as follows. The robot foot's ankle joint for left-right is rotated against the direction of another leg so as not to fall down when one leg is lifted up. The rotation angle varies dependant on the robot's postures such as how much the robot's leg leans or where the body, arms or legs are postured. The lmin θx and lmax θx is measured 10^0 and 15^0 respectively, from experiments. In the same way, rmin θx and rmax θx are 10^0 and 15^0, respectively.

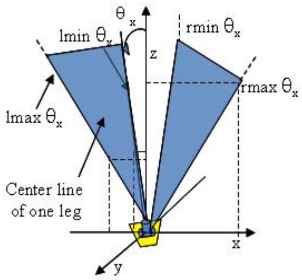

Fig. 6. The stable region for both left and right side

In the same way, the stable region for front-back side, as shown in Fig.7, is measured. The foot's ankle for front-back is moved toward the other direction so as not to fall down when the body is moved front or back. The bmax θx and fmax θx is measured 10^0 and 15^0 respectively.

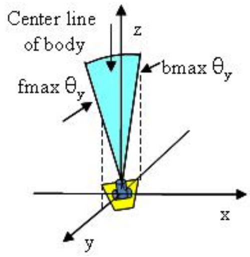

Fig. 7. The stable region for front-back side

Falling time considerations

In the imitation controlling, we have to send control commands or new angular position values to the robot as soon as possible. To get intuition how fast the robot should be controlled, its falling time is discussed.

An inverted pendulum is frequently used as a starting point for researches of how biped robot is maintained during walking. Let us consider the robot as an inverted plane pendulum in the homogeneous gravitational field with acceleration g. As shown in the Fig. 8, the length of the pendulum is L, its mass is m, and its angular position is θ and its moment of inertia is given by the equation (3).

(3) $$J = mL^2$$

The dynamical equation of motion of the pendulum is reduced to the angular momentum equation (4).

(4) $$J\frac{d\omega}{dt} = mgL\sin\theta$$

where ω is the angular velocity defined by the equation (5)

(5) $$\omega \equiv \frac{d\theta}{dt}$$

Solving the differential equation for the time, the formula for the calculation of the falling time of the pendulum is provided by the equation (6) [10].

(6) $$T_{fall}(\theta_0, \omega_0) = \sqrt{\frac{L}{2g}} \int_{\theta_0}^{\pi/2} \frac{d\theta}{\sqrt{\frac{\omega_0^2}{2g} + \cos\theta_0 - \cos\theta}}$$

where θ_0 is the pendulum initial position and initial angular velocity $\omega_0 = \omega(0)$. The result is expressed in terms of elliptic integrals of first kind.

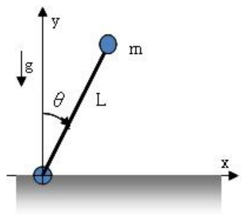

Fig. 8. Pendulum variables

For example, let L= 0.25m, g = 9.8m/s^2 and ω_0 = 0. Then one have $\sqrt{\frac{L}{2g}}$ ≈ 0.1129 so the falling time T_{fall} for initial inclination of $\theta_0 = 1^0$ is 0.827 s. Table 2 lists falling times for different initial inclinations calculated by MATLAB program. The falling times are calculated by less than 1 second.

Table 2. Calculated falling time for the inverted pendulum

Initial inclination θ_0	Falling time T_{fall} [sec]
0^0	∞
1^0	0.827
2^0	0.7219
4^0	0.6177
8^0	0.5166
15^0	0.4306
30^0	0.3483

From the above calculations, the robot can fall down very fast, which depends on the initial inclination of the pendulum.

However, the real robot does not fall down as fast as the ideal inverted pendulum. It is proved the falling time to be delayed in our experiment because of wide foot area. Based on the delayed falling time, the robot walking algorithm is applied in this paper.

Experiments for static walking

Static walking is performed with a few scenarios to know how well the robot imitates the operator. The path to the destination of the robot is determined by the operator depending on the situation. Experiments on the robot's joint motion and walking performance following the operator's joint motion are performed on a flat floor in a usual office environment. In Fig. 9, the operator puts up his left foot and goes forward, and the robot's left foot moves in the same time. In the imitation walking, the robot can modify its posture for keeping its COM in the right foot and preventing fall down to the ground by itself.

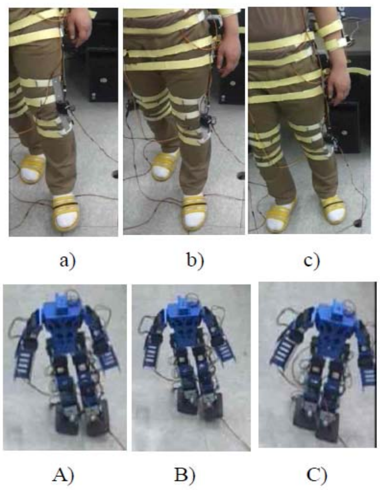

Fig. 9. Static walking of CUSST-1 EX

Conclusion

A new kind of imitation control architecture of biped robot has designed in the paper. This kind of architecture can easily realize a true sense of the humanoid movements' imitation than traditional biped robot architecture. But we must face the challenge of balance control of our robot for the reason why it can't forcast the posture of next time. Some characteristic studies on the question we have faced have been analyzed and verified by experiments. To improve robot walking speed, researches for dynamic walking are underway.

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