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A Stable Foot Teleoperation Method for Humanoid Robots

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Abstract— **The establishment of an intuitive and effective whole body operation method is essential for the utilization of humanoid robots in real world tasks. Here we introduce a method for humanoid robot foot teleoperation, as a part of our whole body teleoperation system using only a simple joystick device. This paper explains a framework for realtime foot operation which incorporates the operator's foot command and robot's autonomy in maintaining balance. We describe the algorithm of an autonomous function which shifts the position of the robot's center of mass interactively based on the operator's command and the current feet condition of the robot. We report on successful experimental results teleoperating a real humanoid robot HRP-2 using the proposed method.**

I. Introduction

Humanoid robots, with their human-like physical form, are potential tools capable of functioning in the real urban environment designed for humans. The quest for a fully autonomous humanoid robot has been the ultimate scientific goal of the Artificial Intelligence community. However due to the limitation of the current recognition and decision making technology, the need for operation systems augmented with human supervision is still essential to utilize humanoid robots in the unstructured real world. Whether the control comes from an autonomous controller or from a human operator, as the robots have to perform various whole body motions which are often unpredictable before hand, the establishment of an effective whole body operation method is of great importance.

There have been a few reports on the development of operation systems for humanoid robots so far [1][2][3][4][5]. However, apart from walking pattern generation, these systems can either only generate arms or head motions on static body postures, or generate preprogrammed behaviors or motions.

One of the most significant advantage of humanoid robots is that they possess feet which can be utilized to perform mobile movement as well as object manipulation. There are times when the feet need to be placed on specific spots, and there are also times when the feet need to be used for pushing and pressing objects(Fig.1). However, the control systems for the feet of most conventional humanoid robots are concentrated in the field of walking pattern generation. The issue of realtime foot operation is rarely discussed.

In the HRP project of Japan, the group succeeded in teleoperating both the feet of a humanoid robot on a seated position using a master foot device [6]. Kagami et. al conducted some foot operation experiments of a small-size humanoid robot using a puppet input device to prove the effectiveness of their autonomous balancing controller[7]. Osuka et. al constructed a master-slave control system and conducted walking experiments on a sagital biped robot[8]. So far, none of the previous works discussed the issue of controlling the position and force of the control foot on a stable standing posture. However this issue is of great importance for utilizing humanoid robots in practical real world tasks.

During foot teleoperation, it is difficult for the operator to judge when it is appropriate to lift the operation foot. To allow the operator to give intuitive commands for foot operation,

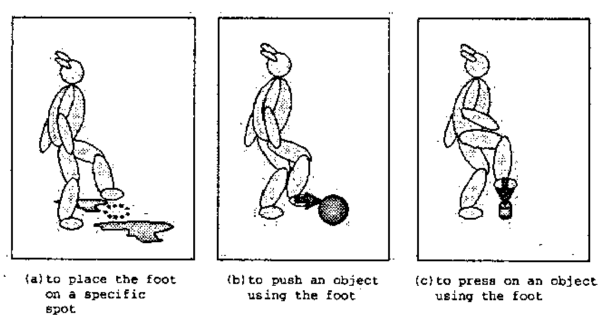

Fig. 1. Examples of Foot Task

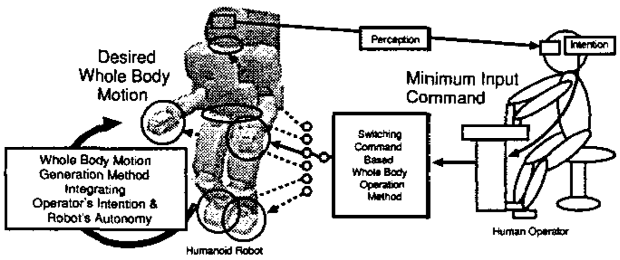

Fig. 2. Integration of operator's intention and robot's autonomy

this paper first explains the framework for foot operation incorporating the operator's foot command and the robot's autonomy. Then we describe the algorithm of an autonomous function which shifts the position of the robot's center of mass interactively based on the operator's foot command and the current feet condition of the robot. Experimental results teleoperating a real humanoid robot HRP-2 are also discussed.

II. The Concept of Integrating Operator's Intention and Robot's Autonomy

Despite having possess a large number of joints in our physical body, we carry out a specific task with our locus of attention focusing only on some specific points of our body. At the highest level of motor control, the brain concentrates its guidance on the most important point of the body for the task[9]. For example, during a task to reach out to a bottle on a table in front, we concentrate on our hand. When we try to lean down to a chair, we shift our attention to the hip. When we try to kick a ball, our locus of attention shifts on to the leg.

Inspired by these characteristics of human motor command, we have designed a whole body teleoperation method integrating the operator's command and the robot's autonomy(Fig.2). Depending on the desired task, the operator selects only the specific points of the robot's body and manipulate the points by using simple devices such as joysticks [13]. In order to maintain the balance of the robot automatically, we have introduced a method using the trajectory of the target manipulation point and the robot balance as the criteria for whole body motion generation and have confirm its effectiveness by teleoperating a real humanoid robot HRP-1S[14].

This method prevents the operator from having to execute command on all joints of the robot. This allows the operator to concentrate on specific body parts without having to take care of the kinematical and dynamical constraints of the robot such as reach limits, balance constraint and etc. We believe this idea of integrating the operator's command and the robot's autonomy in generating whole body motion is of great importance to fill the gap of the existing geometrical and dynamical differences between human operators and humanoid robots.

III. Whole Body Motion Generation Method Satisfying Operator's Desired End-effector's Target Trajectory and Robot's Balance Constraint

A humanoid robot can be modelled as a tree structure mechanism with four open links attached to a 6 DOF body. We define Σ_B as the frame fixed on the body, as well as $\Sigma_i (i = 1,2,3,4)$ as the frame fixed on the respective end-effectors(Fig.3).

We divide the joints of the robot into four sets of joints corresponding to the respective limbs, which are the legs and the arms. The velocity of each end-effector can be selected to be controlled by the operator using our switching command based teleoperation method[13].

With this categorization, we define the velocities for all joints of the robot as

$$\dot{\theta} = [\dot{\theta}_1^T \quad \dot{\theta}_2^T \quad \dot{\theta}_3^T \quad \dot{\theta}_4^T]^T, \tag{1}$$

where $\dot{\theta}$ denotes a column vector consisting of the velocities of all joints. The suffix numbers 1 to 4 denote the corresponding number of the end-effectors, which are the feet and the hands.

The target joint velocities of each limb, $\dot{\theta}_i^{ref}$, can be calculated using

$$\dot{\theta}_i^{ref} = J_i^{-1}\left\{\begin{bmatrix} v_i^{ref} \\ \omega_i^{ref} \end{bmatrix} - \begin{pmatrix} E_3 & -\hat{r}_{B\to i} \\ 0 & E_3 \end{pmatrix}\begin{bmatrix} v_B^{trg} \\ \omega_B^{trg} \end{bmatrix}\right\} \tag{2}$$

where v_i^{ref} and ω_i^{ref} denote the target linear velocity and target angular velocity of the respective end-effector, J_i^{-1} denotes the generalized inverse of the Jacobian matrix calculated from the respective limb configuration, E_3 denotes a 3×3 indentity matrix, $r_{B\to i}$ denotes the position vector from the body frame to the i-th end-effector frame and $\hat{}$ denotes an operator which translates a vector of 3×1 into a skew symmetric matrix 3×3 that is equivalent to an outer product. All vectors and related matrices are described using the Cartesian frame fixed on the ground, Σ_W(Fig.3).

The target linear velocity v_i^{ref} and target angular velocity ω_i^{ref} of each end-effector are determined by the input from the operator. Velocities are set to zero if the end-effector is not selected to be controlled by the operator.

Stable motions of a humanoid robot can be generated by manipulating the total momentum, which consists of linear and angular momentum, of the robot [10]. We can calculate the velocities of the body frame, v_B^{trg} and ω_B^{trg}, that realize the reference momentum of the robot and the target velocities of the end-effectors using:

$$\begin{bmatrix} v_B^{trg} \\ \omega_B^{trg} \end{bmatrix} = A^{\dagger}S\left\{\begin{bmatrix} P^{ref} \\ L^{ref} \end{bmatrix} - \sum_{i=1}^{4}\begin{pmatrix} M_i \\ H_i \end{pmatrix} J_i^{-1}\begin{bmatrix} v_i^{ref} \\ \omega_i^{ref} \end{bmatrix}\right\} + (E_6 - A^{\dagger}A)\begin{bmatrix} v_B^{ref} \\ \omega_B^{ref} \end{bmatrix} \tag{3}$$

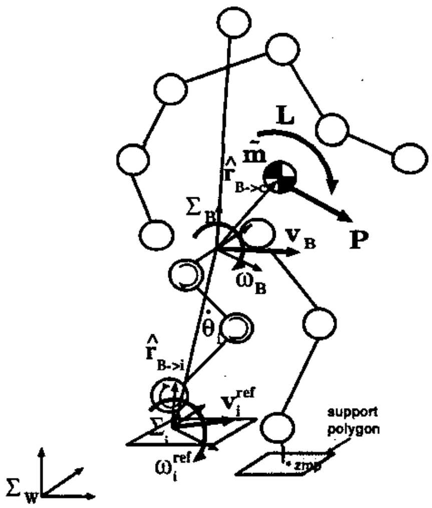

Fig. 3. Humanoid robot modelled as a tree structure mechanism with four open links

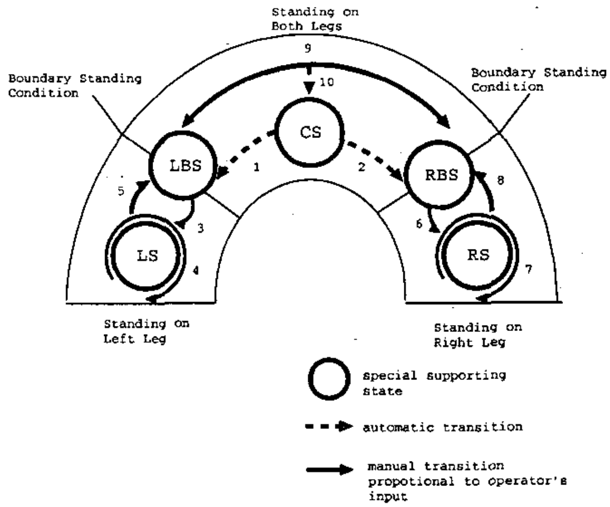

Fig. 4. Classification of CoM and Feet-Ground Contact States

here

$$A \equiv S\left\{\begin{pmatrix} \tilde{m}E_3 & -\tilde{m}\widehat{r}_{B\to c} \\ 0 & \tilde{I} \end{pmatrix} - \sum_{i=1}^{4}\begin{pmatrix} M_i \\ H_i \end{pmatrix} J_i^{-1}\begin{pmatrix} E_3 & -\widehat{r}_{B\to i} \\ 0 & E_3 \end{pmatrix}\right\}$$

$$S \equiv \begin{bmatrix} e_{S_1} & \dots & e_{S_n} \end{bmatrix}^T$$

where P^{ref} and L^{ref} denote the reference linear momentum and reference angular momentum of the robot. $\tilde{m}$ is the total mass of the robot, $\tilde{I}$ is the inertia tensor matrix around the center of mass(CoM), and $r_{B\to c}$ is the vector from the origin of Σ_B to the CoM. M_i, H_i are the inertia matrices of which linear and angular velocities of the respective limb affect the total momentum of the robot. S denotes a $n \times 6$ matrix for the selection of the elements of the total linear and angular momentum for control, which consists of e_i denoting a 6×1 vector with parameter 1 for the activation of the selected i-th momentum and parameter 0 for the other elements of the vector. $A^\dagger$ is the pseudo-inverse of A and E_6 is a 6×6 indentity matrix. v_B^{ref} and ω_B^{ref} denote the adjustments of linear velocity and angular velocity of the body frame that can be made utilizing projection of the null space, depending on the selection of S.

A. Balance Autonomy

During teleoperation it is almost impossible to predict the future command of the operator. Therefore, an effective way to guarantee the generation of balanced motion is to always keep the CoM within the support polygon.

As the time derivative of the position of CoM and the total linear momentum P can be described using

$$P = \tilde{m}\dot{r}_{W\to c}. \tag{4}$$

The position of CoM can be controlled by manipulating the linear momentum P using:

$$P^{ref} = \tilde{m}k(r^{ref}_{W\to c} - r_{W\to c}), \tag{5}$$

where $r^{ref}_{W\to c}$ denotes the reference position for CoM and k denotes the gain of the control scheme.

Using the relation described in (5), the position of CoM is controlled within the support polygon autonomously to allow the operator to only concentrate on manipulating the target points of the robot's body without having to take care of the robot's balance constraint.

In motion generation, it is not possible to make perfect models of the robot and the working environment as well as to predict external forces. In order to fill the gap, we use a reflex controller(stabilizer) to maintain the stability of the motion generated using three control subsystems which controls the body inclination, Zero Moment Point(ZMP)[15], and foot adjustment of the robot respectively[11]. The stabilizer functions in the same way during walking motion control.

B. Foot Operation Autonomy

During foot teleoperation, it is difficult for the operator to judge when it is appropriate to lift the operation foot. To allow the operator to give intuitive command for safe foot operations, we designed an autonomous function which shifts the position of the robot's center of mass interactively based on the operator's foot command and the current feet condition of the robot.

In [7], Kagami et. al introduced 5 discrete states that identify the nature of the contacts between the robot and the ground. Here, we use a similar classification for the conditions of CoM and feet-ground contact(Fig.4).

1) Classifications of CoM and Feet-Ground Contact States: We define the states for the conditions of CoM and feet-ground contact as follows:

- Center Support(CS):
  both feet make contact with the ground and CoM positioned at the center of both feet.
- Left Boundary Support(LBS):
  both feet make contact with the ground and CoM positioned at the center of left foot.
- Left Support(LS):
  only left foot makes contact with the ground and CoM positioned at the center of left foot.
- Right Boundary Support(RBS):
  both feet make contact with the ground and CoM positioned at the center of right foot.
- Right Support(RS):
  only right foot makes contact with the ground and CoM positioned at the center of right foot.

2) Transitions of States According to Operator Command and Foot Contact Condition: The transitions for the states described above, as shown in Fig.4, are designed as follows:

- Transition 1:
  When command for left foot is being input, CS transits to LBS automatically.
- Transition 2:
  When command for right foot is being input, CS transits to RBS automatically.
- Transition 3:
  When the Z-axis command for right foot is positive(going up), LBS transits to LS.
- Transition 4:
  When command for right foot is being input, execute right foot control. The state remains as LS .
- Transition 5:
  When the Z-axis command for right foot is negative(going down) and force sensor's data for right foot exits threshold, LS transits to LBS.
- Transition 6:
  When the Z-axis command for left foot is positive(going up), RBS transits to RS.
- Transition 7:
  When command for left foot is being input, execute left foot control. The state remains as RS
- Transition 8:
  When the Z-axis command for left foot is negative(going down) and force sensor's data for left foot exits threshold, RS transits to RBS.
- Transition 9:
  When the Z-axis command for right/left foot is negative(going down), shift CoM towards right/left foot propotional to the foot command. When the Z-axis command for right/left foot is positive(going up), shift CoM towards left/right foot propotional to the foot command.
- Transition 10:
  When command for return to CS is being input, the state transits to CS automatically.

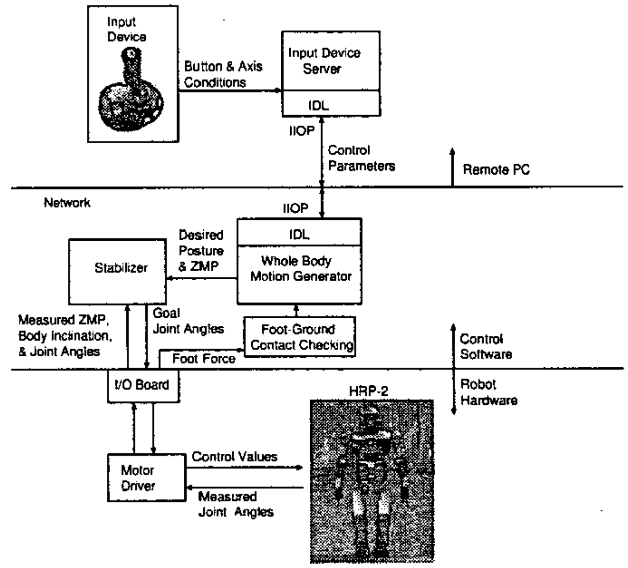

Fig. 5. Whole Body Teleoperation System of HRP-2 using Joysticks

IV. Implementation on Humanoid Robot HRP-2

We implemented the proposed whole body teleoperation method on a real humanoid robot, HRP-2[12]. HRP-2 is a humanoid robot of 154cm height and weighs 58kg, developed in the Humanoid Robotics Project(HRP) of METI. The teleoperation system is equipped with a robot state display which presents the sensory information of the remote robot and two 3-DOF joysticks as the input device for the manipulation of the 30-DOF robot.

Buttons of the two joysticks are allocated for the selection of six target points: head, right/left hand, torso and right/left foot. The operator gives translational and rotational motion commands to the target points by manipulating the lever of the joysticks while pressing the respective buttons. Operation of two out of the six target points simultaneously using two joysticks is possible[13].

The software system is being implemented as a distributed server system using CORBA. The overview of the whole system is shown in Fig.5. The distributed server system consists of an input device server, a whole body motion generator, a stabilizer, and the I/O board of the robot.

The input device server is contructed and implemented on a remote Linux PC. The whole body motion generator and the stabilizer are implemented on a realtime operating system, ART-Linux, on board the slave robot. Motor commands to the I/O board are sent every 5msec, with all the processes and communications between all servers being done within this control cycle[13].

Several experiments have been carried out to confirm the effectiveness of the system.

Fig. 6. Snapshots of Foot Position Control with Balance Control Autonomy

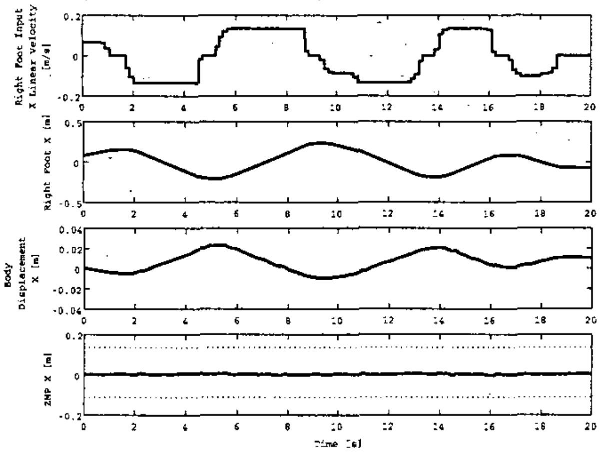

Fig. 7. Experimental Data of Foot Position Control with Balance Control Autonomy

A. Experiment 1: Foot Position Control with Balance Autonomy

This experiment is carried out with the purpose of confirming the effectiveness of the balance control autonomy. The operator manipulates the robot's right foot position about the x-axis of the Cartesian frame fixed on the ground. During the right foot position control, which is the Left Support(LS) state as defined earlier, the reference CoM position, $r^{ref}_{W\to c}$, is set at the center of left foot. For the Balance Autonomy which is described using (5), the gain is set to $k = 10$.

The x-axis linear velocity for right foot $v^{ref}_{1_x}$ changes according to the operator input(filtered with cutoff rate 200 rad/s primary filter). The remaining components of right foot velocity, $v^{ref}_{1_{y,z}}$, ω^{ref}_1, the linear and angular velocities of all other end-effectors and the body frame,v^{ref}_i, ω^{ref}_i, v^{ref}_B, ω^{ref}_B, and the reference angular momentum L^{ref}_z are all set as zero. The selection matrix in (3) is set as $S = [e_1 e_2 e_3 e_6]^T$ to omit the control for the angular momentum about the x, y axises.

The snapshots and the data of the experiment are shown in Fig.6 and Fig.7. When the right foot position changes according to the operator's input, the Balance Autonomy yields torso's translational movement(backward and forward in the x-axis) to compensate the change of linear momentum caused by the operation. With this the linear momentum which causes instability is ceased and the robot is prevented from falling. The results show that ZMP are being maintained at the initial position.

Fig. 8. Snapshots of Stepping Motion

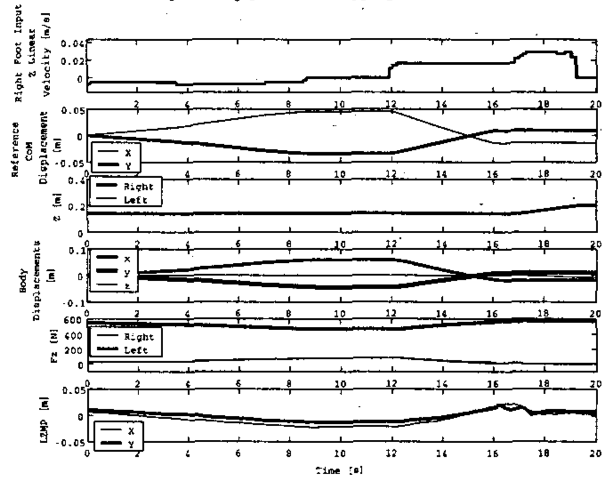

Fig. 9. Experimental Data of Stepping Motion

B. Experiment 2: Stepping Motion

Using the proposed foot teleoperation method with automatic CoM position adjustment functions, the operator teleoperate the robot's right foot to perform forward stepping motion.

During this experiment, the robot starts from the LBS supporting state. As the operator gives right foot z-axis command, Transition 9, which is also defined earlier, begins. The reference CoM position adjustment function shifts the reference position of CoM in between the left foot and the right foot. The right foot is positioned in the positive direction of x-axis and negative direction of y-axis relative to the left foot.

Snapshots and data of the experiment are shown in Fig.8 and Fig.9. During the period 0sec to 8.5sec, within which the Z-axis command for right foot is negative(going down), the reference CoM position is being shifted towards the right foot. From about 12sec to 19sec, as the operator input right foot lifting command (positive Z-axis command), the reference CoM position is being shifted back towards the left foot. and at the 16th second, the support state transited from LBS to LS and as the operator continues the lifting command, the right foot is being lifted off the ground. The right foot lifting motion generated is stable with ZMP maintains at the center of the left foot support polygon, which ranges from -0.11m to 0.135m in the x-direction and from -0.08m to 0.06m in the y-direction.

V. Conclusions

This paper presented a framework for stable foot teleoperation of a humanoid robot. Getting hints from human conscious and subconscious motion generations, this paper first introduced the concept of incorporating the operator's input command and the robot's autonomous functions in teleoperating humanoid robots. A whole body motion generation method which satisfies both the target trajectory of the end-effector and the reference momentum is discussed. Using the motion generation method, balance control autonomy, and the algorithm of an autonomous function which shifts the position of the robot's center of mass interactively based on the operator's command and the current feet condition of the robot is described. This paper ends with two reports on the experiment results teleoperating a real humanoid robot HRP-2 utilizing the proposed method.

Foot teleoperation with higher speed and more robustness are some of the interesting future topics.

Acknowledgements

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