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A Framework for Remote Execution of Whole Body Motions for Humanoid Robots

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This paper introduces a framework for the remote execution of whole body motions for humanoid robots. Humanoid robots are biped machines which usually possess multi degrees of freedom (DOF). The complexity of their structure and the difficulty in maintaining postural stability make the whole body operation of humanoid robots fundamentally different from traditional fixed-base manipulators or stable-base mobile manipulators. Getting hints from human conscious and subconscious motion generations, we propose a method of generating whole body motions which integrates operator's command input and the robot's autonomous functions. Instead of giving commands to all joints all the time, the operator selects only the necessary points of the humanoid robot's body for manipulation. This paper first explains the concept of the system and the framework for integrating operator's command and autonomous functions in whole body motion generation. Using the framework, we constructed autonomous functions for maintaining stability constraint while satisfying the desired trajectory of operation points and a workspace extension autonomy which changes utilization of body parts. Finally the paper reports on the implementation of the proposed method to teleoperate a 30 DOF humanoid robot HRP-2 using only two 3 DOF joysticks. Experiments teleoperating HRP-2 confirmed the effectiveness of the proposed method.

Keywords: humanoid robot; whole body motion; remote execution; teleoperation.

1. Introduction

Building machines with human-like form is not only an interesting scientific challenge but also a practical engineering endeavor. With physical form similar to that of a human, humanoid robots are potential tools to be used as proxies or assistants of human in performing tasks in real world environment, which is designed for human. Recent years have seen humanoid robotics evolving into an active research area with the realizations of several humanoid robot systems[1 2 3 4 5 6 7]. The quest for a fully autonomous humanoid robot has been the ultimate scientific goal[8 9 10 11 12]. Another promising area is to utilize humanoid robots augmented with human supervision to perform remote tasks in the unstructured real world [13 14].

In achieving various tasks in the real world, humanoid robots will have to generate whole body motions in real time interacting with both the environment as well as command input by human. Whether the control comes from an autonomous controller or from a human operator, the establishment of an effective whole body operation method is of great importance.

The execution and control of whole body motions for humanoid robots are fundamentally different from fixed-base manipulators or wheeled mobile robots due to their following characteristics:

- Humanoid robots usually consist of multi degrees of freedom. Due to the complexity, they require an effective method for whole body operation.
- The area of the supporting polygon of the robot is small considering the height of the Center of Mass(CoM) of the robot, resulting in severe balance constraint. Control algorithms which accomplish the desired tasks while satisfying the severe balance constraint are necessary.
- Due to the geometrical and dynamical differences between the operator and the humanoid robot, it is necessary to construct an operation framework which is able to give effective assist to the operator in giving commands.

In the aim of diminishing the above problems, this paper introduces a framework for the remote execution of whole body motions for humanoid robots based on the observations on human conscious and subconscious motion generations. Section 2 introduces some related works. Section 3 explains the concept of our system and Section 4 and 5 explain the framework for integrating operator's command and autonomous functions in whole body motion generation. With the framework explained, Section 6 reports on the implementation of the framework to teleoperate a real humanoid robot HRP-2 using two 3 DOF joysticks. Section 7 shows the experimental results teleoperating HRP-2 and Section 8 concludes this paper.

2. Related Works

There have been a few attempts so far for the construction of motion operation system for humanoid robots. However, apart from walking pattern generations, most of these previous works either can only generate pre-programmed motions or allow only operations on static body postures [15161718192021]. There were also attempts to convert whole body motions of the operator into the command input of all joints of the robot. These methods usually utilize exoskeleton input devices or human motion capture techniques for the generation of full-body humanoid robot motions. Some examples are the system constructed using Optotrak by A. Ude et al.[22] and the Optical Cockpit proposed by K. Kurihara et al.[23]. These systems often require a complex interface and they face drawbacks such as difficulty in generating stable motions in real-time, due to geometrical and dynamical differences between human operators and the humanoid robots. With the aim of creating whole body motions for entertainment, the Sony group has developed a motion editor system

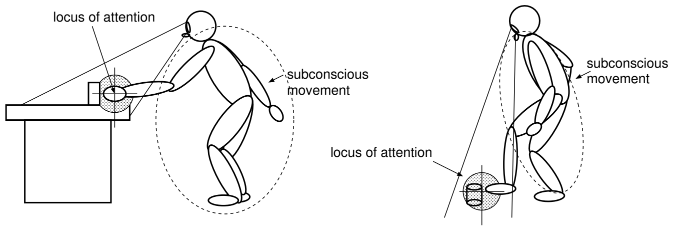

Fig. 1. Shifting of Locus of Attention

which allows users to create motions such as dancing and etc. However, the goal of this system does not seem to require on-line motion generations[24].

In the field of computer graphics, the search for intuitive and efficient methods for generating whole body motions of human figures is as essential as that of humanoid robots. From key-framing to motion capture system, the main goal of the animation techniques of the computer graphics community is generating believable motion, on-line requirement is often not a severe constraint. With the aim for interactive motion generation, by applying constraints on link positions, joint angle errors and joint motion ranges, Yamane et al. developed a computational method for generating whole body motions of human figures using only a simple pin-and-drag interface[25]. Baerlocher et al. demonstrated a kinematic control approach based on the tasks prioritization of obstacle avoidance, center of mass position control and control of end-effectors, for the kinematic control of highly articulated structure such as human figures[26]. For whole body dynamic behavior and control of human-like robots, Khatib et al. developed a prioritized multiple task controller that in real-time dynamically decouples each task[27]. By applying constraints and using prioritization, these approaches are promising examples of the idea of generating complex multi-DOF motions with only a small number of input.

3. The Concept of Integrating Operator's Command and Robot's Autonomy in Whole Body Motion Generation

Despite possessing 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[28]. 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 push a can on the floor, our locus of attention shifts on to the leg (Fig. 1).

During task executions, we consciously control limb position, acceleration and velocity, or its braking to adjust the force of impact and other factors. The controlled variables for a task which has been well learned are movement patterns, such as walking, swimming etc. For new, inexperienced motions, we consciously control the trajectory of the most important point in the movement, for example the hand in

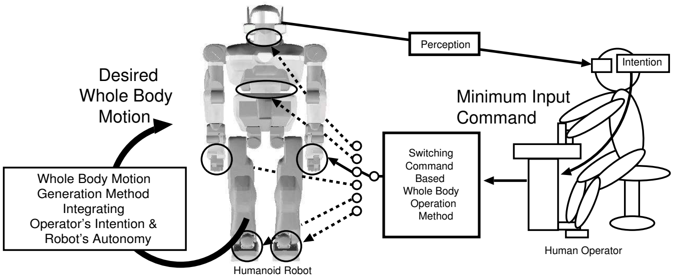

Fig. 2. A Switching Command Based Whole Body Operation

the case of arm movements.

Whole body motions are generated with a mixture of coordinated movements in subsidiary fashion of the joints and muscles that support and transport the point of the attention for the brain (the hand or leg in the above examples). These subconscious movements are believed to be generated in the middle level of the motor control hierarchy using inverse kinematics and dynamics schemes, and coordinated by automatic and reflective motions for postural control, safety of the body and other criterions.

Inspired by these hypotheses of human motor command, we constructed a switching command-based whole body operation method for humanoid robots[30]. Depending on the desired tasks, the operator switches and selects specific operation points between the body parts of the robot and input motion commands using a simple input device. Whole body motions are then generated with autonomous functions for maintaining stability, extending reach and etc. The switching command-based whole body operation scheme is shown in Fig. 2.

This method saves the operator from having to send commands to all joints of the robot. This allows the operator to concentrate on executing commands only to the 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. This framework helps to fill the gap of the existing geometrical and dynamical differences between human operators and the humanoid robots.

4. Whole Body Motion Generation Framework

Fig. 3 shows the model of a typical 30 DOF humanoid robot with a 2 DOF head, two 6 DOF arms with 1 DOF hand gripper, two 6 DOF legs, and a 2 DOF torso. The robot can be modeled as a tree structure mechanism with six links attached to a 6 DOF body. We define 6 DOF body frame Σ_B as the frame fixed on the waist with linear velocities ${}^w\boldsymbol{v}_B$ and angular velocities ${}^w\boldsymbol{\omega}_B$. The leading superscript ^{w} indicates that the velocities are described using the world frame, which is the Cartesian frame fixed on the ground Σ_W(Fig. 3). Similarly, we define Σ_C as the frame fixed on the chest with linear and angular velocities, ${}^w\boldsymbol{v}_C$ and ${}^w\boldsymbol{\omega}_C$, as well

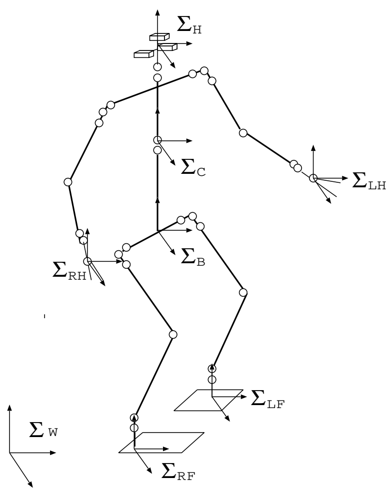

Fig. 3. A Humanoid Robot Model

as $\Sigma_{H,RH,LH,RF,LF}$ as the frame fixed on the head, right hand, left hand, right foot and left foot respectively with linear velocities ${}^{w}\boldsymbol{v}_{H,RH,LH,RF,LF}$ and angular velocities ${}^{w}\boldsymbol{\omega}_{H,RH,LH,RF,LF}$(Fig. 3).

We divide the joints of the robot into six sets of joints corresponding to the body and five other links, which are the head, two arms and two legs. With this categorization, we define the velocities for all joints of the robot as

$$\dot{\boldsymbol{\theta}} = [\dot{\boldsymbol{\theta}}_C^T \quad \dot{\boldsymbol{\theta}}_H^T \quad \dot{\boldsymbol{\theta}}_{RA}^T \quad \dot{\boldsymbol{\theta}}_{LA}^T \quad \dot{\boldsymbol{\theta}}_{RL}^T \quad \dot{\boldsymbol{\theta}}_{LL}^T]^T, \tag{1}$$

where $\dot{\boldsymbol{\theta}}$ denotes a column vector consisting the velocities of all joints. The suffixes C, H, RA, LA, RL and LL denote the chest, the head, right arm, left arm, right leg and left leg. The whole body motion of the robot is determined by the velocities of these six sets of joints.

4.1. *Whole Body Joint Motions*

With the base frame set on the waist frame Σ_B, the relation between the desired velocities of each frame, Σ_i(which is either Σ_H, Σ_C, Σ_{RH}, Σ_{LH}, Σ_{RF} or Σ_{LF}), and the velocities of the respective joints from the waist to each frame can be described using:

$${}^{w}\boldsymbol{\xi}_i^{ref} = J_{Bi}\dot{\boldsymbol{\theta}}_{Bi}^{ref} + \begin{pmatrix} E_3 & -{}^{w}\hat{\boldsymbol{r}}_{B\rightarrow i} \\ 0 & E_3 \end{pmatrix} {}^{w}\boldsymbol{\xi}_B^{ref} \tag{2}$$

where ${}^{w}\boldsymbol{\xi}_B^{ref}$ and ${}^{w}\boldsymbol{\xi}_i^{ref}$ denote the desired velocities of the waist frame and the respective frame of the links, which corresponds to the head, the chest, the hands and the feet. J_{Bi} denotes the Jacobian matrixes calculated from the waist to the respective frame, ${}^{w}\boldsymbol{r}_{B\rightarrow i}$ denotes the position vectors from the waist frame to the respective frame, E_3 denotes a 3×3 identity matrix, 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. $\dot{\boldsymbol{\theta}}_{Bi}$ denotes the column vectors consisting of the target velocities of the respective joints from the waist to each end-effector.

In the case of the chest link and leg links, where $i = C, RL, LL$. As the links are connected to the waist frame:

$$\dot{\boldsymbol{\theta}}_{Bi} = \left[\dot{\boldsymbol{\theta}}_i,\right] \tag{3}$$

In the case of the head and arm links, where $i = H, RA, LA$. As the links are connected to the waist frame via the chest link:

$$\dot{\boldsymbol{\theta}}_{Bi} = \begin{bmatrix} \dot{\boldsymbol{\theta}}_i \\ \dot{\boldsymbol{\theta}}_C \end{bmatrix} \tag{4}$$

4.2. *Reference Frame*

The reference frame for motion command execution during operation is an important factor in achieving smooth operations. Depending on the posture of the humanoid robot during motion execution, the optimal reference frame in which the operator can give a command in the most intuitive manner may differ. To provide the operator with more flexibility, we have designed so that all commands can be selected to be made with the reference frame fixed on the world frame, Σ_W, the body frame fixed at the robot's waist, Σ_B, or the operation point frame fixed at the operation point, Σ_i using:

$$\begin{aligned} {}^{w}\boldsymbol{\xi}_i^{ref} &\equiv {}^{w}_{r}T\,{}^{r}\boldsymbol{\xi}_i^{ref} \\ {}^{r}\boldsymbol{\xi}_i^{ref} &\equiv [{}^{r}\boldsymbol{v}_i^{ref\,T} \quad {}^{r}\boldsymbol{\omega}_i^{ref\,T}]^T \end{aligned}$$

where ${}^{r}\boldsymbol{v}_i^{ref}$ and ${}^{r}\boldsymbol{\omega}_i^{ref}$ denote the desired target linear velocity and angular velocity of the respective operation point, described in the coordinate frame to which they are referenced. ${}^{w}_{r}T$ denotes the transformation matrix which maps the vectors from the reference coordinate frame to the world frame.

4.3. *Whole Body Operation Method*

Depending on the desired task, the humanoid robot may be required to perform operations while standing up or during walking. We have designed a system which allows teleoperation in two operation modes, Standing Operation and Walking Operation, which is selected by the operator depending on the task[a].

[a]There exists control methods which enable the robot to autonomously steps or controls its body pose to increase arm manipulability and robot stability[29]. However, considering motions like extending the arm sideward, in which the center of mass shifts on to the foot in the arm extending

During Standing Operation, whole body operation of the humanoid robot is divided into six operation modes: head, right hand, left hand, chest, right foot and left foot manipulation mode. Each manipulation mode consists of the translational and orientation manipulation of the operation point. Depending on the desired task, the operator can choose to manipulate using any one of the six operation modes or to simultaneously manipulate using more than one operation mode. The desired target linear and angular velocities of the operation points, $\boldsymbol{v}_i^{ref}$ and $\boldsymbol{\omega}_i^{ref}$, are determined by the input from the operator. Velocities of other points which are not selected are determined by the autonomous functions explained in the next section.

For Walking Operation, the operator controls the walking direction, foot step distance and the distance between the two feet to generate walking patterns in real-time using a biped walking pattern generator based on the Three-Dimensional Linear Inverted Pendulum Mode(3D-LIPM) [35]. The reference velocities of both feet and the waist, $\boldsymbol{\xi}_{RF,LF}^{ref}$ and $\boldsymbol{\xi}_B^{ref}$, are generated by the walking pattern generator. The operator can simultaneously control the position and orientation of the head and both hands during walking.

5. Integrating Operator's Command and Robot's Autonomy in Whole Body Motion Generation

Degrees of freedom necessary to realize the desired position and orientation of the target operation points are usually far less than the entire DOF of a humanoid robot. The configurations for the remaining joints which are redundant in achieving the desired task can be determined using pre-defined sets of functions. These functions can be of different nature, like evaluation functions for stability, task performance, obstacle avoidance and etc. In order to maintain the balance of the robot automatically, we have introduced a method using the trajectory of the target operation point and the robot's postural stability constraint as the criteria for whole body motion generation [31].

Here we divide the joints of the robot into control joints and free joints. Control joints are the joints of the control links of which the end-effectors are controlled by the operator consciously. Free joints are the joints of the free links which are controlled by the robot's autonomy. With this categorization we rewrite the column vector $\dot{\boldsymbol{\theta}}$ in Eq.(1) as

$$\dot{\boldsymbol{\theta}} = [\dot{\boldsymbol{\theta}}_{cl_1}^T \quad .... \quad \dot{\boldsymbol{\theta}}_{cl_n}^T \quad \dot{\boldsymbol{\theta}}_{fl}^T]^T, \tag{5}$$

where n denotes the number of end-effectors that the operator controls, $\dot{\boldsymbol{\theta}}_{cl_i}$ denotes the vector for joint velocities of the respective control links and $\dot{\boldsymbol{\theta}}_{fl}$ denotes the

direction, it is difficult to lift the foot for stepping. For human, we can easily perform cross-step motion in which we lift the opposite foot to step. But for most humanoid robots, this kind of cross-stepping is impossible due to the collision of both legs. For this reason, as well as to avoid the difficulty in anticipating foot step timing, we have devided operation into standing operations and walking operations.

vector for the joint velocities of free links. Please note that when n is equivalent to the total number of the links, $\dot{\boldsymbol{\theta}}_{fl}$ will become a null vector.

Stable motions of a humanoid robot can be generated by manipulating the total momentum, which consists of linear and angular momentum, of the robot [32]. We can calculate the velocities of the waist frame $\boldsymbol{\xi}_B^{trg}$ and the joint velocities of the free joints $\dot{\boldsymbol{\theta}}_{fl}^{trg}$ that realize the reference momentum, P^{ref}, L^{ref} and the reference velocities for the control end-effectors $\boldsymbol{\xi}_i^{ref}$ as the least square solution by:

$$\begin{bmatrix} \boldsymbol{\xi}_B^{trg} \\ \dot{\boldsymbol{\theta}}_{fl}^{trg} \end{bmatrix} = A^{\dagger} S \left\{ \begin{bmatrix} P^{ref} \\ L^{ref} \end{bmatrix} - \sum_{i=1}^{n} \begin{pmatrix} M_i \\ H_i \end{pmatrix} \boldsymbol{\xi}_i^{ref} \right\} + (E - A^{\dagger} A) \begin{bmatrix} \boldsymbol{\xi}_B^{ref} \\ \dot{\boldsymbol{\theta}}_{fl}^{ref} \end{bmatrix} \tag{6}$$

here

$$A \equiv S \begin{pmatrix} M_B & M_{fl} \\ H_B & H_{fl} \end{pmatrix}$$

$$S \equiv \begin{bmatrix} \boldsymbol{e}_{S_1} & \dots & \boldsymbol{e}_{S_n} \end{bmatrix}^T$$

$$\begin{pmatrix} M_i \\ H_i \end{pmatrix} \equiv \begin{pmatrix} M_{cl_i} \\ H_{cl_i} \end{pmatrix} J_{cl_i}^{-1},$$

$$\begin{pmatrix} M_B \\ H_B \end{pmatrix} \equiv \begin{pmatrix} \tilde{m}E & -\tilde{m}\widehat{\boldsymbol{r}}_{B\to g} \\ 0 & \tilde{I} \end{pmatrix} - \sum_{i=1}^{n} \begin{pmatrix} M_i \\ H_i \end{pmatrix} \begin{pmatrix} E & \widehat{\boldsymbol{r}}_{B\to i} \\ 0 & E \end{pmatrix}.$$

M_{cl_i}, H_{cl_i} are the inertia matrices of which joint velocities of the respective control link affect the total momentum of the robot. M_i, H_i are the inertia matrices of which linear and angular velocities of the end-effector affect the total momentum of the robot. M_{fl}, H_{fl} are the inertia matrices of which joint velocities of the free links affect the total momentum of the robot. $J_{cl_i}^{-1}$ is the generalized inverse of the Jacobian matrix calculated from the respective link configuration. $\boldsymbol{r}_{B\to i}$ is the position vector from the waist frame to the i-th control end-effector frame. $\tilde{m}$ is the total mass of the robot, $\tilde{I}$ is the inertia tensor matrix around the center of mass (CoM), and $\boldsymbol{r}_{B\to g}$ is the vector from the origin of Σ_B to the CoM. 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 $\boldsymbol{e}_i$ 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 is an identity matrix. $\boldsymbol{\xi}_B^{ref}$ denotes the adjustments of the velocities of the waist frame that can be made utilizing projection of the null space, depending on the selection of S.

5.1. *Balance Autonomy*

The zero moment point (ZMP) is an important measure for the stability of a humanoid robot [33]. The relations between ZMP, the time derivative of the linear and angular momentum about the CoM of the robot, $\dot{P}$ and $\dot{L}$, as well as the position of the CoM of the robot can be described using[31]:

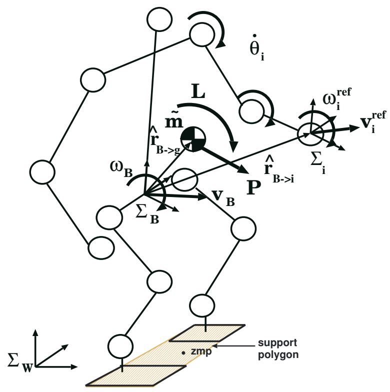

Fig. 4. The Relations between CoM, ZMP and Momentum

$$\begin{bmatrix} zmp_x \\ zmp_y \end{bmatrix} = \begin{bmatrix} \frac{\dot{L}_y + r_{W\to gz}\dot{P}_x + \tilde{m} r_{W\to gx} g_z}{\dot{P}_z + \tilde{m} g_z} \\ \frac{\dot{L}_x + r_{W\to gz}\dot{P}_y + \tilde{m} r_{W\to gy} g_z}{\dot{P}_z + \tilde{m} g_z} \end{bmatrix} \tag{7}$$

suffix x, y and z indicate x, y, z elements of the Σ_W frame. $\boldsymbol{r}_{W\to g}$ denotes the vector from the origin of Σ_W to the CoM of the robot, and g denotes the gravity acceleration vector (Fig. 4).

This equation shows that we can control the position of ZMP by controlling the total linear and angular momentum, P and L, as well as the position of CoM, $\boldsymbol{r}_{W\to g}$.

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

$$P = \tilde{m}\dot{\boldsymbol{r}}_{W\to g}. \tag{8}$$

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

$$P^{ref} = \tilde{m}k(\boldsymbol{r}_{W\to g}^{ref} - \boldsymbol{r}_{W\to g}), \tag{9}$$

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

Using the relation described in Eq.(7), by controlling the CoM using Eq.(9) so that the CoM remains within the area of the support polygon, and setting the reference value for angular momentum L^{ref} as zero or regulating the reference acceleration of the waist frame $\dot{\boldsymbol{v}}_B^{ref}$ and $\dot{\boldsymbol{\omega}}_B^{ref}$, the reference ZMP can be controlled to remain within the support polygon for dynamically stable motions. In our system, these values are controlled autonomously to allow the operator to only concentrate

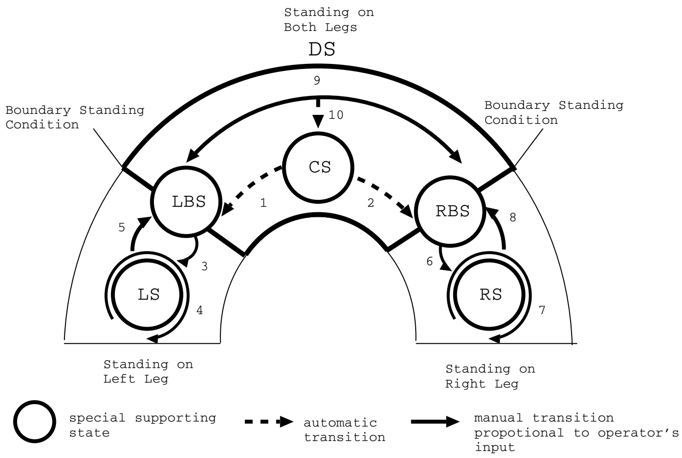

Fig. 5. Classification of CoM and Feet-Ground Contact States

on manipulating the target points of the robot's body without having to take care of the robot's balance constraint.

5.2. *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.

Here, we classified the conditions of the contact between the robot and the ground into six discrete states (Fig. 5):

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

The reference position for CoM, $\boldsymbol{r}_{W\to g}^{ref}$, and reference velocities of the operation

Table 1. Interactive CoM Transition Based on Operator's Command and Feet-Ground Contact State

state	foot sensor	foot command	$\boldsymbol{r}^{ref}_{W\to g}$	${}^{w}\boldsymbol{\xi}^{ref}_{RF,LF}$	next state
CS	-	left foot +	$spline(RF,t)$	0	RBS
	-	left foot -	$\to LF$	0	DS
	-	right foot +	$spline(LF,t)$	0	LBS
	-	right foot -	$\to RF$	0	DS
LBS	-	right foot +	LF	command	LS
	-	right foot -	$\to RF$	0	DS
	-	left foot -	LF	0	LBS
	-	left foot +	$\to RF$	0	DS
RBS	-	right foot +	$\to LF$	0	DS
	-	right foot -	RF	0	RBS
	-	left foot -	$\to LF$	0	DS
	-	left foot +	RF	command	RS
DS	-	right foot +	$\to LF$	0	DS
	-	right foot -	$\to RF$	0	DS
	-	left foot -	$\to LF$	0	DS
	-	left foot +	$\to RF$	0	DS
LS	-	right foot +/-	LF	command	LS
	right foot $\geq F_t$	right foot -	LF	0	LBS
	-	left foot -	LF	0	LS
	-	left foot +	LF	0	LS
RS	-	right foot +	RF	0	RS
	-	right foot -	RF	0	RS
	left foot $\geq F_t$	left foot -	RF	0	RBS
	-	left foot +/-	RF	command	RS

foot,${}^{w}\boldsymbol{\xi}^{ref}_{RF,LF}$, is set interactively according to operator's command and the feet-ground contact state as is shown in Table 1. In Table 1, for foot command, + denotes positive direction of Z-axis (upward), $-$ denotes negative direction of Z-axis (downward). For CoM target position, $spline(A,B)$ denote CoM target position set to A in B time using spline function, LF, RF denote the center of left and right foot frame, and $\to RF, \to LF$ denote the CoM target is set towards the center of the respective foot. F_t denotes the threshold for touching force.

The state transitions, as shown in Fig.5 and Table 1, are designed as follows:

- Transition 1:
  When command for left foot is being input, CS transits to RBS automatically.
- Transition 2:
  When command for right foot is being input, CS transits to LBS automat-

ically.

- 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, reference velocity ${}^{w}\boldsymbol{\xi}_{RF}^{ref}$ is set according to operator's command. 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, reference velocity ${}^{w}\boldsymbol{\xi}_{LF}^{ref}$ is set according to operator's command. 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. The next state being DS.
- Transition 10:
  When command for return to CS is being input, the state transits to CS automatically.

5.3. *Workspace Extension Autonomy by Changing Utilized Body Parts*

The work space of a humanoid robot differs depending on the degrees of freedom being utilized. The work space expands as the number of degrees of freedom increase (Fig. 6). However the complexity of the control strategy increases as the number of joints increase. We seem to utilize only the arm when a required motion is within the arm work space. We start to utilize the chest when the reach utilizing only the arm is not enough. When the reach is not sufficient utilizing the arm and the chest, we will start utilizing our waist.

We designed an algorithm of interactively changing utilized body parts in motion generation by monitoring the condition of the links and the torso of the robot. The conditions of the arms and the legs are monitored all time, and when the links are stretched, the mother link of the links, which will be the chest and the waist respectively, will be utilized for motion generation. The chest and the waist will be pulled back first if the stretching of the links is relaxed, by a returning potential function which is calculated as the stretch from the initial posture.

From Eq.(2), the relations between the desired velocities of the respective end-effector, the velocities of the joints from the waist to the end-effector, and the velocities of the waist frame can be written as:

$$ {}^{w}\boldsymbol{\xi}_i^{ref} = [J_{Ci} \quad J_{BC}] \begin{bmatrix} \dot{\boldsymbol{\theta}}_i \\ \dot{\boldsymbol{\theta}}_C \end{bmatrix} + \begin{pmatrix} E_3 & -{}^{w}\hat{\boldsymbol{r}}_{B\to i} \\ 0 & E_3 \end{pmatrix} {}^{w}\boldsymbol{\xi}_B^{ref} \tag{10} $$

where J_{Ci} denotes the Jacobian matrixes calculated from the chest to the end-effector, and J_{BC} denotes the Jacobian matrixes calculated from the waist to the chest.

In cases where the respective link is sufficient for achieving the desired task, for example when the target trajectories of the hands are within the arm work space, chest joints can be freed from being utilized.

Let's consider the example where the humanoid robot's right hand is desired to be reached out as shown in Fig. 6. By monitoring the stretch of the arm, we can determine if we should extend the body parts used for the reaching. We use the value of the elbow joint angle θ_e as the indicators for the degree of arm stretch. As was explained above, the chest joints can be freed if they are not required.

Here we show the algorithm to determine the use of chest joints for right hand reaching. Please note that we only show here the algorithm when the right hand is selected as the operation point. The same idea can be extended for cases where other operation points are selected.

5.3.1. *Utilizing only the right arm*

if $\theta_e \leq \theta_{e\_stretched}$

$$ \dot{\boldsymbol{\theta}}_{RA}^{ref} = J_{CRA}^{-1} \left\{ {}^{w}\boldsymbol{\xi}_{RH}^{ref} - \begin{pmatrix} E_3 & -{}^{w}\hat{\boldsymbol{r}}_{B\to RH} \\ 0 & E_3 \end{pmatrix} {}^{w}\boldsymbol{\xi}_B^{ref} \right\} $$

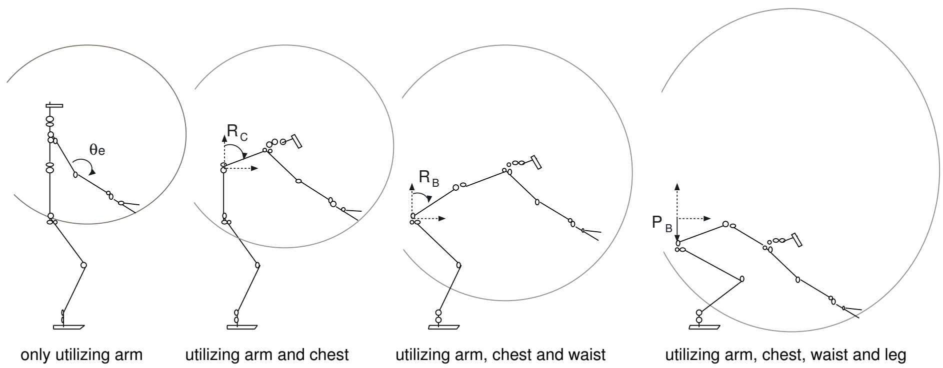

Fig. 6. The Workspace of a Humanoid robot

$$\dot{\boldsymbol{\theta}}_C^{ref} = 0 \tag{11}$$

where $\theta_{e\_stretched}$ denotes the threshold for arm stretch, J_{CRA}^{-1} denotes the generalized inverse of the Jacobian matrixes calculated from the chest to the right hand, ${}^{w}\boldsymbol{\xi}_{RH}^{ref}$ denotes the desired velocities of the right hand frame.

5.3.2. *Utilizing the right arm and the chest*

if $\theta_e > \theta_{e\_stretched}$

$$\begin{bmatrix} \dot{\boldsymbol{\theta}}_{RA}^{ref} \\ \dot{\boldsymbol{\theta}}_{C}^{ref} \end{bmatrix} = J_{BRA}^{-1} \left\{ {}^{w}\boldsymbol{\xi}_{RH}^{ref} - \begin{pmatrix} E_3 & -{}^{w}\hat{\boldsymbol{r}}_{B\to RH} \\ 0 & E_3 \end{pmatrix} {}^{w}\boldsymbol{\xi}_{B}^{ref} \right\} \tag{12}$$

here

$$J_{BRA} = [J_{CRA} \quad J_{BC}]$$

and J_{BRA}^{-1} denotes the generalized inverse of the Jacobian matrixes calculated from the waist to the right hand.

5.3.3. *Utilizing the arm, the chest and the waist and the legs*

When utilizing the arm and chest joints is not sufficient for achieving the task, the waist frame Σ_B can be adjusted to achieve the task (Fig. 6). In our framework, the adjustment of the waist frame $\boldsymbol{\xi}_B^{ref}$ can be done within the balance constraint utilizing the null space motion in Eq.(6).

6. Implementation on a Real Humanoid Robot HRP-2 using Simple Input Device

Based on the switching command based whole body operation concept, we have developed a teleoperation system for a real humanoid robot using only simple input device. The whole body teleoperation system utilizes only two 3-DOF joysticks as the input device for the manipulation of whole body motions of a 30-DOF humanoid robot, HRP-2, developed in the Humanoid Robotics Project (HRP) of METI[36].

The teleoperation system is being implemented as a distributed server system using CORBA. The overview of the whole system is shown in Fig. 7. The distributed server system consists of an input device server, a whole body motion generator and a stabilizer.

The input device server is constructed and implemented on a remote Linux PC. The whole body motion generator and the stabilizer are implemented on a real-time operating system, ART-Linux[34], on board of the robot. Motor commands to the robot's I/O board are sent every 5[msec], with all the processes and communications between all servers being done within this control cycle.

A set of joystick operation rules is designed for the switching of 10 control modes:

- Head Orientation Control Mode
- Chest Position/Orientation Control Mode
- Right/Left Wrist Position/Orientation Control Mode
- Right/Left Hand Grasping Control Mode
- Right/Left Foot Position/Orientation Control Mode
- Walking Control Mode

The input device server receives input from the joystick devices and interprets the conditions of the buttons and the lever of the joystick devices to register them as parameters for operation point manipulations and walking pattern generations.

7. Experiments

7.1. *Whole Body Reaching Experiments*

Reaching experiments were carried out with the operator only specifying the target trajectories of the right hand. Fig. 8 shows the snapshots of the experiment where the operator input velocity command for the right hand to perform horizontal reaching motion in the x-direction of the world frame. The reaching was achieved with first utilizing only the arm, and when the arm is stretched, the chest is being utilized.

Fig. 9 shows the snapshots of the experiment where the operator input velocity command for the right hand to perform horizontal reaching motion in the z-direction

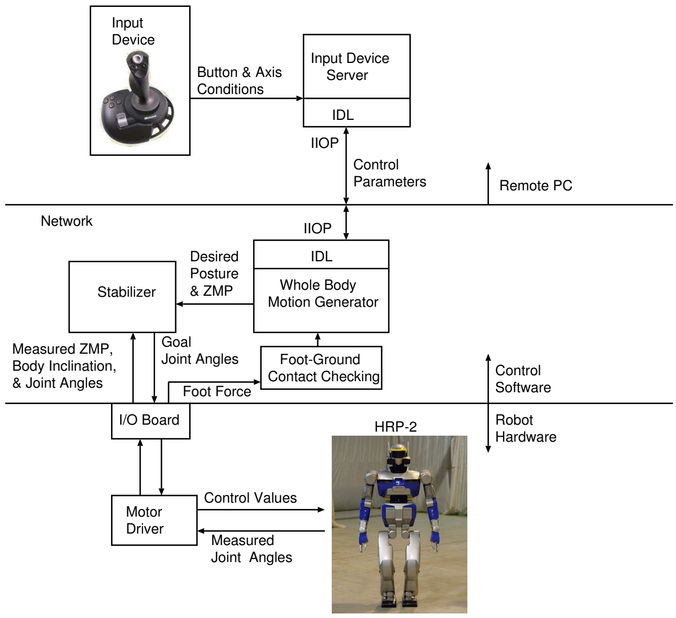

Fig. 7. Software System Overview

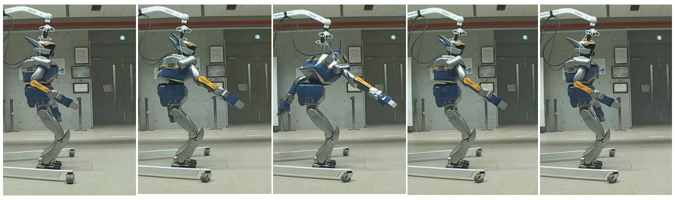

Fig. 8. Forward Reaching Motion

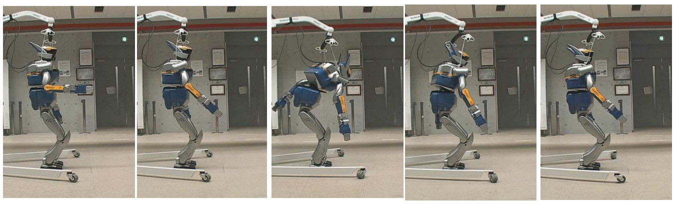

Fig. 9. Downward Reaching Motion

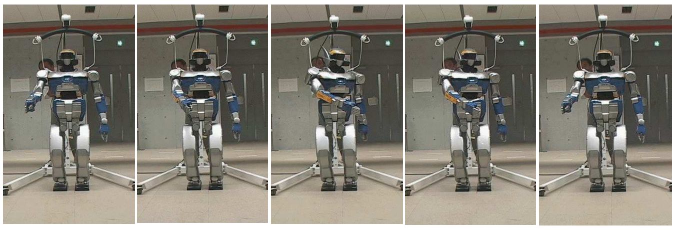

Fig. 10. Sideward Reaching Motion

of the world frame. The downward reaching was achieved with first utilizing only the arm, then utilizing the arm and the chest and finally utilizing the legs, waist, chest and arm.

Fig. 10 shows the snapshots of the experiment where the operator input velocity command for the right hand to perform horizontal reaching motion in the y-direction of the world frame. The sideward reaching was achieved with first utilizing only the arm and then utilizing the arm and the chest.

7.2. *Foot Operation Experiments*

Fig. 11 shows the snapshots of the experiment pushing a can into a can crusher using the right foot. The operator input velocity command for the right foot for the pushing motion in the x-direction of the world frame. The operator only specified the velocities of the right foot, stable foot motions are generated with the automatic CoM transitions and balance autonomy explained above.

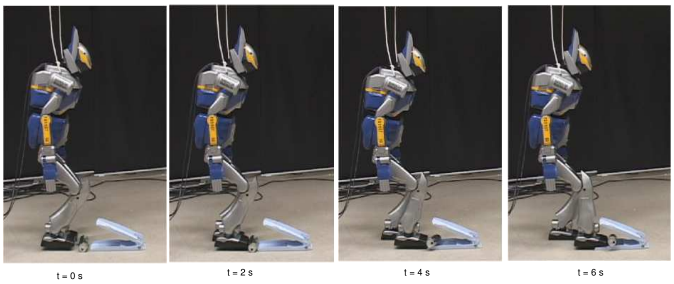

Fig. 11. Pushing a Can with Right Foot

7.3. *Walking Experiments*

Experiments generating walking motions using joystick commands were conducted to confirm the effectiveness of the method. The operator controlled the walking motion generations using joysticks as shown in Fig. 12. TH in the figure denotes the walking direction, SX denotes the distance per step in X-axis direction of the world frame, DSY denotes the distance per step in Y-axis direction of the world frame, and SY denotes the distance between two feet during walking. During the experiment, the minimum feet distance is set to be at a collision-safe distance in the walking motion generation. Fig. 13 shows the snapshots of turning and walking forward experiments.

8. Conclusions

This paper introduces a novel remote motion teleoperation method able to generate whole body motions of a humanoid robot using only simple input device.

Inspired by the observations on human motion generation, we proposed a switching command based whole body operation method of which the operator selects only the necessary point of the humanoid robot's body for manipulation. The concept and the framework for whole body motion generation which integrates operator's command and robot's autonomy is presented. With the motion generation framework, we constructed an autonomous function which generates whole body motions satisfying both the desired trajectory of operation points and the balance constraint, and a workspace extension autonomy which changes the utility of body parts.

Finally, we explained the implementation of the proposed teleoperation method using only two 3 DOF joysticks as the input interface to manipulate whole body motions of a real 30 DOF humanoid robot. Experiments utilizing the proposed method were carried out and the results confirmed the effectiveness of the proposed teleoperation system.

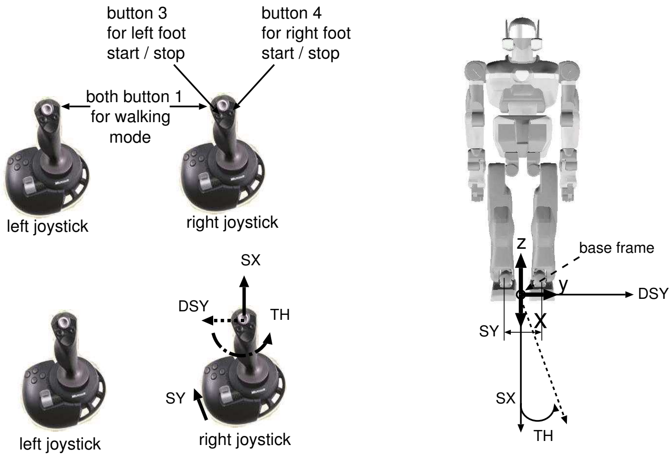

Fig. 12. Joystick Walking Command

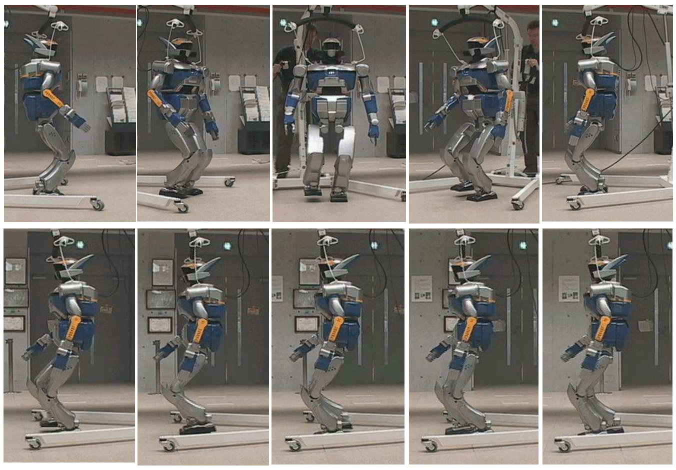

Fig. 13. Walking Motion

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