

# Mobile Manipulation of Humanoids — Real-Time Control Based on Manipulability and Stability —

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## Abstract

*A real-time control method for a humanoid in mobile manipulation, doing tasks with its arms while moving, is proposed. The arm tips always follow their desired position with external force applied to by impedance control, for carrying out a given task with the arms. An evaluation function consisting of not only stability but also arm manipulability—both are important for mobile manipulation—is defined; the humanoid controls its body and legs so that this evaluation may be optimal. As a result, the humanoid autonomously steps or keeps standing, coordinating with the arm tips motion. The effectiveness and usefulness of the proposed method are ascertained by computer simulations on a humanoid of human-size and experiments using a small experimental robot.*

## 1 Introduction

Humanoids are expected as human-friendly robots. Hence most previous studies on humanoids aim at designing human-like structures or realizing human-like motion such as walking, jumping and dancing[1 – 10]. Another important role of humanoids is, however, “doing various tasks” instead of or together with human beings; a few studies applied humanoids to simple tasks: carrying an object and pushing a truck[2, 10]. In the present study, mobile manipulation of humanoids is discussed. Mobile manipulation means that humanoids do various tasks with their arms while moving. We pay attention to the following problems:

1. It is important to keep not only stability but also arm manipulability high. Accordingly, a different control method for mobile manipulation from conventional methods for walking is required.
2. The motion of arm tips depends on objective

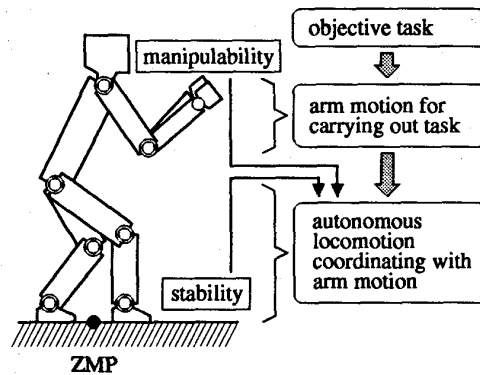


Figure 1: Mobile manipulation of humanoid

tasks and external force may act on the tips. Furthermore, the desired motion of the tips may not be fixed beforehand and the force may be unknown. Hence the humanoid must control its body and legs autonomously and in real-time, coordinating with the tips motion; that is difficult by conventional methods for walking using preset walking patterns.

For these problems, we propose a real-time control method for a humanoid in mobile manipulation (Fig.1):

1. The arm tips always follow their desired position with external force applied to by impedance control, for carrying out a given task with the arms.
2. An evaluation function consisting of arm manipulability and stability is defined; stability is evaluated using static zero moment point. Under the above constraint on the tips motion, the hu-

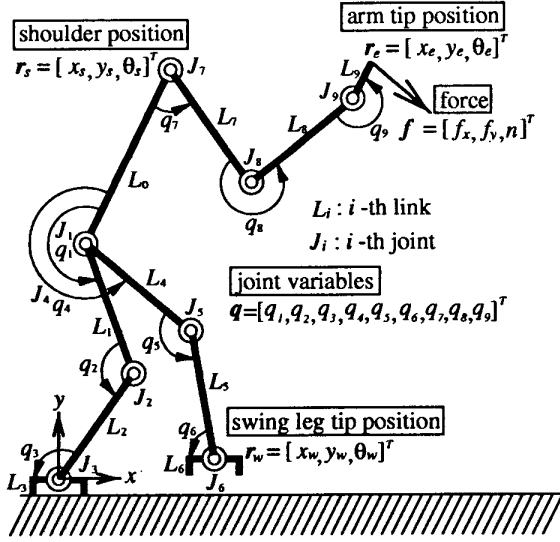


Figure 2: Humanoid and its variables

manoid controls its body and legs so that this evaluation may be optimal.

- In double support state, the humanoid controls its shoulder to optimize the evaluation.
- Assuming that the humanoid takes a step, it compares the evaluation in the double support state after the assumed step and that in the current double support state; the humanoid takes a step if the former is better.
- During single support state, the humanoid controls its shoulder to optimize the evaluation while moving the swing leg.

In this way, the humanoid autonomously steps or keeps standing, coordinating with the arm tips motion and keeping manipulability and stability high. As described above, we focus on not walking but mobile manipulation of a humanoid. Hence a revised method of conventional static walking is applied to one step motion.

The effectiveness and usefulness of the proposed method are ascertained by computer simulations on a humanoid of human-size and experiments using a small experimental robot.

## 2 Model of Humanoid

In this paper, “position and orientation” is simply called “position”, and “force and moment” is called “force”.

In this study, only motion in sagittal plane is discussed. Hence, as shown in Fig.2, the humanoid has one body, two legs and one arm; each leg has three active joints in the hip, knee and ankle, and the arm has three active joints in the shoulder, elbow and wrist. We explain the motion in double support state immediately followed by one forward-step motion, because stepping backward differs from stepping forward only in the moving direction of the swing leg. The global coordinate system  $\Sigma$  is fixed to the ground with  $x$  axis horizontal,  $y$  axis vertical and the origin on the fore-leg tip.  $\mathbf{r}_e \in R^3$ : the arm tip position,  $\mathbf{r}_s \in R^3$ : the shoulder position,  $\mathbf{r}_w \in R^3$ : the hinder or swing leg tip position, and  $\mathbf{f} \in R^3$ : the external force acting on the arm tip; these variables are expressed on  $\Sigma$ .

As is obvious from Fig.2, all joint variables can be calculated from  $\mathbf{r}_e$ ,  $\mathbf{r}_s$  and  $\mathbf{r}_w$  via the inverse kinematics of the humanoid. In the following section, we explain how to control  $\mathbf{r}_e$ ,  $\mathbf{r}_s$  and  $\mathbf{r}_w$ .

## 3 Control Method

### 3.1 Impedance Control of Arm

For the purpose of carrying out an objective task with the arm, the arm tip must always follow its desired position. We assume that external force  $\mathbf{f}$  acts on the tip. Hence, the arm tip position  $\mathbf{r}_e$  is controlled by the following impedance control:

$$M_e \ddot{\mathbf{r}}_e + D_e (\dot{\mathbf{r}}_e - \dot{\mathbf{r}}_{ed}) + K_e (\mathbf{r}_e - \mathbf{r}_{ed}) = \mathbf{f} - \mathbf{f}_d \quad (1)$$

where  $\mathbf{r}_{ed} \in R^3$ : the desired arm tip position,  $\mathbf{f}_d \in R^3$ : the desired external force,  $M_e, D_e, K_e > 0 \in R^{3 \times 3}$ : the desired impedance of the arm tip. When only  $\mathbf{f}_d$  is given (e.g. in the experiment described later), the following impedance control is applied:

$$M_e \ddot{\mathbf{r}}_e + D_e \dot{\mathbf{r}}_e = \mathbf{f} - \mathbf{f}_d \quad (2)$$

### 3.2 Evaluation Function for Mobile Manipulation

It is important for a humanoid in mobile manipulation to evaluate not only stability but also arm manipulability. Under the constraint on the arm tip motion described in Subsection 3.1, the humanoid must control its body and legs to make both manipulability and stability high. As shown in Fig.3, the situations where manipulability and stability are contrary to each other occur: (a) the motion when evaluating only stability

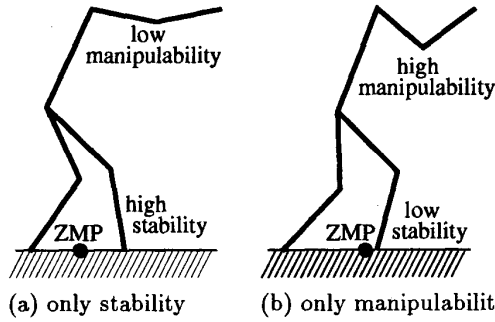


Figure 3: Motion of humanoid based on different evaluation

may reduce manipulability; (b) the motion when evaluating only manipulability may lessen stability. Thus evaluation function  $U$  for mobile manipulation including manipulability and stability is defined.

$U_a$ : **arm manipulability**—The humanoid must keep arm manipulability high to carry out the task with the arm. The evaluation  $U_a$  on manipulability is defined using the relative shoulder position to the arm tip,  $(\mathbf{r}_s - \mathbf{r}_e)$ :

$$U_a(\mathbf{r}_s, \mathbf{r}_e) \equiv \mathbf{r}_{se}^T \frac{K_a}{2} \mathbf{r}_{se} \quad (3)$$

$$\mathbf{r}_{se} \equiv (\mathbf{r}_s - \mathbf{r}_e) - \bar{\mathbf{r}}_e$$

where  $K_a > 0 \in \mathbb{R}^{3 \times 3}$ .  $\bar{\mathbf{r}}_e \in \mathbb{R}^3$  is the ideal value of  $(\mathbf{r}_s - \mathbf{r}_e)$ , which is determined so that the manipulability measure of the arm may be maximum.

$U_z$ : **stability**—The humanoid is required to stand stably, or not to tumble. We evaluate stability using zero moment point (ZMP). If the desired ZMP  $\mathbf{x}_{zd}$  is set within the stable region, the evaluation  $U_z$  on stability is defined by

$$U_z(\mathbf{r}_s, \mathbf{r}_e, \mathbf{r}_w, \mathbf{f}) \equiv k_z (\mathbf{x}_z - \mathbf{x}_{zd})^2 \quad (4)$$

where  $k_z > 0$ .  $\mathbf{x}_z$  is ZMP neglecting inertial force, called “static ZMP” in this paper; it is different from the projection of center of gravity on the ground because of including the external force acting on the arm tip.  $\mathbf{x}_z$ , thus  $U_z$ , depend on the shoulder position  $\mathbf{r}_s$ , the arm tip position  $\mathbf{r}_e$ , the hinder or swing leg tip position  $\mathbf{r}_w$  and the external force  $\mathbf{f}$ . How to determine  $\mathbf{x}_{zd}$  will be explained later.

$U_b$ : **body posture**—In addition to  $U_a$  and  $U_z$ , we define the ideal shoulder position  $\bar{\mathbf{r}}_s \in \mathbb{R}^3$  in order to keep two legs away from their singular points and to prevent unnatural posture of the body; the evaluation

$U_b$  on body posture is defined by

$$U_b(\mathbf{r}_s) \equiv \{\mathbf{r}_s - \bar{\mathbf{r}}_s\}^T \frac{K_b}{2} \{\mathbf{r}_s - \bar{\mathbf{r}}_s\} \quad (5)$$

where  $K_b \geq 0 \in \mathbb{R}^{3 \times 3}$ .

The sum of these evaluations gives the total evaluation  $U$  to be minimized for mobile manipulation.

$$U(\mathbf{r}_s, \mathbf{r}_e, \mathbf{r}_w, \mathbf{f}) \equiv U_a + U_z + U_b \quad (6)$$

Thus  $K_a$ ,  $k_z$  and  $K_b$  represent the weights for  $U_a$ ,  $U_z$  and  $U_b$ , respectively.

### 3.3 Leg Control in Double Support State

In double support state, the desired ZMP  $\mathbf{x}_{zd}$  is set to the center of the stable region between two feet. The hinder leg tip position  $\mathbf{r}_w$  is constant, and the arm tip position  $\mathbf{r}_e$  and the external force  $\mathbf{f}$  are determined by the control law of the arm. Thus we control the shoulder position  $\mathbf{r}_s$ , so that the evaluation  $U$  may decrease:

$$M_s \ddot{\mathbf{r}}_s + D_s \dot{\mathbf{r}}_s = -\frac{\partial U}{\partial \mathbf{r}_s} = K_a \{(\mathbf{r}_e + \bar{\mathbf{r}}_e) - \mathbf{r}_s\} + k_z \{\mathbf{x}_{zd} - \mathbf{x}_z\} \frac{\partial \mathbf{x}_z}{\partial \mathbf{r}_s} + K_b \{\bar{\mathbf{r}}_s - \mathbf{r}_s\} \quad (7)$$

where  $M_s, D_s > 0 \in \mathbb{R}^{3 \times 3}$ : the desired impedance of the shoulder. Letting  $\mathbf{r}_{sd} \in \mathbb{R}^3$  be  $\mathbf{r}_s$ , when  $\partial U / \partial \mathbf{r}_s = 0$ , the actual shoulder position  $\mathbf{r}_s$  is controlled toward  $\mathbf{r}_{sd}$  via Eq.(7). Hence we call  $\mathbf{r}_{sd}$  the optimal shoulder position.

Moving the shoulder slowly by this impedance control reduces inertial force. For this reason, we can keep ZMP including inertial force within the stable region by controlling the static ZMP  $\mathbf{x}_z$  toward the center of the stable region,  $\mathbf{x}_{zd}$ .

### 3.4 Judgement of Step

When the arm tip moves in narrow space, the humanoid keeps manipulability and stability high by the above-mentioned method, standing in double support state. If the tip must be moved in wide range or large external force acts on the tip, the humanoid should step in order to recover manipulability and stability in new double support state. Furthermore, the humanoid must judge whether it steps or not from the current situation.

We use the evaluation  $U$  for this judgement. In Fig.4,  $U_{m1}$  denotes  $U$  when the shoulder is on the optimal

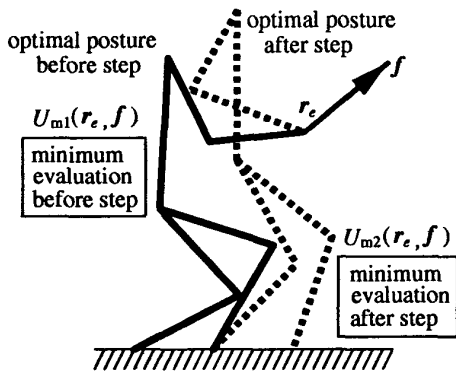


Figure 4: Minimum evaluations before and after step

position in the current double support state; assuming that the humanoid takes a step,  $U_{m2}$  denotes  $U$  when the shoulder is on the optimal position in the double support state after the assumed step.  $U_{m1}$  and  $U_{m2}$  depend on the arm tip position  $r_e$  and the external force  $f$  ( $r_w$  is constant). The step length  $w_s$  is constant in this study.

If  $U_{m1} < U_{m2}$ , the humanoid should keep the current double support state; if  $U_{m1} > U_{m2}$ , it should take a step and shift to new double support state. Practically, the step motion requires the step time  $t_s$ , which is also given beforehand in this study. Therefore, we compare  $U_{m1}(\tilde{r}_e, \tilde{f})$  and  $U_{m2}(\tilde{r}_e, \tilde{f})$  for the predicted arm tip position  $\tilde{r}_e$  and external force  $\tilde{f}$  in  $t_s/2$  from now.  $\tilde{r}_e$  and  $\tilde{f}$  are predicted by

$$\tilde{r}_e = \hat{r}_e + \dot{\hat{r}}_e(t_s/2), \quad \tilde{f} = \hat{f} \quad (8)$$

where  $\hat{r}_e$ ,  $\dot{\hat{r}}_e$  and  $\hat{f}$  are the arm tip position, velocity and external force after passing low pass filters. If  $U_{m1}(\tilde{r}_e, \tilde{f}) > U_{m2}(\tilde{r}_e, \tilde{f})$ , the humanoid begins to step.

### 3.5 Leg Control in Step Motion

As described in Section 1, we do not focus on walking method; the purpose of the step motion is shifting to new double support state which is better than the current one. Hence a revised method of conventional static walking is applied to one step motion.

The step motion consists of three phases shown in Fig.5. The step length  $w_s$ , the step time  $t_s$  from PHASE I through PHASE III and the time of single support state(PHASE II)  $t_w$  are constant and given beforehand.

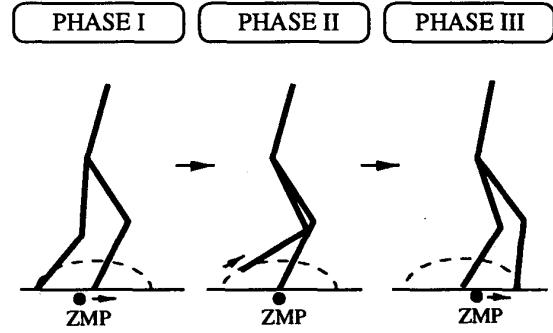


Figure 5: 3 phases in step motion

**Shoulder Control**—The shoulder position  $r_s$  is controlled also in the step motion using the control law, Eq.(7). The desired ZMP  $x_{zd}$  is moved from the center of the stable region of the current double support state to the center of the sole of the support leg in PHASE I, fixed during PHASE II, and moved again to the center of the stable region of the next double support state in PHASE III. As a result, the shoulder moves coordinating with the desired ZMP, so that arm manipulability and stability can be maintained during the step motion.

**Swing Leg Control**—The swing leg tip position  $r_w$  is moved along the given elliptical trajectory in PHASE II.

## 4 Simulation

We show the simulation results using a humanoid of human-size: 1.6[m] height and 130[kg] weight. It has two legs and two arms without wrists; two arms are moved in the quite same way because only motion in sagittal plane is discussed. Tables 1 and 2 summarize chief parameters of the humanoid and the proposed method. Eq.(1) is applied to the arm control. The objective task is to move the arm tip forward at constant rate 0.05[m/s]. The external force and its desired value equal zero.

As shown in Fig.6(a), the arm tip is moved at the same constant velocity as the desired one. Coordinating with the tip motion, the humanoid controls its shoulder and autonomously alternates double support state and step motion. The normalized manipulability measure of the arm and the stability margin shown in Fig.6(b) and (c) are always kept high in double support state. The stability margin in step motion is forced to be small because the ZMP must be moved for

Table 1: Parameters of humanoid used in simulation

part	length [m]	weight [kg]
body	0.624	34.8
thigh	0.542	11.5
shank	0.434	17.0
foot	0.380	0.00
upper arm	0.542	19.0
forearm	0.597	0.00

Table 2: Parameters of control method in simulation

arm control		
mass	$m_e$ [kg]	0.900
viscous frictional coef.	$d_e$ [Ns/m]	8.00
stiffness	$k_e$ [N/m]	21.0
leg control		
mass	$m_s$ [kg]	3.00
viscous frictional coef.	$d_s$ [Ns/m]	57.0
stiffness	$k_a$ [N/m]	$4.98 \times 10^1$
	$k_z$ [N/m]	$2.23 \times 10^3$
	$k_b$ [N/m]	$1.70 \times 10^2$
desired distance between arm tip and shoulder	$\bar{x}_e$ [m]	0.804
desired height of shoulder	$\bar{y}_s$ [m]	1.36
step motion		
step length	$w_s$ [m]	0.300
step time	$t_s$ [s]	3.00
single support time	$t_w$ [s]	1.20

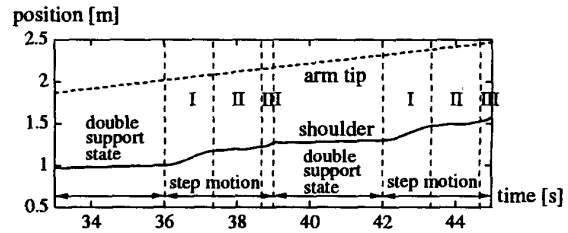
(same desired impedance in  $x$  and  $y$  direction)

stepping. It is not significant that the stability margin just before landing is very small, since the humanoid is ready to land.

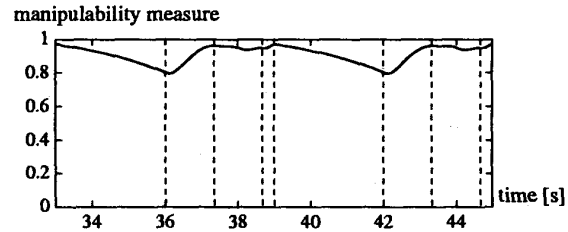
Arm manipulability and stability cannot be kept constant during 1 cycle motion, because biped locomotion requires alternating two different states—double and single support states. This is distinctive feature of humanoids compared with wheeled mobile manipulators which can move continuously.

## 5 Experiment

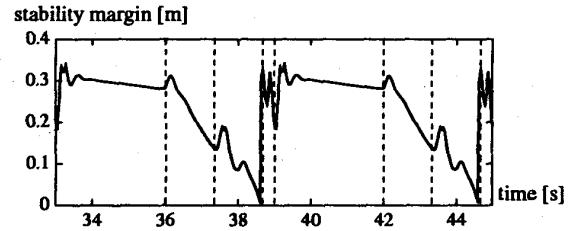
We made a small 14-DOF experimental robot shown in Fig.7, which is similar to remote-brain robots made by Inoue, Inaba, et al.[3] This robot does not have



(a) arm tip and shoulder motion in  $x$  direction



(b) normalized manipulability measure of arm



(c) stability margin

Figure 6: Simulation result

wrists. Two arms are moved in the quite same way. The force sensor for detecting the external force is attached to the center of the bar connecting two arm tips. The robot leans in lateral direction using the joints  $J_1$  and  $J_8$  when it steps.

Fig.8 shows the experimental result when a human operator directly gives arbitrary external force to the arm tip and the arm is controlled via Eq.(2). The robot autonomously steps coordinating with the applied force, while keeping the ZMP within the stable region. Fig.9 illustrates the experimental robot stepping backward.

## 6 Conclusion

We have proposed a real-time control method for humanoids in mobile manipulation. Coordinating with the arm tips motion depending on objective tasks, a

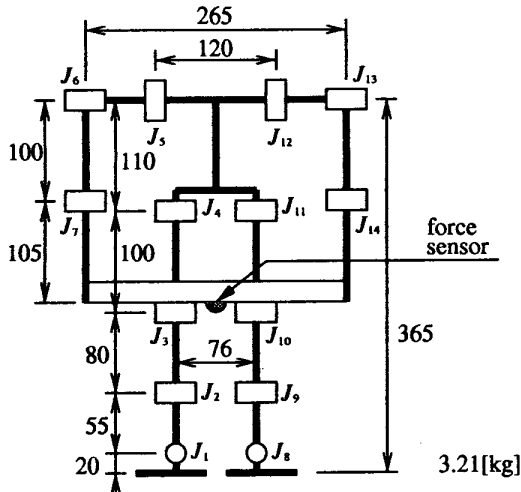


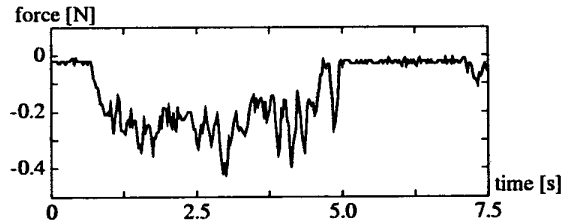
Figure 7: 14-DOF experimental robot

humanoid autonomously steps or keeps standing with arm manipulability and stability high.

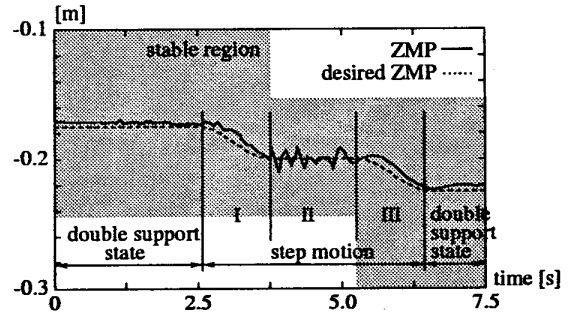
The effectiveness and usefulness of the proposed method are ascertained by computer simulations on a humanoid of human-size and experiments using a small experimental robot.

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(a) applied external force in  $x$  direction



(b) ZMP(calculated using the model of robot)

Figure 8: Experimental result



Figure 9: Experimental robot stepping backward

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