A biped hopper controlled around yaw axis by body-twisting motion

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SYNOPSIS

The purpose of this study is to realise various 3D motions by a new 3D biped robot. This new robot has a rotor rotating around yaw axis. It enables the robot to perform quick turn around yaw axis. This paper provides hardware overview of the robot, simulation of turning and lateral stabilisation, and preliminary experiments of walking.

1 INTRODUCTION

The performance of the existing biped robots is still limited because they are developed for some specific motion tasks only. The robot that can perform various motions like walking and running at once has not been realised yet. Although there have been many excellent dynamic 3D biped walking robots [1][2], most of them are focused on the stable walking in a specified direction and their walking speed is slow. 3D biped running robot was realised by Raibert and co-workers [3]. Their robots can hop, run, and even perform somersault [4], but it cannot walk.

In addition, there are some important and interesting motion tasks that have never been performed by biped robots. "Quick turn" is one of such examples. Although there are many ways to do this, it is intuitively clear that the most rapid turning is gained by rotating on one foot by twisting the body. This paper proposes a new biped robot to realise such a quick turning motion, as well as various 3D motions including walking and running.

2 A NEW BIPED ROBOT - *SKIPPER*

Figure 1 shows a prototype of the new 3D biped - *Skipper*. It has two telescopic legs swinging around pitch axis and a rotor which is located at the neck of the robot and rotates around yaw axis. There is no actuator at each foot, that is, the robot stands on the ground with point contact. The actuated DOF is five in all and it is relatively small compared to that of existing 3D biped robots.

2.1 Model description

Figure 2 shows the simplified model of *Skipper*. The generalised coordinates are defined as the position of centre of mass (COM) $x = (x_g, y_g, z_g)$, the attitude (roll-pitch-yaw) of the torso $e = (e_1, e_2, e_3)$, and joint angles $p = (\psi_1, \psi_2, \psi_3)$. The generalised focus are $\tau = (\tau_1, \tau_2, \tau_3)$ and $f = (f_1, f_2)$, where τ_1, τ_2 are the hip torques, τ_3 is the torque of the rotor, and f_1, f_2 are the leg forces.

2.2 Hardware overview

Overall height of *Skipper* is 840 mm and the total weight is about 8 kg. To allow the robot to move three-dimensional space freely, all the control circuits and switching regulators are on board. Each joint is driven with geared servomotor whose rated power is 20W. For the telescopic joint at the knee, high-lead ball screw is used. In addition, coil springs are installed parallel to the ball nut. The springs assist knee actuator, especially when performing compliant walking or running. Sensors are five rotary encoders at each joint, three rate gyros in the head, and the foot switches. The controller consists of 5 one-chip microcomputers (Hitachi H3048), and the control period is about 5 ms. Power source is six 7.2 V NiCd batteries mounted on the yaw-axis rotor.

3 SIMULATIONS

Skipper has a rotor rotating around yaw axis, which makes it possible to perform quick turn. Moreover, if we add one more DOF of roll axis to the rotor, it can be used for lateral stabilisation.

3.1 Turning motion control

Turning motion is relatively easy if the motion starts from almost equilibrium configuration (see Fig. 3 for simple open-loop turning control). However, turning while walking or running is a very challenging task. In addition, there are unknown disturbances, for example, friction between the foot and ground. Therefore, feedback controller is crucial for this kind of turning motion.

There are two possible ways to control turning during walking or running; turning at stance phase, or turning at the flight phase. Since the feedback controller at stance phase is under construction, here a controller at flight phase [5] is presented. The control problem is stated as follows: *Within a given flight time, turn to the direction where lateral levelling is achieved, and, dead-beat touchdown leg angle to arbitral value.* The controller is designed exactly based on mathematical model. Because of the lack of the space, we provide only the outline:

(1) Decouple the dynamics about the attitude of torso
(2) Set three target dynamics; lateral levelling constraint, virtual angular momentum constraint, and linearised dynamics of swing leg
(3) Design a dead-beat touchdown controller for swing leg
(4) Substitute the results of (2) and (3) into (1) to obtain the control inputs

As an example, 90 deg turning and touchdown control within given flight time of 0.2 s was simulated. Figure 4 shows the animation. For details of controller, refer to [5]. Simulation model is built using 3D dynamics simulator - DADS and the controller is implemented by MATLAB/SIMULINK (http://www.cybernet.co.jp).

3.2 Lateral stabilisation control

Since the prototype of *Skipper* has no DOF around roll axis, the leg forces should be controlled appropriately to produce controlling moment around roll axis, for lateral stability. However, too large leg forces may damage stability of pitch, and more importantly, if the distance between the legs is short, the robot cannot produce enough moment to control itself around roll axis.

Although there are many ways to stabilise roll motion [6], the most reliable and simplest way for prototype - *Skipper* will be giving one more actuated DOF to the rotor along roll axis. Then, lateral stability will be obtained by rotating the rotor around its roll axis, based on double inverted pendulum controller as

$$\tau = -K_1 e_1 - K_2 \dot{e}_1 + K_3 \psi_4 + K_4 \dot{\psi}_4 \tag{1}$$

where τ is the applied roll torque and $K_i \quad (i = 1, 2, 3, 4)$ are the gains.

Figure 5 shows a simulation result of stable stamping motion. The figure shows that roll attitude e_1 is stabilised and joint angle ψ_4 is converging to zero. It should be noted that the lateral stability is improved by shortening the distance between two legs.

4 EXPERIMENTS

To check the validity of the mechanical model, planar walking experiments were carried out. In the experiments, two large plates pinch the robot and constrain the motion of it to the sagital plane. Stabilisation of pitch controller was also designed based on the double inverted pendulum model, as described below (Leg 1 is assumed to be supporting leg).

$$\tau_1 = -K_5 e_2 - K_6 \dot{\phi} + K_7 x_g + K_8 \dot{x}_g, \tag{2}$$

$$\tau_2 = -K_9 (e_2 + \psi_2) - K_{10} (\dot{e}_2 + \dot{\psi}_2) \tag{3}$$

where $K_i \quad (i = 5, 6, ...)$ are the gains. Equation (2) means that the hip actuator of supporting leg controls directly the pitch of torso like an inverted pendulum control, while Eq. (3) means that the angle of swinging leg is controlled to be zero. Of course some desired values could be introduced when control of forward speed or position is needed.

Figure 6 shows an experimental result of planar walking. Top graph shows the time evolution of attitude of torso. This shows the amplitude of attitude is well suppressed. On the other hand, bottom two graphs show the time evolutions of leg lengths. It seems surprising that two legs get synchronised, because the controller of each leg is not coupled each other but independent. However, the legs cannot be synchronised without pinching plates. Therefore, for stable walking or running in 3D space, some suitable controller about roll axis, e.g. feedback controller shown in Section 3.2, is required. Since introducing DOF of roll axis is ongoing task, the experimental results of lateral stabilisation will be presented in the near future.

5 CONCLUTIONS AND ACKNOWLEDGEMENT

A new 3D biped robot - *Skipper*, which can probably perform various 3D motions including walking, running, or turning, was developed. In this paper, the hardware overview, the simulation of turning and stabilisation around roll axis, and preliminary walking experiment are presented. Even though the robot is constrained to sagital plane at present, the simulation and experimental results indicate that it can perform 3D walking and running if roll axis DOF is given to the rotor. The authors give thanks to Dr. Kumagai, M. for his contribution to a mutual communication program for one-chip microcomputers.

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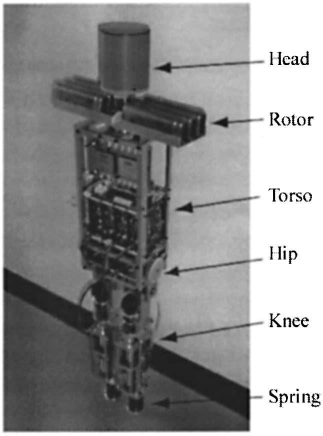

Fig. 1 3D biped robot – *Skipper*

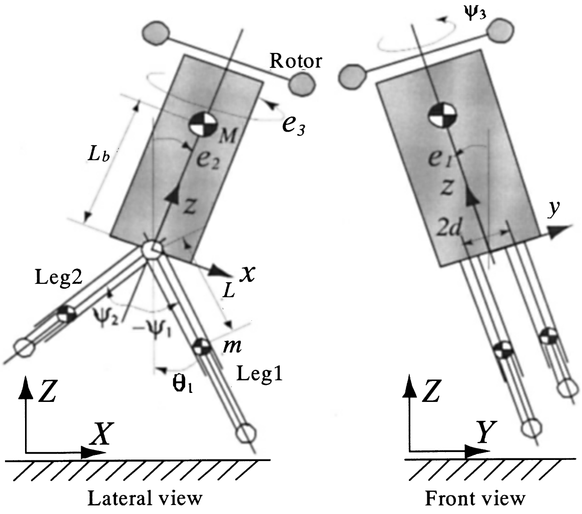

Fig. 2 Simplified model

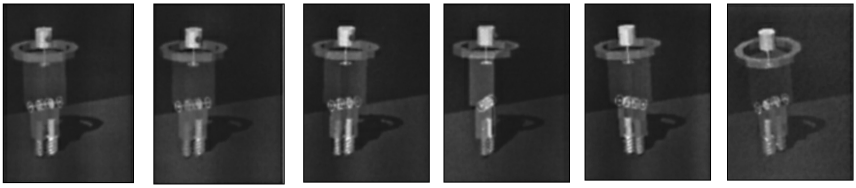

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Fig. 3 Simulation of simple (open-loop) turning control

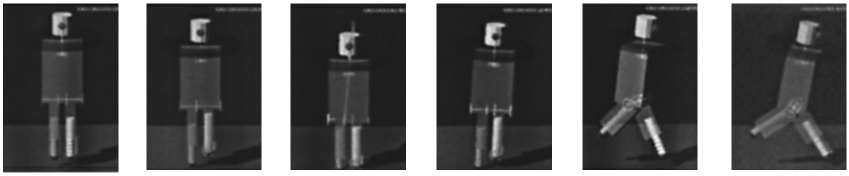

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Fig. 4 Simulation of (feedback) turning control at flight phase

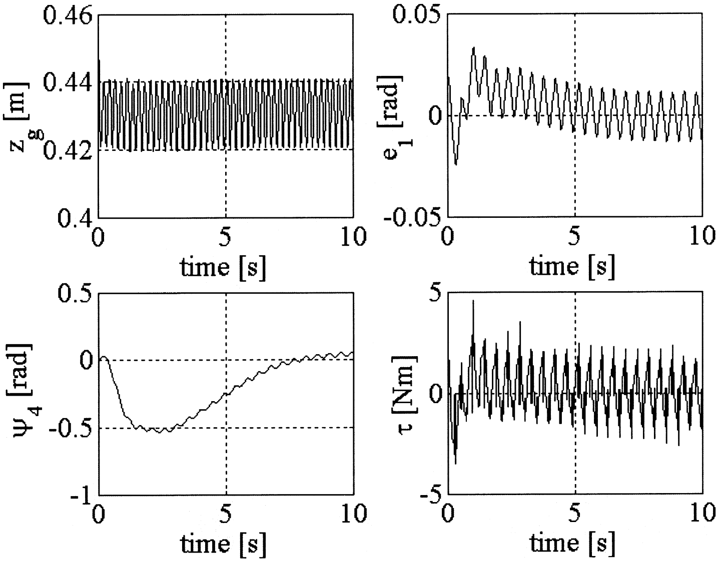

Fig. 5 Simulation result of lateral stabilisation: ψ_4 is the roll joint angle of rotor and τ is the applied torque

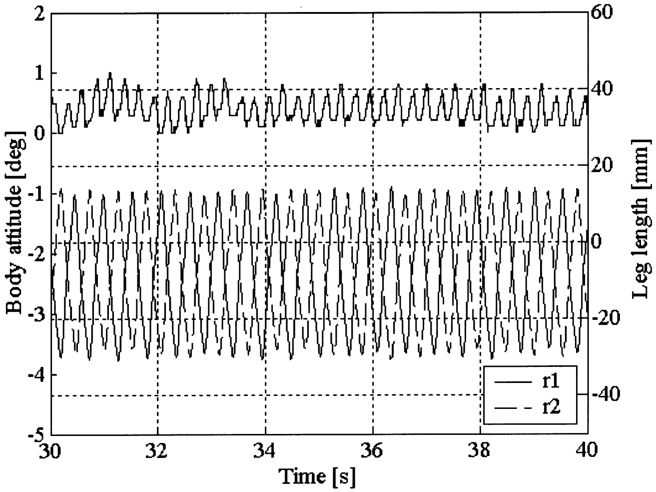

Fig. 6 Experimental data of planar walking