

Design and Control of a Pendulum Driven Hopping Robot

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Abstract

In this paper a new kind of hopping robot has been designed which uses inverse pendulum dynamics to induce bipedal hopping gaits. Its mechanical structure consists of a rigid inverted T-shape mounted on four compliant feet. An upright “T” structure is connected to this by a rotary joint. The horizontal beam of the upright “T” is connected to the vertical beam by a second rotary joint. Using this two degree of freedom mechanical structure, with simple reactive control, the robot is able to perform hopping, walking and running gaits. During walking, it is experimentally shown that the robot can move in a straight line, reverse direction and control its turning radius. The results show that such a simple but versatile robot displays stable locomotion and can be viable for practical applications on uneven terrain.

1 Introduction

The design and implementation of the Stumpy II¹ hopping robot is an exploration of a novel morphology for locomotion, with an inverted pendulum inducing rhythmic hopping and a transverse rotational degree of freedom for direction control. Its unique structure and dynamics are capable of producing both biped-like and quadruped-like gaits. In addition it can also display some effective non-biomimetic gaits.

Such use of pendulum dynamics in movement has been only partially explored. Hayashi *et al* [3] have designed a pendulum-type jumping machine which uses inverted pendulums as swinging arms to propel the robot to jump. This machine was capable of jumping up stairs, but not of regulating its movement direction or velocity. In another interesting example, Ioi *et al* [4] applied pendulum dynamics to the problem of wheeled locomotion and designed a robot comprised of two big parallel wheels, with a pendulum hanging between them. This robot was able

to roll up slopes and control forward velocity and turning. However, the use of pendulum dynamics to drive legged locomotion has not been previously considered².

The control of gait and balance in hopping robots has been widely studied by Raibert and his colleagues, for one-legged, two-legged and four-legged hopping robots, in two and three dimensions [10] [9] [12] [11]. Such robots have been shown to successfully produce bounding gaits, through control of hopping height and forward velocity. They have also been able to perform somersaults [8]. These robots have long narrow legs each with a single spring-loaded prismatic joint. The legs are attached to the body mass, by a roll and (for 3D motion) a pitch degree of freedom, by which they can influence foot placement. Due to this mechanical structure, these robots are statically unstable, and therefore must continue to hop in order to stabilize their body. For practical applications this presents a considerable limitation. In the Stumpy robot, the four legs also consist of a spring loaded prismatic joints, but are much shorter. Also, they do not have any other degrees of freedom with respect to the robot’s upper body, and control of foot placement is accomplished by the upper body. This has the advantage that the structure is statically stable, while allowing for dynamically stable locomotion. This enables the robot to smoothly transition between standing still, walking, running, and coming to a stop again, which is more practical for real world applications.

The dynamic stability of the Stumpy robot is comparable to that of the monopod hopping robot developed by Ringrose [13]. The monopod was able to achieve self-stabilizing running, without any sensors or active control, by simply moving the single actuator of the robot, through a fixed repetitive cycle. Due to the interaction of this simple control with a carefully designed self-stabilizing mechanical structure, the robot was able to correct its posture despite

*The names of the authors are presented in random order. Each author has made an equal contribution to this work.

¹Videos available at
<http://www.ifi.unizh.ch/ailab/robots/Stumpy/>

²This is conceptually different from using inverse pendulum dynamics in ZMP-based balance control, which is common in legged robots

the effects of destabilizing forces. According to Murphy [5], self-stabilizing posture of the body can be achieved in a two legged robot during bounding gait, if the normalized moment of inertia of the mechanical structure is less than 1. Since the interaction between controller and the mechanical structure of the Stumpy robot fulfills this condition, it displays a similar self-stabilizing property. Thus, it is able to perform locomotion with high tolerance to environmental disturbances.

The mechanical structure of the robot has been designed according to the principles of *cheap design* and *ecological balance* described by Pfeifer *et al* [7]. Thus, only the minimum number of sensor and actuators that are necessary to perform the task have been used. This is similar to the design of the Scout robot, built by Buehler *et al* [2], which uses a small number of actuators for quadruped locomotion. The design of Stumpy has also incorporated the use of mass distribution in control, an optimization method described by Paul *et al* [6]. The controller for the robot is designed according to the principles of behavior based control [1].

The following section, Section 2, describes the design of the Stumpy robot. The behavior of the robot is then mathematically modelled in Section 3. Then the control of straight line movement, direction, and turning radius are developed in Section 4. These controllers are tested on the robot, and data is presented from real world experiments. In Section 5, a short discussion of the robots performance on these tasks follows, with implications for future work. Section 6 ends with conclusions.

2 Robot Mechanical Structure

The robot (Figure 1) was designed through the development of three prototypes. The Stumpy II robot's lower body is made of an inverted "T" mounted on wide springy feet. The upper body is an upright "T" connected to the lower body by a rotary joint providing one degree of freedom in the frontal plane (see Figure 1). This enables the upper body to act as an inverted pendulum. For simplicity in nomenclature, we call this the "waist" joint. The horizontal beam of the upright "T", is weighted on the ends to increase its moment of inertia. It is connected to the vertical beam by a second rotary joint, providing one rotational degree of freedom, in the plane normal to the vertical beam of the upper "T". This joint is labeled the "shoulder" joint. Stumpy's vertical axis is made of aluminum, while both its horizontal axes and feet are made of oak wood.

The total mass of the robot is approximately 1.9 kg. The mass and length parameters of the robot, as

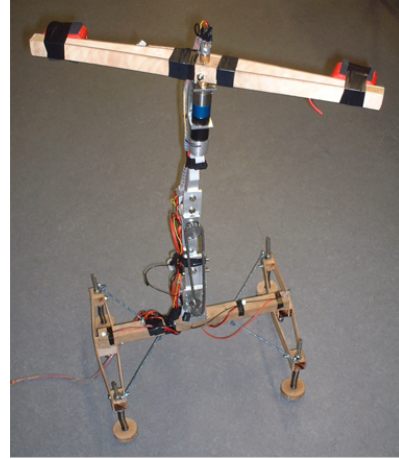


Figure 1: Stumpy II Robot

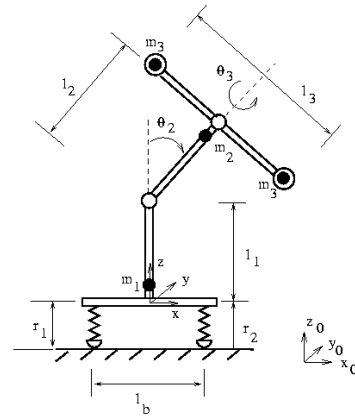


Figure 2: Schematic diagram of the Stumpy Robot, with variables which are used in modelling and analysis.

shown in Figure 2 are detailed in the Table 1 below. The joints are actuated using Minimotor DC-Micromotors. The waist motor is a 3042 012C with a 43:1 gear reduction, and shoulder motor is a 2342 012C, also with 43:1 gear reduction. The joint angles are measured using rotary potentiometers. The control is performed via off-board motor control boards with a PIC16F877 microcontroller and a standard motor driver with PWM output.

3 Modelling and Analysis

The following variables are used in the analysis of the robot:

- x_0, y_0, z_0 : origin of the world coordinate system
- $[x, y, z], \theta_1$: origin of the robot, inclination in frontal plane

Table 1: Mass and length parameters of the robot mechanical structure

Parameter	Description	Value
r_1, r_2	rest length of feet	10 cm
l_b	length of base	15 cm
l_1	length of lower vertical beam	21 cm
l_2	length of the upper vertical beam	26 cm
l_3	length of shoulder horizontal beam	41.5 cm
m_1	mass of lower body	1.2 kg
m_2	mass of upper body	0.43 kg
m_3	mass on shoulder	0.12 kg

τ_1, τ_2 : waist motor torque, shoulder motor torque
 θ_2, θ_3 : joint angles of the robot
 J_l : moment of inertia of the lower body

To analyse the behavior of the robot, the model is orthogonalized into models for the frontal and sagittal planes. In the frontal plane, the waist motor serves to accelerate the waist joint and induce hopping motion.

$$\tau_1 = m_2 l_2 \ddot{\theta}_2 - m_2 g l \sin(\theta_1 + \theta_2) \quad (1)$$

We assume that in this motion, the effects of external forces are negligible, and that conservation of angular momentum holds. According to this the following relation can be stated:

$$J_l \dot{\theta}_1 = m_2 l_2 \dot{\theta}_2 \quad (2)$$

where J_l is the moment of inertia of the lower body.

During walking, where at least one foot is always on the ground, the following relations arise:

$$x = l_b \cos \theta_1, z = l_b \sin \theta_1 \quad (3)$$

By substitution of Equation 3 into Equations 1 and 2, the following relations result:

$$J_l \dot{x} = (\tau_1 + m_2 g l \sin \theta_2)(-r \sin \theta_1) \quad (4)$$

$$J_l \dot{z} = (\tau_1 + m_2 g l \sin \theta_2)(-r \cos \theta_1) \quad (5)$$

In the sagittal plane, motion is induced by application of torque at the shoulder joint. The shoulder torque first accelerates the shoulder beam.

$$\tau_2 = m_3 l_3 \ddot{\theta}_3 \quad (6)$$

This motion causes two effects. One is a reaction torque, $\tau_r = -\tau_2$, which must be produced to conserve the angular momentum due to the rotation of the shoulder beam. The second is an impulse torque produced due to the collision of the shoulder beam with the joint stop τ_c . At any given angular velocity of the shoulder joint $\dot{\theta}_3$, the reaction torque τ_r will have the opposite sign as $\dot{\theta}_3$, and τ_c will have the same sign.

The rotation of the lower body in the plane normal to the reaction torque, θ_{τ_r} , caused by shoulder motion, is thus given as follows:

$$\tau_r + \tau_c = J_l \theta_{\tau_r}'' - \tau_f \quad (7)$$

where τ_f is the friction torque produced by the coefficient of static friction between the ground and the feet.

4 Control

Stumpy is controlled to move in a unique way by actuating its waist joint, with a back and forth swinging motion. This motion of the upper body imparts angular momentum to the base which creates a rhythmic hopping motion. During hopping, each lateral pair of foot contacts which can be considered together as a “foot”, experiences two phases: stance phase, in which the foot is on the ground and flight phase, during which the foot is airborne. At low frequencies of the upper pendulum, one foot completes its flight phase and returns to stance phase, before the second foot initiates flight phase. As a result, there are two phases in the gait cycle: single support and double support. Therefore, we term this gait “walking”. At higher frequencies, one foot is still in flight phase when the next foot enters flight phase, so the two phases in the gait cycle are single support, and airborne. Therefore we term this gait “running”. At the transition frequency, there is only one phase: single support. If the “shoulder” joint is unused, the robot will hop in place. The shoulder joint can be used to control movement in the sagittal plane. When a lateral forward rotation of the shoulder joint occurs, the foot will acquire a slight angular momentum during flight phase, which serves to project the foot forward. Thus the shoulder joint can be used to control movement direction, forward velocity and turning rate.

The control parameters are the frequency ω_1 , amplitude α_1 and setpoint θ_1^* of the waist joint oscillation, the frequency ω_2 , amplitude α_2 and setpoint θ_2^* of the shoulder joint oscillation, and the phase difference, ϕ , between ω_1 and ω_2 , when they are oscillating at the same frequency. The basic control for the waist motor is a simple reactive algorithm, which outputs a

constant motor voltage until the joint angle sensor detects the maximum amplitude α_1 , and then reverses the direction. Thus, the waist motor oscillates approximately between α_1 and $-\alpha_1$. The control of the shoulder joint is reactively coupled to the waist and functions in a similar way. The shoulder motor voltage remains constant, until the waist joint angle sensor detects that it has crossed the maximum amplitude α_1 . At this instant, the shoulder joint instantaneously reverses the motor torque. Due to this coupling, the waist and the shoulder joints are phase locked, such that the phase relationship ϕ between the waist and the shoulder joint is constrained to be either 0° or 180° . The hopping height of the robot mainly depends on the angular acceleration of the waist joint periodic motion. The maximum amplitude of the swing determines the region of stability of the structure during hopping. As in Raibert’s hopping robots, it has been experimentally found that the control of hopping height in this robot can be separated from the control problems of forward velocity, gait direction, and the radius of curvature of the robots turning trajectory. As the main focus was the control of movement direction, the hopping was tuned to a constant frequency, which produced a suitable hopping height and allowed for a wide range of motions. Controllers were then developed for straight walking, reversing direction and turning.

These controllers were implemented and tested on the robot. Data on position and velocity of the robot during locomotion was collected using a CCD camera suspended from the ceiling above a 3.0 m x 2.0 m experimental arena, and a framegrabber which recorded the movement of the robot at 25 frames/sec. For each experiment, the robot was initially positioned at the center of the image. It was equipped with four high-intensity LEDs, two on each side of the base and recorded in a darkened room. The camera image was then processed to identify the locations of the LEDs, from which the robots position and orientation was extracted and plotted once every second. The following sections describe the design and implementation of the controllers and present experimental data collected using this setup.

4.1 Tuning the Hopping Height

The hopping height and frequency were experimentally tuned by adjusting the motor voltage of the waist motor. It was found that if the motor voltage is too low, the angular acceleration is not fast enough to lift the feet off the ground for a significant amount of time. As, the motor voltage gets higher a stepping motion is induced but the frequency is not in tune with that of the mechanical structure. Within a small range of motor voltages, resonance with the mechanical structure produces a stable hop-

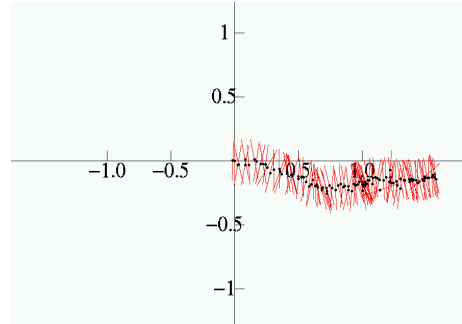


Figure 3: Forward walking, produced when $\nu_s^+ = \nu_s^-$, $\phi = 0^\circ$

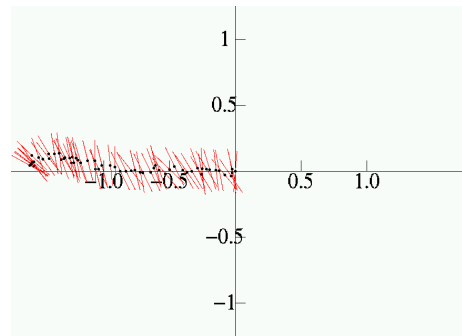


Figure 4: Backward walking, produced when $\nu_s^+ = -\nu_s^-$, $\phi = 180^\circ$

ping pattern is produced with high dynamic stability. Informal tests show that even large disturbances caused by accidental human intervention, such as “stepping on the robot’s foot”, are corrected by its self-stabilizing nature. In this range, the robot produces a “walking” gait, where one foot is always on the ground, and therefore lends itself to good direction control.

4.2 Straight Walking

As described above, the shoulder joint is coupled to the waist joint angle, and reverses the motor voltage at the maximum amplitude values. Thus, the basic control is such that ν_s^+ , the motor voltage applied to the shoulder during clockwise rotation, and ν_s^- which is the motor voltage applied to the shoulder during counter-clockwise rotation are related by relationship, $\nu_s^+ = -\nu_s^-$. In this situation, the forward momentum acquired by the left foot during flight phase, is equal to the forward momentum acquired by the right foot and, therefore, the alternating step sizes of the left and right foot are equal and the robot walks in a straight line. Results of the robot performing this behavior are shown in Figure 3. (The axes in this figure, and all other performance graphs are in metres).

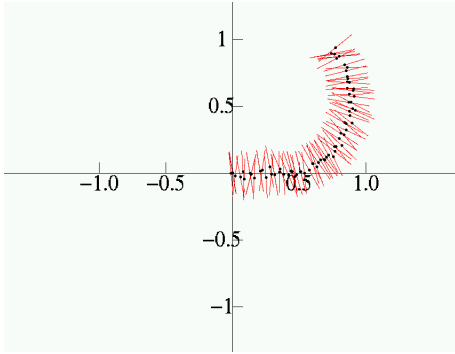


Figure 5: Turning left, with a small turning rate, produced when $\nu_s^+ < \nu_s^-$.

4.3 Reversing Direction

It was found that the direction of the robot, that is whether it would move in the forwards or backwards direction, was only dependent on the phase parameter ϕ . The following graph in Figure 4 shows how changing the phase from 0° to 180° , makes the robot move in the opposite direction from that in Figure 3.

4.4 Control of Turning Rate

The control of turning rate is achieved using an enhanced forward walking controller. In forward walking, the step lengths on the left and right sides are approximately equal. Using a similar controller, but by increasing the step length of one foot and shortening the other, the robot can achieve turning. Thus, we focus on the turning rate induced by the difference between the clockwise and counter-clockwise voltages applied to the shoulder motor. The turning rate, R , can be approximately given as $\dot{R} = K(\nu_s^+ - \nu_s^-)$. Thus, for example, in the case of $\nu_s^+ > \nu_s^-$, while the motor rotates clockwise, the foot in flight phase takes a large step, but while the motor rotates counter-clockwise, the other foot takes a smaller step, causing the robot to turn at a constant rate. The control of movement in the forward or backward direction, discussed in the previous subsection, is also independent of turning rate. Various combinations of ν_s^+ and ν_s^- have been tested, to exhibit different turning rates in both forward and backward walking. Figure 5 shows a small turning rate produced by the motor control of $\nu_s^+ < \nu_s^-$. Figure 6 also shows the performance with the same turning rate, but in the other direction, that is where $\nu_s^+ > \nu_s^-$. Figures 7 and 8 show the same behaviors but in the reverse direction. Then, larger turning rates are produced, when the difference between ν_s^+ and ν_s^- is greatly increased, which effectively produces turning in place, as shown in Figure 9 and 10.

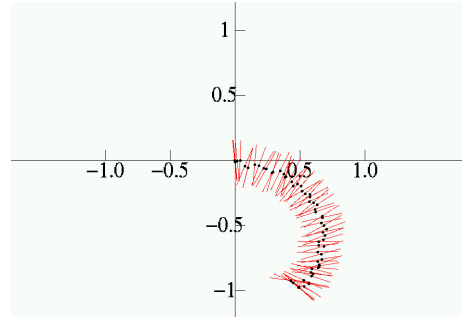


Figure 6: Turning right, with a small turning rate, produced when $\nu_s^+ > \nu_s^-$.

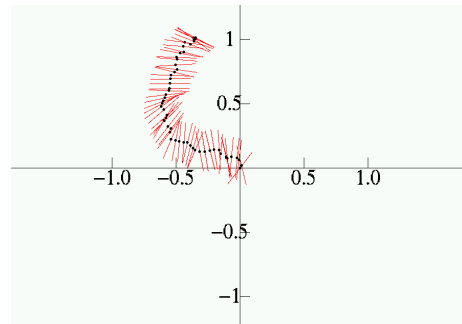


Figure 7: Going backwards and turning right, with a small turning rate, produced when $\nu_s^+ > \nu_s^-$. Simply by changing ϕ to 180° , the robot walks backward, as it slowly turns right.

5 Conclusions

In this paper a new kind of hopping robot with two feet, and no legs, has been presented. The controllers tested for control of forward motion, change of direction and turning rate, as described in the previous sections, achieved considerable success in displaying the desired behavior in real world experiments. The results showed that the preliminary controller concepts developed, were sufficient to fulfil the requirements of the tasks. However, the controllers were all open loop with respect to movement direction and velocity, and were thus sensitive to slight changes in mechanical biases in the robot, and environmental irregularities such as frictional differences on the ground and slight ups and downs of the terrain. To account for these uncertainties closed-loop control using sensor feedback must be added to these controllers. The selection of appropriate sensors and their use in a closed-loop control algorithm, are topics of further investigation.

In addition, many other interesting issues with respect to the performance and control of this robot remain to be investigated. One such topic is the self-stabilizing property of the robot. In this paper,

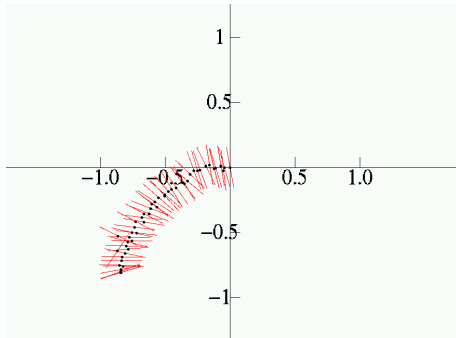


Figure 8: Going backwards and turning left, with a small turning rate, produced when $\nu_s^+ < \nu_s^-$.

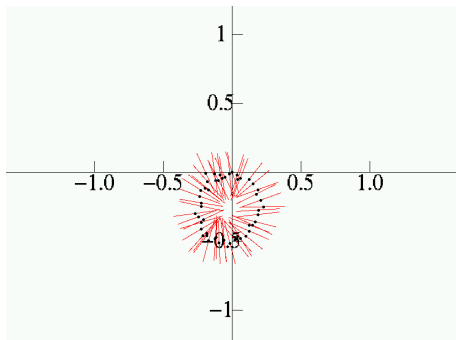


Figure 9: Turning right, with a large turning rate, produced when $\nu_s^+ \gg \nu_s^-$. With this controller the robot can effectively turn in place.

this property was exploited to achieve high dynamic stability during locomotion. However, it would be interesting to focus on this aspect more closely, and explicitly analyse the domain of attraction and its relationship to mechanical and control parameters. Another topic of potential interest would be the accurate control of forward velocity. Finally, what would also be of interest is the investigation of different gait patterns. The Stumpy mechanical structure is capable of moving in a variety of different ways, one of which (walking) has been investigated in this work. The exploration of some of the other dominant modes of locomotion such as running, quadruped-like lateral bounding, and “diagonal” gaits, will be exciting topics of further investigation, which will further exploit the versatility of the robot.

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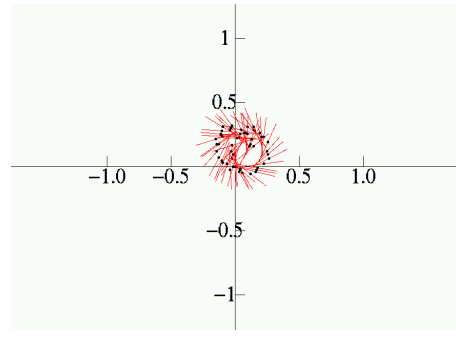


Figure 10: Turning left, with a large turning rate, produced when $\nu_s^+ \ll \nu_s^-$. Again the robot can effectively turn in place

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