

# Control of Lateral Bounding for a Pendulum Driven Hopping Robot

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## ABSTRACT

In this paper a novel hopping robot is introduced that uses inverse pendulum dynamics to induce several different 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, the robot is able to perform lateral bounding in addition to hopping forward, reversing direction and turning. Here, the control of lateral bounding is investigated and experimentally tested. The results show that two unique limit cycles exist for lateral motion. Ipsilateral bounding, in the same direction as upper body motion, is fast but unstable and could be used for emergency situations. Contralateral bounding, on the other hand, is stable and robust, and can be viable for practical long-range applications on uneven terrain. The characteristics and control of these two modes of locomotion are explored in this paper.

## 1 INTRODUCTION

The design and implementation of the Stumpy II<sup>1</sup> 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.

Use of pendulum dynamics in movement has been only partially explored. Hayashi *et al* [1] have designed a pendulum-type jumping machine which was capable of jumping up stairs. In

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

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

another example, Ioi *et al* [2] applied pendulum dynamics to the problem of wheeled locomotion, to roll up slopes and control forward velocity and turning. However, the use of pendulum dynamics to drive legged locomotion has not been previously considered<sup>2</sup>.

The control of gait and balance in hopping robots has been widely studied by Raibert and his colleagues [4] [5]. In these robots as the legs are long and narrow, they are statically unstable, and must continue to hop in order to stabilize their body. In the Stumpy robot, the four legs consist of a spring-loaded prismatic joints, but they are short and do not have any other degrees of freedom. Only the upper body is actuated. This has the advantage that the structure is statically stable, while allowing for dynamically stable locomotion.

The first studies conducted on the Stumpy robot [3], showed that it could hop forward, with both “walking” and “running” gaits, reverse direction, and turn with a variable radius. Here it will be shown that the robot is also able to hop in a direction lateral to its body, using only a single degree of freedom. The existence of such “lateral bounding” proves that the robot is holonomic, that is it can control its two translational degrees of freedom, and orientation independently. Moreover, since the hopping height can also be controlled, the robot actually controls four degrees of freedom, with only two degrees of actuation.

The following section, Section 2, describes the design of the Stumpy robot. The control of two modes of lateral bounding are developed in Section 3. The overall behavior of the robot is then experimentally demonstrated in Section 4. In section 5, the viable range of operation of the robot is experimentally determined by systematic variation of control parameters. Section 6 ends with a short discussion and conclusions.

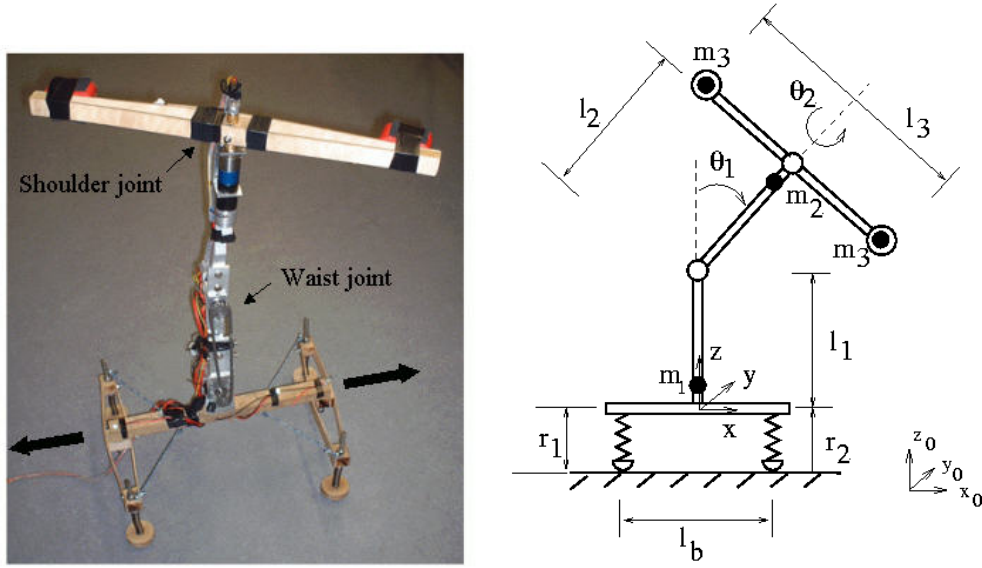
## 2 Robot Mechanical Structure

The lower body of Stumpy II (Fig. 1(a)) 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 (“waist”) providing one degree of freedom in the frontal plane. This enables the upper body to act as an inverted pendulum. 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 (“shoulder”), providing one rotational degree of freedom (in the plane normal to the vertical beam of the upper “T”). 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 shown in Figure 1(b) are detailed in the Table 1 below.

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



**Fig. 1: (a) photograph of the Stumpy II robot, indicating waist and shoulder joints. The dark arrows represent the lateral direction of motion. (b) schematic diagram of the robot labeled with variables used in analysis**

| 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 |

**Table 1: Mass and length parameters of the robot**

The joints are actuated using DC-Micromotors from Minimotor. 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 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 hopping motion. The control parameters are the amplitude of the oscillation about the setpoint,  $\alpha_1$ , the setpoint  $\theta_1^*$  and motor voltage  $u_1$  of the waist joint, amplitude  $\alpha_2$ , setpoint  $\theta_2^*$  and motor voltage  $u_2$  of the shoulder joint, and the phase difference,  $\phi$ , between the waist and shoulder oscillation when phase-locked. When one of the two joints is fixed at a constant angle, the fixed angle is represented by the setpoint  $\theta_1^*$  or  $\theta_2^*$  with  $[\alpha = 0, \omega = 0]$ .

Proportional position control is used to control the oscillation of the waist joint as follows:

$$u_1 = k_1(\theta_1 - \theta_d) \quad (1)$$

where  $u_1$  represents the waist motor voltage,  $\theta_d$  represents the desired position reference, and  $k_1$  the feedback gain.

The position reference trajectory is generated according to a linear velocity graph as follows:

$$\dot{\theta}_d = k_2((\theta_1 - \theta_1^*) - \alpha) \quad (2)$$

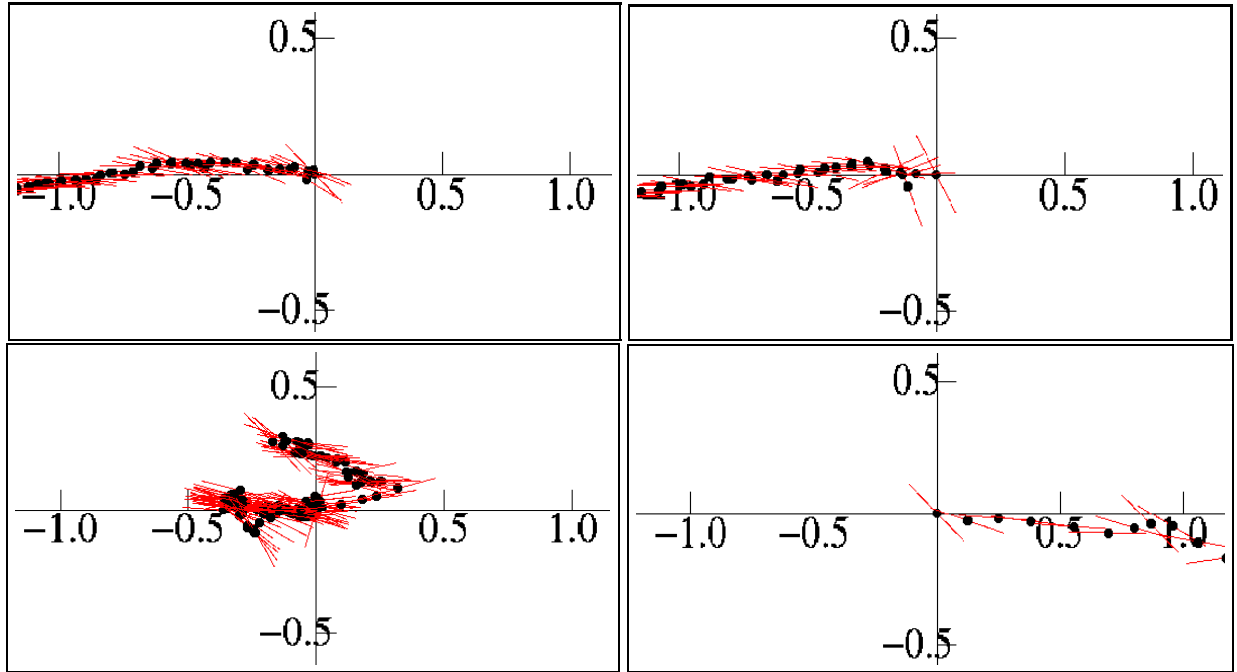
where  $k_2$  is a constant which determines the maximum desired angular velocity of the oscillation.

Thus, the waist motor oscillates approximately between  $\alpha_1$  and  $-\alpha_1$ , when  $\theta_1^*$  is 0. In this case, the robot hops in place. However, if the setpoint  $\theta_1^*$  is changed to a non-zero value, the robot changes its behavior to *lateral bounding*, that is, bounding in a direction lateral to the base of the robot. The direction of bounding is parallel to the frontal plane of the lower body, when the shoulder joint angle is fixed at  $\theta_2^* = 0$ . The shoulder joint can be used to control direction.

Lateral bounding can be produced over a large range of parameter values. The stability of the locomotion is greater in certain regions of the parameter space, where phase locking of the upper and lower body occurs. In a complex non-linear system such as Stumpy, in which factors such as joint friction, inherent compliances, and ground characteristics play a vital role, deriving and accurate analytical model can be challenging. In order to develop and validate such a model, a preliminary qualitative analysis of the system can prove fruitful. Therefore, the behavior of the system is studied experimentally. Data is collected on the overall behavior of the system, as well as through systematic variation of control parameters along the three axes of amplitude, setpoint and motor voltage of waist joint oscillation. The results are presented in the following sections.

#### 4 Overall Behavior

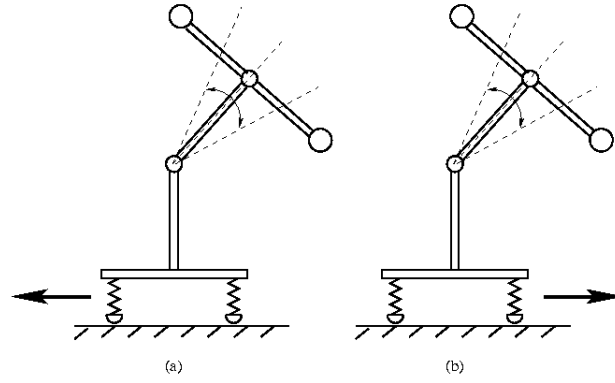
In the first set of experiments the goal was to study the overall characteristics of lateral bounding. The setpoint and amplitude were kept constant and the voltage was varied from 8V-12V in 1V increments. Data on position and velocity of the robot was collected using a CCD camera suspended from the 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



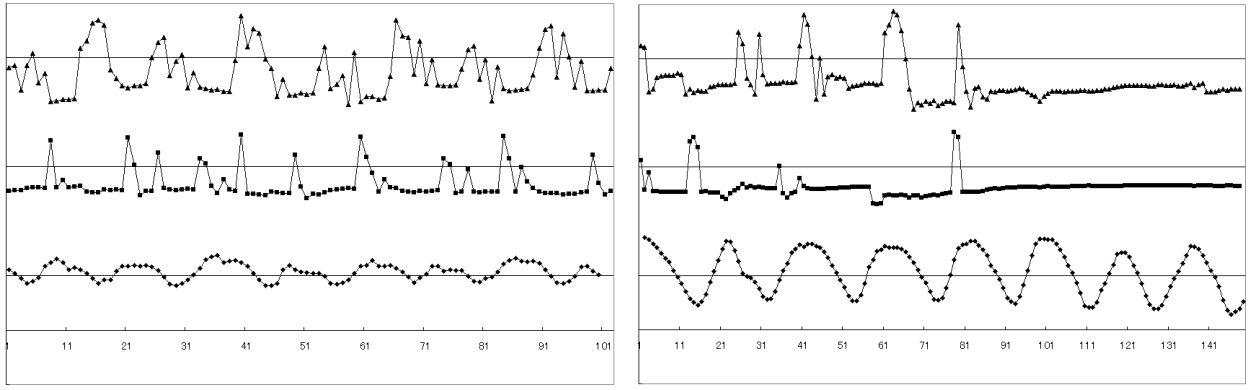
**Fig. 2: Position of robot, with oscillation setpoint of  $15^\circ$  and amplitude  $25^\circ$ , sampled at 25Hz (a)Top left: 9V (b) Top right: 10V (c) Bottom left: 11V (d) Bottom right: 12V (The axes are labeled in metres)**

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 robot's position and orientation was extracted and plotted once every second. The Figures 2(a)-(d) show some results of these experiments.

The results at 9V and 10V are very similar (Fig. 2(a)(b)). In both cases the robot moves in a direction opposite to the direction of the swinging of its upper body. However, at 11V an unusual phenomena occurs (Fig. 2(c)). The robot starts its motion in the same direction as in the previous cases, but then switches and continues to move in the opposite direction! At 12V the robot moves in the opposite direction from the very beginning (Fig. 2(d)). The interesting feature that can be observed in the graphs, is that there need not be any change in the direction or orientation of the base for this switch in direction to occur. Although different gait patterns are observed in each case, both gaits can be characterized as lateral bounding as the base of the body remains parallel to the direction of motion. Borrowing terminology from physiology, we describe the first motion as *contralateral* bounding, that is, motion in a direction opposite to the upper body movement. and the second as *ipsilateral* bounding, that is motion in the same direction as the upper body motion (Fig. 3).



**Fig. 3: (a) Contralateral bounding (b) Ipsilateral bounding**



**Fig. 4: Effect of Amplitude: (a) Amplitude 25°: stable contralateral motion (b) Amplitude 50°: Began ipsilateral motion and fell forward**

## 5 Effect of Control Parameters

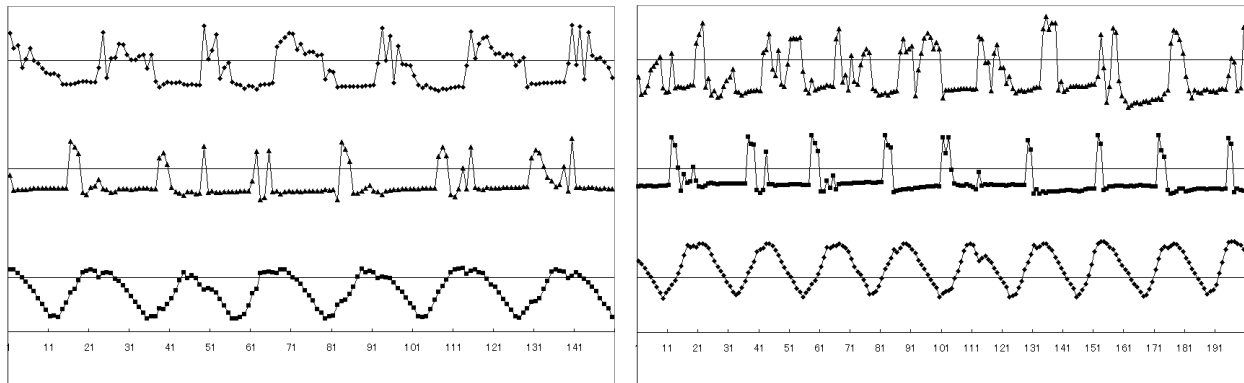
In order that lateral bounding be a viable form of locomotion for the robot, it was important to identify the regions in parameter space where stable gaits could be produced. Three sets of experiments were conducted, varying amplitude, setpoint and motor voltage. In the first set,  $[\alpha = 25, \theta_1^* = 30]$ , in the second  $[\alpha = 50, \theta_1^* = 30]$  and in the third  $[\alpha = 45, \theta_1^* = 50]$ . For each condition the motor voltage  $u_1$  was varied in 1V increments from 8V to 16V. This range was chosen as it was the range in which the robot showed lateral bounding behavior. At any voltage lower than this the robot barely moved, and at any voltage higher than this the robot mostly fell over.

### 5.1 Effect of Amplitude

Variation in amplitude, had a large effect on the motion (Fig. 4). At a setpoint of 30°, the gaits produced at an amplitude of 25°, had higher frequencies than their counterparts at 50°. This

was predictable as a much angular distance had to be traversed during each swing in the latter case. The amplitude  $25^\circ$  motion was also much more robust in that none of the cases fell over, compared to 3 out of 9, in the  $50^\circ$  case. However, in most cases, the graphs looked qualitatively similar in their pattern, and the most stable gait was produced at 10V in both cases.

## 5.2 Effect of Setpoint



**Fig. 5: Effect of setpoint: (a) At setpoint  $15^\circ$ : stable contralateral gait (b) At setpoint  $45^\circ$ : Random switching between gaits**

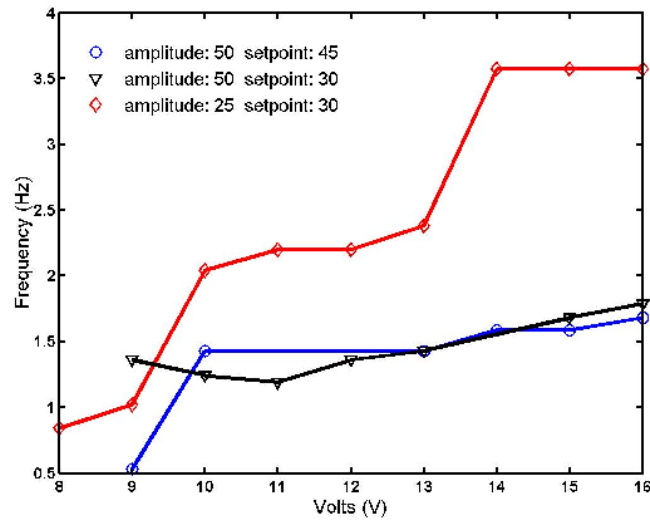
Variation in setpoint, seemed to have a very little effect on the gait pattern. At an amplitude of  $50^\circ$ , varying the setpoint from  $30^\circ$  to  $45^\circ$  made no change to the frequency of motion (Fig. 5). The stability of the rhythmic motion was also only slightly affected by the setpoint. At a setpoint of  $45^\circ$  the robot fell over four times, compared to three times in the  $30^\circ$  case. However, the difference may not be statistically significant. The pattern was also observed at other values of amplitude and voltage.

## 5.3 Effect of Voltage

Increase in the motor voltage lead to an increase in the frequency of the robots bounding motion. This can be seen in Figure 6. (Some points are missing in the figure; in these cases the robot fell to the ground soon after starting.) However, the effect of motor voltage on frequency was non-linear, as it caused a bifurcation between the two modes of bounding.

## 6 Conclusions

In this paper a novel pendulum driven hopping robot has been presented. The hopping of the feet is induced indirectly by the motion of the upper body. Control of this mechanical structure has been investigated for lateral bounding gaits, which are a subset of the set of possible gaits of the robot. Experimental evidence shows that the robot is capable of producing two different



**Fig. 6: Plot of voltage vs. period of bounding.**

kinds of lateral bounding. The conditions under which these gaits are produced, and the control parameters which influence them have been explored. The results show that lateral bounding is a viable mode of locomotion, which is robust to environmental disturbances.

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