

# Minimalistic Control of a Compass Gait Robot in Rough Terrain

Fumiya Iida and Russ Tedrake

**Abstract**—Although there has been an increasing interest in dynamic bipedal locomotion for significant improvement of energy efficiency and dexterity of mobile robots in the real world, their locomotion capabilities are still mostly restricted on flat surfaces. The difficulty of dynamic locomotion in rough terrain is mainly originated in the stability and controllability of gait patterns while exploiting the natural mechanical dynamics of the robots. For a systematic investigation of the challenging problem, this paper presents the simplest control architecture for the compass gait model which can be used for locomotion in rough terrain. Locomotion of the model is mainly achieved by an open-loop oscillator which induces self-stabilizing gait patterns, and we test the proposed control architecture in a real-world robotic platform. In addition, we also found that this controller is capable of varying stride length with a minimum change of control parameters, which enables locomotion in rough terrains. By using these basic principles of self-stability and gait variability, we extended the proposed controller with a simple sensory feedback about the location in the environment, which makes the robot possible to control gait patterns autonomously for traversing a rough terrain. We describe a set of experimental results and discuss how the proposed minimalistic control architecture can be enhanced for dynamic locomotion control in more complex environment.

## I. INTRODUCTION

Since the pioneering work of the Passive Dynamic Walkers (PDWs: [1], [2]), the problem of dynamic walking has attracted a number of researchers in order to understand and improve locomotion capabilities of legged robots. Previously many dynamic walking robots demonstrated fascinating properties of self-stability in mechanical walking dynamics and energy efficiency. More recently, to increase their adaptability to variations of environment, the PDWs were extended with actuators [3], [4], [5], [6], [7], [8], but the problem of actuation and control of the PDWs appears to be non-trivial because of the nonlinearity originated in complex mechanical dynamics, and the locomotion capabilities of these robots are still restricted in a flat environment.

For a systematic investigation of dynamic walking, the so-called compass gait walking model has been intensively studied. There are a few important advantages in the compass gait model. First, the model is sufficiently simple that the walking dynamics can be analytically tractable. Second, unlike most of the dynamic walking robots which have large curved feet, the compass gait model generally assumes point feet, which facilitates control of foot placement in rough terrains. And third, due to its simplicity, the model can be easily extended to its variations for a systematic analysis.

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Previously this simple model showed limit cycles of passive dynamic walking in slopes [9], and the model was enhanced with various motor control to deal with a flat terrain [10], [11], [12], [13] and with the other variations of environment [14], [15], [16], [17], [18]. The investigations of this model, however, were mainly conducted in simulation with a few exceptions [10], [12], and the model has not been tested in the real-world rough terrains previously.

The primary goal of this paper is to propose a minimalistic control strategy of the compass gait model and test it in a real-world robot platform. Based on the original model of compass gait biped, we developed a robotic platform with three actuators in hip and feet to cope with the real-world constraints in rough terrains (all of the experimental results in this paper were generated by this robotic platform). These motors are then controlled by the simplest controller which is an open-loop sinusoidal oscillator. Despite its simplicity, this controller exhibits surprising stability of periodic locomotion on a level ground as well as downhill/uphill slopes. In addition, we will also show that, with a slight change of control parameter in the oscillator, this controller is able to vary stride length which can be used for control of foot placement in rough terrains. As a case study of locomotion in rough terrain, we will finally demonstrate how the proposed open-loop control architecture can be extended with a sensory feedback, and analyze the capabilities and limits of the proposed approach.

In the next section, we will first explain the design and control architecture of the compass gait robot. We will then analyze walking dynamics on a level ground generated by the open-loop controller, and the influence of control parameters with respect to gait variability. And finally, we will show a case study of the proposed control strategy in a rough terrain.

## II. COMPASS GAIT ROBOT

We developed a robot platform based on the compass gait model as shown in Fig. 1. The robot consists of two leg segments connected through a hip joint, where a direct-drive motor (Maxonmotor RE40 with no gear reduction) exerts torque between two legs. The hip joint is then connected to a boom that allows pitch rotation while restricting yaw and roll. At the other end of the boom, we installed a counter weight to avoid a large ground impact of every step, and of harmful crashes of the entire robot. Each leg segment has a servomotor (Hitech HSR-5980SG) that extends and retracts a foot segment for ground clearance during swing phase (see Table I for more specifications of the robot platform).

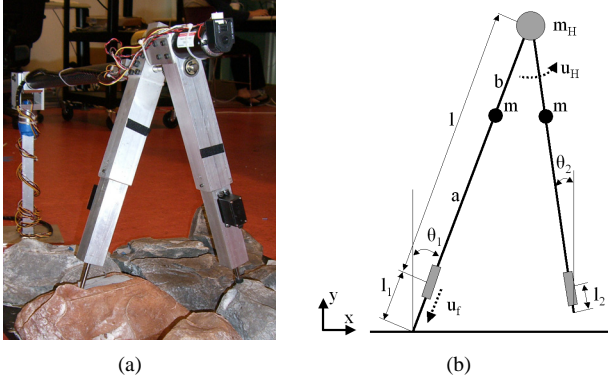


Fig. 1. a) Photograph of Compass Gait Robot and (b) Compass Gait Model with hip and foot actuators (gray circle and rectangles). Black circles denote the centers of mass of legs, which are determined by  $a$  and  $b$ .

TABLE I  
SPECIFICATION OF THE ROBOT.

Param.	Description	Value
$a$	Lower Leg Segments	0.260 m
$b$	Upper Leg Segments	0.055 m
$l_1, l_2$	Foot Segments	0.000-0.040 m
$m$	Mass of Leg	1.3 kg
$m_H$	Mass of Body	0.2 kg
$CW$	Counter Weight	4.1kg
$BL$	Boom Length to Robot	1.210m
$BL2$	Boom Length to Counter Weight	0.560m
$A$	Amplitude of Oscillation	1.0Nm
$P_{r,l,12}$	Amplitude of Foot Extension	0.000 – 0.015m
$\phi$	Phase Delay of Foot Oscillation	2.2rad

The swing-leg dynamics of the compass gait model can be described as follows.

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) = Bu \quad (1)$$

where  $q = [\theta_1, \theta_2, l_1, l_2]^T$ , and  $u = [0, u_H, u_f, 0]^T$  ( $u_H$  and  $u_f$  are torque generated by the hip and stance foot actuators). Note that, compared with the original compass gait model, this model has additional state variables  $[l_1, l_2]$ , which represent extension and retraction of massless foot segments.

At the ground contact of the swing leg and switching to the stance leg, the compass gait model generally assumes the conservation of angular momentum around the hip joint and the toe of the swing leg.

$$\dot{q}^+ = Q\dot{q}^- \quad (2)$$

where  $Q$  represents a transition matrix of swing and stance legs, + and - signs denote the state variables right after and right before the swing leg touchdown.

For sensory feedback and measurement of locomotion dynamics, we implemented an encoder at the hip motor (Maxonmotor HEDS5540), force sensitive resistors in both foot segments, and a potentiometer that measures horizontal

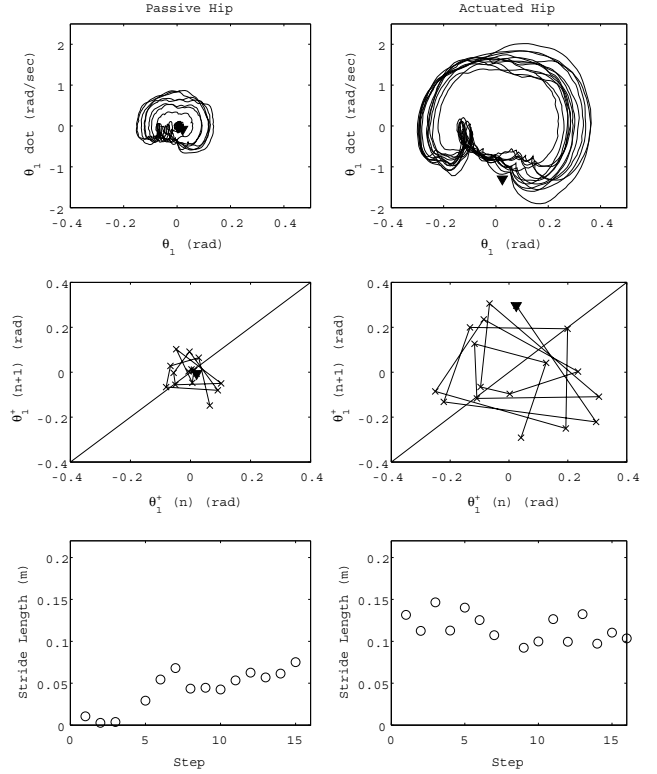


Fig. 2. Basin of attraction with and without hip actuation. Phase plots (top), return maps of the robot's outer leg (middle), and corresponding stride length (bottom). Black triangles denotes the beginning of data recording.

position around the boom. These motors and sensors are connected to a PC104 computer (Digital-Logic MSM-P5SEN) with a sensor board (Sensoray Model-526), which allows us the control bandwidth of approximately 100 Hz. In addition, in order to measure the overall dynamics of the robot during locomotion, we conducted the experiments under the motion capture systems (Vicon MX consisting of 16 cameras, which use infrared light to track reflective markers on the robot at approximately 120Hz sampling rate).

In the rest of paper, we consider a minimalistic control strategy in which an open-loop low-level motor controller plays an important role to induce self-stabilizing walking dynamics. The controller uses a sinusoidal oscillator with no sensory feedback which regulates a synchronous periodic movement of all three motors of the robot (the hip and foot actuators). More specifically, torque of the hip motor  $u_H$  is determined by the output of sinusoidal oscillation, and target positions of the foot motors  $P_{\{r,l\}}(t)$  are specified by a square wave synchronized with the sinusoidal oscillator with a phase delay  $\phi$ :

$$u_H(t) = A \sin(2\pi ft) \quad (3)$$

$$u_f(t) = K_p(l_i - P_{ri}(t)) + K_d(\dot{l}_i - 0.0), \quad (4)$$

$$P_{\{r,l\}}(t) = \begin{cases} P_{\{r,l\}1} & : \sin(2\pi ft + \phi) > 0 \\ P_{\{r,l\}2} & : otherwise \end{cases} \quad (5)$$

where  $A$  and  $f$  are amplitude and frequency parameters that

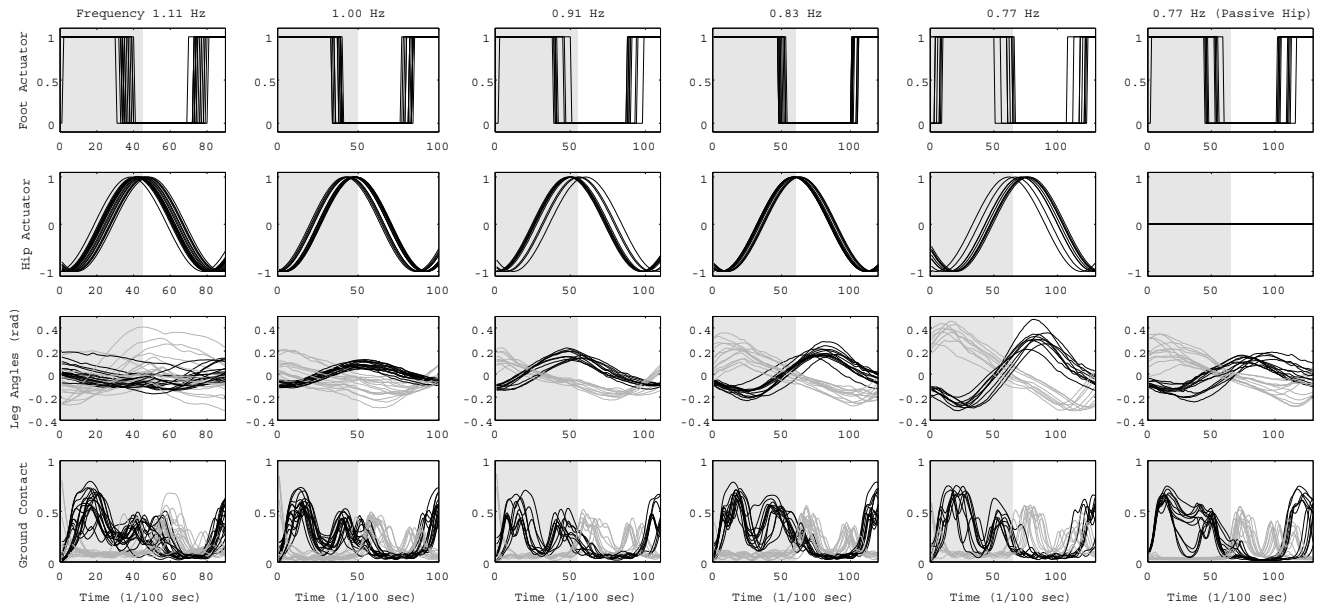


Fig. 3. Time series trajectories of walking dynamics with different frequency parameters. Experimental data of 10 steps are aligned with respect to the ground reaction force of a leg. The gray rectangles in each plot represents the stance period of a leg based on the ground reaction force. The trajectories of foot and hip actuators, and the ground reaction force are normalized.

determine hip joint torque,  $K_p$  and  $K_d$  are the proportional and differential gains of PD controller, and  $P_{\{r,l\}\{1,2\}}$  represents given setpoints of the right and left foot segment.

### III. LOCOMOTION DYNAMICS AND CONTROL

When we properly set the parameters of the controller described in the previous section, the compass gait robot exhibits stable periodic walking gait on a flat terrain. This section explains self-stability and gait variability induced by the proposed low-level motor controller through the experimental results of steady state locomotion.

#### A. Steady State Dynamics

The stable walking of the compass gait robot is a result of the interaction between the hip and foot actuators. The first set of experiments was conducted on a flat terrain with a few different configurations of control parameters to characterize the self-stability induced by the proposed control strategy.

Fig. 2 shows a phase plot and return map of one of the legs, and stride length of every step with and without the hip motor control. As shown in the left plots of Fig. 2, the basic locomotion dynamics of the compass gait robot can be generated simply by using the foot segment control without hip actuation (i.e.  $u_H = 0.0$ ). Specifically, even with an initial condition of  $[\theta_1, \theta_2, \dot{\theta}_1, \dot{\theta}_2]^T = [0, 0, 0, 0]^T$ , walking dynamics of the robot reaches a limit cycle of dynamics resulting in steady stride length after several steps. While this walking dynamics is relatively stable on a flat terrain, the walking direction is not controllable (the limit cycle of forward or backward walking is largely dependent on the initial conditions and environment), and the robot is not able to walk uphill. In contrast, with the hip actuation, we can

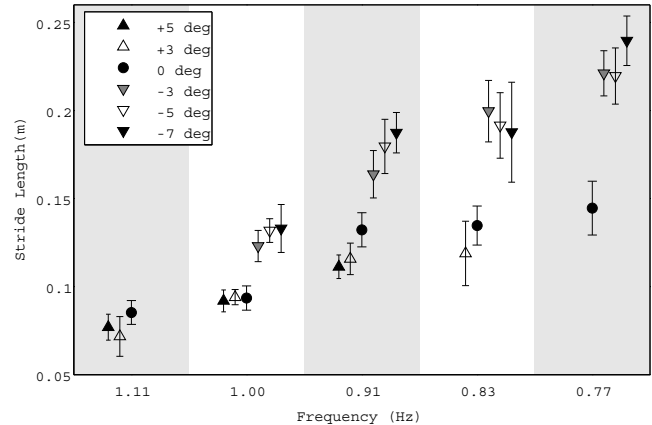


Fig. 4. Variability of stride with respect to five frequency parameters in the different inclinations of slope (downhill -3, -5, -7 degrees, level ground, and uphill: +3 and +5 degrees). Every plot represents a mean stride length of 10 steps and their standard deviation in each environment.

observe a similar limit cycle of locomotion (Fig. 2 right plots), but the amplitude and the perturbation of leg swing are much larger resulting in the longer stride.

Fig. 3 shows the trajectories of motor command  $[u_H, u_f]$  and leg angles  $[\theta_1, \theta_2]$  of successive ten steps, which are aligned with respect to the ground contact detected by the foot pressure sensor. The locomotion with passive hip joint (right most figure) shows how the foot retraction (the foot actuator value switching from 1 to 0) is corresponding the transition of stance to swing phase at about 0.6 sec. With the hip actuation, although the amplitude of leg swing is much larger, the stance-swing transition happens as soon as the foot actuator retracted. This explains that the basic principle of

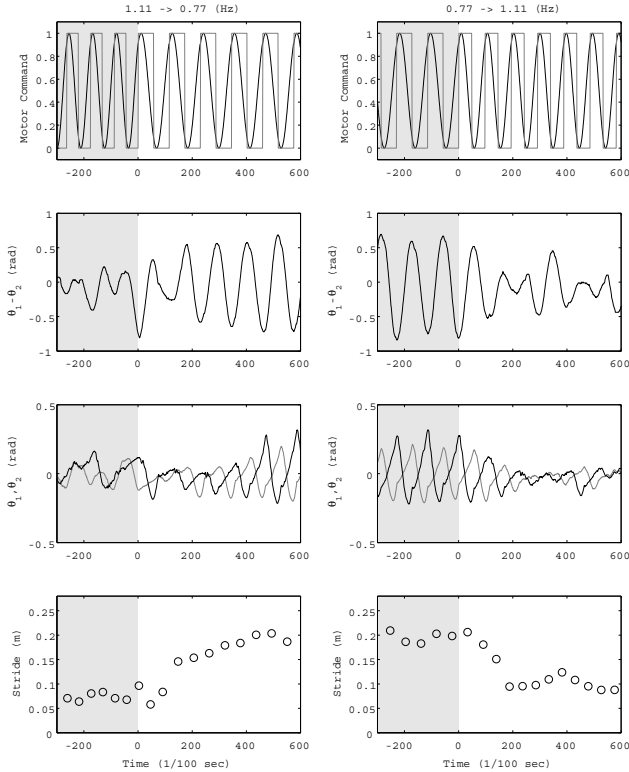


Fig. 5. Walking dynamics at the change of frequency parameter. The frequency was switched from 1.11 to 0.77 Hz at time  $t = 0.0$  (left figures), and from 0.77 to 1.11 Hz (right figures). The time series data of motor command of hip and foot actuators, inter-leg angles, left and right leg angles, and stride length (from top to bottom figures) are shown.

self-stabilizing gait pattern lies in the extension and retraction of foot actuation.

### B. Gait Variability

The self-stability of walking dynamics works also for a certain range of the frequency parameter  $f$  of the oscillator. Fig. 3 shows that the transitions between stance and swing legs take place slightly after the retraction of the foot segments, although the time delay becomes larger with the higher frequency of the oscillator. In addition, this figure also shows that the amplitude of leg swing becomes larger as the period of oscillator increases because of the larger energy provided by the hip actuators. The variability of swing amplitude with respect to the frequency parameter is particularly important as it influences the stride length of walking. Fig. 4 (the filled circle plots) shows the mean stride length and standard deviation of ten steps of walking with respect to the set of frequency parameter. From this figure, it is possible to increase stride length of the steady state locomotion approximately 50% by changing the frequency from 1.11 to 0.77 Hz.

The same set of frequency parameters was also tested in different inclinations of slopes in order to analyze controllability of foot placement in rough terrains. Fig. 3 shows that the robot is able to walk with different stride length in large variety of slopes (between +5 and -7 degrees). On

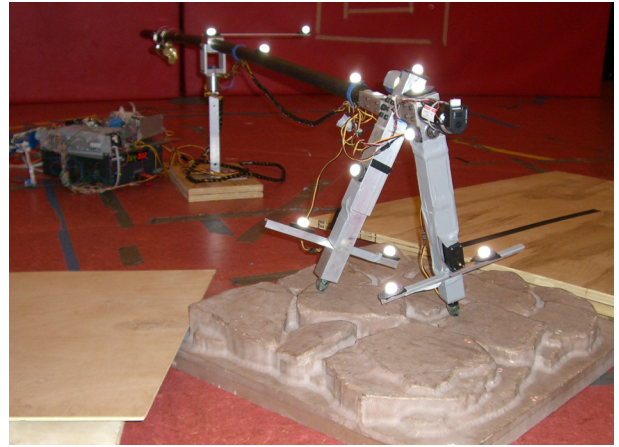


Fig. 6. Rough terrain experiment with the motion capture system. 12 markers are attached in the boom and legs.

the level ground, the variability of stride length is between approximately 0.09 and 0.15 m. With the same range of the frequency parameter, the stride length becomes larger in downhill, and smaller in uphill environments. An important characteristic of the proposed control architecture is the fact that, the robot is not able to walk uphill with the lower frequency of oscillator, and downhill with the higher frequency. More specifically, the +5 degree uphill can be dealt with by the frequency of 0.83Hz and larger, and the robot can walk down -7 degree slope with the frequency of 1.0Hz or lower. In other words, the limit of the proposed controller is the control of small stride in downhill, and large stride in uphill.

### C. Dynamics at the Transition of Control Parameter

Although gait patterns can be varied with the different frequency values as shown in the previous subsection, we generally observe time delay in convergence of stride length when the frequency parameter is changed during locomotion. Since the dynamics of such a transition could be critical in autonomous control of locomotion in rough terrain, here we analyze the transition dynamics in detail.

It generally requires a few steps before converged to a steady stride length, but the duration and the number of steps during transitions depends on the frequency values. Fig. 5 shows typical two cases of dynamics at transitions of the frequency parameter. When the frequency is switched from 0.77 to 1.11 Hz (right figures in Fig. 5), stride length is converged to a steady state after three steps, although it requires more steps when decreased from 1.11 to 0.77 Hz (left figures). From the time-series trajectories of inter-leg angles and absolute leg angles, it appears to require more time to increase the amplitude of leg swing than to decrease.

## IV. LOCOMOTION CONTROL IN ROUGH TERRAIN

One of the most significant advantages of the proposed control architecture lies in the fact that, by exploiting the self-stability, one control parameter is sufficient to vary the basic

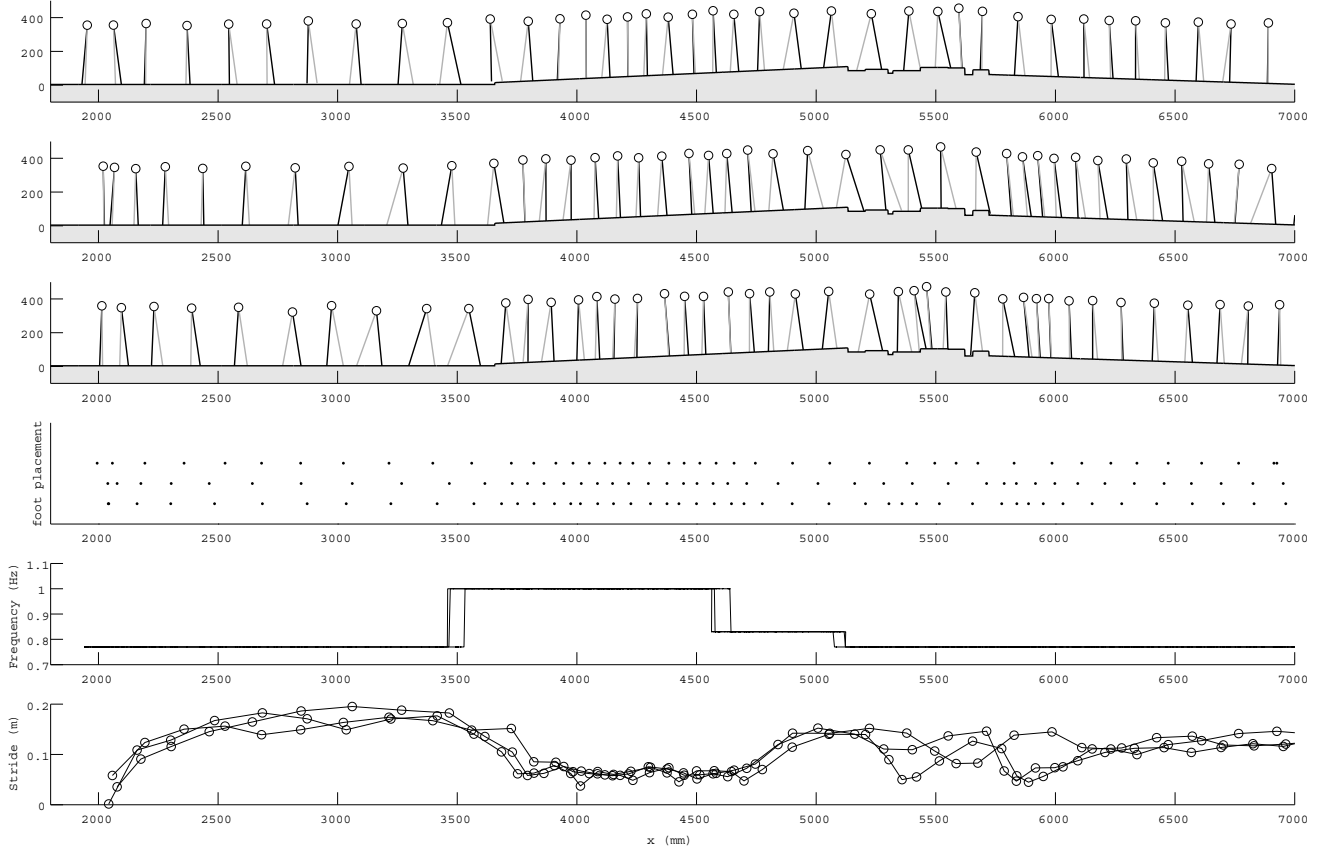


Fig. 7. Walking experiments in rough terrain. Top figures show the trajectories of the three successful travels of the rough terrain. The location and pose of the robot are depicted every 0.8 second. The dots in the middle plot represent foot placement over three successful trials. The lower plots show the frequency parameter of oscillator, and the stride length of every step during the three successful trials.

walking dynamics, and as a result, optimization of the feedback control to deal with rough terrains can be significantly simpler. This section explains how the aforementioned open-loop controller can be extended with a sensory feedback about the environment, and analyzes the performance of locomotion in a rough terrain.

#### A. Feedback Controller

For the sake of simplicity, we assume that the feedback controller receives only the location on the horizontal axis every control step, and determines the frequency value of the oscillator. The feedback controller, therefore, can be described as

$$f = freq(x, t) \quad (6)$$

where  $x$  represents the current horizontal position of the hip joint with respect to an absolute coordinate system. The function  $freq(x, t)$  also depends on the time variable of oscillator, because the controller is allowed to change the frequency only at the end of every oscillation period for smooth transitions of motor command.

In the following case study, we heuristically determined the function  $freq(x, t)$  for a given rough terrain. Owing to the minimalistic control architecture, it requires only several

trials and errors until we found a set of thresholds for the parameter  $x$  for multiple successful travels over the rough terrain.

#### B. Experiments

The rough terrain that we tested in this case study consists a flat terrain, an uphill slope, molded "flat rocks", and a downhill as shown in Fig. 6 and 7. The important features of this terrain are a +3.75 degree uphill, -2.60 degree downhill, 0.60m of rough terrain with the largest gap length of 0.03m and the largest step height of +0.02m and -0.03m.

After several trials and errors, we set the control parameters as follows:

$$freq(x, t) = \begin{cases} 0.77 \text{ Hz} & : x < 3.4m \\ 1.11 \text{ Hz} & : x \geq 3.4 \text{ and } x < 4.5m \\ 1.00 \text{ Hz} & : x \geq 4.5 \text{ and } x < 5.1m \\ 0.77 \text{ Hz} & : x \geq 5.1m \end{cases} \quad (7)$$

This controller was tested under the motion capture system to record the kinematics of the robot, and three successful travels over the rough terrain are reproduced in Fig. 7. In general, the controller is able to maintain the locomotion mostly on the flat surfaces including the uphill, the downhill, and the small step around  $x = 3.6m$  (See also the video

attached to this paper). It is important to note that, even though there are some variance in the foot placement, the controller is able to cope with locomotion over sparse gaps and steps on the ground by appropriately setting the function  $freq(x, t)$ . Note also that the stride length with respect to the frequency parameter is mostly comparable to the steady state locomotion experiments in Fig. 4 (i.e. 0.19m stride length at the frequency of 0.77Hz, and 0.05m at 1.11Hz, for example).

The limitation of the controller, however, is that it occasionally failed on the rocks ( $x = 4.9 - 5.5m$ ). Considering the large variance of stride length in this area of the terrain shown in Fig. 7, the main reason of failures seems to be originated in the irregular ground interactions.

## V. CONCLUSION

This paper presented a minimalistic control architecture of a biped robot for dynamic walking in rough terrain. By exploiting self-stabilizing property of the open-loop control architecture, we analyzed how the frequency parameter of oscillator influences gait patterns of the compass gait robot, and walking dynamics in rough terrain. The main contribution of this paper lies in the fact that a simple open-loop based controller can deal with various uneven terrains such as steady walking in uphill and downhill slopes as well as controlling foot placement to deal with gaps and steps. This simple controller is particularly important for planning and optimization of locomotion control in moderately complex environment. In the case study we showed in Section IV, for example, it required only several trials and errors until we found the set of parameters. It should, therefore, be straight forward to automate the search process of control parameters by using a depth-first algorithm, for example.

For dynamic locomotion in more complex environment, however, we also identified a few limitations of the proposed control framework. As the angle of slope increases, for example, controllability of stride length is degraded. More specifically, it is difficult to control short stride length in a steep downhill slope, and large stride length in uphill. Another limitation of the proposed control framework is the time delay of control: it requires a few steps of time until the stride length converges to a desired target. And finally, more precise control of foot placement is still an open issue for higher success rate of traverse in complex terrains.

For a systematic investigations toward these problems, we expect that the proposed simple model can be extended to its variations. A few potential research directions in the future include the extension of physical model with knee and ankle joints as previously shown in [10], [12], [19], and the enhancement of the control architecture with more dynamic features [13], [18], [20], [21].

## ACKNOWLEDGMENTS

This work is supported by the National Science Foundation (Grant No. 0746194) and the Swiss National Science Foundation Fellowship for Prospective Researchers (Grant No. PBZH2-114461).

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