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Exploiting Friction for the Locomotion of a Hopping Robot

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Abstract

For the locomotion of animals and machines, the friction between the body and the ground is one of the most crucial factors for stability and mobility. In this paper, we investigate how the friction could be exploited for the purpose of adaptive locomotion. At first, we propose two conceptual working hypotheses, especially focusing on two important issues, (1) how to control the friction to increase the stability of a locomotive system, and (2) how the friction could mobilize a system for a form of adaptive locomotion. Secondly, by using a hopping robotic platform we have developed, we evaluate the proposed ideas with three experimental case studies. The experimental results show the statistical plausibility of the proposed idea of increasing the stability of locomotion. Furthermore, it is shown that, by properly taking advantage of the friction, the robot could enlarge the repertoir of locomotion behaviors, which could presumably enhance the adaptability of robot locomotion.

1. Introduction

Compared to artificial locomotive systems, animals are capable of remarkable adaptive locomotion in an unpredictable environment. One interesting phenomenon is that, for locomotion purposes, biological systems adaptively take advantage of the friction between the ground and the contact points of their body. Moreover, the use of such a mechanism of locomotion covers a wide variety of species in nature, from worm/snake style locomotion to shuffling locomotion of legged-animals. In this paper, by using synthetic methodology, we investigate how the friction between a system and the ground could be exploited for the purpose of locomotion.

A number of the snake-like robots developed by Hirose and his colleagues is one of the pioneering studies in which artificial robotic systems actively exploit the friction for a form of adaptive locomotion [2]. In these studies, inspired by biological studies of snakes, they have successfully demonstrated snake-like locomotion. For legged-locomotion, although the designs of robotic morphology and controllers largely take account of the friction force, the friction is only partially exploited, i.e. in a hold-or-release fashion. For example, the ZMP-based control generally assumes that the friction force should be sufficient to prevent sliding of the legs [6]. One of the disadvantages of such a design strategy is that the ecological niche of a robot is quite often very limited, and that it results in a restricted locomotion capability.

To complement these points, in this paper we propose two working hypotheses with which artificial systems could actively exploit the friction for locomotion in the real world. The first hypothesis concerns the stability of the robot locomotion process. And, for the second hypothesis, we propose a conceptual design principle with which a legged-robot could actively take advantage of ground friction to mobilize itself. These hypotheses are then tested by using a hopping robotic platform we have developed.

The structure of this paper is as follows. We first propose two conceptual design principles of such a form of locomotion based on simple physics. By using a hopping robot described in section 3, these design principles are then tested with 3 case studies explained in sections 4, 5 and 6. We will discuss further issues in section 7.

2. Design Principle to Exploit Friction for the Locomotion

In this paper, we consider how friction could be exploited for a form of locomotion. We propose two working hypotheses; (1)friction could contribute to increase the stability of locomotion processes and (2)it could be possible to mobilize a system for a form of adaptive locomotion by properly exploiting the friction. In this section, we consider simple physics as a basis of argument. Since the physics of friction is highly complicated and depends on many parameters, the purpose of the following consideration is not to prove the hypotheses, rather we attempt to characterize the concepts above.

2.1. Increasing the stability of locomotion

Figure 1 shows a schematic to consider locomotion stability of a robot. When an external force F is exerted to an end of the rectangular object on the ground, the movement of the object could be either translational or rotational with respect to the ground. In other words, it would slip or fall down. The parameters which determine the movement are, at least, the friction (coefficient of the friction and mass of the object), the external force F, and the shape of the object (h and d in Figure 1).

Although it is difficult to derive the necessary conditions from this static analysis, a design principle of a stable system could be shape and mass of the object and coefficient of the friction. We will discuss further issues of this working hypothesis in the following sections.

2.2. Locomotion by controlling the friction

In this subsection, we propose the second hypothesis in which we consider how the friction could be actively exploited for locomotion. The conceptual idea is illustrated in Figure 2. In this figure, there are two oscillatory forces generated (for instance, by motors) in an object, F_h and F_v, that are represented as follows.

$$F_h = A_0 sin(\omega_0 t) \tag{1}$$

$$F_v = A_1 sin(\omega_1 t + \phi) + B_1 \tag{2}$$

where A_0 and A_1 are amplitude, ω_0 and ω_1 are frequency, ϕ is a phase between two oscillations, and B_1 is a set point. Here, we assume that the friction F_r between the object and the ground can be approximated by the following equation.

$$F_r = \mu \cdot F_v \tag{3}$$

where μ is a nominal coefficient of friction. The equation of the object movement, therefore, can be represented as follows.

$$\begin{aligned} \frac{d(mv)}{dt} &= F_h - F_r \\ &= A_0 sin(\omega_0 t) \\ &\quad -\mu(A_1 sin(\omega_1 t + \phi) + B_1) \end{aligned} \tag{4}$$

From this equation, the major parameters that govern the object movement can be the amplitude A, the friction coefficient μ, the frequency ω, and the phase ϕ.

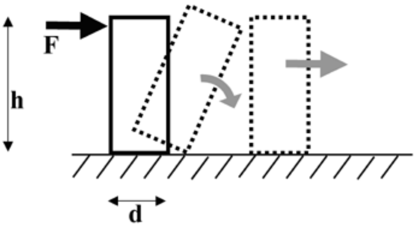


Figure 1: Concept of increasing stability

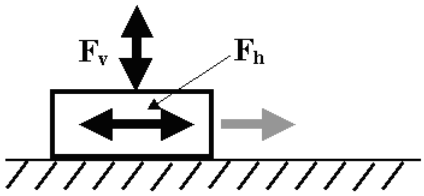


Figure 2: Concept of the locomotion by exploiting friction

Note that, in the case of locomotion, B_1 can be regarded as a gravitational force induced by the mass of the object itself, therefore it should be assumed as a constant. Many forms of locomotion can be described by this equation. For instance, this system can be applied to one of the legs of a walking biped. In this case, the value of amplitude A_1 could be large enough to lift a leg, which results in an optimal energy efficiency for moving forward without the energy loss due to the friction. However, F_v does not need to be greater than the force which requires to lift a foot. This is the point of our interest in this paper.

The intention of introducing this equation is to characterize a conceptual form of locomotion. Therefore, one of the purposes of this paper is to elucidate to what extent this conceptual form of locomotion can be applicable. In the following sections, we investigate this concept by using a robotic platform we developed.

3. Robotic Platform

In this section, we describe the design and control of the Stumpy robot [3] [4] we have developed as an experimental platform. In the later sections, the behaviors of this robot will be analyzed to examine the hypotheses explained in the previous section.

3.1. Mechanical design of the Stumpy robot

The morphology of the Stumpy robot consists of two "T" shape components, called "upper body" and "lower body" (Figure 3). The Stumpy robot's lower body is made of an inverted "T" mounted on

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

Param.	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
s	spring constant of feet	1.11 kg/cm

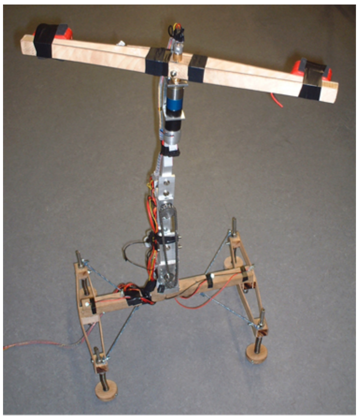


Figure 3: Photograph of the Stumpy robot

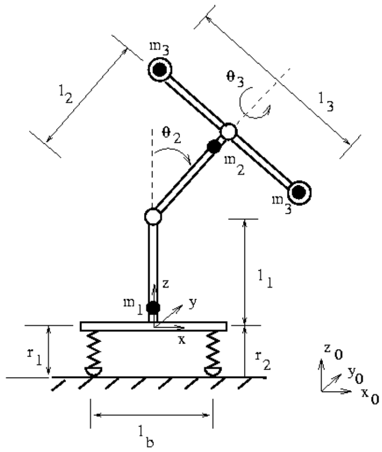


Figure 4: Schematic illustration of the Stumpy robot

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. 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. Table 1 shows more detailed specifications.

3.2. Control of the robot

Stumpy is controlled to move in a unique way by actuating its waist joint, with a right and left swinging motion. This motion of the upper body imparts angular momentum to the base which creates a rhythmic hopping motion. In this study, we employ a proportional control to track simple sinusoidal target trajectories for this upper body oscillation. For the sensory feedback, the angular position of the upper body with respect to the base is acquired by a potentiometer incorporated in the waist joint. The parameters we tested in the following experiments are, therefore, set point, amplitude, and frequency of the sinusoidal oscillation. The second motor which is equipped in the shoulder joint is also controlled in a oscillatory manner, although we did not use the potentiometer feedback, but it is simply synchronized to the control of waist motor.

3.3. Friction

The friction during the operation of Stumpy is very difficult to measure, but a good estimate to represent the friction between the robot and the floor would be a nominal coefficient of friction. In the following sections of this paper, we will conduct comparative studies of robot's behaviors in two different flat terrains in order to compare the effect of different friction force to the behaviors of robot, which we call "Terrain 0" and "Terrain 1" for the sake of convenience. The nominal friction coefficients are approximately, 0.29 in Terrain 0, and 0.46 in Terrain 1. This data provide us a good approximation of the slipperiness of these two environments, i.e. Terrain 0 is more slippery than Terrain 1 for the robot.

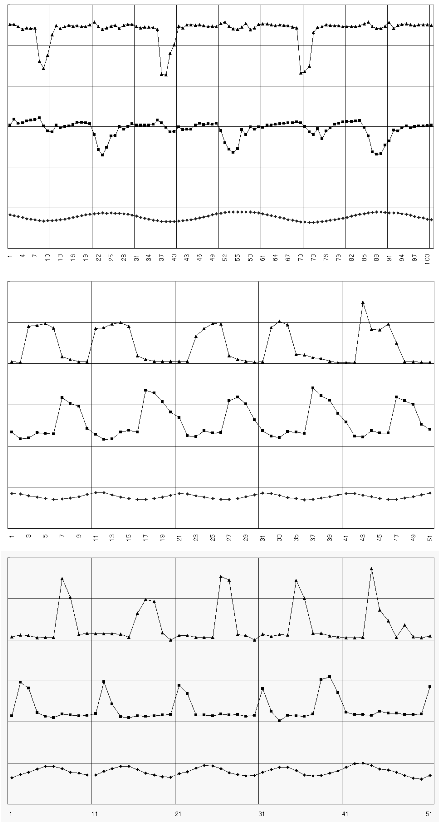


Figure 5: Three typical gaits, Shuffling (Top), Walking (Middle), and Hopping (Bottom). Each diagram includes time series values of pressure sensors on the right foot(Top), the left foot(Middle) and the angle between the upper and lower bodies(Bottom).

4. Stability and Gait Analysis

In this section, we explain the first set of experiments, in which we analyze Stumpy's typical gaits and its stability by using only the waist motor. Note that, in this paper, we use the term "gait" in a broad sense. Generally a gait represents a spatiotemporal pattern of ground contacts of an interested subject, however, in this paper, we call the spatiotemporal "pressure" patterns at the ground contacts instead. Namely, we call two different pressure patterns two different gaits, even if all of the feet are on the ground and stay at the same positions.

For the purpose of measuring such pressures at the ground contacts, we installed pressure sensors on the right and left soles of the robot. These sensors output analog signals which are digitized with 10-bit resolution and stored in a host computer.

4.1. Method of the experiment and observed gaits

In the first set of experiments, we use only the waist motor and a potentiometer. The target trajectory is a sinusoidal oscillation of the upper body with a fixed set point at the middle, i.e. the center of oscillation is upright with respect to the lower body. Under this condition, we analyzed the relation between the gait of the robot and the target oscillation trajectories, i.e. the amplitude and the frequency parameters. We conducted 100 experiments each in Terrain 0 and 1. In each experiment, we set different parameters of amplitude and frequency in which the amplitude ranges from 2.5 to 25 degrees in steps of 2.5 degrees, and the frequency from 0.3 to 2.3 Hz at 0.2 Hz stepwise. At the same time the potentiometer and pressure sensor signals were registered for 500 operation cycles of the host computer (one operation cycle is 20ms). By analyzing the pressure sensor data, we categorized the gait observed during each experiments into 5 categories listed in Table 2. The time series data of three typical pressure patterns, thus "gaits", are plotted in Figure 5.

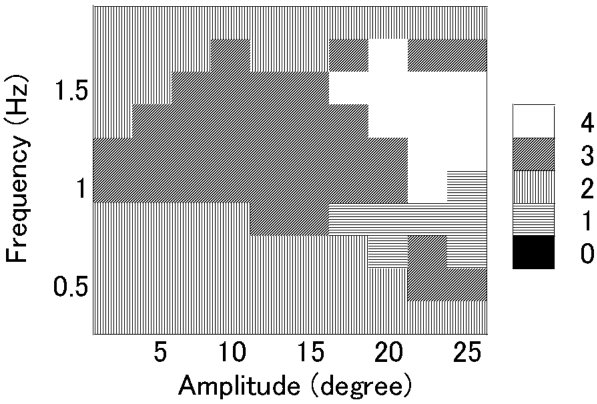
The first gait, "Shuffling gait", is usually observed when the upper body oscillates at a smaller amplitude. In this gait, the robot simply swings the upper body which does not affect lower body very much. From Figure 5 (Top), the feet of the robot are mostly on the ground during the shuffle gait, and the pressure sensors indicate the lower state only for a short time in one cycle of the upper body oscillation.

The second gait, "Walking gait", can be observed when the amplitude and frequency of the waist motor oscillation are increased, in which one of the feet is off the ground while the other foot is on the ground. As shown in Figure 5, this behavior is clearly distinguishable from the shuffling gait by comparing the period of time during which one of the feet is on the ground.

The "Hopping gait" is then emerged at even larger amplitude of the waist motor oscillation, in which both of the feet are off the ground during a certain period in a cycle of the upper body oscillation. This gait can be also clearly distinguished from the shuffling and walking gaits by comparing the two pressure sensor values on the right and left soles.

Another category of the gaits is called the "unstable gait", in which there is no stable gait pattern. The typical behavior in this category shows two foot-steps during one foot-step of the other foot. A similar behavior can sometimes be observed during a mixture of the walking and hopping gaits, which is also included in this category.

Finally, the fifth category is called "Fall", in which the robot falls down to the ground and fails to continue



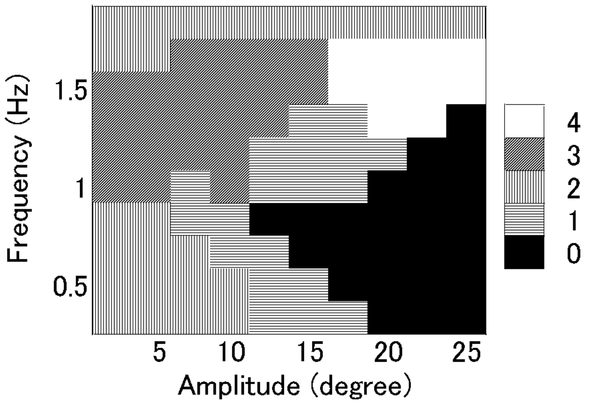


Figure 6: Gait distribution diagrams in Terrain 0 (Top) and Terrain 1 (Bottom). Numbers of the texture patches correspond to “4”: Hopping, “3”: Walking, “2”: Shuffling, “1”: Unstable, and “0”:Fall.

Table 2: The observed gaits and identification numbers which are used in Figure 6.

No.	Gait
4	Hopping
3	Walking
2	Shuffling
1	Unstable
0	Fall

In addition, a design which exploits such a slippery property could suppress instability of oscillatory processes and avoid fatal crush.

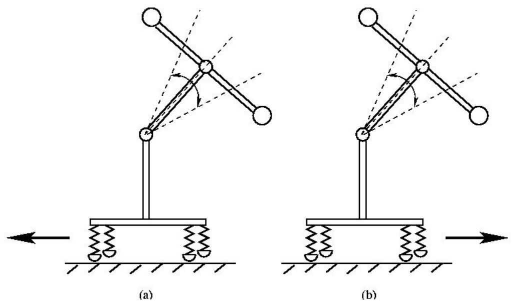


Figure 7: Two typical locomotion behaviors of lateral bounding; Ipsilateral bounding (Right) and contralateral bounding (Left).

the operation.

4.2. Stability analysis

Based on the category above, we analyze the gait at each amplitude and frequency of the oscillation. Figure 6 shows the result of this analysis, in which rectangular texture patches denote the observed gait. Comparing these two gait distribution diagrams, a salient difference is the large regions of “Fall” and “Unstable” in the diagram of Terrain 1. Moreover, there is a relatively larger regions of the walking and hopping gait in the diagram of Terrain 0, whereas these regions are squeezed by the “Fall” and “Unstable” regions in the diagram of Terrain 1.

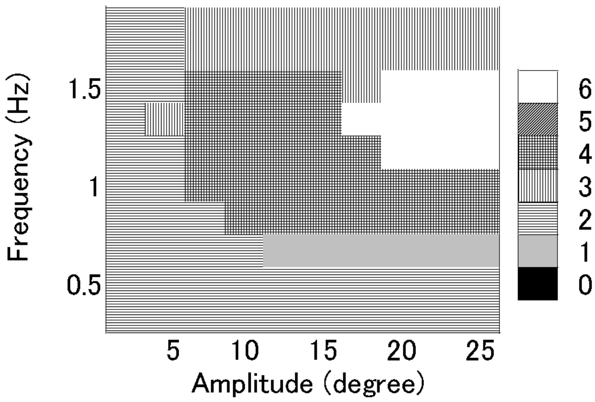
The main conclusion derived from these experimental results is that, statistically, slippery interactions between the robot and the ground, such as the experiments in Terrain 0, could increase the stability, particularly during the hopping and walking gaits.

5. Lateral Bounding

A novel locomotion method called the “lateral bounding” was previously proposed and tested in [4]. By using the “waist” motor with a biased set point of the oscillation, Stumpy can move in lateral direction. The previous experiments have shown two unique lateral locomotion behaviors, so-called “ipsilateral bounding” and “contralateral bounding”, which are illustrated in Figure 7. In this section, we investigate this interesting phenomenon further.

5.1. Experiments of the lateral bounding and the observed gait

We have performed another set of experiments in a similar manner to the experiments described in section 4. In this experiment, however, we set the set point at 30 degree to the right side and conducted 100 sets of experiments each on Terrain 0 and Terrain 1. We



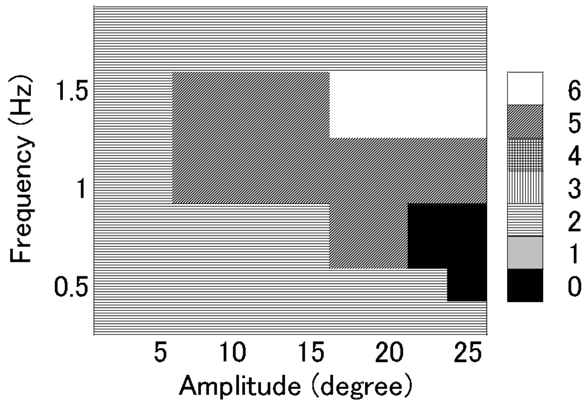


Figure 8: Gait distribution diagrams of the lateral bounding experiments on Terrain 0 (Top) and Terrain 1 (Bottom).

applied the same range of amplitude and frequency parameters as were used for the experiments in section 4.

There are 4 different locomotion behaviors observed during these experiments, i.e. ipsilateral locomotion, contralateral locomotion, the mixture locomotion of these two behaviors, and "Fall". Again we define the categories for these behaviors, "Right","Left","Stay", and "Fall", respectively. These behavior categories are determined by measuring the physical displacement (a threshold of 30 cm from the starting location) of the robot, after 500 operation cycles. Concerning the gait in the lateral bounding, we did not observe the walking gait, only shuffling and hopping gaits, by applying the same categorization framework which was used in section 4. In total, therefore, there are 7 different patterns of behaviors in these experiments as shown in Table 3.

5.2. Gait analysis

Figure 8 shows the gait distribution diagrams of the lateral bounding experiments. One of the major contrasts between the gait distributions in Terrain 0 and 1 is a region of the "Fall" category shown in the Terrain 1 diagram, whereas it does not appear in the Terrain 0 diagram, which is similar to the results shown in Figure 6 explained in the previous section. This result can also be another evidence that supports the hypothesis of increasing the stability of locomotion by exploiting friction.

Table 3: Observed gaits and behaviors during the lateral bounding experiments and identification numbers which are used in Figure 8.

No.	Gait	Behavior
6	Hopping	Right
5		Stay
4		Left
3	Shuffling	Right
2		Stay
1		Left
0		Fall

Another interesting contrast of the diagrams in Figure 8 is the fact that the number of different types of behaviors observed in Terrain 0 is greater than that in Terrain 1. More specifically, in the Terrain 0 diagram, "Right" and "Left" behaviors were observed in both "Hopping" and "Shuffling" gaits. On the contrary, the Terrain 1 diagram shows mostly "Stay" behavior except for a relatively small region of the "Hopping Right" behavior.

Note that the informal experiments have shown that the gait distribution is also dependent on the set point. For example, the gait distributions of the set points 30 degrees and 45 degrees would be different. Further comprehensive analysis of this phenomenon is expected.

An important aspect of these experimental results is that, by using a simple 1-DOF inverted pendulum oscillation, Stumpy shows 6 qualitatively different behaviors in one dimensional lateral locomotion, which are controlled by 4 partially coupled redundant parameters, i.e. friction coefficient, amplitude, frequency and the set point of the oscillation. This variety of behaviors could probably enhance the adaptability of a locomotive system. For instance, the ipsilateral bounding is faster and more unstable than contralateral bounding [4]. Therefore, the ipsilateral behavior could be used for emergency situation. The contralateral one is, on the other hand, stable and robust which can be viable for practical long-term applications.

6. Controlling the turning rate

In this section, we reconsider another locomotion method of Stumpy originally proposed in [3], in which the robot is capable of moving forward, reversing direction, and changing the turning rate as shown in Figure 9.

The control of moving forward/backward direction can be realized as follows. The waist motor oscillation with constant amplitude and frequency generates a periodic gait of either hopping or walking. And at the same time, the robot rotates the shoulder motor also in a oscillatory fashion by synchronizing with the waist motor oscillation. With this control, the oscillatory yaw momentum produced by the swing of the shoulder beam drives one foot in the air moving forward or backward. Thus, the periodic operation of this control results in either moving forward or backward, and the direction of the robot's movement can be controlled by changing the phase between the waist and shoulder motors by 180 degrees. The control of turning rate uses the same principle, although the speed of shoulder beam oscillation should be biased, i.e. the clockwise speed is faster than that of counter-clockwise, or vice versa. Therefore the turning rate of the locomotion can be approximately proportional to the speed difference between clockwise and counter-clockwise.

The control of turning rate is a very good practical case study in which the second hypothesis described in section 2 is effectively used. In this control of Stumpy, by analogy, the oscillation of the waist motor produces F_v and the oscillation of the shoulder motor gives F_h. It is observed that, for the control of the robot moving direction and turning rate, the gait of the robot does not need to be walking, but it can also be hopping or shuffling. The significance of this fact is, again, that the qualitative diversity of the behaviors.

An interesting argument is that, Stumpy has a rotational oscillation provided by the swing of its shoulder, whereas the second hypothesis in section 2 assumes a linear oscillation. Interestingly, due to its rotational momentum, rather than a linear one, Stumpy can produce 3 degrees-of-freedom movement in two-dimetional space, i.e. moving forward/backward, right/left, and rotating on its own axis. This argument needs to be elaborated in the future.

7. Discussion

In this paper, we propose two working hypotheses described in section 2 with respect to how the friction could contribute to a form of locomotion. In this section, we discuss further issues on these hypotheses.

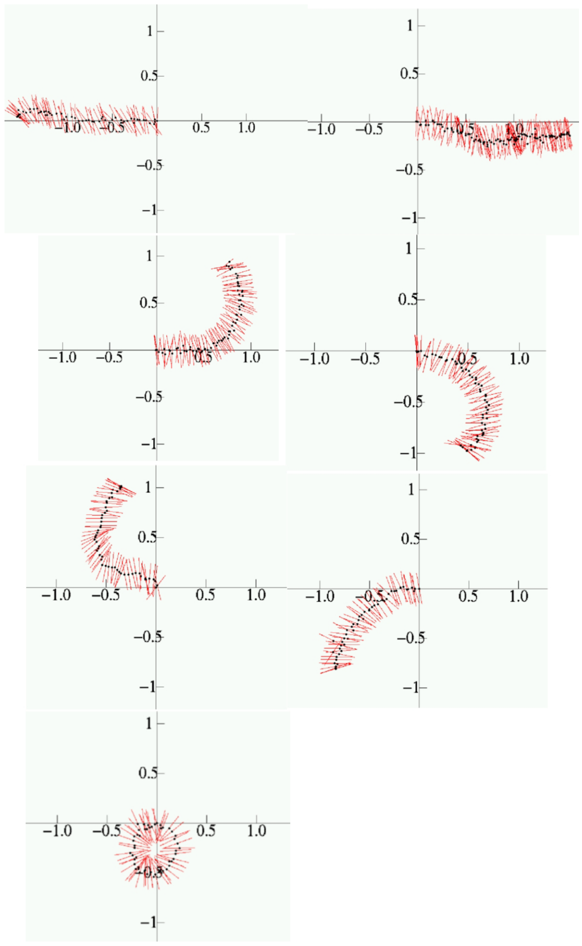


Figure 9: Overall behaviors of Stumpy's turning rate control. These diagrams illustrate the top view of the robot trajectories which is visually analyzed (For more detail, refer to [3]).

Concerning the first hypothesis mentioned in subsection 2.1, the experimental results in section 4 and 5 show that the friction can be one of the significant parameters which largely increases the stability of a locomotion process. However, it is still an open question regarding to what extent this hypothesis could be applicable. As mentioned in section 2, the principle of increasing the stability depends not only on the friction force, but also on the shape of the object (e.g. d and h in Figure 1), the external force, at least. Additional comprehensive experiments and analysis on this issue is expected, including Stumpy's morphological design of l_b, r, l_1, and l_2 in Figure 4.

Another interesting discussion would be whether the variety of locomotion behaviors on Terrain 0 in Figure 8 could be explained by the second working hypothesis described in subsection 2.2. In these experiments, by analogy, one could assume that the swing of the inverted pendulum (i.e. the oscillation of the upper body) produces both the vertical force F_v and horizontal force F_h in equation(4). If this is the case, the friction coefficient μ could be a control parameter for locomotion as well as amplitude A and frequency ω. However, it has to be mentioned that these control parameters are only partially independent in such a sense that the friction force cannot be larger than the horizontal force F_h.

As mentioned in section 2, there are two possible ways to control the friction. According to equation (3), one is to control the coefficient of friction, μ, and the other is to control the vertical force F_v at the ground contact. The former one mainly depends on the material property, and the latter is mostly realized by shifting the center of gravity of a locomotive system. The material property of the sole, therefore, plays a very important role in locomotion of the robot, which can be categorized as the first point. However an active control of the friction coefficient could be potentially an alternative parameter to control the locomotion.

In relation to the vertical force F_v, the springs which are vertically installed in the Stumpy robot would also be a point of dispute, since they significantly affect the force F_v and most probably also the phase ϕ in equation(4). As has been known in biological studies of running animals (e.g. [1]), the passive spring component can increase the energy efficiency, i.e. converting the kinetic energy to the potential elastic energy. However, the vertically equipped springs could also be an additional control and design parameter for the locomotion exploiting the friction force.

Finally, the concept of locomotion presented in Figure 2 assumes two oscillatory forces given to the system. In this paper, therefore, we have applied only simple sinusoidal oscillation controls. Considering that the friction is usually a highly nonlinear interaction, an adaptive control method (e.g. one used by [5]) might enhance the locomotion stability of the system as well.

8. Conclusion

In this paper, we propose two working hypotheses in which we discuss how an artificial system could actively exploit the interaction between a system and the ground for the purpose of adaptive locomotion. In order to test these hypotheses, we have conducted three case studies by using a robotic platform which we have developed. The experimental results show the statistical plausibility of the first hypothesis, where stability of locomotion could be increased by properly exploiting the friction. Furthermore, it is shown that, by properly taking advantage of the friction, the robot could enlarge the repertoir of locomotion behaviors. A criticism to what we discuss in this paper might be whether it is worth exploring all the possible locomotion behaviors exploiting the slippery interaction between a system and the ground, since the energy efficiency of locomotion is always lower with respect to traveling distance as long as there is a friction force. However, our interest of this research is not to focus on the efficiency, rather we are interested in a comprehensive understanding of adaptive locomotion, where a repertoir of locomotion behavior would play an important role.

Acknowledgments

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