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Towards fast running: Open-loop speed and direction control of a single-legged hopper

Farrukh Iqbal Sheikh

Abstract— **Traditional 2D single-legged hoppers were able to demonstrate stable bi-directional running in a closed-loop approach. In contrast, we employ an open-loop control to achieve high-speed ($\approx$0.8 m/sec or 1.78 mph) bi-directional dynamic running of the reconfigurable leg length hopper (RLLH). Our hopper has variable linear joint in series with a passive spring that allows changing its effective leg length in real-time. Furthermore by instantaneously changing the leg length at a particular amplitude and frequency. The required "thrust-forces" can be produced. We hypothesize that the direction and the speed of our hopper can be smoothly controlled by only changing the phase of the thrust-forces being applied to the ground, i.e., the change in phase between the leg-reconfiguration and the leg-oscillation. This is experimentally evaluated by varying the phase of leg-reconfiguration up-to the range of 0-2π rad (0-360 deg). Our results show a large region of a symmetric running. Moreover, a novel gait called "in-place running[1]" is found, where the speed of running is zero. We demonstrate that by only altering the phase of applying thrust-forces together with a constant leg oscillation can robustly control the speed and transition in the direction of locomotion.**

Keywords: Thrust-forces, in-place running, and bi-directional running.

I. INTRODUCTION

Wheeled robots can accelerate in a forward and a backward direction by simply changing the rotational phase of the wheels. Despite the limited performance of the wheeled robots in an unstructured environment, the control of wheeled robots is fairly simple compared to many existing legged robots. On the other hand legged robots have complex dynamics and control. Perhaps by advancing a simple open-loop approach in a legged robot, a fast and a stable bi-directional locomotion can be achieved.

Dynamically stable legged robot locomotion is being researched to understand the underlying mechanics of animals and humans locomotion [1]. In addition this research may lead us to develop a legged vehicle that will not be restricted to a particular terrain. A step towards a practical prototype that bounce over obstacles and run on legs, Raibert and his colleagues [1] built a series of legged robots: single-legged, two-legged, and four-legged. Each of these robots was controlled in hierarchy of three closed-loop control laws: one corrects the hopping height, second controls the forward speed, and third ensures the balance. These three control laws were coupled together in a state machine to achieve a stable running with varying speed. Moreover, by applying the rules of body and leg symmetry [2], the control was simplified further to achieve locomotion in a specified direction. However, how the principle of symmetry holds in a physical single-legged robot locomotion is not experimented in detail.

Existing legged robots [1], [3], [4] are designed to demonstrate the role of a closed-loop approach to achieve stable running; however, the dynamically self-stable running of a legged robot can also be achieved in an open-loop without any sensory feedback [5], [6]. The open-loop requires no sensory feedback; therefore, it is more suited to exploit inherent self-stability of a robot morphology during locomotion that results in a rapid dynamic running [7]. By employing this simple open-loop approach many under-actuated robots [8], [9] were successfully controlled. These robots exploit the passive-dynamic function of the compliant element in a single and a bipedal configuration to demonstrate a stable walking and hopping; nevertheless, the motion of these robots [8], [9] were optimized for a unidirectional locomotion, i.e., the importance of controlling the speed and the direction of locomotion was rarely addressed in an open-loop control. In this work, we explore the basis of a rapid bi-directional dynamic running of a single-legged robot in an open-loop control because this exploration may serve as a better foundation for a robust closed-loop control [10] of a legged robot.

Legged animals use muscles to exert forces on a ground through tendons to achieve bouncing (running) locomotion in varying directions [11]. Such bouncing or running locomotion in animals and humans can be described by the motion of a point mass in series with the mass less spring - SLIP model [12]. Similarly, this model also describes the bouncing locomotion of a robot that rebounds its body by exerting force to the ground. However, it is unable to explain that how the multiple joints in a robotic leg should actuate that accelerates the robot body in a specified direction. Inspired by the SLIP model, we developed a single-legged 2D hopper, called the "Reconfigurable Leg Length Hopper (RLLH)" [13] because the linear joint in series with the mechanical spring is a variable (reconfigurable) that functions as a biological muscle [14]. This joint can shorten and lengthen the robotic leg, such that the required forces can be exerted to the ground through a mechanical spring (tendon). We used this bio-inspired 2D hopper (RLLH) to conduct experiments based on our hypothesis that the speed and the direction of motion can be smoothly controlled in a simple open-loop control.

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[1]Farrukh Iqbal Sheikh is working at the Artificial Intelligence Laboratory, Department of Informatics, University of Zurich, Andreastrasse 15, 8050, Zurich. fsheikh@ifi.uzh.ch

[1]In-place running is like an in-place jogging, in which the motion of the body is mainly restricted in-place by the continuous movement of each joints of the leg.

This paper is organized in following sections: Section II briefly explains the mechanics and electronics of the robotic leg. Section III describes a feed-forward control approach. Section IV illustrates the concept of thrust-forces in a legged locomotion. Section V provides a detail of the experimental setup. Section VI discusses results of the experiments performed. Finally, Section VII draws a conclusion and highlights the future work.

II. MECHATRONIC DESIGN

The reconfigurable leg length hopper (RLLH) prototype [13] was designed to be modular in mechanics and electronics such that wide range of different morphologies and their influence on control, and vice-versa can be physical experimented.

A. Mechanical Design

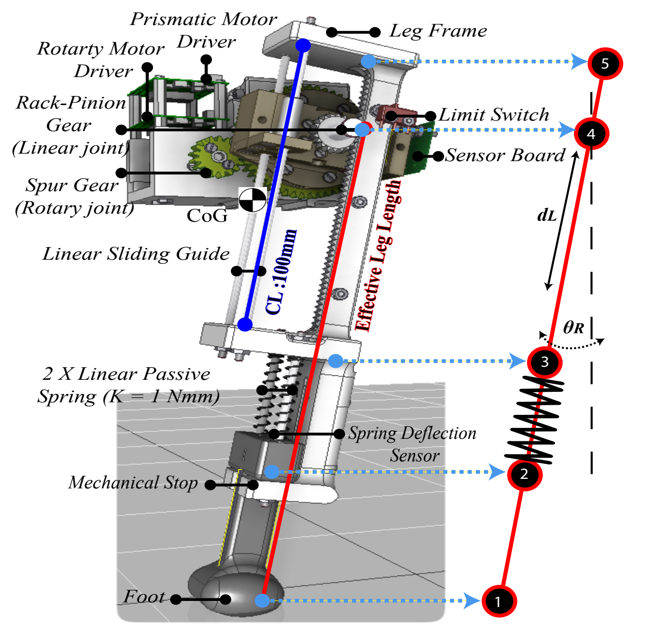

Fig. 1. Reconfigurable Leg Length Hopper (RLLH). The volumetric dimension of the robotic leg is LxWxH: 258x39x47 mm^3; total weight (including the weight of the boom rod (see section V)) is 0.870 $\pm$ 0.001 kg. Red-line indicates the leg length at rest, which is defined as the effective leg length of the robotic leg. Blue-line indicates a distance within which leg length can be changed, CL: 100 mm. The kinematic-stick shown in right, is used in Fig. 7 to describe the dynamic motion of forward and in-place running of the RLLH over time. Each circle over the red-stick represents a joint that corresponds to the joint of the physical platform, as indicated by the dotted light-blue arrows.

The mechanical design of the robotic leg consist of two active joints (revolute and prismatic) and a passive joint (linear spring). The active joints are powered by the conventional DC brushed motors that permit a fixed joint rotary and a reconfigurable joint linear motion. As shown in Fig. 1, the linear motion in our design is obtained by the pinion-rack gear mechanism that enables us to accommodate both the actuators (DC motor) and their electronics on the trunk (body). This allows us to considerably reduces the weight of the leg and its inertia, which is very essential to use low-cost actuators. In addition, the motion of the linear joint is coupled in series with a mechanical spring (passive compliant element) through a rigid single-segment leg-frame. This mechanical configuration work in three ways: it can exert required forces to the ground by doing an oscillatory work on a passive spring, to reduce ground impact at touch-down by shortening the robotic leg and by changing the effective leg length of the robotic leg a speed can be adjusted.

B. Custom Motor Driver

Each active joint in the RLLH is controlled by the custom developed motor control board, as shown in Fig. 2. This motor control board (MCB) uses a 16 bit high performance micro-controller to execute low-level motor control algorithms, such as the low-level positional PID (proportional, integral and differential). Each MCB board is capable of communicating with other boards on a long distance half duplex RS-485 protocol in a master-slave configuration.

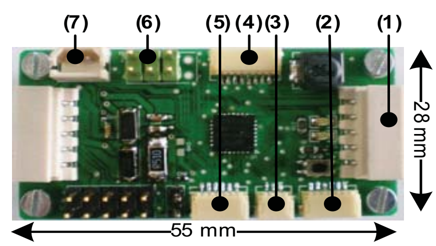

Fig. 2. Motor control board (MCB), (1) Power and RS-485 communication bus, (2) Programming connector, (3) 1 Analog input, (4) 4 DIO/ANA, (5) Secondary UART/I2C/SPI, (6) motor encoder, (7) 2 pins motor connector.

Four MCB boards are used in the construction of the experimental platform (see section V). Two MCB boards are responsible to control the rotary (leg-oscillation) and the linear (leg-reconfiguration) motion of the reconfigurable leg length hopper (RLLH) and other two, executes high-level tasks, e.g., foot trajectory. They are all mounted on the trunk. Moreover numbers of sensors are added to the mechanical design to monitor the internal state of motion of the robotic leg in time. These sensors are as follows: two limit switches, one rotary position sensor and one linear potentiometer.

III. FEED-FORWARD POSITIONAL CONTROL

The control of the two active joints in the RLLH is feed-forward (open-loop). The open-loop control means, no external sensory information is utilized to modify the prescribed shape of a command signal. This reduces the control-loop bandwidth to achieve a fast dynamic legged robot locomotion. This minimalistic feed-forward positional control signal of each active joint, namely the rotary and the linear joint, is sinusoidal, as defined in equation 1 and programmed in a master-controller 1 (see Fig. 4 b)). Master controller 1 processes equation 1 to produce a desired motion trajectory for the linear and the rotary joint respectively. The result of equation 1 is then transmitted to their respective low-level PID motor controller (slave) on a connected RS-485 bus to execute desired motion.

$$\begin{bmatrix} \theta_R \\ d_L \end{bmatrix} = \begin{bmatrix} A_R + O_R + \Delta A_R \sin(\omega_R t + \phi_R) \\ d_0 + O_L + \Delta d_L \sin(\omega_L t + \phi_L) \end{bmatrix} \quad (1)$$

where, θ_R is the high-level oscillatory positional commands for the fixed rotary joint, O_R is the offset in leg oscillation (offset), A_R is the reference position of the robotic leg, ΔA_R is the amplitude of change in leg oscillation, $\omega_R = 2\pi f_r$ is the angular frequency of the oscillator, and ϕ_R is the phase shift in the oscillator. d_L is the high-level oscillatory positional commands for the reconfigurable linear joint, d_0 is the initial effective leg length of the robotic leg at rest, O_L is the offset in change in leg length (offset), Δd_L is the change in leg length (amplitude) during motion, $\omega_L = 2\pi f_L$ is the angular frequency of the oscillator, and ϕ_L is the phase shift in the oscillator. Note that $-\theta_R$ swing the leg in forward direction and $-d_L$ reduce the leg length.

IV. CONCEPT OF THRUST-FORCES IN FORWARD RUNNING

Thrust-forces in legged human locomotion are the result of external forces that act in the direction of movement during a ground contact phase [15]. These forces are also known as the propelling forces. In this particular design of the robotic leg, the thrust-forces can be generated by doing an oscillatory positive (increasing leg length) and negative (decreasing leg length) work at the passive mechanical spring. We previously [13] demonstrate that the dynamically stable vertical in-place hopping can be achieved by applying a simple sinusoidal control function to the reconfigurable linear joint. Using this similar control signal with zero phase-shift between the rotary and linear actuation, results in running forward.

A concept of thrust-forces in a single stride of forward running is graphically shown in Fig. 3. As can be seen in Fig. 3, the control signal (LM) that alters the leg length of the robotic leg, decreases during the negative half duration of the control signal. When the robotic leg touches the ground surface at point (1), the following sequence of events occurs: the linear joint start increasing the robotic leg length by doing a positive work at the mechanical spring, spring starts accumulating elastic energy by the compression against the ground, and finally the ground reaction force starts increasing by reflecting all the external forces during the contact phase. This duration from the touch-down point (1) to the lift-off point (3) is known as a "contact phase or stance". The forces exerted by the robotic leg, from point (2) to (3) are defined as the duration of thrust-forces. In short, it can be identified where Fx is positive by looking the ground reaction force after the mid-stance (see the GRF plot in Fig.3). The motion of the robotic leg along the direction of these thrust-forces defines the direction of locomotion. We hypothesize that by simply changing the phase ϕ_L of the sinusoidal LM (Linear Motor) control signal d_L, i.e., change in the phase of exerting force to the ground, at constant leg oscillation θ_R, the direction and the speed of running hopper can be controlled.

Similar concept is well described theoretically in [2] by a simple mechanical model that uses a mass-less leg and a point-foot. In this model [2] the effect of the rotary joint's torques and the leg forces are considered on the robot CoG that describes the rules of symmetry in dynamic running.

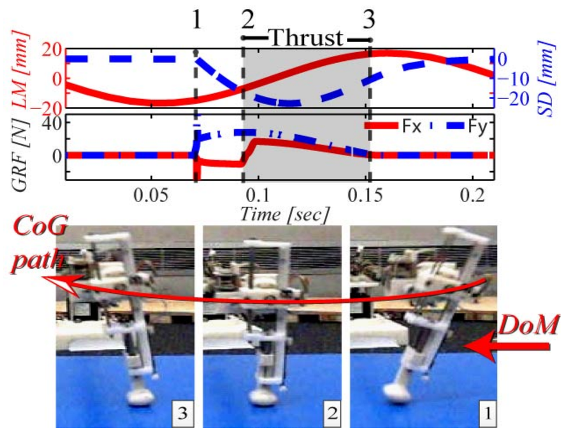

Fig. 3. Thrust-forces in a single cycle of actuation. First plot shows the compression of the spring (SD) and a single cycle of sinusoidal control signal (LM or d_L) over time. While the second plot shows the vertical and horizontal components of the GRF (ground reaction force). The duration of thrust-forces is indicated by the duration from mid-stance$-(2)$ to lift-off$-(3)$. DoM means the direction of motion.

V. EXPERIMENTAL SETUP

The concept of controlling the direction and the speed of running hopper is experimentally evaluated using the platform shown in Fig. 4. As can be seen in Fig. 4, a). The single-legged 2D reconfigurable leg length hopper module is attached to the fixed boom that constrains the motion of the robotic leg in two DOF (degrees of freedom), namely a yaw (about z-axis) and a pitch (about y-axis) axis of the fixed boom coordinate.

The base-shaft of the fixed boom, that permits a rotary (yaw) motion around the wooden-floor is physically coupled to the high-power-slip ring. The high-power-slip ring in our construction provides an uninterrupted electrical power up to N number of revolutions to the electronics placed at the upper-body of the robotic leg, i.e., prevent wire folding in multiple revolutions during N number of experiments. While the pitch motion about the boom-fixed coordinate is achieved by connecting the boom-rod of length 1.02 m in perpendicular to the rotary base shaft. The motion of the robotic leg relative to the fixed-boom is measured by the following sensors: IMU (6 DOF inertial measurement unit equipped with 3 axes accelerometer and 3 axes gyro sensors), and a rotary-position-sensor around the pitch axis. The Z-axis component of the IMU-gyro measures the speed about z-axis, which later converted in to the planar speed for compiling results, and the rotary-position sensor attached to the y-axis which measures the motion of the robotic leg body or in other words motion of the CoG (Center of Gravity). Moreover, a

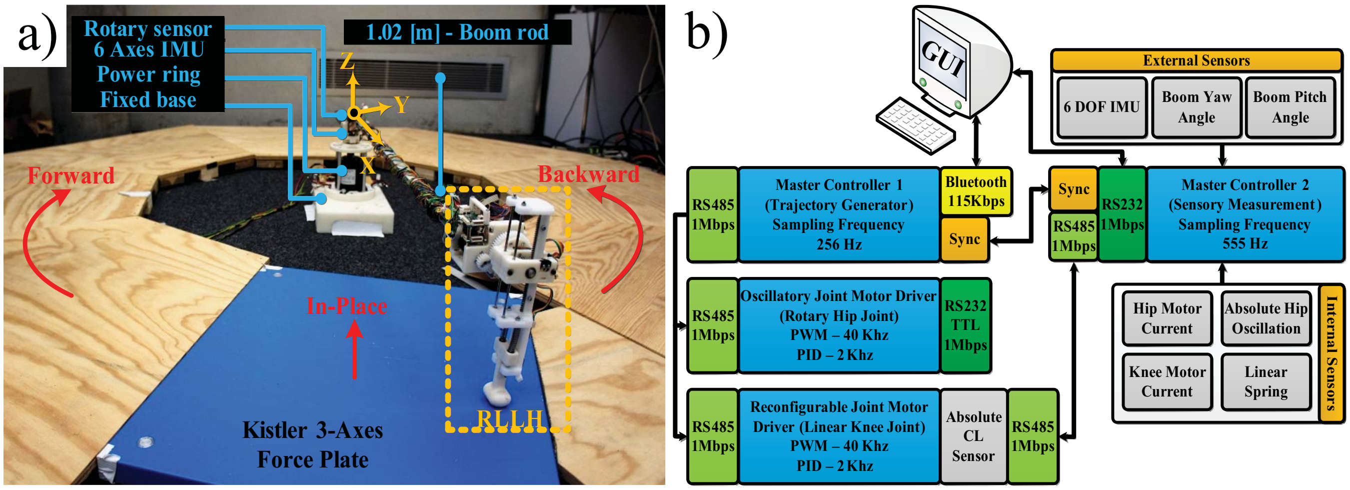

Fig. 4. Experimental setup of a two dimensional bi-directional running. a) The robotic leg is tethered to the fixed boom that constrained the motion of the robotic leg in a circular path (yaw and pitch) around a stiff-wooden-floor. A clockwise motion of the robotic leg about the z-axis of boom fixed coordinate is defined as the forward motion and the anti-clockwise motion is indicated as backward. An average speed of the robotic leg in either direction is measured by the 3D gyro of IMU (Inertial Measurement Unit), which is mounted at the boom fixed coordinate. b) shows the embedded feed-forward control and sensor data acquisition architecture. This setup uses four 16-bit custom developed micro-controller boards, two of them act as master and remaining two act as slave; Master controller 1 generates trajectory command by processing the equation 1 and transmits its result to the respective slave controllers on RS-485 Bus at the data transmission rate of 1 Mbps. Each slave controller receives the data packet and decodes its commanded signal to execute the desired motion command; Master controller 2 samples the internal sensors and external sensors at the sampling frequency of 555 Hz. Both master controller 1 and 2 are connected to the main computer, where GUI (graphical user interface) supervises the execution of control commands and records all the sensory data for further analysis.

3-axes kistler force plate was placed in the motion path of the RLLH to measure the ground reaction forces during each trial of the experiment per control parameter.

The control parameters are derived from our previous work in [13], where the frequency and the amplitude of sinusoidal leg reconfiguration for the energetic vertical in-place hopping were experimented. In [13], we showed the importance of two frequency values: one where the robotic leg exhibit higher ground clearance by consuming more power (maximal) and other where the robotic leg consumes less power (optimal). In this study, we specifically chose the operating frequency of the maximal power consumption, i.e., $4.5Hz$. Additional control parameters for the sinusoidal rotary and linear joint command signal were set to the following values: $f_R, f_L = 4.5Hz$, ΔA_R = $0.056\pi \pm 0.005$ rad (10 deg), Δd_L = 15 $\pm$ 1 mm, and d_0 = 135.5 $\pm$ 1 mm. Only the phase parameter (ϕ_L) of the linear actuation control signal was varied, as defined in equation 1 to establish the relation between the phase of exerting force to the ground with respect to the change in speed and direction of running hopper. This ϕ_L parameter is systematically changed starting from 0-2π rad with an increment of step-size 0.027π rad. At each change in control parameter four trials were performed and at each trial the robotic leg completes two revolutions around the fixed-boom on a stiff wooden-floor that has a frictional coefficient of $\approx 0.4 - 0.5$. The total distance covered by the robotic leg in two revolutions about the fixed boom frame is approximately equivalent to the planar distance of about 12.8 m in length. We use this as a criterion to quantify the robustness of stable running per control parameter in our experiment. As all the trial per experiment are synced, therefore the standard deviation among trials per control parameter can be used to quantify stability.

VI. RESULTS AND DISCUSSION

Fig. 5 shows the planar speed of running as a function of different phase (ϕ_L) that starts from 0 to 2π rad. As it can be seen in Fig. 5, at zero phase-shift (ϕ_L = 0) between the active rotary and the linear joint control signal, running in a forward direction occurs with an average speed of ≈0.8 m/s. By systematically increasing the phase-shift further from 0 to 0.53π rad, no change in the average running speed was observed. Thus, the phase duration from 0 to 0.53π rad is defined as the forward hopping (FH) region. Further increase in the phase-shift starting from 0.53π to 0.805π rad, decreases the average speed of locomotion until the point, where the in-place running was achieved (zero locomotion speed, despite the time varying sinusoidal actuation of each active joint) and then additional increase in phase-shift causes increase in speed by changing the direction of motion. This duration is indicated as the phase transition (PT) region in Fig. 5 and 6. By increasing in the phase values further from 0.805π to 1.53π rad, flatten out the average speed of locomotion at -0.8 m/s in reverse direction. The effect of the change in phase shift until 1.53π rad indicates that the direction of hopping is changed by the change in phase of exerting thrust-forces to the ground surface. However, if the mechanical design of the robotic leg is symmetric then the phase-transition region should repeat again. In order to confirm the symmetry of a thrust-cycle, the effect of phase-shift was further explored up to 2π rad. As it can be seen in Fig. 5, the thrust-cycle is symmetric, as the robotic leg design.

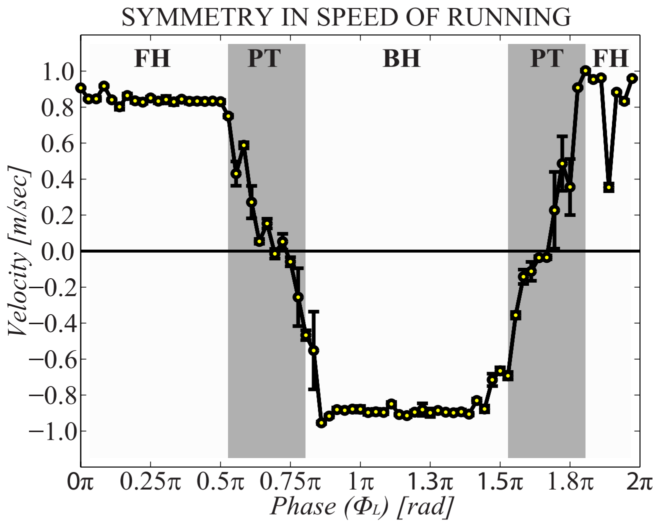

Fig. 5. Symmetry in speed of running. This shows the change in locomotion speed over different phases of applying external forces (thrust-forces) to the ground surface. X-axis indicates the change in the phase parameter (ϕ_L). Y-axis indicates the average speed taken over 3 synced trials per control parameter. The change in running speed and direction with respect to different phase (ϕ_L) values are categorized in three regions: FH (forward hopping) region, PT (phase transition) region, and BH (backward hopping) region. The forward hopping (FH) region is defined as the region, where the speed of locomotion remains constant in the clockwise direction about fixed boom. Its is highlighted by the phase duration $0{-}0.52\pi$ rad and $1.8\pi{-}2\pi$ rad. The phase transition (PT) region is indicated by the phase duration $0.52\pi{-}0.80\pi$ rad and $1.5\pi{-}1.8\pi$ rad, where the speed of locomotion changes significantly by passing through a zero speed (as shown by the speed transition from $+$ve speed values to $-$ve and vice versa). Similarly the backward hopping (BH) starts from phase (ϕ_L) 0.8π rad and ends at 1.5π rad, where the speed remains constant (-0.8 m/s) in an opposite direction.

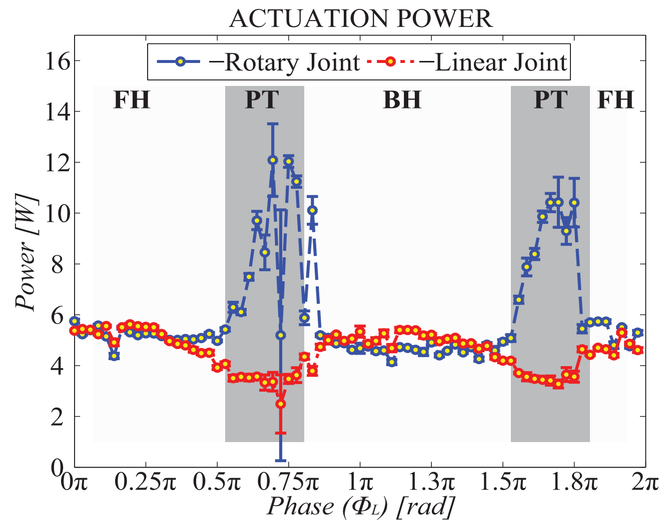

Fig. 6. Electrical power consumed by the active (fixed rotary) and variable (linear) joints per change in phase (ϕ_L) parameter is shown. The electrical power used by each active joint (DC motors) are nearly constant during forward (FH) and backward (BH) hopping region. However, the electrical power changes significantly during the phase transition region, where the speed starts dropping to zero before changing the direction of motion. It can be noted that the total power was mainly increased by the rotary joint power that limits the motion in-place by counteracting to the thrust-force.

It is important to note that the phase of in-place running in our experiments occurred approximately at phase 0.66π and 1.64π rad. But can it be influenced further? As the in-place running is a result of highly non-linear dynamical interaction between the robotic foot and the ground; therefore, the phase at which the in-place running was achieved, can easily be affected by the following factors: shape of the foot, friction of the ground, asymmetrical position of the robot CoG (Center of Gravity), and gains of the low-level PID control etc.

Fig. 6 shows the electrical power consumption of each active joint with respect to various thrust phases. This allows us to determine the overall cost of transport to change the direction of motion. As it can be seen in Fig. 6, each active joint power consumption was nearly constant during the forward (FH) and the backward (BH) region, same as the magnitude of running speed (see Fig. 5). While in phase transition region, the power consumption of the rotary joint was significantly affected. Especially at the phase value of the in-place running, where the electrical power consumption of the rotary joint reaches its peak. This indicates that the torque applied by the rotary joint, were acting against the thrust-forces that caused an increase in electrical power consumption of this joint. Based on these results, we can characterize the in-place running as a highly energy in-efficient gait because the speed of locomotion becomes zero (v = 0), i.e., specific resistance ($\epsilon = p/mgv = \infty$), where p is the electrical power consumption, mg is the weight, and v is the velocity.

As it can be observed further in Fig. 5, the speed and the direction of the single-legged hopper was mainly affected in the phase transition region (PT). Operating the robotic leg within this region also affected the total power consumption. Therefore, we can conclude that the change in speed and the direction by using the phase transition parameters is costly but it provides a way to smoothly control the speed and the direction of locomotion in open-loop control. The role of the phase transition parameters, as a control to alter the speed and the direction of dynamic running online, is further demonstrated in section VI-C).

A. Forward and In-place Running

Instantaneous dynamic motion of each joint in the RLLH during two strides of a forward and an in-place running are shown in Fig. 7 a) and b) respectively. First two plots of Fig. 7, a) the motion of body joint, i.e., the motion of the robot CoG (Center of Gravity), is indicated by the red line, while the compression of the passive spring is shown by the green line. Both of these plots describe the dynamics of a forward and an in-place running in time, whereas the third plot (foot motion) is depicted with respect to the distance covered by the robotic leg during two strides. In Fig. 7, a) The vertical motion of the body joint (CoG motion) with respect to the foot in forward running decreases at the beginning of a ground contact phase, then it decreases further until mid-stance; from where it starts increasing again in the direction of thrust-forces. This motion of the robot CoG that acts in the direction of thrust-force, causes the robotic

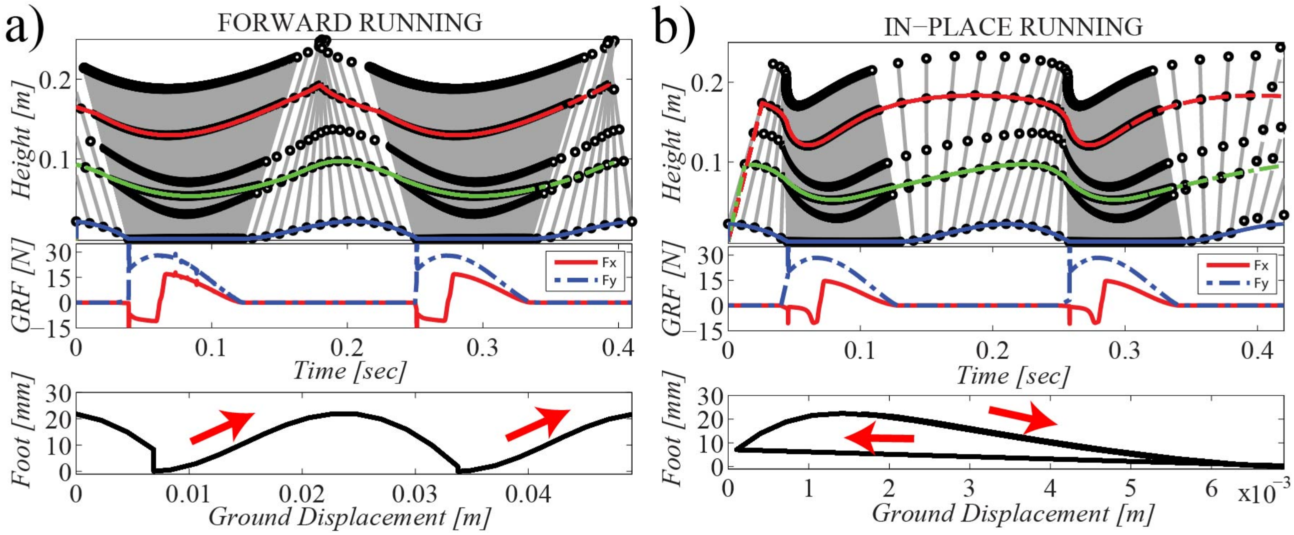

Fig. 7. 2D dynamics of the forward and the in-place running of the RLLH. First two plots in a) and b) show the dynamic motion of each joint with respect to the time duration of two strides. The first plot is a stick diagram that the motion of robot CoG (Center of Gravity) is shown by a red line and the deflection of spring is indicated by a green line. While the foot motion is indicated by a blue line. Second plot shows the vertical (Fy) and the horizontal (Fx) component of the GRF (ground reaction forces). These two plots (stick diagram and GRF) in column a) and b) are synchronized in time. This illustrates a complete dynamic of the robotic leg with respect to the thrust-forces (GRF, where Fx is positive) exerted on the ground surface. However, the third plot in a) and b) indicates the foot motion of the robotic leg with respect to the ground displacement covered during two strides. Moreover, this also provides a measure of ground clearance in an aerial phase. The contact phase and the aerial phase can be identified by the GRF plot in a) and b), i.e., aerial phase is the duration where GRF is zero ($Fx = 0$ and $Fy = 0$), and ground contact phase is the duration, where GRF is not zero ($Fx \neq 0$ and $Fy \neq 0$). Red arrows inside the foot motion plot of a) and b) indicate the direction of motion before and after touch-down.

leg to run in a forward direction. During in-place running joints motion of the robotic leg act against the direction of thrust-forces that causes the robotic leg to lift-off in a backward direction before retracting the robotic leg back at the same position (see foot motion in Fig. 7, b)). This behavior emerges, when the phase difference between the continuous joint motions constrains the direction of motion against the thrust-forces. Thus, the power consumption of the rotary joint increases (see Fig. 6), because the motion of the active rotary joint is acting against the thrust-forces of the GRF. As a result of this, the robotic leg runs in-place, while maintaining the ground clearance. It is very interesting to note that the motion of passive spring in both the cases (forward and in-place running) is nearly same, hence the vertical component of the ground reaction forces (GRF) is same as well. However, the horizontal (Fx) component of GRF and the body motion change significantly. Furthermore, the foot motion with respect to the planar distance per stride is indicated in Fig. 7, a) and b). Fig. 7, a) shows the robotic leg hop in a forward direction by covering a ground distance of approximately 27 mm in length per stride, whereas Fig. 7, b) indicates the robotic leg jump first in a backward direction and then bring the foot forward to the same location from where it lifts off.

B. In-place Running and In-place Hopping

The in-place running is different from the vertical in-place hopping, as shown in Fig. 8. The vertical in-place hopping can be achieved by the following steps: by keeping the robotic leg vertically straight to the ground, i.e., fixed angle of attack $\alpha_R = 90\ deg$ or $\theta_R = A_R$, and by actuating the reconfigurable linear joint in a feed-forward control. Consequently, the force exerted to the ground by the motion of the reconfigurable joint in series with the mechanical spring directly translated into straight vertical jumps. On the other hand, in the in-place running both joints (rotary and linear) of the robotic leg are operated by a continuous time-varying sinusoidal command signal, whose phase difference mainly restricts the foot motion of the robotic leg in-place while running at high-sped. In this way, we can characterize the in-place hopping gait further into the vertical and the oscillatory in-place running.

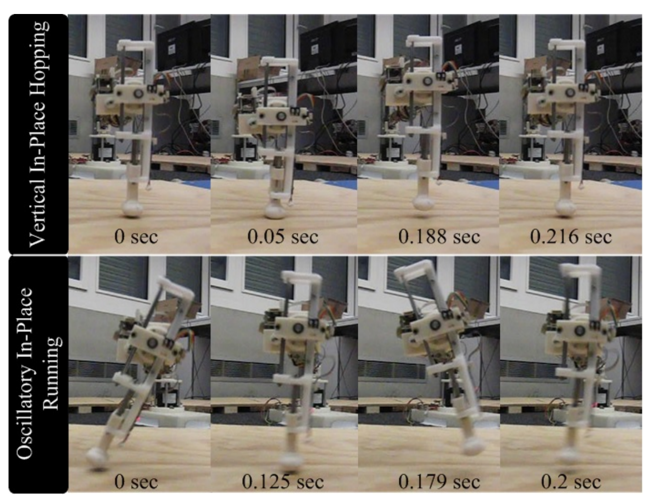

Fig. 8. High-speed video frame sequences of the vertical in-place hopping and the oscillatory in-place running.

C. Online Speed and Direction Control

Fig. 9 demonstrates the effect of varying the phase parameter (ϕ_L) online as a control of speed and transition in direction of a single-legged running. As it can be seen in the first plot of Fig. 9, at phase $(a) - (\phi_L = 0)$ the running speed of the hopper increases in the forward direction and reaches the steady-state speed of 0.8 m/sec. When the phase (ϕ_L) advances to the value 0.53π rad or enters into the phase transition (PT) region, decreases in the speed of locomotion by increasing in the electrical power consumption of the active rotary joint. However, at phase of the in-place running $(b) - (\phi_L = 0.66\pi\ rad)$, the speed gradually drops to zero and causes further increase in the rotary joint power, as also described in section VI-A. Additional increase in phase (ϕ_L) to the value $(c) - (\phi_L = 1.3\pi\ rad)$, causing the robotic leg to smoothly switch its direction of motion, as indicated by the negative sign of speed. It can be noted that the total actuation power is affected in phase transition region, which is indicated by the PT in Fig. 9. However, at phase (a) and (c) the actuation power of each joint is at the nominal value.

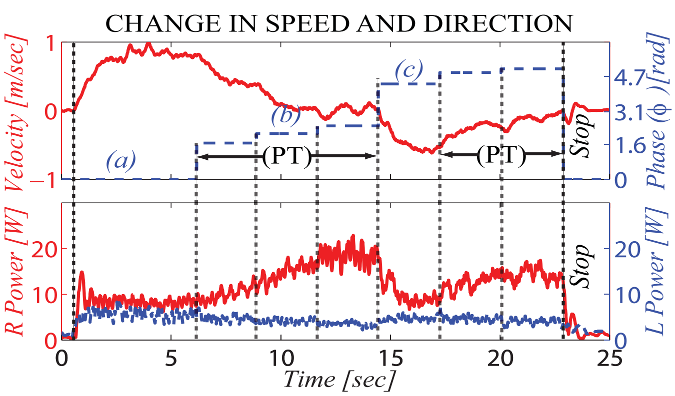

Fig. 9. Online speed control of bi-directional running. First plot shows the effect of different phase values to control the speed and the direction with respect to time. Second indicates the progression of the change in electrical power of each active joint with respect to time. The phase values used in this process are the following: Phase (a) $\phi_L = 0$ rad shows forward running, (b) $\phi_L = 0.53\pi$ rad indicates in-place running, and (c) $\phi_L = 1.38\pi$ rad shows backward running. PT defines the region of phase transition parameters.

VII. CONCLUSION AND FUTURE WORK

We demonstrated a simple way of controlling the speed and the direction of high-speed single-legged running. It is achieved by only altering the phase relation between the linear and the rotary joint in open-loop control. Initially, we explore a complete effect of this parameter on the speed and the electrical power consumption of each active joint and later we demonstrate this as a control to alter the speed and transition in the direction in real-time. A complete exploration reveals that the designed robotic leg exhibits a large stable region of forward and backward running, where the speed of locomotion and the total electrical power consumption are nearly constant. While the speed and the direction of locomotion are only affected by operating the robotic leg in a phase-transitional (PT) region, where the robotic leg starts changing its direction of motion from forward to backward and vice versa. This phase transition (PT) region can be described as: firstly at the phase; where the speed of locomotion starts decreasing, secondly at the phase; where the speed of locomotion becomes zero, and thirdly; where it increases the speed in an opposite direction of locomotion. The phase parameter at which the speed of locomotion becomes zero, is defined as "the phase of a novel gait called In-place running". The in-place running is another form of the vertical in-place hopping that restricts the motion of the robotic leg in-place by the continuous sinusoidal actuation of each active joint. Overall results strongly suggest that the proper phase relation among number of active joints in a robotic leg is a highly important parameter that can be used to smoothly control the speed and the dynamic transition in particular direction of a legged robot locomotion.

We intend to extend this control approach to design and control dynamic gaits of our four-legged robot that may run at high-speed without using any external sensory feedback. Perhaps this approach may be useful to achieve gait transitions in a four-legged system in future.

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REFERENCES

[1] M. H. Raibert, "Legged robots," *Communications of the ACM*, vol. 29, no. 6, pp. 499–514, May 1986.

[2] M. H. Raibert, "Running with symmetry," *The International Journal of Robotics Research*, vol. 5, no. 4, pp. 3–19, Dec. 1986.

[3] M. Ahmadi and M. Buehler, "The ARL monopod II running robot : control and energetics," *Proc. of the 1999 IEEE International Conference on Robotics and Automation*, vol. 1, pp. 1689–1694, 1999.

[4] S. H. Hyon, "Development of a biologically inspired hopping robot "kenken"," *Proc. of the 2002 IEEE International Conference on Robotics and Automation*, pp. 3984–3991, 2002.

[5] J. G. Cham and M. R. Cutkosky, "Dynamic Stability of Open-Loop Hopping," *Journal of Dynamic Systems, Measurement, and Control*, vol. 129, no. 3, pp. 275–284, 2007.

[6] J. Seipel and P. Holmes, "A simple model for clock-actuated legged locomotion," *Regular and Chaotic Dynamics*, vol. 12, no. 5, pp. 502–520, Oct. 2007.

[7] R. J. Full and D. E. Koditschek, "Templates and anchors: neuromechanical hypotheses of legged locomotion on land." *The Journal of experimental biology*, vol. 202, no. Pt 23, pp. 3325–3332, Dec. 1999.

[8] F. Iida, Y. Minekawa, J. Rummel, and A. Seyfarth, "Toward a human-like biped robot with compliant legs," *Robotics and Autonomous Systems*, vol. 57, no. 2, pp. 139–144, Feb. 2009.

[9] J. Rummel, F. Iida, J. A. Smith, and A. Seyfarth, "Enlarging regions of stable running with segmented legs," *Proc. of the 2008 IEEE International Conference on Robotics and Automation*, pp. 367–372, May 2008.

[10] S. Schaal and C. Atkeson, "Open loop stable control strategies for robot juggling," *Proc. of the 1993 IEEE International Conference on Robotics and Automation*, pp. 913–918, 1993.

[11] M. H. Dickinson, C. T. Farley, R. J. Full, M. A. Koehl, R. Kram, and S. Lehman, "How animals move: an integrative view." *Science (New York, N.Y.)*, vol. 288, no. 5463, pp. 100–106, 2000.

[12] R. Blickhan, "The spring-mass model for running and hopping," *Journal of Biomechanics*, vol. 22, no. 11-12, pp. 1217–1227, Jan. 1989.

[13] F. I. Sheikh and R. Pfeifer, "Adaptive locomotion on varying ground conditions via a reconfigurable leg length hopper," *Proc. 15th International Conference on Climbing and Walking Robots*, pp. 527–535, 2012.

[14] A. A. Biewener, *Animal Locomotion*. Oxford University Press, 2003.

[15] V. M. Zatsiorsky, *Kinetics of Human Motion*. Human Kinetics, 2002.