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Instantaneous control of a vertically hopping leg's total step-time

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***Abstract*— The main contribution of this paper is a new step-time controller for a vertically hopping robot leg capable of meeting a demanded step-time instantaneously, meaning within a single hop.**

The ability to perform hops of an arbitrary and changing size accurately forms the motivation behind the work done here. This would allow control of a running robot's foot placement and thus fast traversal of terrain with limited safe foot placement spots.

In this paper, the hopping controller is developed and validated using an articulated, hydraulically actuated leg from the HyQ robot which has been modified to include an elastic foot and constrained to hop vertically. It is shown that instantaneous control over the step-time can be achieved using only joint positions and ground contact senses. This was achieved with a simple feedforward lookup in combination with a proportional and integral action.

I. Introduction

From millipedes to kangaroos many animals have used legs to traverse the Earth's terrain. This has been so successful that legged animals are found virtually everywhere on our planet. This ability of legs to traverse almost any terrain has fascinated many researchers and motivated them to build legged machines [1]. Various approaches have been taken by researchers trying to build and control walking and running robots. Pioneered by Raibert and his colleagues, one of the most successful approaches for robotic running has been to construct robots featuring elasticity in their legs. Then the problem of making the robot run can be treated as one of controlling the passive dynamics of a springy inverted pendulum [2]. One way to achieve this is to separate the controller into 3 parts: vertical hopping; horizontal speed; and body orientation. Most researchers have applied such a controller with a focus on steady-state running [3]. This means that the robot cannot achieve the step by step performance required for targeted foot placement.

Rock wallabies and mountain goats can navigate steep and mountainous terrain by hopping accurately from one safe foot placement spot to the next. This requires instantaneous control over the ballistic trajectory of their hops. For a robot to achieve something similar would require solving a number of control problems including: assessing the surrounding terrain for safe foot placement surfaces; forming a trajectory as a series of stepping points in safe areas; and a low-level controller which executes a series of hops from one stepping point to the next. This paper looks at an aspect of the last of these. Specifically, the aim here has been to develop a controller that achieves a desired total step-time within a single hop.

II. Background

Among the class of legged robots which dynamically balance and feature elastic energy storage as part of their running cycle, researchers have mainly focussed on steady-state locomotion. Most researchers have focussed on maintaining a steady hopping height and rejecting disturbances. When foot placement surfaces are limited, however, it can become necessary to vary the size of the step on each step in order to avoid poor spots. This problem has been tackled most directly by Hodgins [4]. Hodgins experimented with a planar biped robot featuring prismatic legs. The legs consisted of a hydraulic actuator and pneumatic spring in series. The thrust of the hydraulic actuator was varied in order to achieve hops of different sizes but specific details on how thrust was controlled were not provided. Rapid changes in hopping height control were also attempted in [5], [6]. Here a DC motor and leadscrew actuated prismatic leg with mechanical spring in series was used. The authors attempt to control hopping height by fitting experimental data to a 9 parameter non-linear function which is then inverted for control purposes. The approach proposed in this paper is significantly simpler. A similar DC motor actuated leg is also employed in [7]. Here the authors controlled the energy imparted by the leg on the robot during stance. This was done by employing a controller which integrated an estimate of the spring force with actuator velocity during stance. It is unclear whether this approach would allow instantaneous changes in height because the authors' purpose was steady-state locomotion so the performance of the robot with changing hopping height demand was not assessed.

The contribution of this paper is a new method for hopping control which:

- Does not control the height, but explicitly controls the step-time. The benefits of this are that an assumption that the stance phase has a fixed duration is not required. Additionally, no sense of height is required.
- Demonstrates instantaneous changes in the step-time, meaning a desired step-time can be achieved in one hop.
- Does not require force sensors.
- Includes integral actions allowing adaptation to changes in ground or hydraulic properties.

III. Fundamentals of hopping control

In the case of a single-legged hopping robot, each step can be split into two phases. During contact with the ground, the leg is in stance phase and at all other times it is in the flight phase. The total step-time $T = T_s + T_f$ where T_s and T_f are the durations of the stance and flight phases.

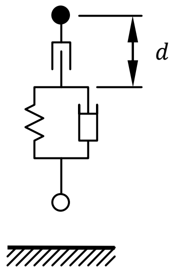

Fig. 1. Model of hopping robot in series with actuator [8].

The ballistic trajectory of a hopping robot during flight means that, if the stance time is assumed to be constant, there is a simple relationship between the total step-time $T = T_s + T_f$ and the square root of the hopping height $\frac{1}{2}T_f = \sqrt{2h/g}$. Controlling the hopping height would then amount to the same thing as controlling the flight time and hence the step-time. In reality however the stance time is not constant due to the effects of damping and the dynamics of the leg as it sweeps when running with a horizontal velocity. Given this, if the larger objective is foot placement it may be desirable to have a hopping controller work in terms of the step-time. For example when running with a velocity u on level ground the length of a step is given by uT. Another reason is that the step-time may be measured more easily and directly than the hopping height. The hopping controller developed in this work is in terms of the step-time.

Consider the simplified model of a vertical hopping robot shown in Fig. 1. Hopping can be achieved and controlled using a two state controller as shown in Fig. 4. A simple control strategy is to retract the actuator d during flight to a home position and extend with constant velocity $\dot{d}$ during stance to impart energy into the system. Steady hopping is easily achieved by maintaining a fixed $\dot{d}$ for each hop. This is because losses (due to damping) increase as a function of height. As a result, the hopping robot, for a steady input, will converge to a particular steady-state hopping height where the input energy matches the losses. Once the relationship between the steady-state hopping height and the control variable, in this case $\dot{d}$, has been mapped for a given robot then a look-up table or fitted equation can be used to achieve a desired steady-state hopping height or step-time. Although this achieves steady-state hopping, it is inadequate if instantaneous step-time changes are required. However, earlier simulation work [8] showed that the introduction of a simple proportional gain on the step-time error, properly tuned, achieved instantaneous step-time control for the model. In the following sections, we show that, nothing much more elaborate is required to achieve instantaneous step-time control in a real robot either.

IV. Experimental Apparatus

A photo of the experimental rig used in this paper is shown in Fig. 2 and key parameters are listed in Table I. Fig. 3 also shows a schematic view of this leg from the 'HyQ' robot [9] which has been constrained by a pivoting beam to hop

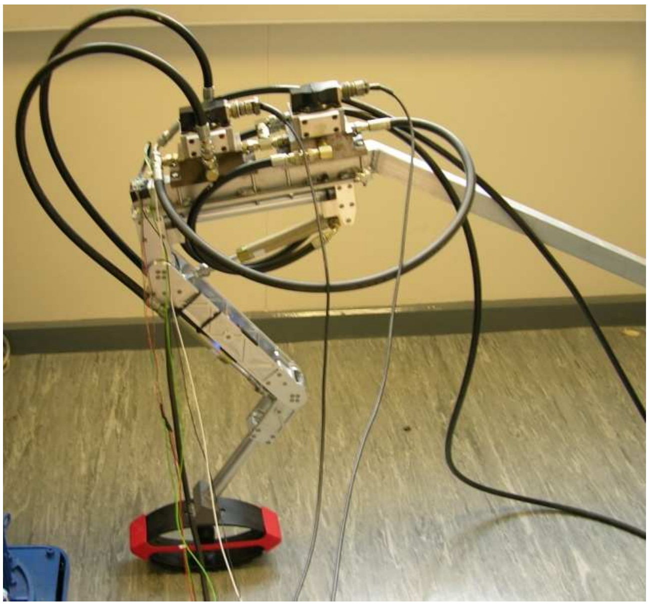

Fig. 2. Robot leg in the home position it returns to during flight state.

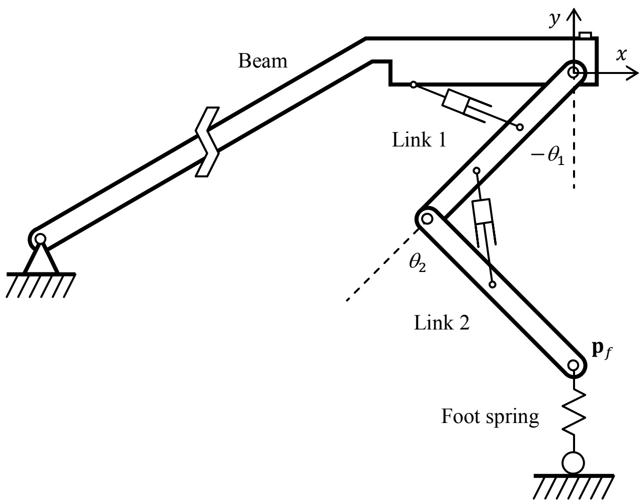

Fig. 3. Schematic drawing of experimental rig.

TABLE I
Experimental Rig Key Parameters

Parameter	Value
Hip-knee link length	0.35 m
Knee-foot link length	0.33 m
Total mass	18 kg
Approximate foot stiffness	10000 $\mathrm{N\,m^{-1}}$
Hip-beam pivot distance	2 m

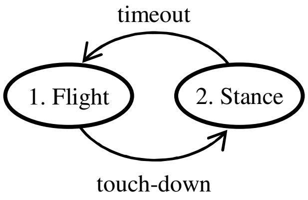

Fig. 4. Controller states.

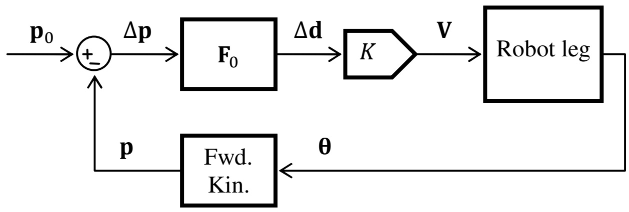

Fig. 5. Foot position controller in flight state.

vertically. The leg and rig have the following degrees of freedom:

- Two hydraulically actuated joints. Extension and retraction of the hydraulic cylinders corresponds to extension and flexion of the leg.
- Passive elastic foot.
- Beam angle. The constraining beam is long with respect to the hopping height of the leg so approximately constrains the leg to hop vertically.

The two hydraulic actuators are controlled via proportional control valves. Each valve is controlled by a current amplifier which generates a current in proportion to signal voltages V_1 and V_2 in the range ± 10 V to position the valve spools. The control voltages are supplied by the controller. Sensor inputs to the controller include:

- Joint angle position sensors at the hip θ_1 and knee θ_2.
- An accelerometer to measure vertical accelerations (2).
- Pivot sensor returning angle and angular velocity of beam.

A 'CompactRIO' controller [10] running with a fixed sample rate of 250 Hz was used in all experiments in this paper. Hopping was achieved by having the controller alternate between two states as shown in Fig. 4:

1) During the flight state the leg resets to a home position as shown in Fig. 2. The flight state ends when the foot touches down on the ground. At that point the controller state is switched to stance.
2) During the stance state a constant control signal is output to extend the foot downwards for a fixed amount of time. The effect of this is to add energy in the vertical direction. When the stance state times out, which was experimentally found to be 0.13 s, the controller state switches back to flight.

A. Flight

During the flight state, the controller returns the leg to a home position $\mathbf{p}_0 = (0, -0.56)$ m. A foot position controller to do this can be implemented in a number of ways but the controller shown in Fig. 5 was used in this work. In this controller a matrix $\mathbf{F}(\theta)$, analogous to the inverse Jacobian, relates a differential change in Cartesian coordinates $\Delta\mathbf{p}$ to a differential change in actuator displacements $\Delta\mathbf{d}$ for a given leg position. Computed for the home position $\theta = \theta_0$ it is:

$$\mathbf{F}_0 = \begin{pmatrix} -0.0758 & 0.10798 \\ -0.0001 & 0.22585 \end{pmatrix} \tag{1}$$

The flight state is supposed to end when the foot touches the ground. Again, this can be accomplished in a number of ways but here this touch-down event was detected using an accelerometer on the leg. A large acceleration is detected at touch-down. When the rising acceleration signal from the accelerometer crosses a threshold value, it is detected as a touch-down event and the controller switches from flight state to stance. The threshold value was tuned to be sensitive enough to trigger a touch-down controller event close to the actual event while avoiding detecting any events erroneously due to noise or vibration.

B. Stance

The step-time T is calculated by subtracting the time of the previous touch-down time from the current time upon touch-down. A control action is then taken based on T and the demanded step-time T_d for the upcoming hop. The output of the controller during stance is the control variable V_c. This is then used to select actuator signal voltages in a ratio that results in a vertically downwards motion. The valve control voltages are held at these values throughout the stance state which ends after a fixed duration. When the stance state times out the controller reverts back to the flight state.

There is a ratio of valve voltages which results in a downwards motion of the foot. This is given by the right column of the $\mathbf{F}_0$ matrix. Matrix $\mathbf{F}_0$ transforms, around the home position, differential changes in Cartesian foot position to differential changes in actuator displacements:

$$\mathbf{F}_0 \times \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 0.10798 \\ 0.22585 \end{pmatrix} \tag{2}$$

Actuator voltages can be applied in this ratio using:

$$\mathbf{V} = \begin{pmatrix} V_1 \\ V_2 \end{pmatrix} = -V_c \begin{pmatrix} 0.48 \\ 1.00 \end{pmatrix} \tag{3}$$

The negative sign in (3) ensures a downwards motion of the foot for a positive control output V_c. However, when the hydraulic cylinders are in retraction, when $V_c < 0$, they will displace with a greater speed than when in extension. This is due to the fact that the area on the annulus side of a single-ended actuator is smaller than the area on the piston side so a similar flow rate will result in greater cylinder motion. In order to linearise this effect the following logic is added:

$$\textbf{if } V_c < 0 \textbf{ then } V_c \leftarrow R V_c$$

Where R is the ratio of the annulus area to piston area. For a cylinder with a piston diameter of 0.016 m and rod diameter of 0.010 m, $R = 0.61$.

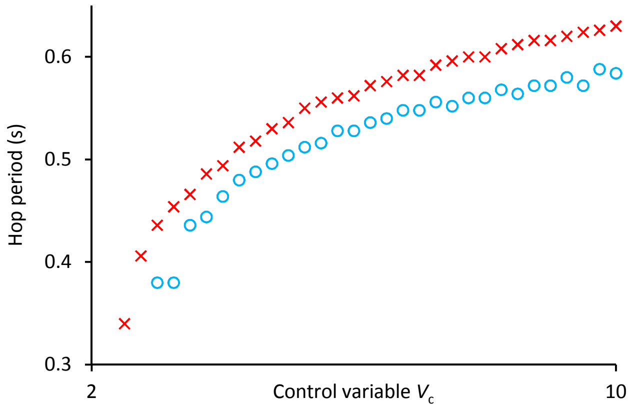

Fig. 6. Relationship between control variable V_c and steady-state hopping step-time on hard (crosses) and soft (circles) ground.

V. Controller Development

A. Steady-state hopping

If the control variable V_c is kept constant, the robot settles at a steady hopping height. Fig. 6 shows the steady-state relationship obtained this way between the control variable V_c and the step-time T (crosses). By fitting a cubic function to the results ($V_c = f(T)$) it becomes possible to create an open-loop hopping controller which references the fitted function in order to achieve a demanded steady-state step-time. It should be noted however that the relationship between steady-state step-time and the control input changes with different ground properties and robot masses. The same figure also shows another set of data obtained by placing a soft cloth matting on the floor (circles).

Fig. 7 shows the results of applying an open-loop controller using the cubic function fitted to hard ground in Fig. 6. There is a noticeable steady-state error even on hard ground from which the lookup/feedforward function was derived. It is thought that this is due to a change in hydraulic fluid properties between the time the feedforward data was gathered and the time of other experiments. On soft ground when using the reference function fitted to hard ground data the steady-state error is even worse.

B. Closed loop hopping

For the open-loop controller (Fig. 7), two obvious problems are the steady-state error and the slow convergence to the demanded step-time. Both of these can be improved upon by forming a closed-loop controller using the error between the demanded step-time T_d and the most recent completed step-time T. An integral action on the error can remove steady-state errors and a proportional gain can improve dynamic performance. Adding these actions results in a PI plus feed-forward controller as illustrated in Fig. 8. Because the job of the integral gain is to remove steady-state errors, the integral gain is programmed to switch to $K_I = 0$ when the demand is not steady $T_{d(n+1)} \neq T_{d(n)}$.

1) Tuning gains: The closed loop controller in Fig. 8 requires the tuning of two controller gains:

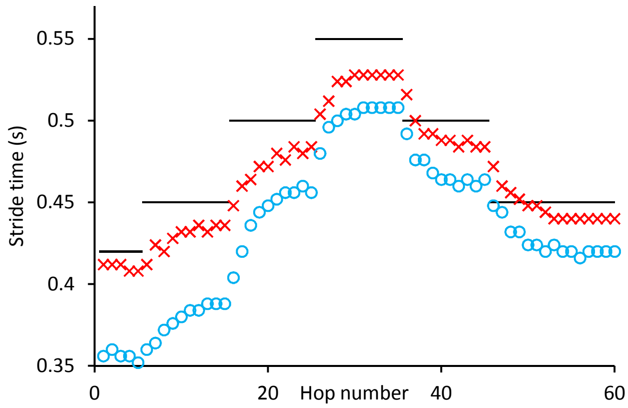

Fig. 7. 'Open-loop' hopping control on different grounds. Solid lines show demanded step-time. Steady-state error is smaller on hard ground because the open-loop controller references a function fitted to hard ground data. The three reference step-times correspond to approximate hopping heights of 0.10 m, 0.13 m and 0.17 m.

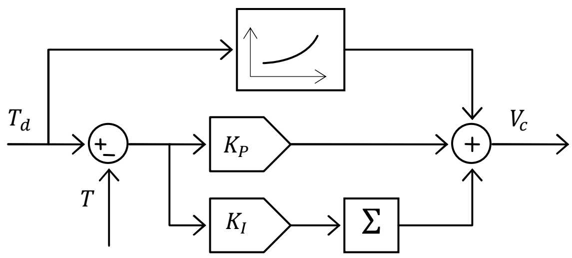

Fig. 8. Block diagram of PI plus feed-forward step-time controller.

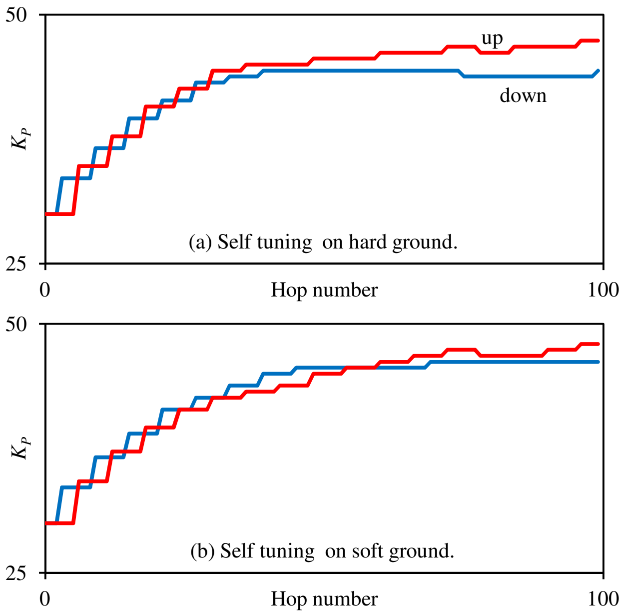

Fig. 9. Convergence of controller gain $K_P^{\pm}$ by automatic tuning.

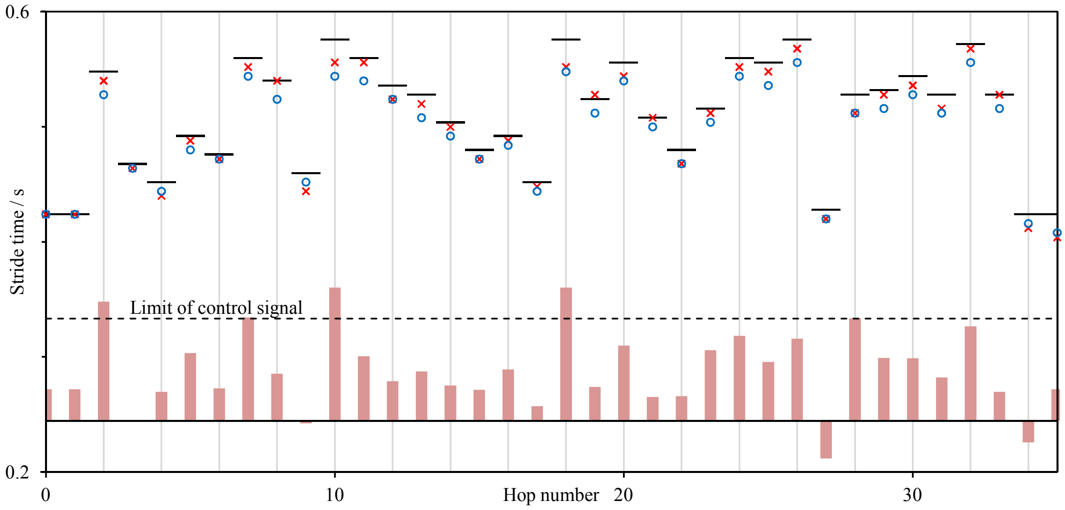

Fig. 11. Results for PI+feed-forward controller with random hopping demand. Step-times range from 0.38 s to 0.58 s which corresponds to hopping heights of 0.08 m and 0.24 m respectively. Controller was auto tuned before beginning random demand input (horizontal lines). The same experiment was performed first on hard (crosses) ground then on soft ground (circles). The control variable V_c has also been plotted for the case of hard ground.

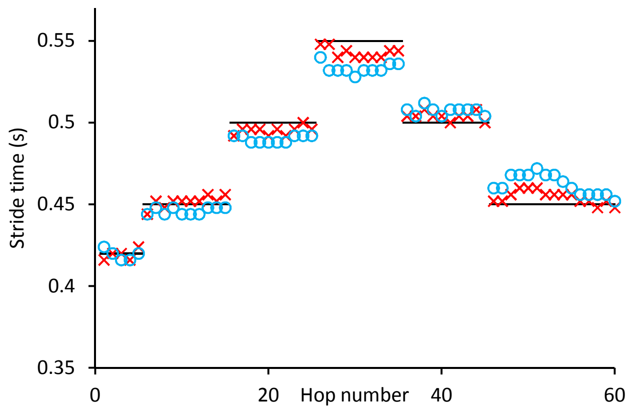

Fig. 10. 'Closed-loop' hopping control on different grounds. Hard ground (crosses); soft ground (circles).

- The integral gain K_I was manually tuned to remove the steady-state error seen in open-loop results (Fig. 7) within 10 hops.
- The proportional gain K_P can be tuned manually but a more systematic and convenient method of self-tuning was adopted to allow faster tuning for different ground properties and robot parameters.

In order to investigate whether there is a difference between increasing step-time (and therefore hopping height) and decreasing it, the controller gain K_P was split into two:

- $K_P = K_P^+$ when increasing height $T_d - T > 0$
- $K_P = K_P^-$ when decreasing height $T_d - T < 0$

To automatically tune these values, the demanded value of step-time was set to alternate every 3 hops between 0.43 s and 0.48 s. The values for K_P were then updated in proportion to the error in the just completed hop. When stepping up:

$$K^+_{P\,(n+1)} = K^+_{P\,(n)} + \alpha\,(T_{d(n-1)} - T_{(n)}) \tag{4}$$

When stepping down:

$$K^-_{P\,(n+1)} = K^-_{P\,(n)} + \alpha\,(T_{(n)} - T_{d(n-1)}) \tag{5}$$

The value of α can be used to change the rate at which the tuned gains converge on a final value. Figure 9 shows how the controller gains converged with this tuning from initial values of 30. It can be seen that K_P tunes to a similar value regardless of whether the ground is hard (a) or soft (b) or whether increasing or decreasing hopping height.

2) Results: The final tuned values of K_P and K_I were utilized in experiments with step (Fig. 10) and random (Fig. 11) changes in demand.

The step demand results show the improvement over open-loop control. The PI plus feed-forward controller meets and keeps the demand within two or three ticks of the 250 Hz controller.

A more challenging demand is shown in Fig. 11. Here random step-times are demanded in the range 0.42 s to 0.58 s. This corresponds to hopping heights ranging from 0.07 m to 0.20 m. It can be seen that the large shortfalls on hops 10 and 18 occur because the control signal had reached saturation. This can be avoided by limiting demanded step-times to within the performance envelope of the robot. Additionally, it should be noted that some hops require a negative value for the control variable V_c. This means that the leg retracts, rather than extending during stance. Retraction is required when the passive damping is insufficient to remove enough energy to reduce height to the required level. The actuators then act to remove energy from the system. The performance for random hopping can also be judged using Fig. 12.

VI. Conclusion

In this paper it has been demonstrated that the simple addition of a PI controller to a steady-state height feedforward model is sufficient to achieve instantaneous step-time control. Meaning the robot can change its ballistic trajectory within

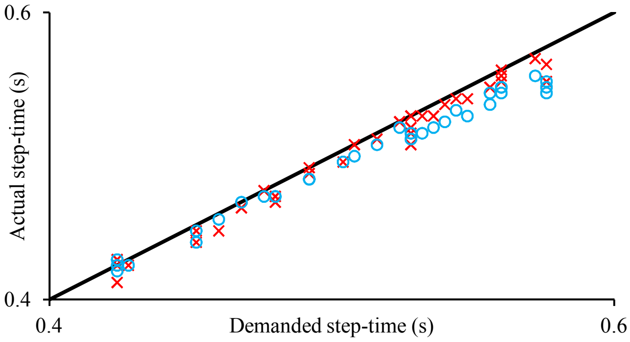

Fig. 12. Performance of step-time controller for random hops showing demanded vs actual step-time.

a single step when combined with additional controllers for balance and hopping speed. This is a requirement for foot placement while running or hopping. Related work simulating a hopping leg with a simple mass-spring-damper model suggests that the controller developed here could also be applied to legs with different structures and systems of actuation.

In future work it will likely be necessary to extend the hopping controller to correct for the changing angle at which thrust is applied when running with any speed. A treadmill added to the experimental rig is being used to investigate this. The long term direction of this work is the development of a controller which can be deployed by multi-legged robots when accurate foot placement is required to hop or run across the challenging terrain of Earth or another rocky planet.

Foot placement allows traversal of rough terrain by taking advantage of isolated footholds. Foot placement while hopping, running or jumping allows faster locomotion with footholds placed further apart.

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