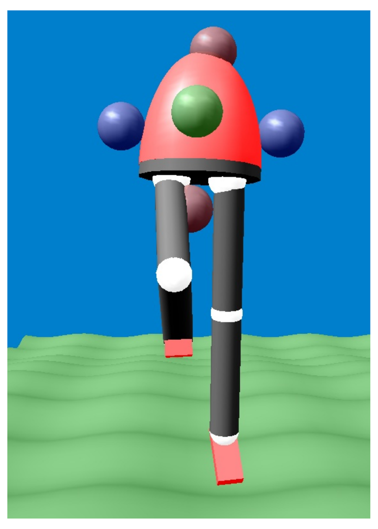

Locomotion with 3D Bipedal Robot: A Fast Running Algorithm

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Problem

Running is a high dynamic motion easily performed by humans and hardly achieved by humanoid robots. The control algorithm needs to provide reactive behaviors while keeping the robot's balance. For 3D and complex bipedal robots, running is a difficult problem for the following reasons:

1. Naturally unstable system
2. High dynamic forces
3. Flight phase

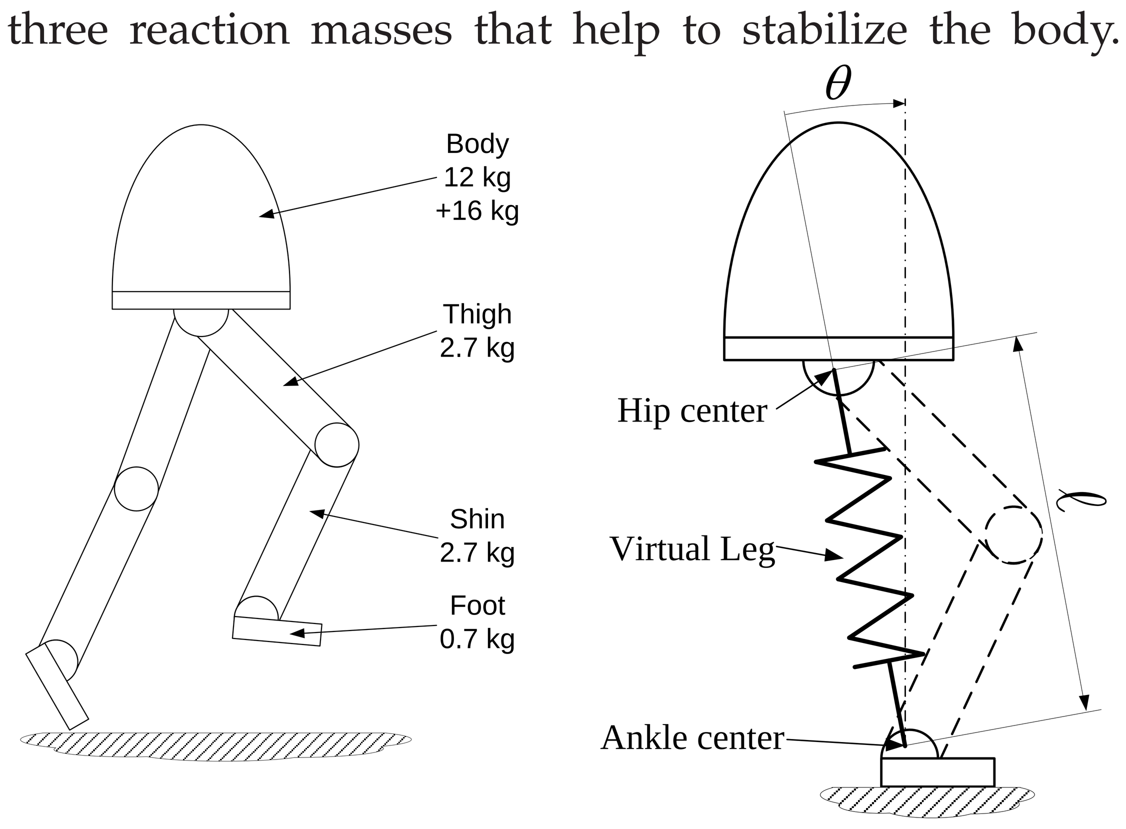
Contributions

We formulated the control as the composition of various intuitive laws for each part of the robot. The architecture is based on [1, 2], aims to be as simple as possible, and to provide a basis for testing complex mechanic principles. Our main contributions are:

1. Spring-mass model for complex 3D biped robot
2. Coordination law for the swing leg
3. Stability of the system even at high velocities (up to $6\,m.s^{-1}$)
4. Stability of the system even with ground perturbations

Robot

The robot simulated is M2 which was developed at the MIT Leg Laboratory. It was augmented with three reaction masses that help to stabilize the body.



Perspectives

1) We are incorporating evolutive gains that change of value to reach one or various target(s).

2) The spring-mass model has to be studied in more details. It can provide an efficient foot placement prediction in the frontal plane. More, it is possible to study its stability basin and to make a foot placement which is as far as possible from the basin boundaries.

3) Without physical meaning, the three reaction masses have to be replaced by an anthropomorphic upper-part.

4) It is possible to extend the spring-mass model to the walking motion [3, 4]. Thus, is it possible to design a unified control method for walking and running?

References

[1] Jerry E. Pratt and Gill A. Pratt, "Exploiting Natural Dynamics in the Control of a 3D Bipedal Walking Simulation", *In Proc. of CLAWAR, 1999.*

[2] Jerry E. Pratt, "Exploiting Inherent Robustness and Natural Dynamics in the Control of Bipedal Walking Robots", Ph.D. dissertation, M.I.T., 2000.

[3] A. Seyfarth, H. Geyer, R. Blickhan, S. Lipfert, J. Rummel, Y. Minekawa, and F. Iida, "Running and Walking with Compliant Legs", *Fast Motions in Biomechanics and Robotics, 2006.*

[4] F. Iida, Y. Minekawa, J. Rummel, and A. Seyfarth "Toward a human-like biped robot with compliant legs", *Robotics Autonomous Systems, 2009.*

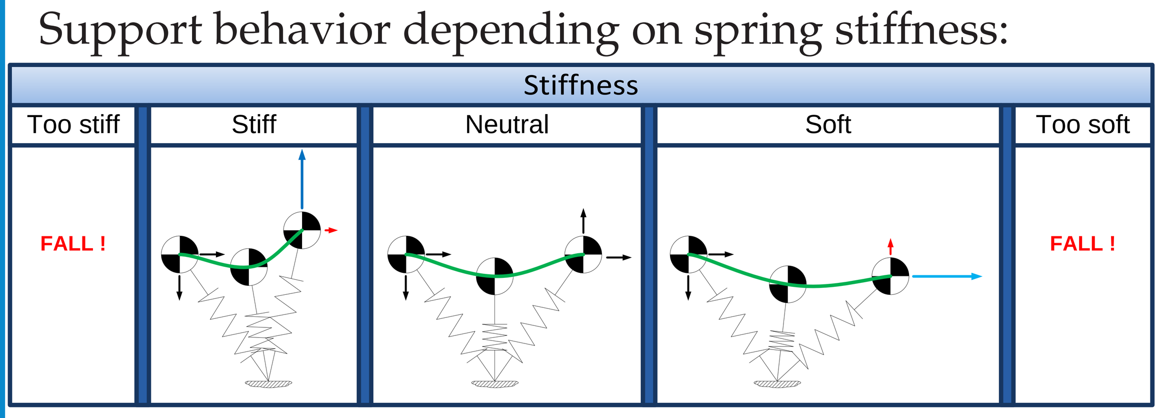
Spring-Mass (Stance)

Linear spring leg behavior using the knee:

$$F^{\text{spring}} = \hat{K}\,(l_0 - l)$$

$$\tau^{\text{knee}} = -L^{\text{thigh}} \sin\left(\frac{q^{\text{knee}}}{2}\right) F^{\text{spring}}$$

Support behavior depending on spring stiffness:



Stiffness estimation at touch down for neutral behavior:

$$\hat{K} = \frac{m\,g}{l_0}\left(\frac{C_1\,\dot{x}_0\,\dot{z}_0 + (C_2 + C_3\,\dot{x}_0)\,\theta_0}{(C_4\,\dot{z}_0 + (C_5 + C_6\,\dot{x}_0)\,\theta_0)\,\theta_0}\right)^2$$

$C_1 = 6.058$, $C_2 = 10.05\,m^2.s^{-2}$, $C_3 = 10.75\,m.s^{-1}$

$C_4 = 12.17\,m.s^{-1}$, $C_5 = 12.17\,m^2.s^{-2}$, $C_6 = 5.272\,m.s^{-1}$

Accuracy (K: neutral stiffness numerically computed):

$$P = 1 - \sqrt{\frac{\sum\left(K - \hat{K}\right)^2}{\sum K^2}} = 99.56\%$$

- Support behavior adjustment with respect to the system behavior at touch down.
- Easy way to control the system behavior by simply hardening or softening the stiffness.

Coordination (Swing)

Assumption:

$$\ddot{\theta} = 0\,rad.s^{-2}$$

Prediction of stance duration:

$$T^{\text{stance}}_{\text{pred1}} = -2\,\frac{\theta_0}{\dot{\theta}_0}; \qquad T^{\text{stance}}_{\text{pred2}} = C\left(T^{\text{stance}}_{\text{pred1}} + \frac{\Delta\theta}{\dot{\theta}_0}\right)$$

$$\Delta\theta = \left(\theta_0 + \theta_f^{\text{real}}\right)_{\text{last step}}$$

$${}^{d}\dot{q}^{\text{hip}}_{\text{pitch}} = \frac{q^{\text{hip}}_{\text{pitch}} - {}^{d}q^{\text{hip}}_{\text{pitch}}}{T^{\text{stance}}}$$

Law based on a simple PD controller:

$$\begin{aligned}\tau^{\text{hip}}_{\text{pitch}} = \;& K_p\left({}^{d}q^{\text{hip}}_{\text{pitch}} - q^{\text{hip}}_{\text{pitch}} - \varphi_y\right)\\ &+ K_v\left((1 - S_1)\,{}^{d}\dot{q}^{\text{hip}}_{\text{pitch}} - \dot{q}^{\text{hip}}_{\text{pitch}}\right)\end{aligned}$$

with:

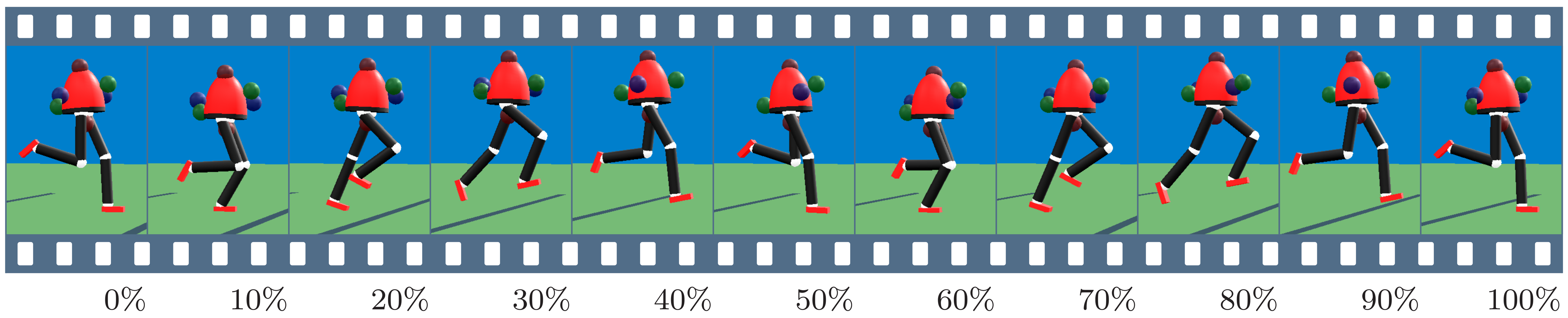
$$S_1 = \begin{cases} 0 & \text{if: } \theta < 0 \\ 1 & \text{if: } \theta_f = 0 \text{ or: } \theta > \theta_f \\ (\theta/\theta_f)^2 & \text{else} \end{cases}$$

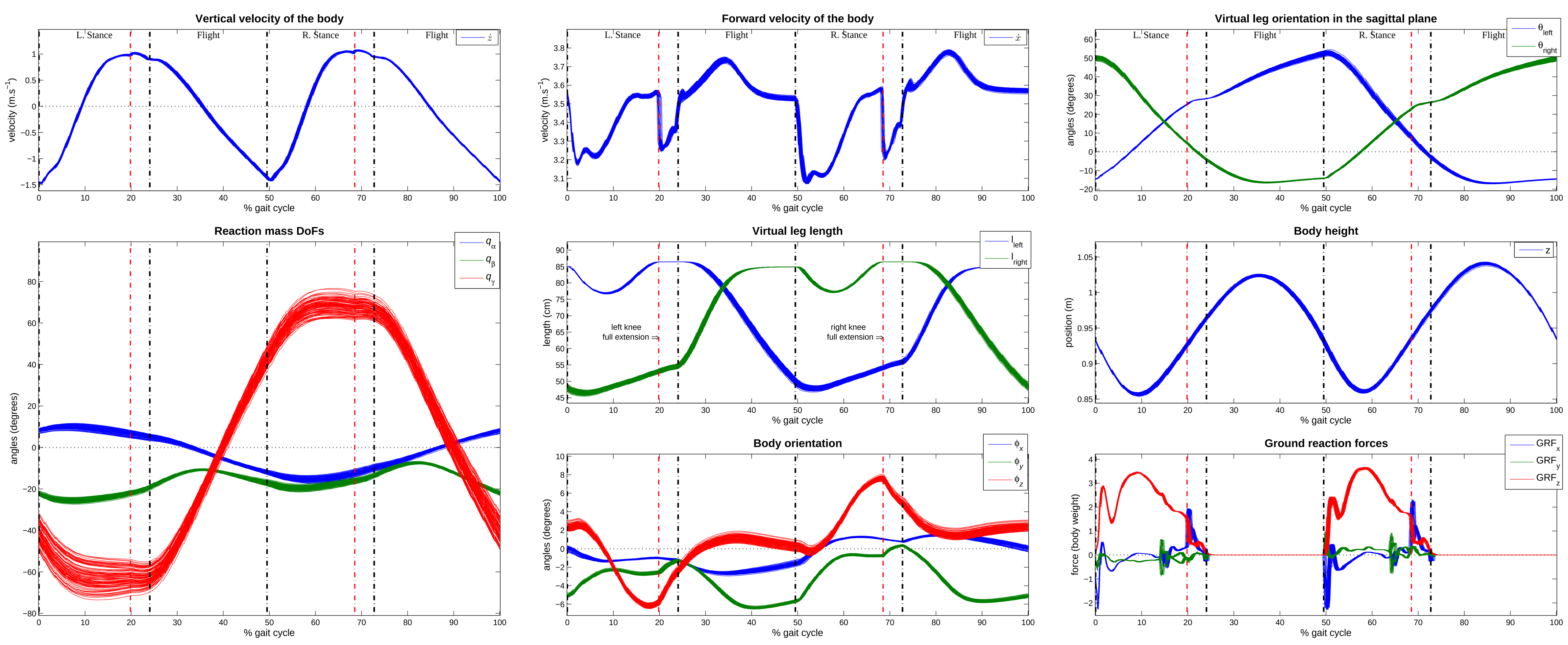
Results:

	Value	Error	
	(ms)	(ms)	$(\%)$
$T^{\text{stance}}_{\text{meas}}$	211.7	–	–
$T^{\text{stance}}_{\text{pred1}}$	137.6	74.2	35.04
$T^{\text{stance}}_{\text{pred1}} + \Delta\theta/\dot{\theta}_0$	199.4	12.3	5.83
$T^{\text{stance}}_{\text{pred2}}$	211.8	< 0.1	0.01

- Simple control law for the swinging hip to react with respect to the system state at touchdown.

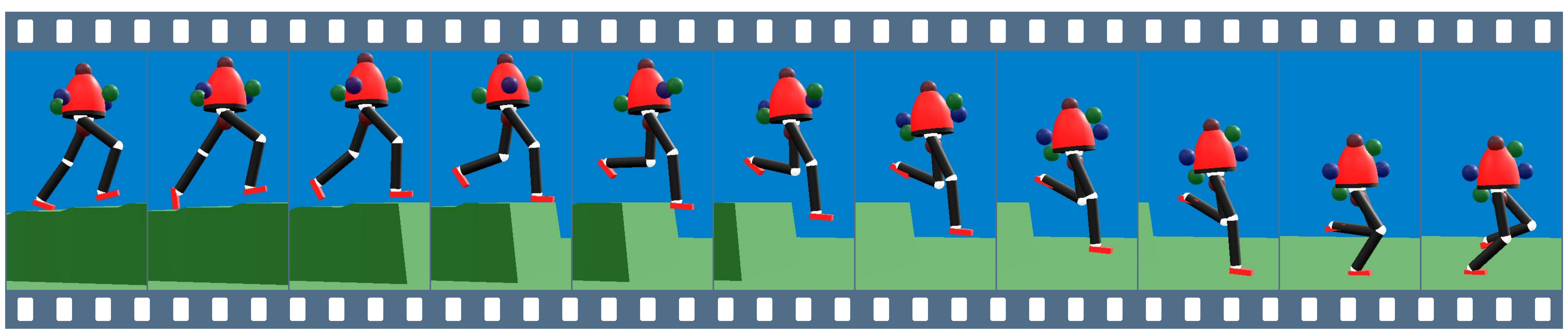
Results





Results of 100 successive gait cycles of one simulation at $3.5\,m.s^{-1}$.
Each cycle begins and ends at left foot touchdown.

Ground Perturbations



Obstacle height variation: $66.5\,cm$, forward speed: $3.2\,m.s^{-1}$.