Towards Agility in Compliant Point-Foot Bipeds

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Objectives

Our goal is to make a robot explore any types of terrain. Our robot, Hume, has three main characteristic features to accomplish it.

- **No ankle actuation.** Keeping legs being light for agile motion,
- **Point feet.** To be adaptable to any kinds of surface,
- **Compliant structure and control.** To reduce the impact coming from violent motion.

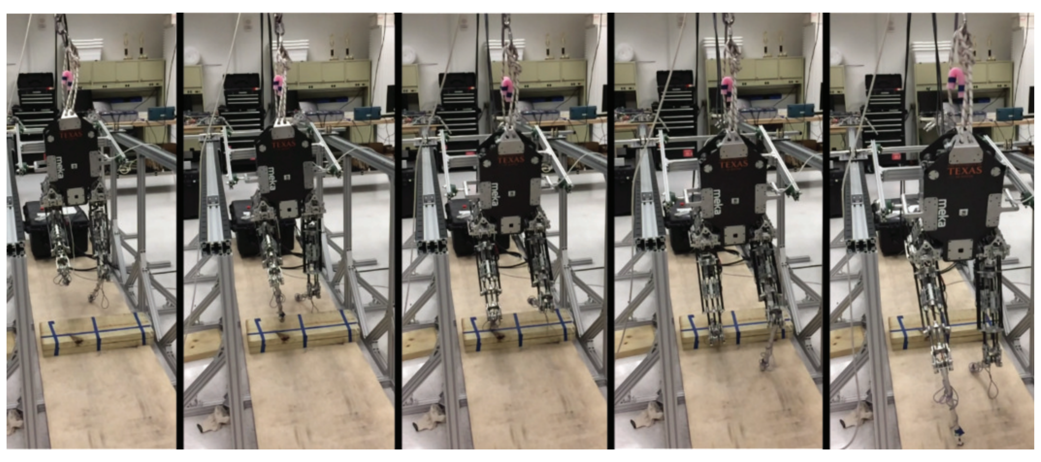
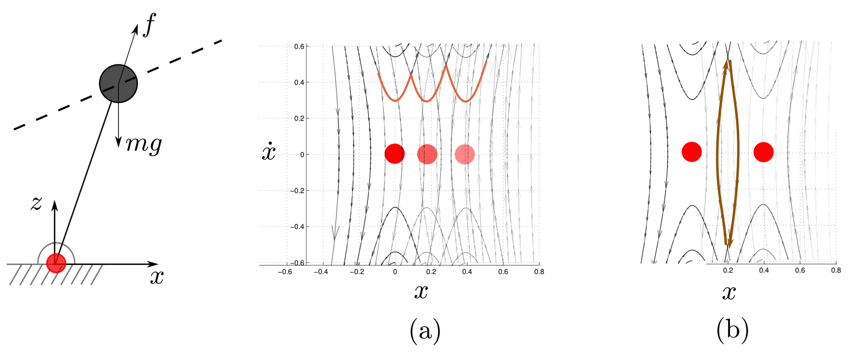


Figure 1: Hume is taking three steps on the non-flat terrain.

Phase Space Planner

Overlapping phase portraits of Prismatic Inverted Pendulum Model (PIPM) according to the pre-defined foot positions makes it easy to find the phase path of center of mass (COM).



To account arbitrary height surfaces parameterized by x, the equation for $\ddot{x}$ is presented as follow, rather than the Linear Inverted Pendulum equation, $\ddot{x} = \frac{g}{h}(x - x_p)$. x_p means a supporting point.

$$\ddot{x} = \frac{g + \frac{d^2 z}{dx^2}\dot{x}^2}{z - (x - x_p)\frac{dz}{dx}}(x - x_p), \qquad (1)$$

A main benefit of our planner is to manage the complex Equation (1) by a numeric solver, which means that the planner can handle non constant COM surface.

Closed Loop Control Scheme

- Ensuring 3D underactuated point-foot biped remains blanced while stepping.
- Simplifying behavioral analysis by using Prismatic Inverted Pendulumm Model.
- Re-planning the path in phase space based on the observed initial error to find the proper landing location of each step.

State machine (Fig. 2) guides the robot through the discrete phases of stepping. Once per step, the state machine activates the online footstep re-planner, which decides the placement of the upcoming footstep.

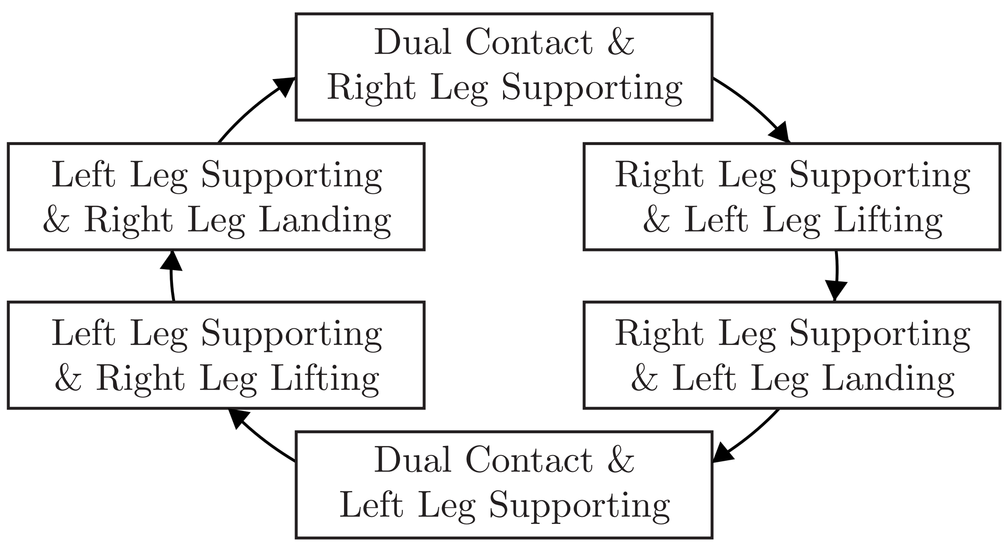


Figure 2: State Machine

Whole Body Compliance Control

The controller is tasked with achieving

- a body height,
- a constant body pitch,
- a constant body roll,
- trajectory tracking of the swing foot.

while in single support. Whole Body Compliance Controller generates torque commands to accomplish above Cartesian tasks while obeying a contact constraint.

Re-Planning Strategy

Many times the COM path deviates from the planned path because of uncertainties. The process to recover the balance is described in Fig. 3.

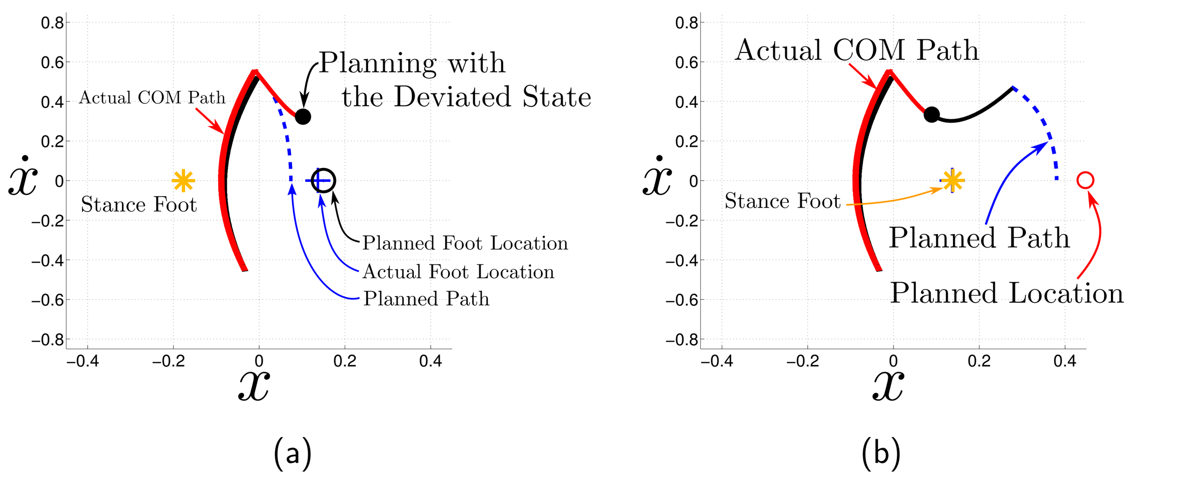
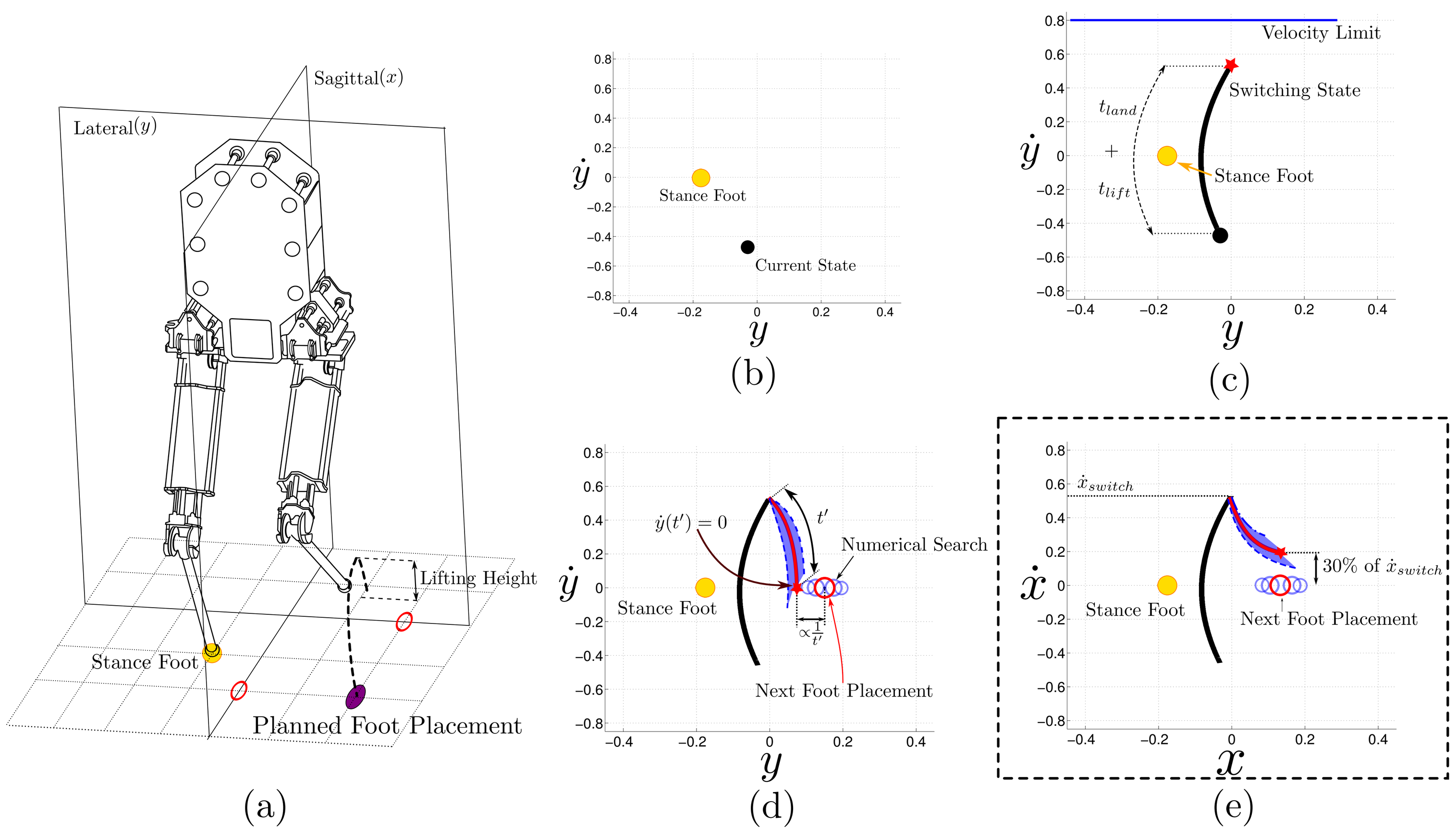


Figure 3: **Online Planning Process.** (a) Periodically, the planner plans the next trajectory and the associated foot placement. When the planner kicks in, it starts with the currently deviated trajectory. (b) The planner then attempts to find the next foot placement such that it reverses the COM velocity.

Foot Placement Planner



(a) The planner searches for the foot landing placement for each plane (lateral and sagittal). The COM state and the position of the stance foot location are delivered to the planner.

(b) We depict the current COM state and stance foot locations in phase space. The planner searches the landing location first in the lateral plane, y.

(c) Based on PIPM dynamics, the position and velocity of COM are projected into the future.

(d) The planner searches for the foot placement that will make the COM velocity equal to zero at time t'.

(e) If the planned foot placement is out of range, the robot makes one more step. This strategy is only allowed in the sagittal plane, x, to avoid hitting abduction/adduction joint limits on the hip.

3D Dynamic Simulation

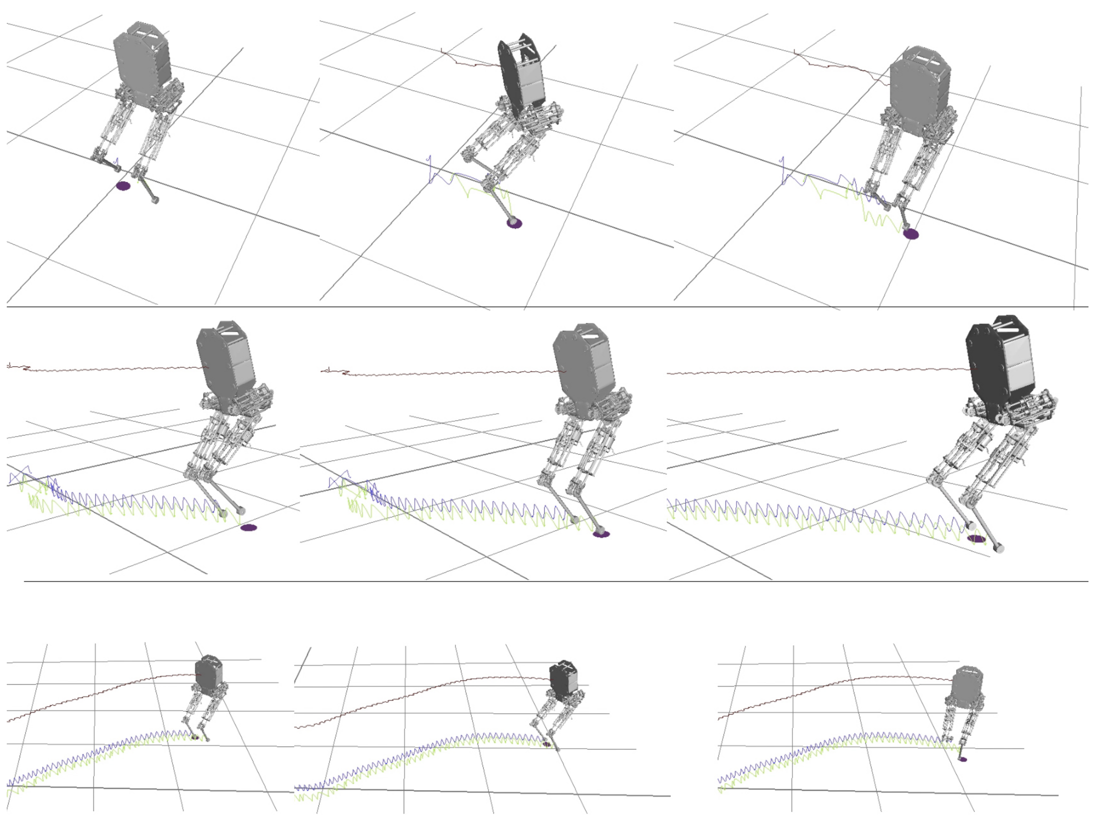


Figure 4: **Dynamic Simulation** Hume reamins balanced for more than 40 seconds.

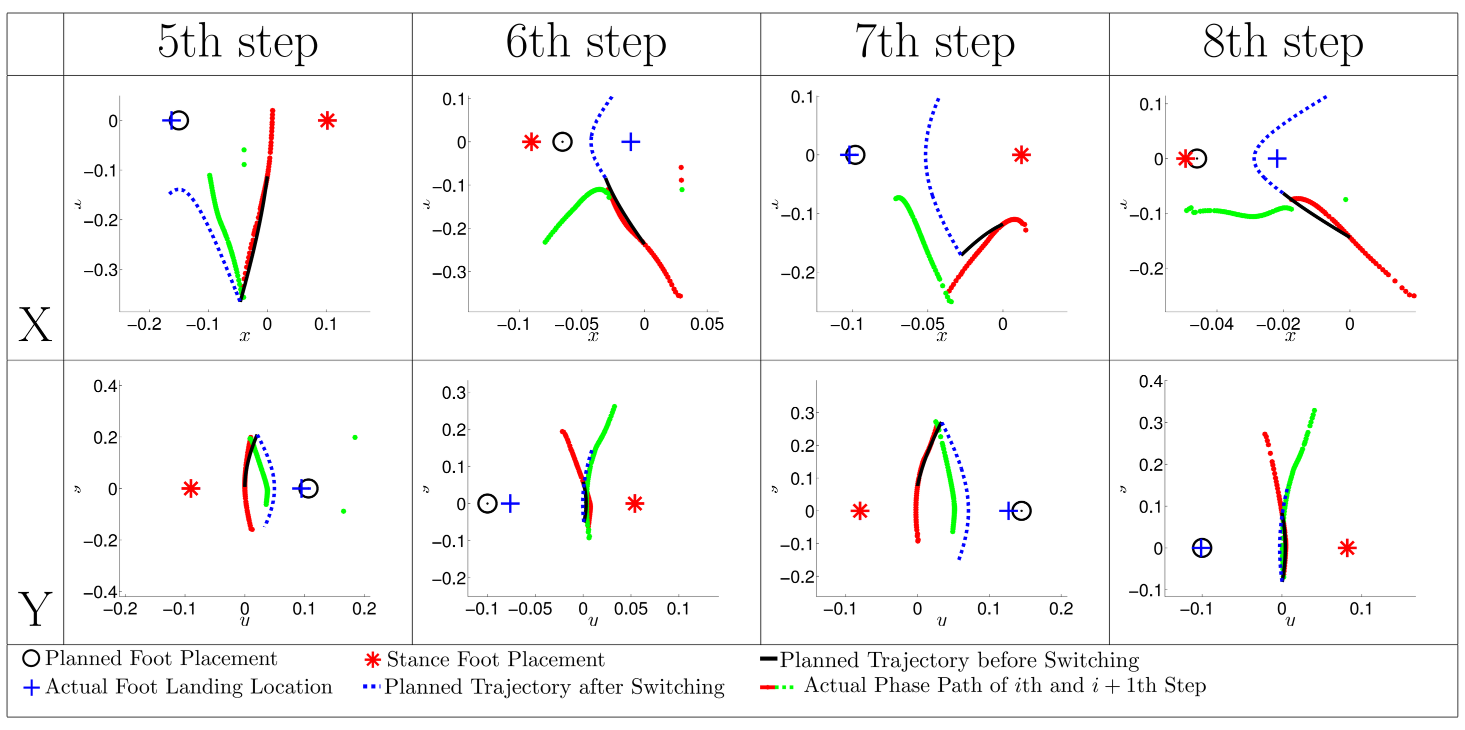


Figure 5: **Phase Portrait in the x (Sagittal) and y (Lateral) Planes.** Black solid lines are the planned trajectories. Blue dashed lines are the planned trajectories after changing the stance foot. We demonstate that we achieve cyclic motion in the lateral plane, while we recover from deviations on the saggital plane by continuously replanning.

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