Journal Reading Presentation:

Motion Planning for Legged Robots on Varied Terrain

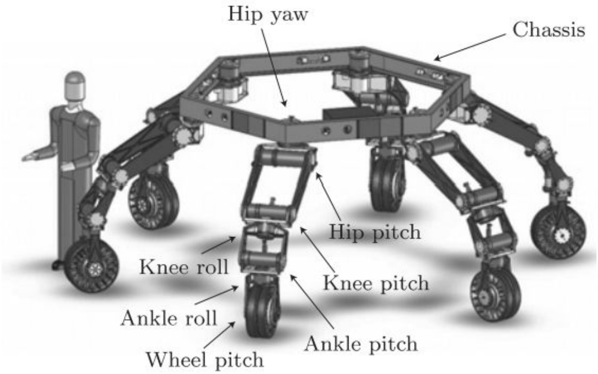
Hauser et al. - 2008

Jacob Miska and Peera Tienthong

Motivation

Inciting Problems:

- It is difficult to navigate rough and varied terrain
- Previous motion planners cannot optimize robotic capabilities
- Motion planners struggle to compute both leg movements and body movements without a fixed gait pattern



Motivation

Previous Work:

- For robots traversing rough terrain
  - Does not consider the level of irregularity or steepness as in this study
  - Does not consider robotic equilibrium for a system with so many DOFs

Problem Statement:

Construct a motion planner capable of solving the above problems and improve the motion quality of legged robots on varied terrain, applying to ATHLETE and HRP-2.

Methods: Concepts

- Planner- Choose footfalls before motion sequences:
  - Previous planners often fails to traverse irregular and steep terrain because they disregard surface contact constraints
  - Because of varied terrain, the planner explores distinct robot’s configuration in order to balance itself at local contact

- Motion Quality
  - The motion the planner generates from scratch usually erratic and unnecessary movement
  - Motion primitives are incorporated to guide the planner for generating efficient motion

Methods: Motion constraints

Sufficient conditions to traverse on varied terrain

- Reachable contact: robot pose is limited by contact locations
- Static equilibrium: balance gravitational force
- Joint torque limits: torque exerted to all joints to remain equilibrium
- Collision avoidance: satisfy joint angle limits

Note: Lack of these constraints means inefficient motion especially on irregular and steep terrain.

Method: Two-Stage-Search Algorithm

1. Explore Footfalls
    a. The planner explores stance (set of contacts) library, filters only candidate stances which are able to generate transition
    b. A heuristic cost function is used to prioritize the explored stances obtained based on planning time, distance to goal, footfall distribution and equilibrium criteria
2. Explore Transitions
    a. Verify that the candidate of stances is feasible to generate motion using an inverse kinematic sequence that “repairs” the typical mathematical limitations like function discontinuities
    b. To reduce the rejection rate, constraints are written as differentiable inequalities and enforce constraints with repaired contact configuration
    c. Finding paths between the transitions

Method: Motion Quality

- This method was centrally created for irregular terrain with many constraints due to the environment, however with areas with very few constraints motion can seem erratic and unnecessary
- “Primitive” motion profiles are overlaid into the motion profile to post-process and smooth out the motion of the robot

Method: More on Motion Primitives

- Primitives are pre-computed offline through hours of motion optimization before it is included in the code as a primitive
- The primitive is then transformed to better fit the needs and is used as a bias in the sampling strategy used by the planner
- Contacts on the terrain are found and then the best primitive is chosen based off of the available contacts
- The primitive chosen is used as a selection bias

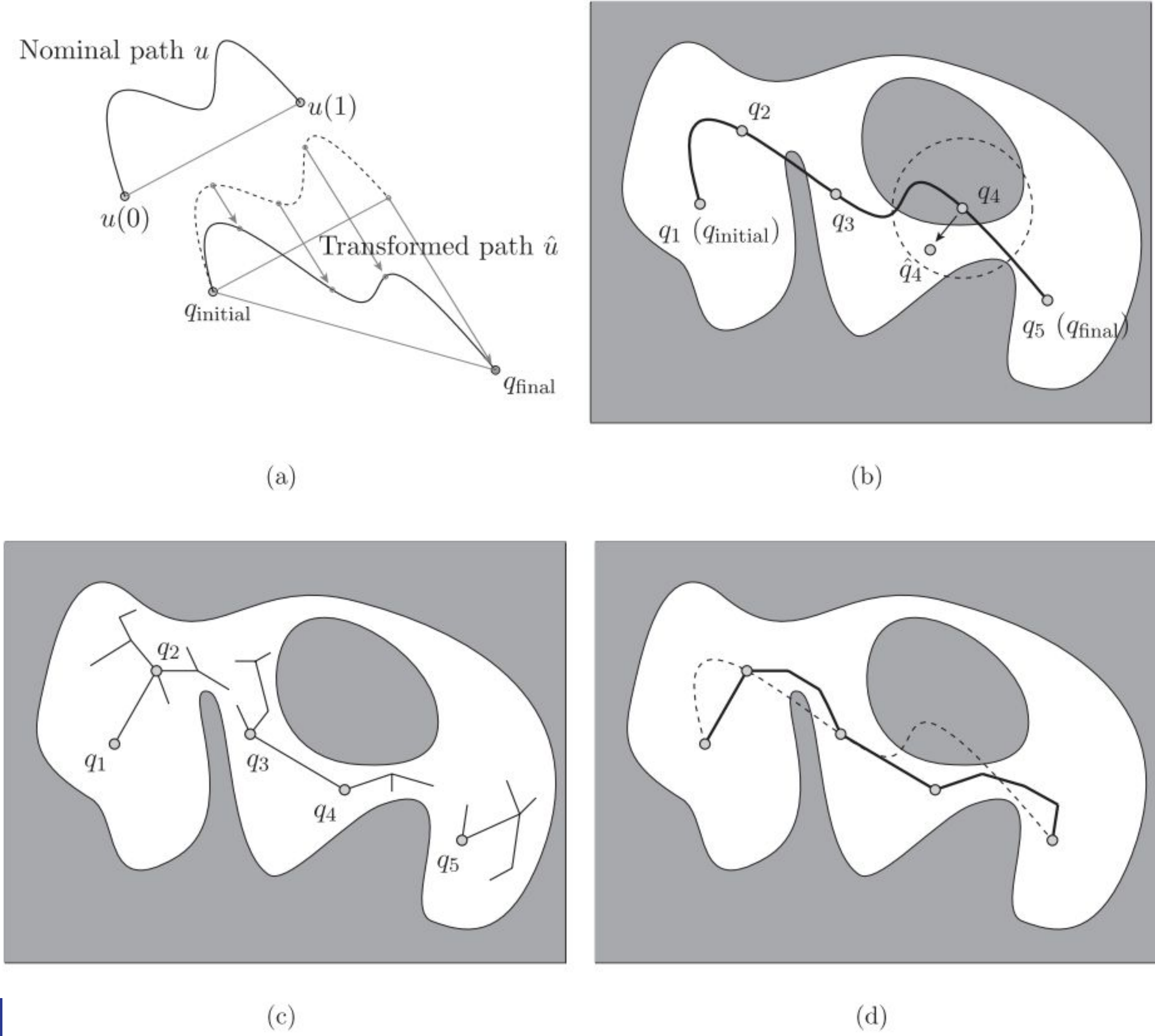
Methods: More on Primitives

a) Transforming primitive to fit desired path

b) Sampling root milestones along transformed path to check for interference

c) Grow trees to connect to neighboring roots

d) Resulting motion path



Results

ATHLETE

- Simulations run with both a fixed gait and using the planner
- The fixed gait resulted in failure on an uneven terrain
- The planner resulted in traversing successfully over the uneven terrain

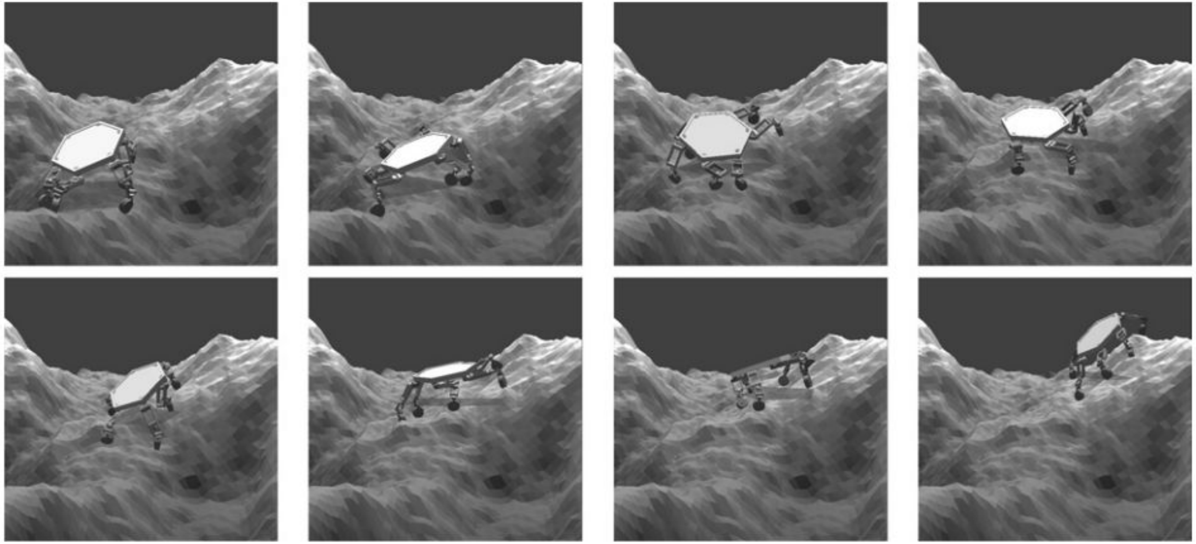


Fig. 11. Walking on steep, uneven terrain with no fixed gait (see Extension 6).

Results
ATHLETE

- Additional test done comparing different fixed gaits on stairs of different heights, manual controls, and the planner

Table 1. Stair steps planned with various methods. Dashes indicates failure. Planner times are averaged over four runs.

	Gait				
Height	Tripod	Four	Six	Planner	Manual
0.2	✓	✓	✓	8 min	5 min 40 s
0.3	—	—	—	8 min 30 s	14 min
0.4	—	—	—	16 min 15 s	—
0.5	—	—	—	15 min 15 s	—

Results

HRP-2

- This robot benefited more from the addition of primitives into the planner algorithm, but showed that the planner was also successful here

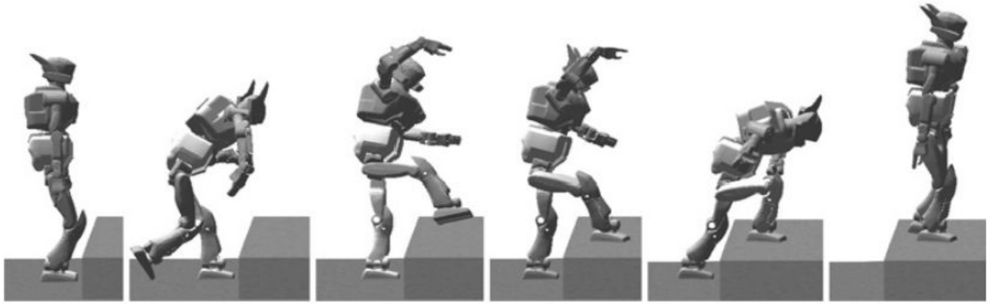


Fig. 13. Stair step planned entirely from scratch.

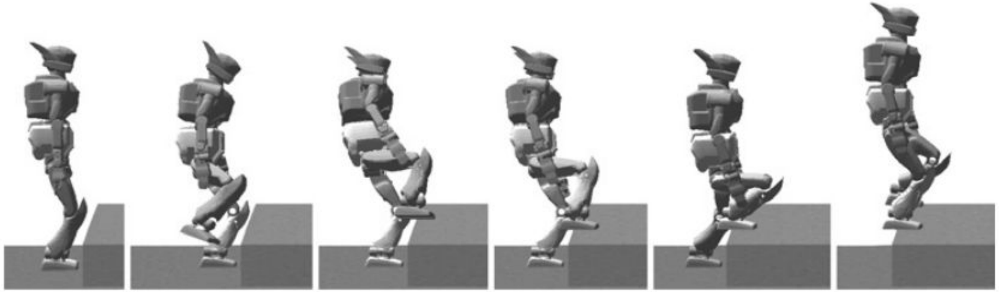


Fig. 16. Primitives guide the choice of contact, resulting in an easier step.

Results

HRP-2

- The HRP-2 was tested in many different settings including climbing a ladder, using stairs, sidestepping a boulder, and climbing over rough terrain (below)

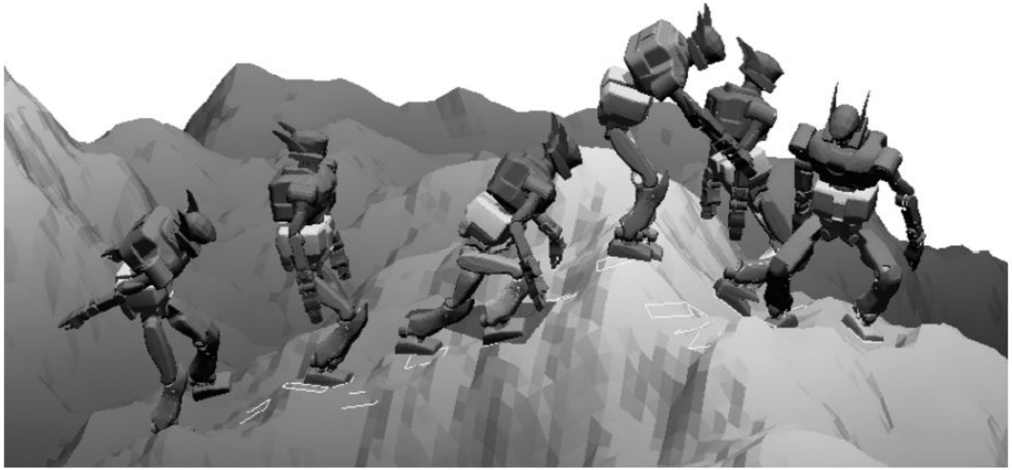


Fig. 21. A motion on steep and uneven terrain generated from a set of several primitives. A hand is being used for support in the third configuration (see Extension 11).

Contribution

The design, development, and implementation a motion planner that enables legged robots with many DOFs to walk safely across rough, irregular terrain.

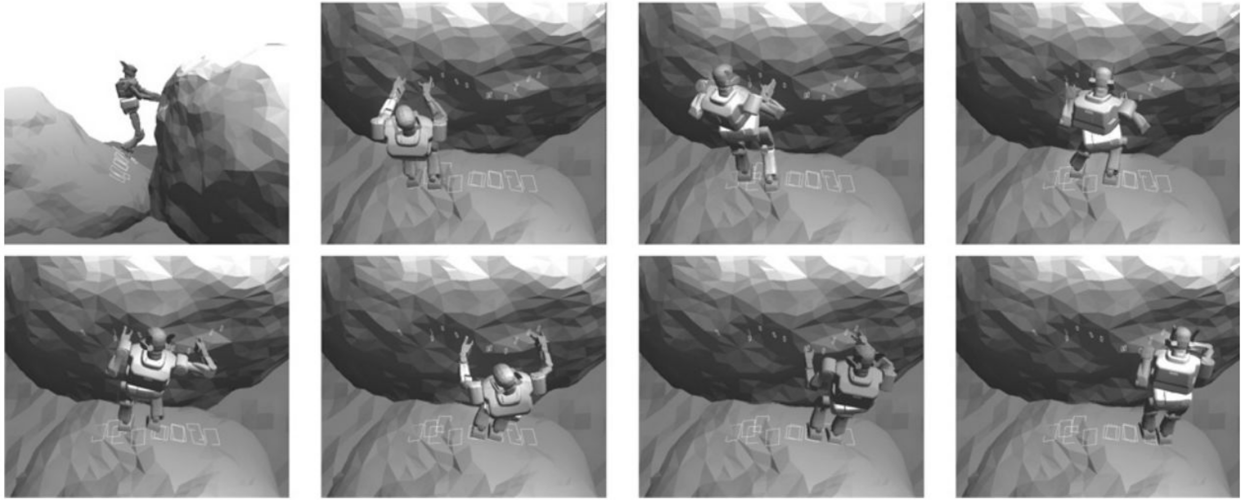


Fig. 20. A side-step primitive using the hands for support, adapted to a terrain with large boulders. Hand support is necessary because the robot must walk on a highly sloped boulder (see Extension 10).

Questions

Additional Slides: Motion Planner Methodology

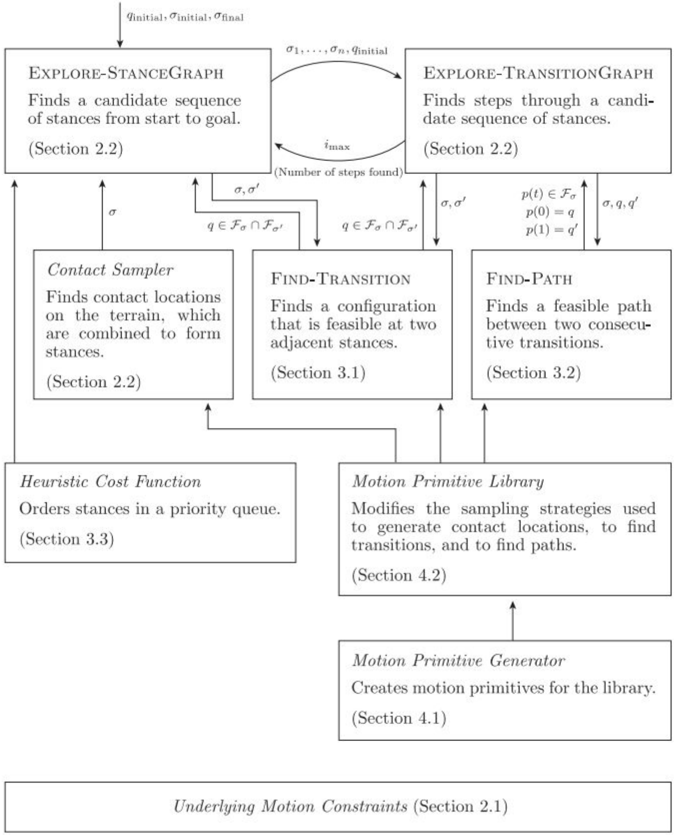


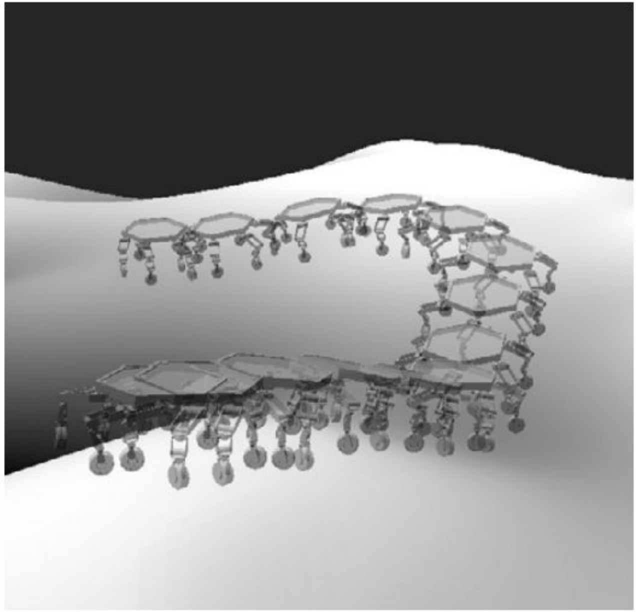
Fig. 4. Overall structure of the motion planner.

Additional Slides: Search Algorithm Pseudocode

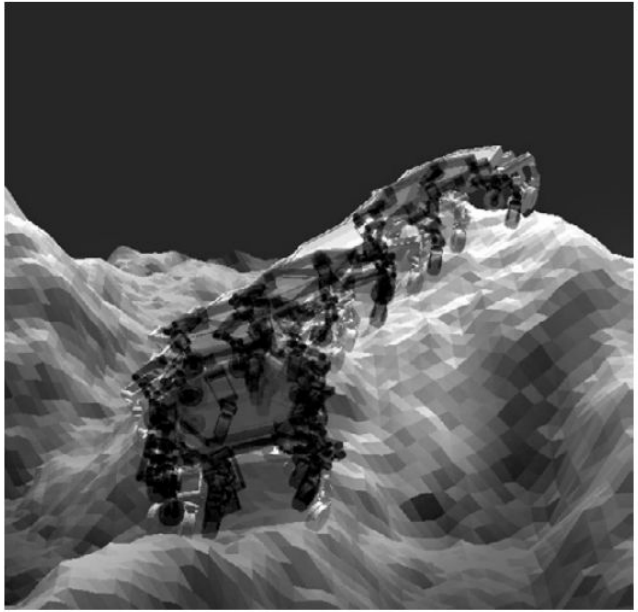
```
EXPLORE-STANCEGRAPH($q_{\text{initial}}, \sigma_{\text{initial}}, \sigma_{\text{final}}$)
$Q \leftarrow \{\sigma_{\text{initial}}\}$
while $Q$ is non-empty do
    unstack a node $\sigma$ from $Q$
    if $\sigma = \sigma_{\text{final}}$ then
        construct a path $[\sigma_1, \ldots, \sigma_n]$ from $\sigma_{\text{initial}}$ to $\sigma_{\text{final}}$
        $i \leftarrow$ EXPLORE-TRANSITIONGRAPH($\sigma_1, \ldots, \sigma_n, q_{\text{initial}}$)
        if $i = n$ then
            return the multi-step motion
        else
            delete the edge $(\sigma_i, \sigma_{i+1})$ from the stance graph
    else
        for each unexplored stance $\sigma'$ adjacent to $\sigma$ do
            if FIND-TRANSITION($\sigma, \sigma'$) then
                add a node $\sigma'$ and an edge $(\sigma, \sigma')$
                stack $\sigma'$ in $Q$
return "failure"

EXPLORE-TRANSITIONGRAPH($\sigma_i, \ldots, \sigma_n, q$)
$i_{\max} \leftarrow i$
for $q' \leftarrow$ FIND-TRANSITION($\sigma_i, \sigma_{i+1}$) in each component of $\mathcal{F}_{\sigma_i} \cap \mathcal{F}_{\sigma_{i+1}}$ do
    if FIND-PATH($\sigma_i, q, q'$) then
        $i_{\text{cur}} \leftarrow$ EXPLORE-TRANSITIONGRAPH($\sigma_{i+1}, \ldots, \sigma_n, q'$)
        if $i_{\text{cur}} = n$ then
            return $n$
        elseif $i_{\text{cur}} > i_{\max}$ then
            $i_{\max} = i_{\text{cur}}$
return $i_{\max}$
```

Fig. 5. Algorithms to explore the stance graph and the transition graph.

Additional Slides: ATHLETE Simulation Test



(a)



(b)

Fig. 9. Walking with an alternating tripod gait is (a) feasible on smooth terrain but (b) infeasible on uneven terrain due to violations of equilibrium and torque constraints. Extensions 3 and 4 show exactly when these constraints are violated.

Additional Slides: ATHLETE Simulation Test

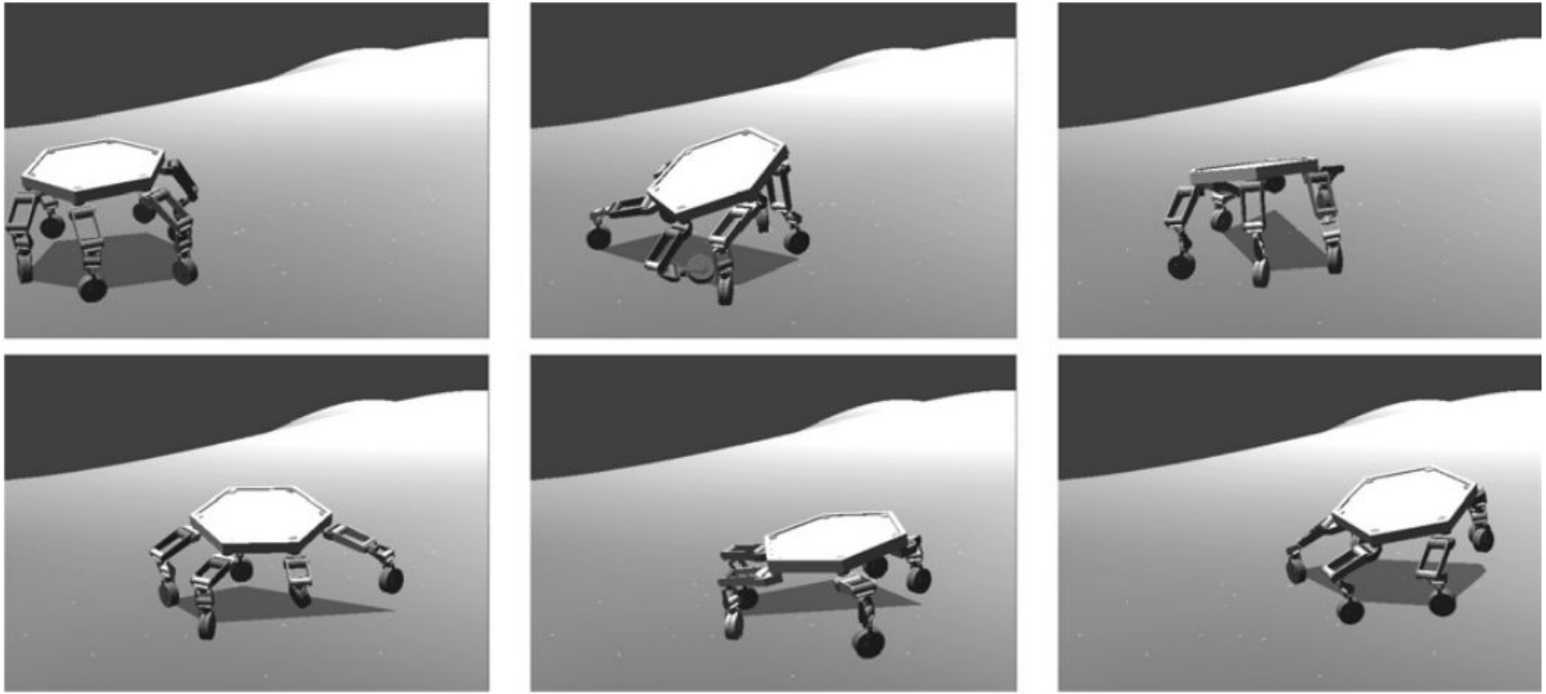


Fig. 10. Walking on smooth, undulating terrain with no fixed gait (see Extension 5).

Additional Slides: ATHLETE Rappelling Simulation Test

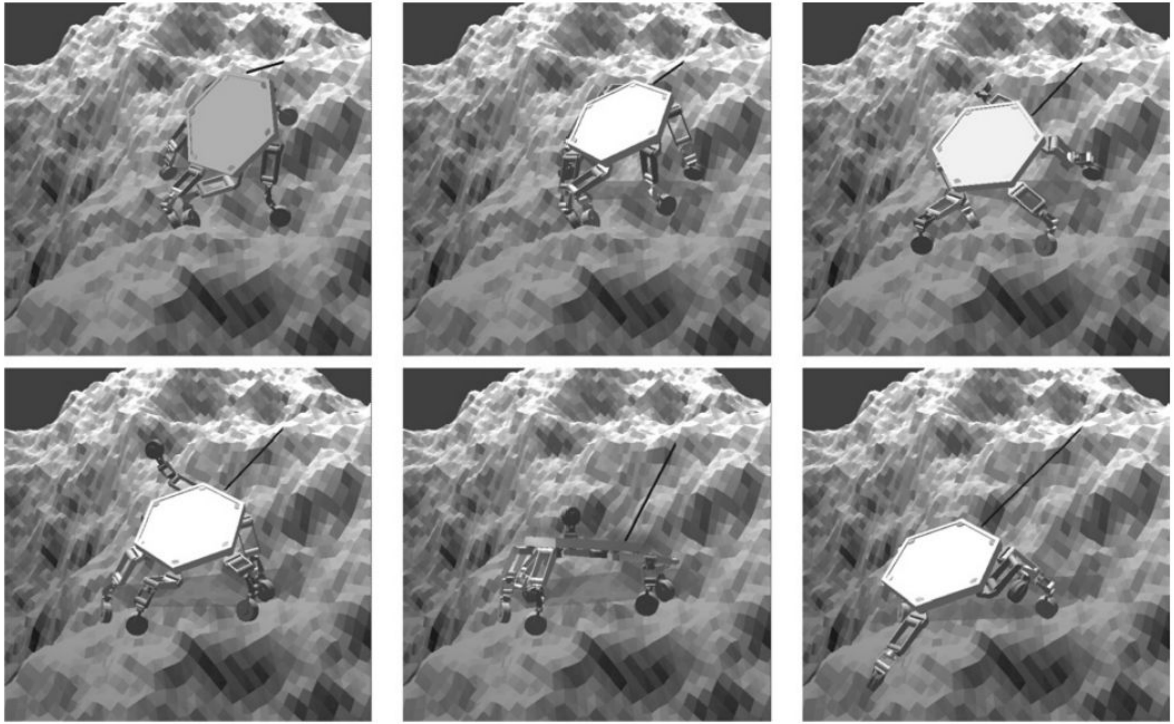


Fig. 12. Rappelling down an irregular 60° slope with no fixed gait (see Extension 7).

Additional Slides: HRP-2 Simulation Test

Fig. 13. Stair step planned entirely from scratch.

Fig. 14. Primitives guide path planning, reducing unnecessary leg motions.

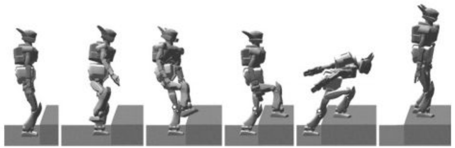


Fig. 15. Primitives guide transition sampling, reducing unnecessary arm motions.

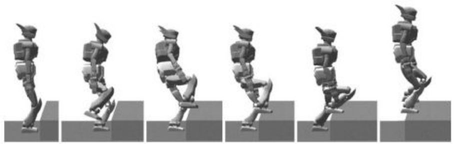
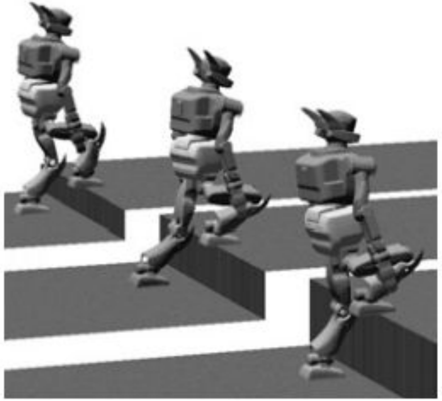


Fig. 16. Primitives guide the choice of contact, resulting in an easier step.

Additional Slides: HRP-2 Step Simulation Test



Stair	From scratch		Adapt primitive		Optimal
height	Time	Objective	Time	Objective	objective
0.2 m	8.61	5.03	5.42	3.04	2.19
0.3 m	10.3	4.67	4.08	2.31	2.17
0.4 m	12.2	5.15	10.8	3.27	2.55

Fig. 17. Planning time and objective function values for stair steps, averaged over five runs.

Additional Slides: HRP-2 Simulation Test

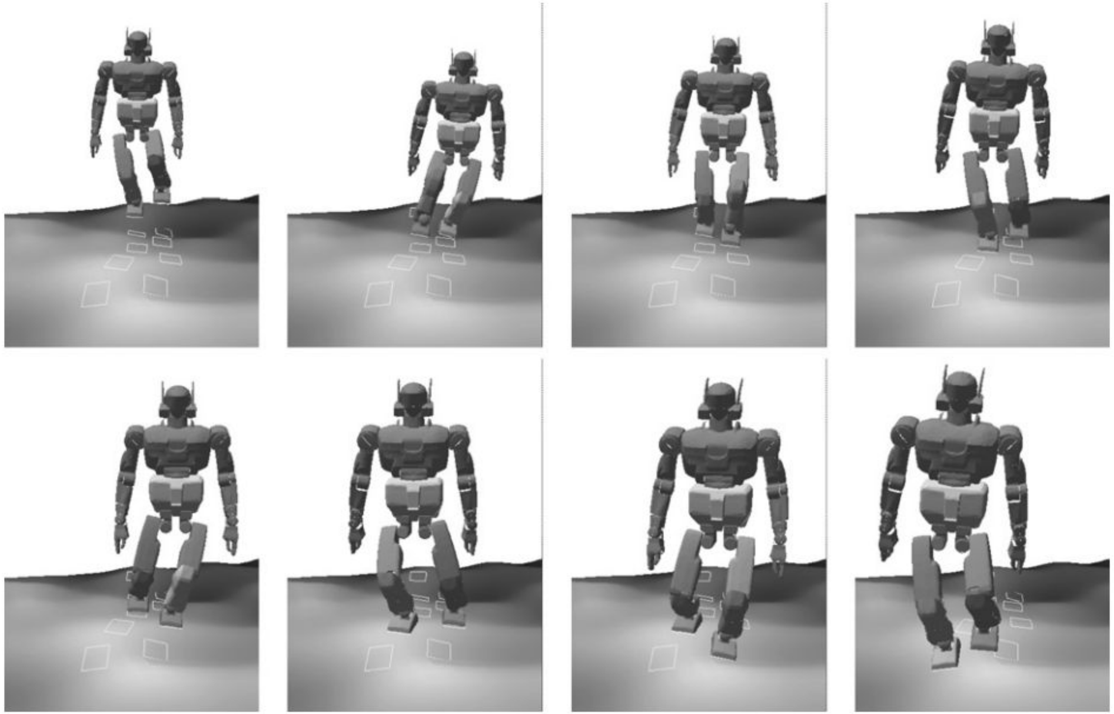


Fig. 18. A planar walking primitive adapted to slightly uneven terrain (see Extension 8).

Additional Slides: HRP-2 Ladder Simulation Test

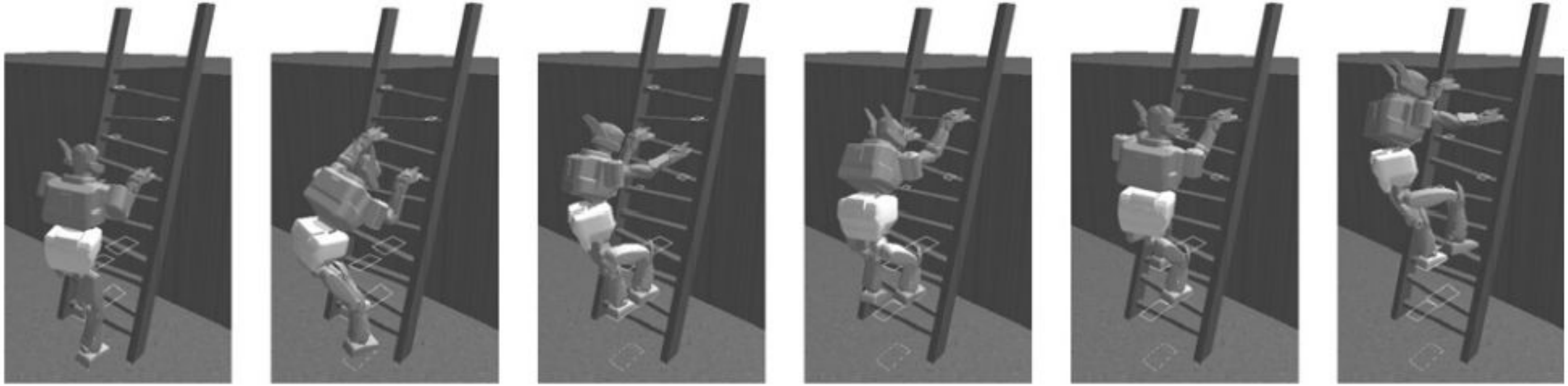


Fig. 19. A ladder-climbing primitive adapted to a new ladder with uneven rungs (see Extension 9).