RHex: A Simple and Highly Mobile Hexapod Robot

Saranli, Buehler, Koditschek

2001

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Executive Summary

Which type of robot?

Hexapod

Which type of control?

Overall Open-loop control
and
Joint torque closed-loop control

Which type of design method?

Simulation and hand-tuned

Which type of gait?

Tripod walking gait

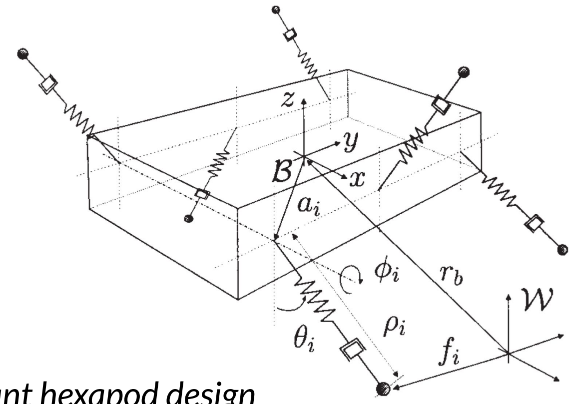
Inspiration

Results

New [3]

Introduction

- Autonomous, mechanically simple
- Design: 6 compliant legs, each powered by a single actuator, completing a full revolution
- Advantage of legs: control of ground reaction forces



Compliant hexapod design

Notation

States	
$\mathbf{r_b}, \mathbf{R_b}$	Body position and orientation
α	Body yaw angle
Leg states and parameters	
$\mathbf{a_i}$	Leg attachment point in $\mathcal{B}$
$\mathbf{f_i}$	Toe position in $\mathcal{W}$
$\mathbf{v_i}$	$:= [\theta_i, \phi_i, \rho_i]^T$ leg state in spherical coordinates
$\bar{\mathbf{v}}_\mathbf{i}$	$:= [v_{x_i}, v_{y_i}, v_{z_i}]^T$ leg state in Cartesian coordinates
leg_i	Stance flag for leg i
Forces and torques	
F_{r_i}	Radial leg spring force
τ_{θ_i}	Bend torque in θ_i-direction
τ_{ϕ_i}	Hip torque in ϕ_i-direction
Controller parameters	
t_c	Period of rotation for a single leg
t_s	Duration of slow leg swing
ϕ_s	Leg sweep angle for slow leg swing
ϕ_o	Leg angle offset
$\mathbf{u}$	$:= [t_c, t_s, \phi_s, \phi_o]$ control vector
$\Delta\phi_o$	Differential change in ϕ_o for turning
Δt_s	Differential change in t_s for turning

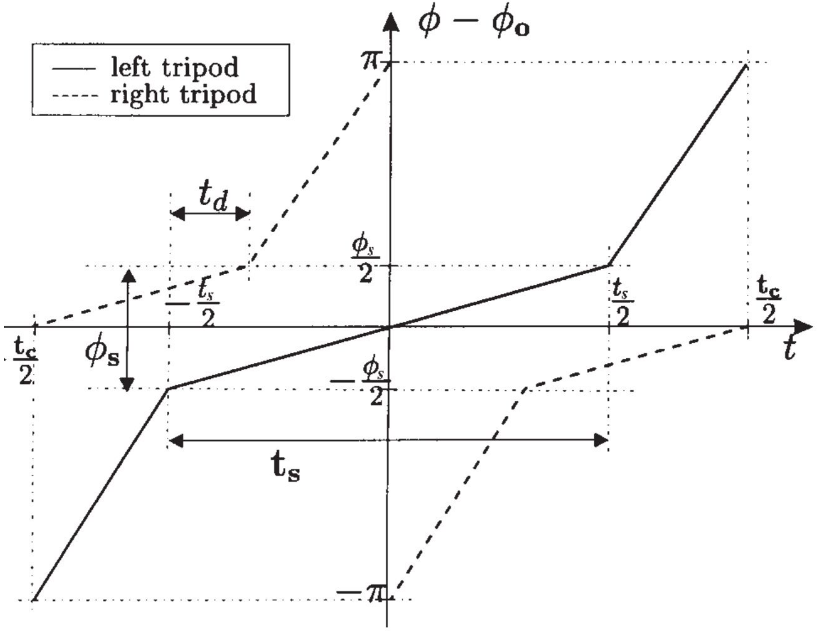
Design

- Importance of a simple mechanical design
- C-shaped legs to increase radial compliance
- Alternating tripod gait
- Sum of forces:

$$\mathbf{F_T} = \boxed{\begin{bmatrix} 0 & 0 & -mg \end{bmatrix}^T} + \boxed{\mathbf{R_b} \sum_{i=1}^{6} leg_i \mathbf{F_i}} \quad (1)$$

Gravity

Ground reaction forces



Motion profiles for left and right tripod

Tripod Gait

Control

- Sensorless Robot
- Open-loop control
  “Joint-space closed-loop, task-space open-loop”

t_c	Period of rotation for a single leg
t_s	Duration of slow leg swing
ϕ_s	Leg sweep angle for slow leg swing
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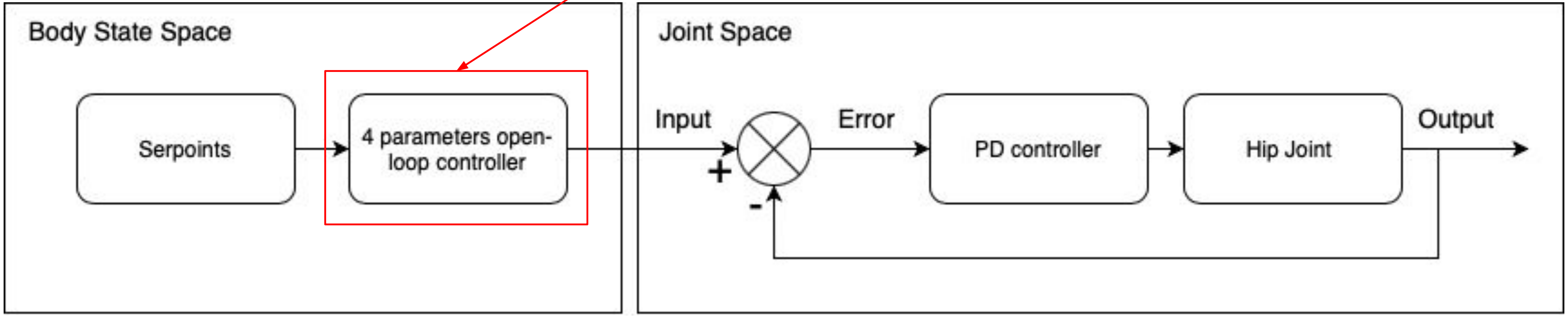


Control: Turning

2 different strategies

- Turning in place:
  - opposite rotation for contralateral leg

- Turning in movement
  - differential perturbations

[4]

Simulation studies

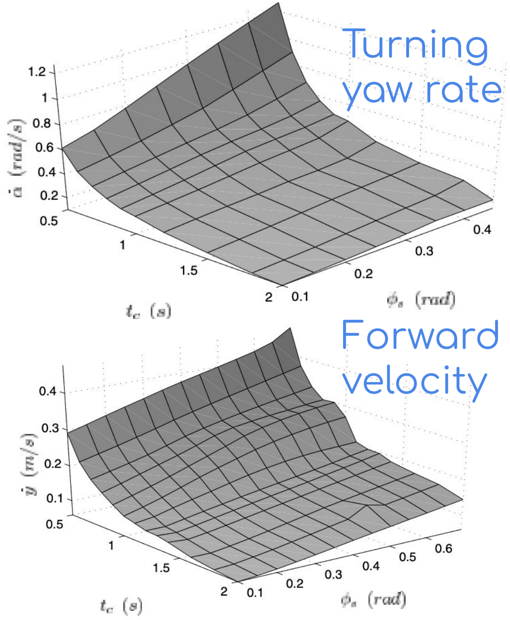
GOAL : Test the calculations and Justify the building of a prototype and future expensive experiments

Simulation environment :
SimSect
(Home made)

Simulation Properties :
- Real mass
- Real dimensions

Manual tuning :
- ts = tc/2
- Phi_0 = 0

Results



Adding feedback to improve performances

Limitation : Leg spring damping constant and ground friction coefficient not experimentally verified → Simulation accurate regarding morphologie and mass parameters only.

Experimental Platform

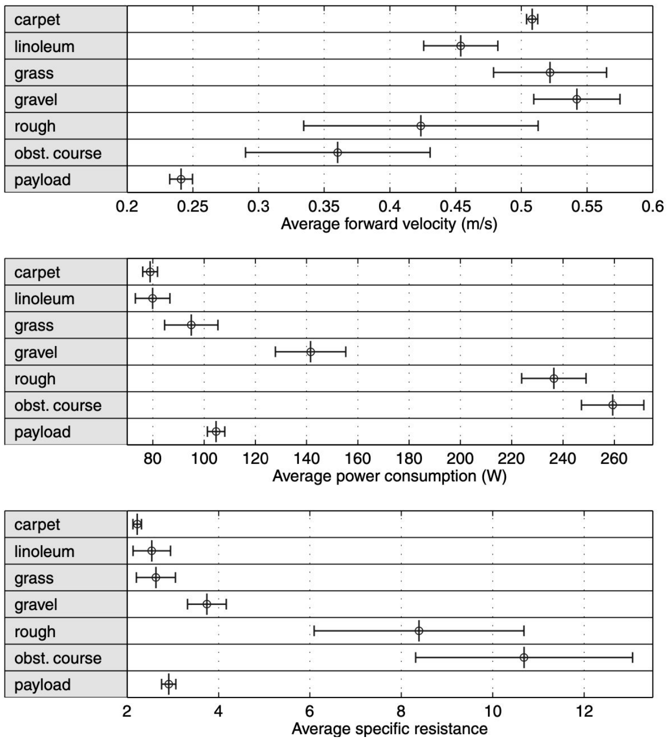
- Forward locomotion on different surfaces
- Turning
- Obstacle crossing
- Obstacle course
- Rough surface
- Payload and Runtime

→ Robots controlled by an external operator

	Carpet	Linoleum	Grass	Gravel	Rough	Single Obstacle	Comp. Const.	Obstacle Course
Total number of runs	10	11	16	25	32	14	14	26
Successful runs	10	10	10	10	16	10	10	10
Electronics and hardware problems	—	—	1	5	6	—	—	2
Deviation from course	—	1	—	5	7	—	—	5
Operator mistake[a]	—	—	5	5	—	3	2	2
Stuck on obstacle	—	—	—	—	3	1	2	7

Experimental Platform: results

- Velocity without obstacles between 0.45 and 0.55 m/s
- Average consumption without obstacles between 80 and 140W



Experimental Platform: results

- Turning in movement:
  - yaw rate depends of the forward velocity
  - constant turning radius of 2m
- Turning in place:
  - higher yaw rate : 0.7 rad/s

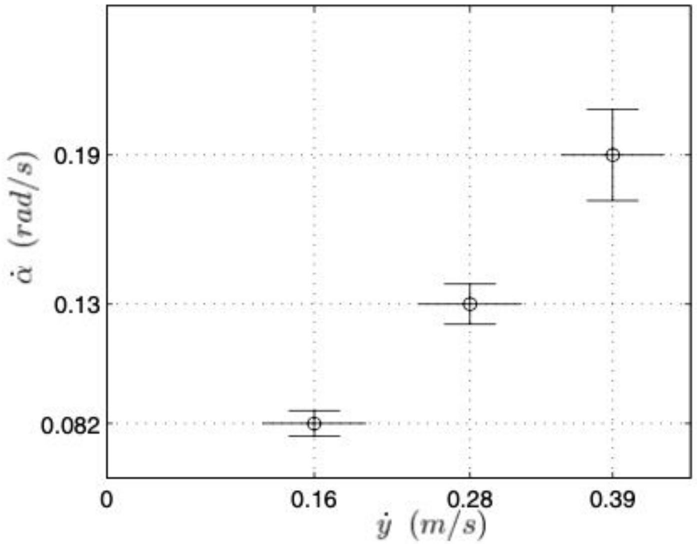


Fig. 9. Turning yaw rate as a function of forward velocity. See Extension 9 for all the data and analysis scripts associated with the turning experiments.

Experimental Platform: results

- Rough surface:
    - Random height variations of up to 20.32 cm (116% leg length)
    - Average velocity of the fastest run: 0.56m/s

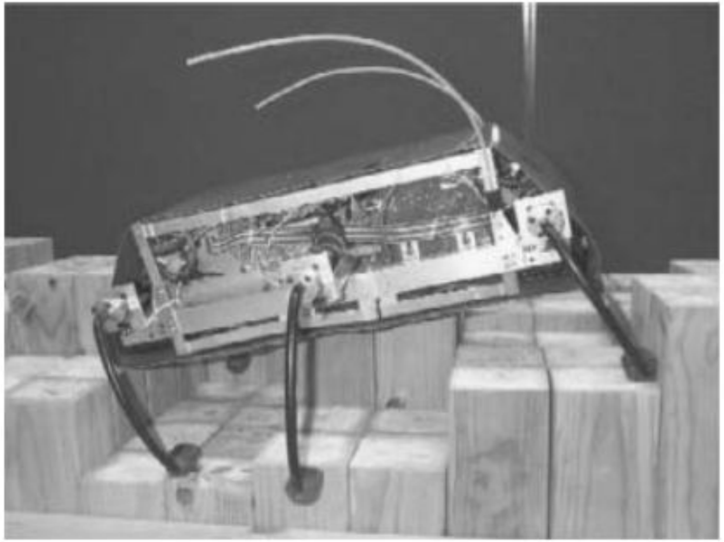


Fig. 13. Sample profiles of row 6 (columns 8, 9, and 10) with RHex statically posed for comparison.

Robot deviation

Impact

Bio-inspired design/
hexapod design

Compliant legs
(-> SLIP model) [2]

"The first autonomous, dynamically stable, legged machine to successfully run over rugged and broken outdoor terrain" [1]

Number of time cited on Google scholar

1569

Pros and Cons:

Pros:

- Simple + robust
- Versatility
- Power autonomy

Cons:

- No feedback -> Open loop
- Proof-of-concept design -> Basic

Possible Exam Questions

1. Explain the advantages of using simpler mechanical design?
    - Better autonomy
    - Less likely to break
    - Easier to tune

2. Explain basically how RHex is controlled
    - Open loop control for the robot position
    - Closed loop control for the joints angle/torque

Thank you for your attention

Do you have any questions ?

References

- Images:
  - Title slide: https://www.rhex.web.tr
  - Executive Summary: https://www.researchgate.net/figure/Rhex-Saranli-Buehler-Koditschek-2001_fig3_266473429
- Impact
  [1] *https://epubs.siam.org/doi/pdf/10.1137/S0036144504445133*
  [2]https://link.springer.com/article/10.1023/A:1012426720699
- Videos :
  - [3] https://youtu.be/ntlI-pDUxPE
  - [4] https://youtu.be/ISznqY3kESI
  - [5] https://sponberg.gatech.edu/2015/10/09/how-roaches-run-on-rough-terrian/