How one might realize practical, energy-efficient legged robots: 19 thoughts/ideas from the Cornell Ranger project

Pranav A. Bhounsule (talking),
Jason Cortell and Andy Ruina

Biorobotics and Locomotion Laboratory,
Cornell University

21 May, 2012

Introduction to Cornell Ranger

- 1m tall, 9.91 kg, 4 legged knee-less biped.
- 6 on-board computers, around 30 sensors, 4 direct current motors, battery powered.
- Fully autonomous, except radio controlled steering.

Ranger Walking Video

BIG goal

Walk a marathon (26.2 miles) on a single charge.

- Energy-effective.
- Robust.
- Reliable.

Timeline of walks

3 December 2006: 0.6 mi, TCOT $= 1.6$

3 April 2008: 5 mi, TCOT $= 0.6$

5-6 July 2010: 14.3 mi, TCOT $= 0.49$

1-2 May 2011: 40.5 mi, TCOT $= 0.28$ **(Distance record)**

25 June 2011: 5 meters, TCOT $= 0.19$ **(TCOT record)**

NOTE:

$$\text{Total Cost Of Transport (TCOT)} = \frac{\text{Total energy used}}{\text{Weight}\times\text{Distance travelled}}$$

① Few degrees of freedom

Four degrees of freedom

1 @ hip,

1 @ inner ankle,

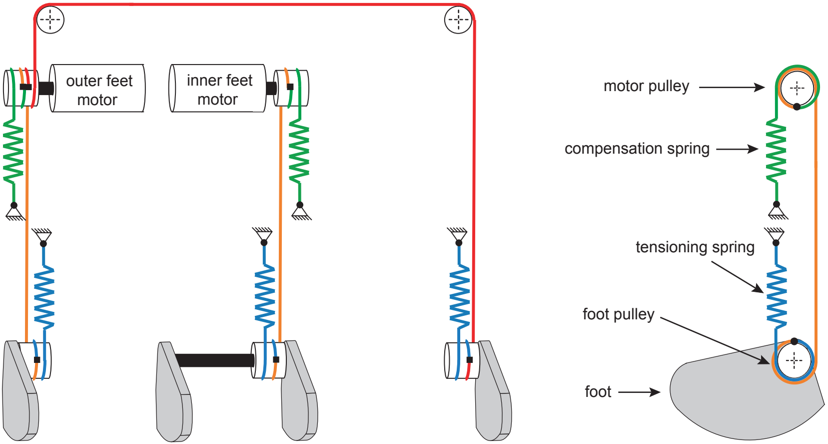
1 @ outer ankle,

1 @ inner ankle twist.

② Mechanical layout: Heavy hip; light legs and feet

- Hollow carbon Fiber tubes for legs (light)
- High-strength aluminum for feet (light)
- Aluminum box shaped thighs.
  - High strength, high stiffness, light weight.
  - House motors and electronics. Attach batteries.

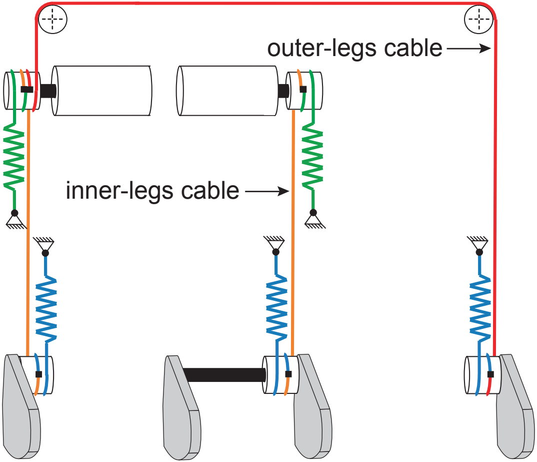
③ Cable drivetrain for ankles



(a) Front view (b) Side view

This design moves ankle motors up near the hip and helps keep the feet light.

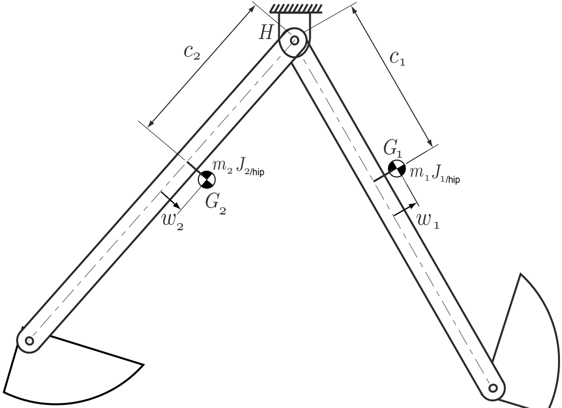
④ Cable drive symmetry



Stiffness of inner-legs cable should be twice that of outer-legs cable.

⑤ Dynamic symmetry

4 things to match $m_1 = m_2$, $J_{1/hip} = J_{2/hip}$, $c_1 = c_2$, $w_1 = w_2$.

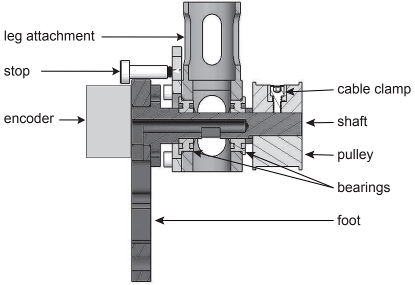


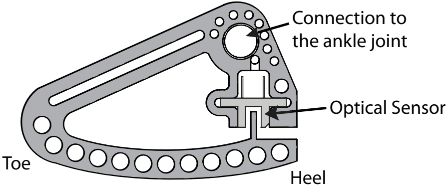
But only 3 conditions need to be met.

$c_1 m_1 = c_2 m_2$, $w_1 m_1 = w_2 m_2$, $J_{1/hip} = J_{2/hip}$

These can be measured without dis-assembling the robot.

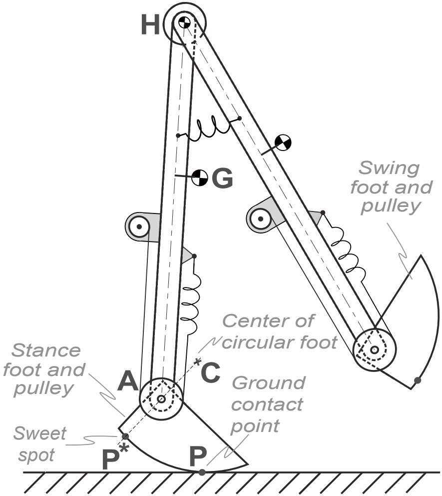
⑥ Foot as a load-cell





Gap at heel on foot $\propto$ Vertical load.
Gap measured by an optical sensor.

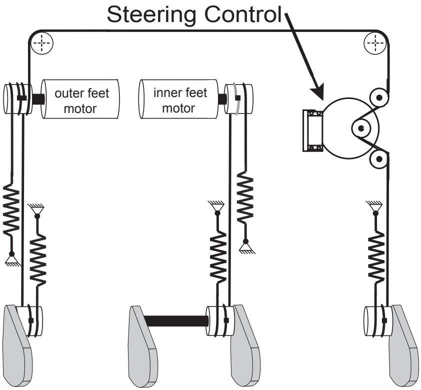
⑦ Circular shape foot



- Almost no motor torque when the sweet spot # is the ground contact point.
- Allows toe-off, push-off, flip-up for leg clearance.
- Model as rolling cylinder.

$P^\star$ (sweet spot) = physical point on the foot where the line joining the center of circle to the ankle intersects the foot

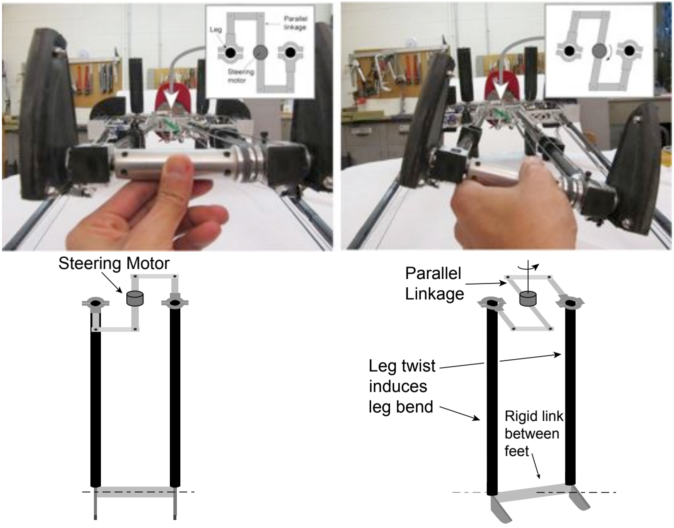
⑧ Steer a 2-D robot in 3-D (turn by breaking symmetry)



Turn by differential rotation of outer ankles.

- Robot ran into sand-pit in the 0.6mi attempt ending the walk.
- Robot almost went out of course during 5mi attempt.

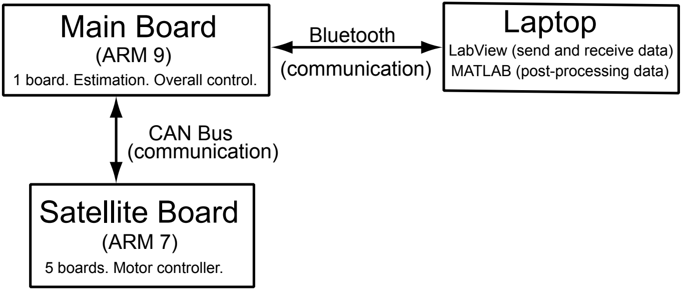
⑧ Steer a 2-D robot in 3-D (turn by twisting)



a) neutral steering

b) steered

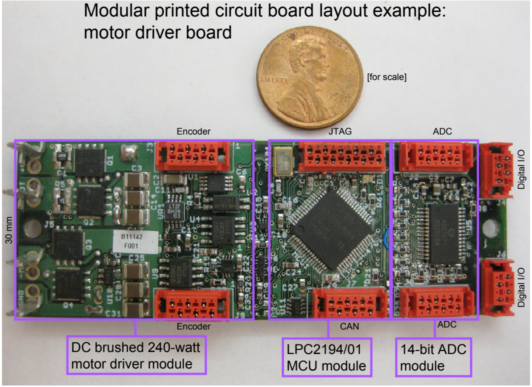
⑨ Overall electronics architecture



Distributed network-based sensing and control.

- Main controller (ARM-9): High level control and estimation.
- Control Area Network (CAN): Nervous system that is reliable and modular.
- Satellite controller (ARM-7): Joint level control and estimation.

(10) Custom built processor board



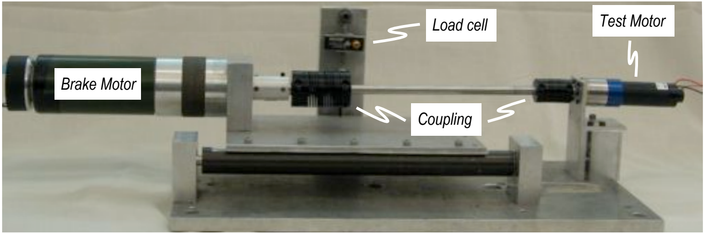
- Each satellite board controls a joint.
- Small footprint.
- Modular, i.e. allows for reuse of code and electronics.

⑪ Energy-efficient electronics

Total overhead* power = 5.15 W.

*overhead = sensors, microprocessors, motor controllers

(12) Better DC motor model



Need DC motor model for model based controller design.

We found:

- Load dependent friction $\propto$ Current.
- Brush contact resistance $\propto \frac{1}{\text{Current}}$.

⑬ Specification sheets could be wrong/incorrect

We found:

- Motor terminal resistance twice of what was reported.
  (Doubled the resistive losses)
- Motor inductance a third of what was reported.
  (Energy losses in motor controller)
- Motor had brush contact resistance and this was not reported.
  (Increased the resistive losses)

14 Model validation led to motor controller re-design

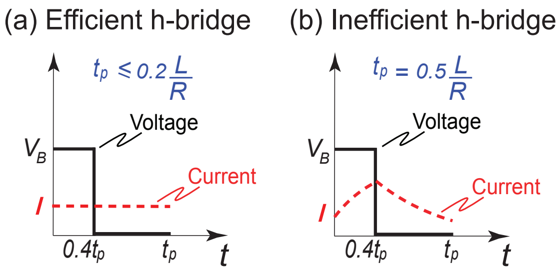
We fitted a physics based model of robot + actuators and then did a validation test.

Video: Ranger model fit

Gait Parameter	Experiment	Simulation
Step Time (s)	0.65	0.66
Step Length (m)	0.32	0.32
Velocity (m/s)	0.49	0.48
Double Stance Time (s)	0.02	0.008
Total COT •	0.55	0.38
Motor COT †	0.36	0.19

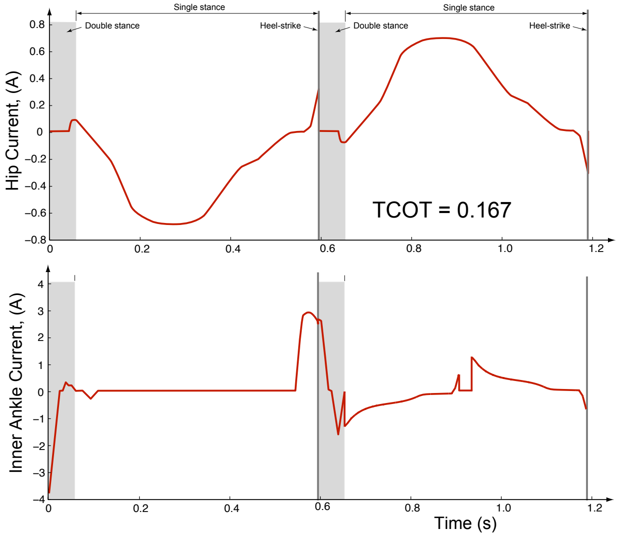
Percentage error in energetics is 47 %. Why?

⑭ Model validation led to motor controller re-design



- Measured inductance was a third of reported value. We added more inductance.
- Motor controller frequency was increased from 20 kHz to 100 kHz.

⑮ Optimal trajectory control



Use optimization to discover best way to move around.

16 Walking cost does not dominate the total cost

Results of energy-optimal trajectory control

Energy partition:

- Electronics (Overhead): 49 %
  (Need more efficient electronics)
- Foot-flip (No-scuffing): 23 %
  (Would knees be a better idea?)
- 'Walk': 28 %
  - Hip: 11 %
  - Ankles: 17 %

(16) Simplify and stabilize the optimal trajectory solution

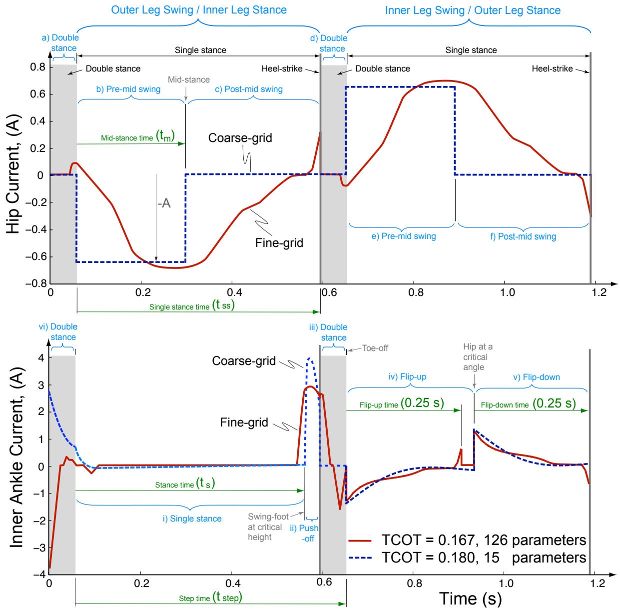
Let control command be I (=current). Than,

$$I = I_{\text{trajectory-generator}} + I_{\text{stabilization}}$$

– Trajectory generator.
  Goal: Approximate energy-optimal trajectory.

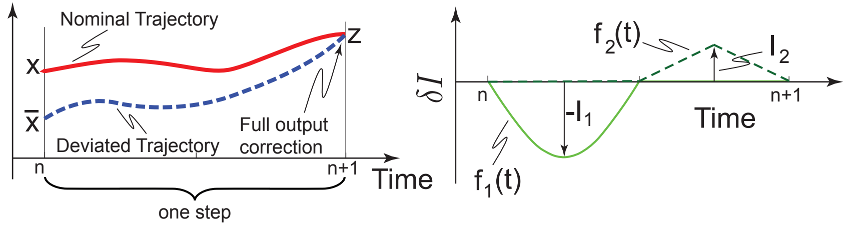
– Stabilization.
  Goal: Stabilize the trajectory.

Trajectory-generator: Approximate optimal trajectory



16 Stabilization: Discrete intermittent linear feedback

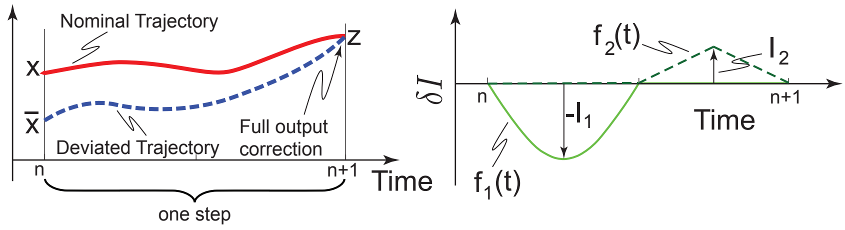
Fictitious example:



$$I = I_{\text{trajectory-generator}} + I_{\text{stabilizing-control}} \quad (I = \text{command current})$$

(16) Stabilization: Discrete intermittent linear feedback

Fictitious example:



$$\delta x_{n+1} = A\delta x_n + B\delta I_n$$
$$\delta z_{n+1} = C\delta x_n + D\delta I_n$$

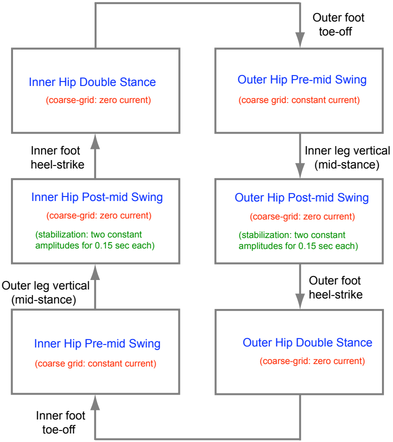
Find gain K using pole placements or linear regulator.

$$\delta I_n = -K\delta x_n$$

- n - When to measure.
- x - Measurements.
- z - Quantity to be regulated.
- I - Controls.

17 Implementation on the robot

Example: Hip state machine .



- Concurrent augmented state machine.
- Reflex based control approach.

$$I = f(\text{full dynamical state})$$
$$= A + C_1\theta + C_2\dot{\theta} + D$$

θ, I - angle and motor current.
A, C_1, C_2 - constants.
(trajectory-generator)
D - constant
(stabilization controller)

(18) Estimation

- No model based estimation.
- Push-off time is critical for energetics.

Could have done a better job.

(19) Testing

- Error logs, Flashing Light Emitting Diodes.
- Rapid data logging and analysis capability.

Collect data while testing → Robot fails → Analyze data → Understand failure → Fix bugs → Test again

Ranger Team: 2006 - 2011

Principal Investigator: Andy Ruina

Lab Manager: Jason Cortell

Visiting students: Danil Karssen, Bram Hendriksen, S. Javad Hasaneini, Feng Shuai, Pulkit Kapur, Kang An.

Graduate students: Pranav Bhounsule, Leticia Rojas-Camargo, Rohit Hippalgaonkar, Ko Ihara, Sam Hsiang Lee, Gregg Stiesberg, Andrey Turovsky, Kevin Tang, Nan Xiao, Anoop Grewal, Petr Zaytsev, Atif Chaudhry.

Undergraduates: Carlos Arango, Steve Bagg, Megan Berry, John Buzzi, Amy Chen, Alexis Collins, Stephane Constantin, James Doehring, Gregory Falco, Hajime Furukawa, Alex Gates, Matt Haberland, Avtar Khalsa, Andrew LeClaire, Emily Seong-hee Lee, Reubens Lee, Alexander Mora, Andrew Mui, Nicole Rodia, Andrew Spielberg, Yingyi Tan, Chen Kiang Tang, Kevin Ullmann, Max Wasserman, Denise Wong, Joshua Petersen, Matt Coryea, Jehhal Liu, Ming-Da Lei, Dapong Boon-Long, Kirill Kalinichev, Saurav Bhatia, Thomas Craig, Phillip Johnson, Katie Hartl, Andrew Nassau, Brian Clementi, Kevin Boyd, Emily McAdams, Satyam Satyarthi, Sergio Biagioni, Nicolas Williamson, David Bjanes, Violeta Crow, Mike Digman, John Kuriloff, Hellen Lopez, Lauren Min. Visiting scholars: Chandana Paul, Li Peng Yuan, Amur Salim, Dong Chun.

High school student: Ben Oswald

Thank You