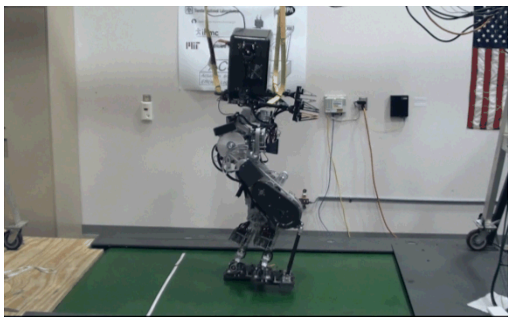
SAND2015-4290PE

ACSEL
Actuation and Control System for Efficient Legged Locomotion



WANDERER Energy Performance Data Summary and Projections

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Demonstrated WANDERER Performance

- Long walk, onboard batteries and computers, full robot
  - 1.001 km traveled
  - 90 minutes of walking
    - Up to 40 minutes continuous forward stepping at full speed
  - Full walking speed: 0.2 m/s
  - Overall average speed: 0.185 m/s
    - Includes stepping in place, periodically speeding up & slowing down
  - Total energy consumed walking: 680 Wh
  - Average power during all walking: 453 W
  - Cost of Transport: 2.74
- Walking in a "good groove" (~10 minute stretches)
  - Average power: 410 W
  - Average speed: 0.2 m/s
  - Cost of Transport: 2.3

Anticipated Full Battery Performance

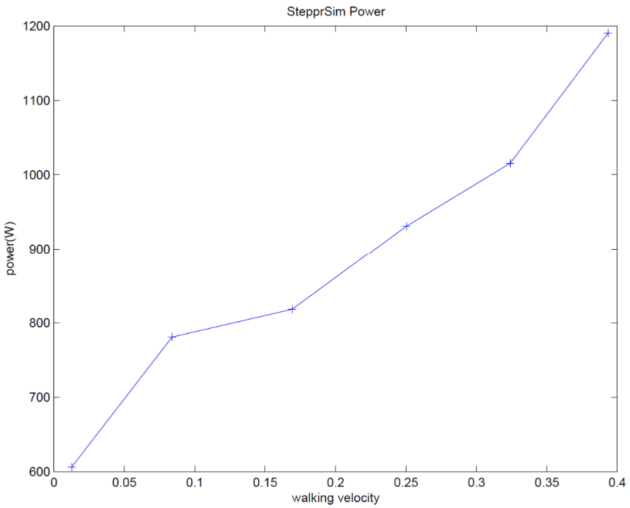
- Battery capacity is 2350 Wh
- Extrapolating from long walk
  - Distance: 3.46 km
  - Time: 311 min (5 h 11 min)
- Extrapolating from "good groove" walking
  - Distance: 4.13 km
  - Time: 344 min (5 h 44 min)

Approximate Power Budget

- Total System: ~430 W (<1/2 power of small microwave oven)
  - Overhead: ~100 W
    - Control PC & smart router: ~40 W
    - Distributed logic & communications: ~40 W
    - FET switching: ~10 W
    - Arms during walking: ~10 W
  - Locomotive power: ~350 W
    - Hip adduction / abduction: ~10 W
    - Hip flexion / extension: ~50 W
    - Hip rotation: ~30 W
    - Knees: ~65 W
    - Ankles: ~175 W
    - Back: ~0 W

Reducing Cost of Transport (1)

- Reduce COT by walking faster
  - Power depends *weakly* on speed in low speed, low power regime
- STEPPR (uncompensated) simulations
  - Speed ↑2x, Locomotive power ↑25-40%
  - So, Speed ↑2x, COT ↓30-38%
- STEPPR data
  - @ 0.15 m/s: 750 W
  - @ 0.3 m/s: 920 W
  - Speed ↑2x, Locomotive power ↑23%
    - COT ↓39%
  - Uncompensated, no battery mass



Reducing Cost of Transport (2)

- Limited WANDERER data, pre-tuning
  - @ 0.2 m/s: P_{avg} ~ 530 W
  - @ 0.25 m/s: P_{avg} ~ 560 W
  - Speed ↑25%, P_{avg} ↑6%, COT ↓15%
    - Implies Speed ↑2x, P_{avg} ↑20%, COT ↓42%
- WANDERER COT extrapolations, with stable faster walking:
  - Present (real data):
    - 0.2 m/s, P_{avg} = 330 W + 100 W, COT 2.4
  - Extrapolate based on simulations, STEPPR & WANDERER
    - @0.4 m/s, P_{avg} = (406 W to 460 W) + 100 W, COT 1.39 to 1.57
    - @0.6 m/s, P_{avg} = (460 W to 565 W) + 100 W, COT 1.01 to 1.24
    - @0.8 m/s, P_{avg} = (500 W to 647 W) + 100 W, COT 0.81 to 1.05

As speed approaches 1 m/s, COT should drop well <1

Impact of Support Elements (SEs)

- STEPPR, joint by joint:
  - Ankle: 205 W → 185 W (10% saved)
  - Knee: 275 W → 60 W (78% saved)
  - Hip Adduction: 370 W → 200 W (46% saved)
- STEPPR, full system (locomotive power only):
  - @ 0.15 m/s, uncompensated: 870 W
  - @ 0.15 m/s, compensated: 550 W (37% saved)
- WANDERER, by estimating SE compensation:
  - Ankle: 275 W → 175 W (36% saved)
  - Knee: 315 W → 65 W (80% saved)
  - Hip adduction: 77 W → 7 W (90% saved)
  - Full system: 750 W → 330 W (56% saved)