EPFL

Low-bandwith reflex-based control for lower power walking: 65 km on a single battery charge

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Cornell Ranger comes to a stop after walking 65 km (see 1 min 18 sec)
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Main contribution

Challenge

High reliability **and** low power usage of a walking person

Ranger

Energetically **and** computationally autonomous robot

Main contribution

65.2 km in **31h**
without human help

TCOT = 0.19 [P/mgv]

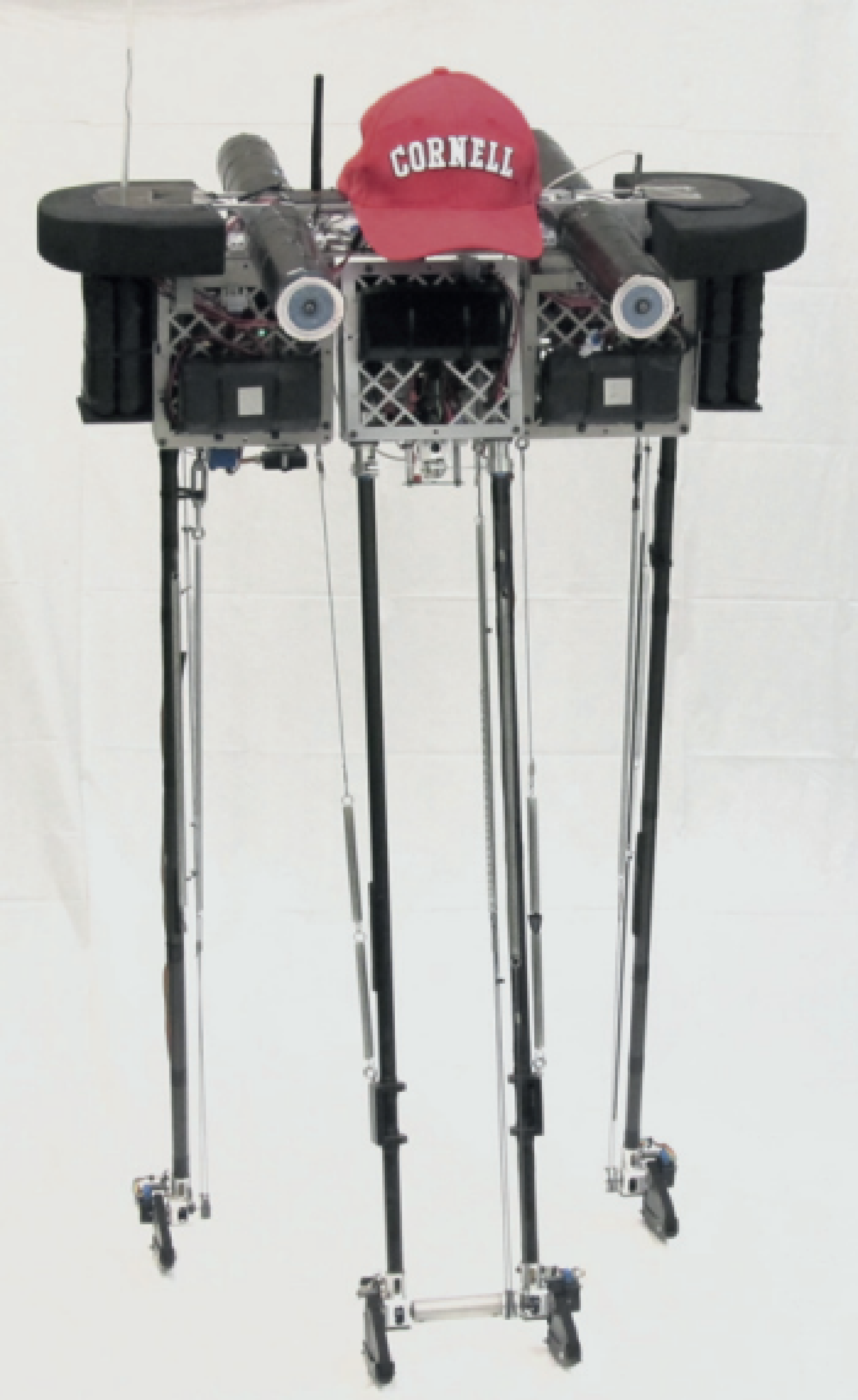
Ranger

TCOT = 0.3

Human

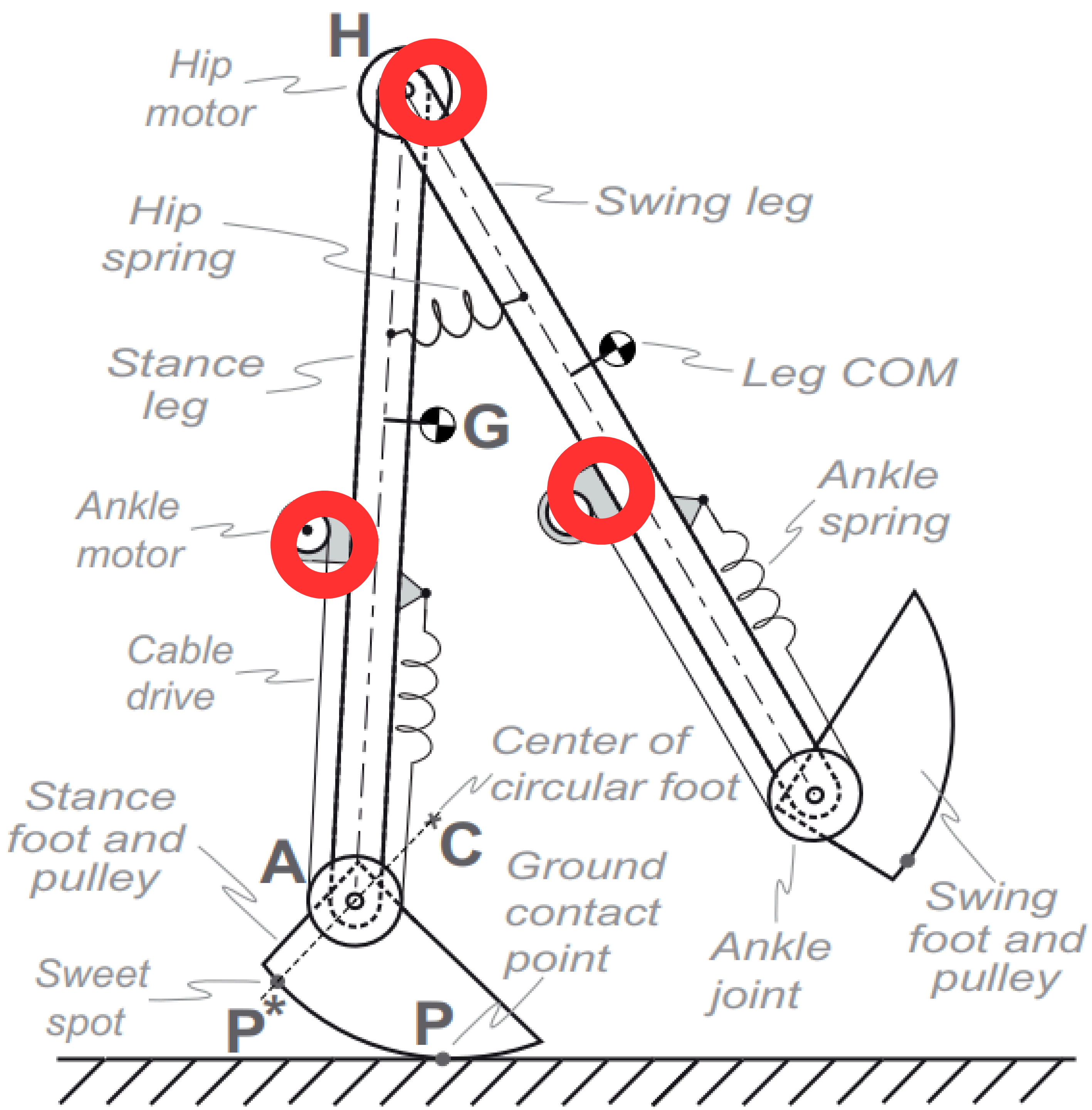
Executive Summary

- Knee-less, four-legged ‘bipedal’ robot
- Steady walking on flat ground
- Control: trajectory planner + stabilizing reflex-based controller
- Initial hand tuning + numerical optimization



Hardware

- Bipedal



- Key sensors
  - Motor (encoders, voltage, current)
  - IMU
  - Strain gauges (foot distortion)

Modeling

2 smooth phases

Single-stance
= 1 foot on ground

Double-stance
= 2 foot on ground

2 instantaneous transitions

Heel-strike collision

Toe-off transition

Overall control approach: Sparse state machine

Combines open-loop trajectory planning with intermittent feedback control

State Machine Design Uses triggers and states to determine actions at different points in the walking cycle

Control Structure

- ***Trajectory Generator:*** Provides a nominal trajectory for the robot
- ***Feedback Controller:*** Stabilizes by applying corrections at specific intervals

Reflex feedback: Discrete intermittent feedback control

Low-Bandwidth Reflex Feedback: *at mid-stance and heel-strike*

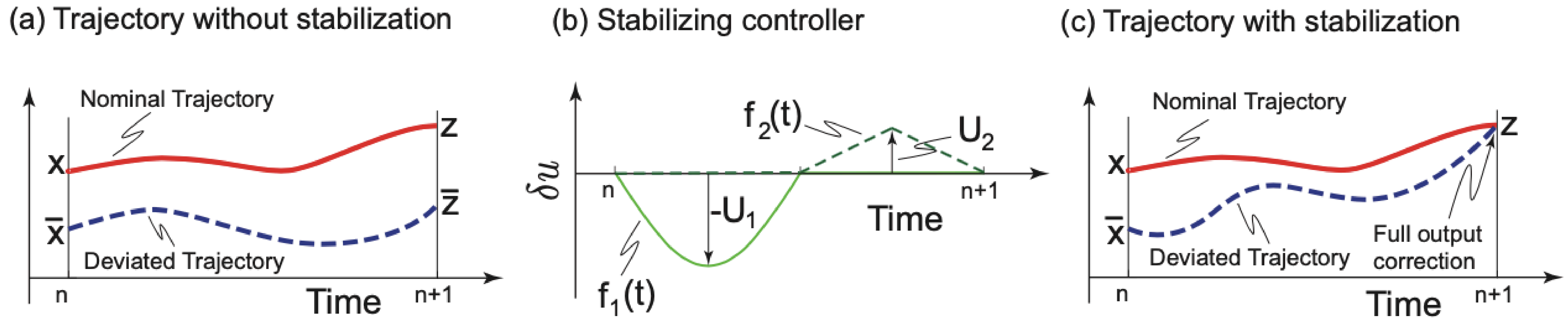
$$\delta x_{n+1} = \mathbf{A}\delta x_n + \mathbf{B}\delta U_n$$
$$\delta z_{n+1} = \mathbf{C}\delta x_n + \mathbf{D}\delta U_n$$

Variables to tweak: *Push-off force and step length*

downward velocity

stance leg rate

step length



Used as inspiration for other research

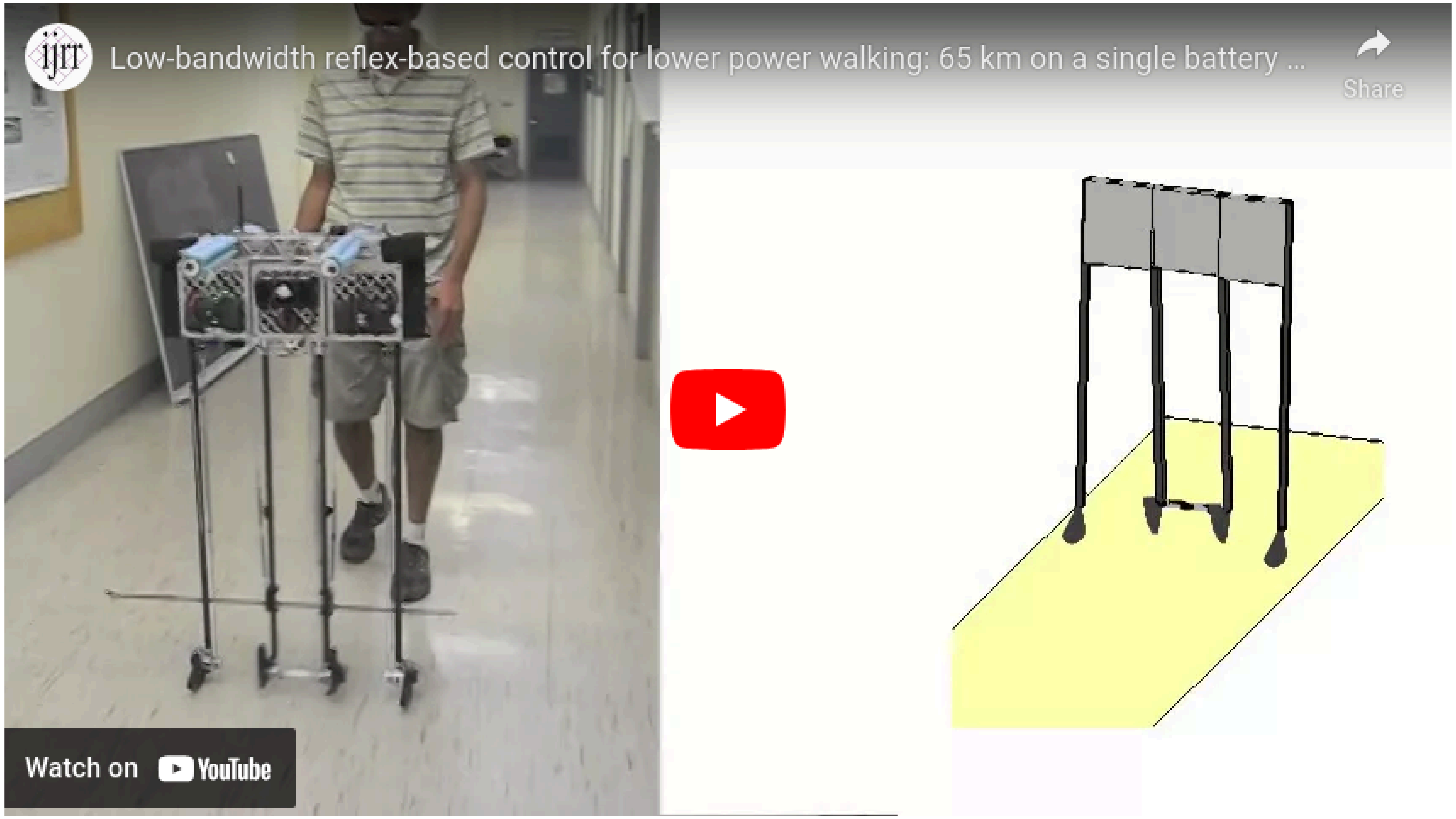
Malcolm et al. for the Journal in Neuro-engineering and Rehabilitation

- ***Prosthesis*** that actively provides ***push-off power***
- Reduces the metabolic cost of walking for individuals with transtibial (below-knee) amputation

Instead of continuous power, push-off power is applied at key moments (end of stance phase)

Results

Simulation validation



Results

Long distance walking record

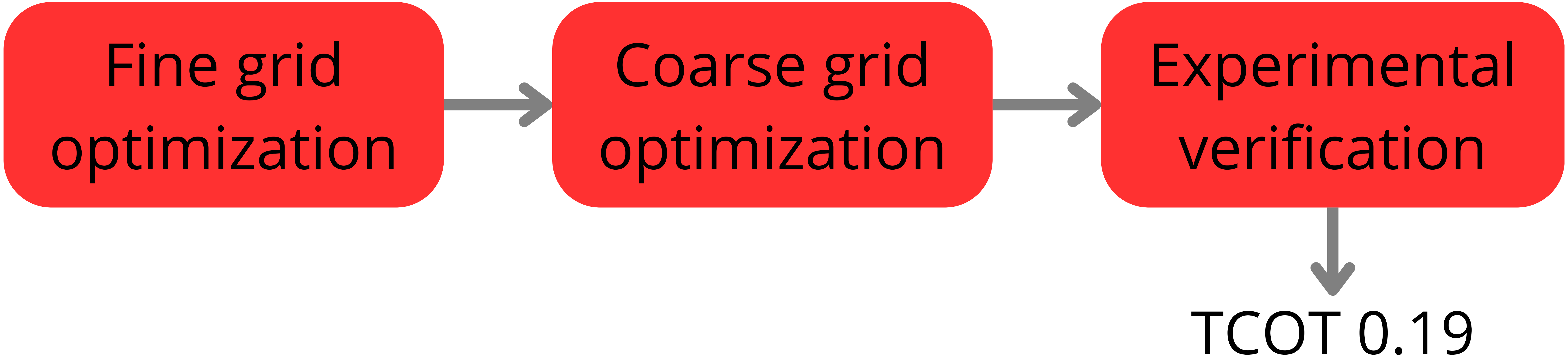
65.2 km in **31h**
without human help

Steps	Energy consumption	TCOT	Pace
186.076	0.493 kWh	0.28	2.12 km/h

Results

Energy-efficiency record

- Optimization problem
- TCOT as cost metric



Discussion and conclusion

- Energy efficiency
- Simplicity
- Long-distance walking
- Low power
- Low computation requirements

- Limited functionnality
- Mechanical simplicity
- Control and stability limitations
- Dependency on offline trajectories

Possible exam questions

1. What would be a method to be energy efficient for bipedal robots ?
2. What are the two optimal times during the gait cycle to enable feedback ?