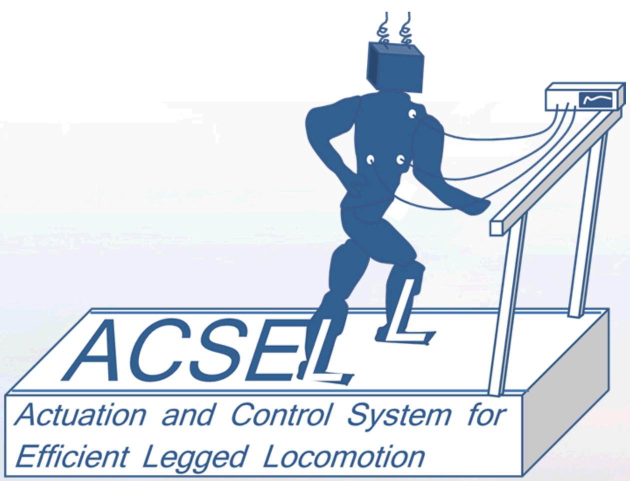
SAND2014-19375PE

ACSELL: Actuation and Control System for Efficient Legged Locomotion



Team:
Sandia National Laboratories
Institute for Human and Machine Cognition
Open Source Robotics Foundation
Massachusetts Institute of Technology
Globe Motors

PI: Steve Buerger, Sandia

October 7, 2014

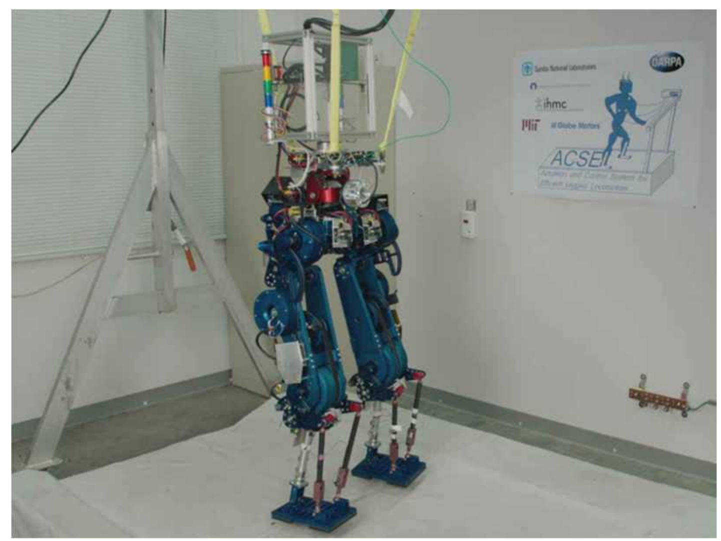
Sandia National Laboratories / Buerger

<u>Accomplishments</u>

- Completed 15 DOF mechanical & electrical integration for STEPPR
- Integrated with IHMC software
- STEPPR position controlled & standing
- Validated all high-efficiency support elements at full load on bench
- STEPPR 2.0 kit (mostly) fabricated
- Increased rope transmission life to ~100k cycles
- Began WANDERER detailing

<u>Plans</u>

- Get STEPPR walking
- Install retrofit kit to STEPPR (2.0)
- Demonstrate efficient STEPPR 2.0 walking
- Complete WANDERER design, fabricate, integrate, get walking
- Demonstrate at DRC Finals



The Sandia Transmission-Efficient Prototype Promoting Research (STEPPR) robot.

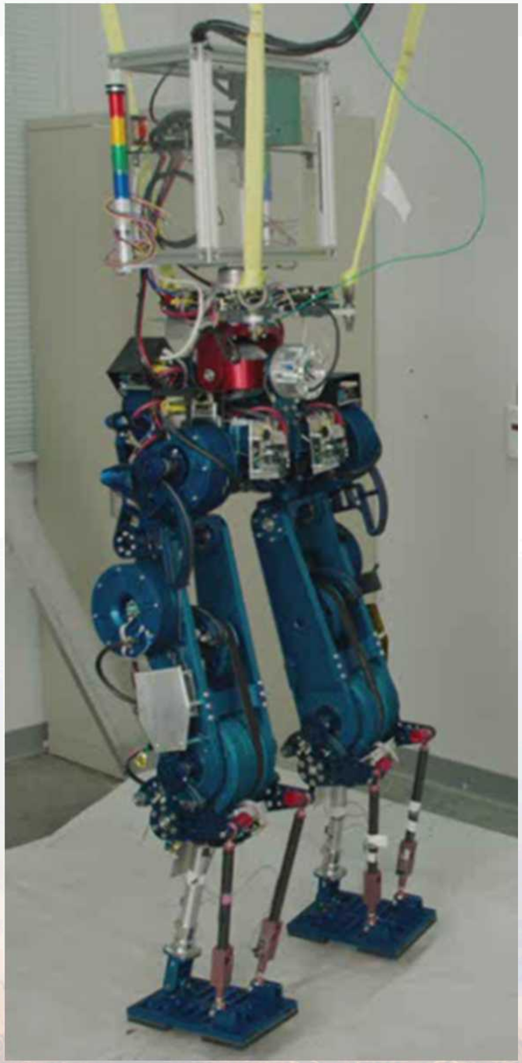
Goals and Approach

- **Legged robots: radically mobile, but need to be more efficient**
- **Energy efficiency targets**
  - **BAA: Improve endurance / efficiency 20x vs. DRC GFE robot**
  - **Proposal**
    - **Efficient gaits PLUS**
    - **Efficiently produce joint work from battery (30-50%)**
    - **Be efficient across a range of locomotive behaviors**
- **Approach**
  - **2 robot design cycles: baseline (STEPPR) & final (WANDERER)**
  - **Core EM actuators plus "support elements"**
  - **Major energy sinks to target**
    - **Operating actuators at inefficient speed / torque points**
    - **Suboptimal drive impedance**

Goals: ●Develop new actuation systems that enable dramatic improvements in energy efficiency of legged robots ●Demonstrate in a humanoid platform

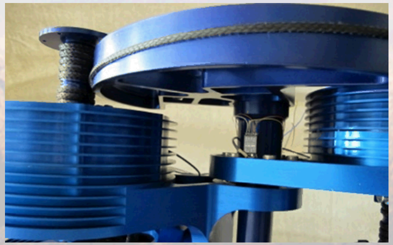
Baseline Robot: STEPPR

- STEPPR: Sandia Transmission-Efficient Prototype Promoting Research
- Design goal: as close to direct drive as reasonable
  - High torque motors, minimal gear ratios (≤10:1)
  - Single-stage, high-efficiency transmissions
  - Low intrinsic mechanical impedance for high quality torque / impedance control
  - Backdrivable for recovery of negative joint work
- Drivetrain
  - Allied Megaflux frameless motors
  - Synthetic rope transmissions
  - Differential pushrods at ankle



Frameless Motor

Rope transmission



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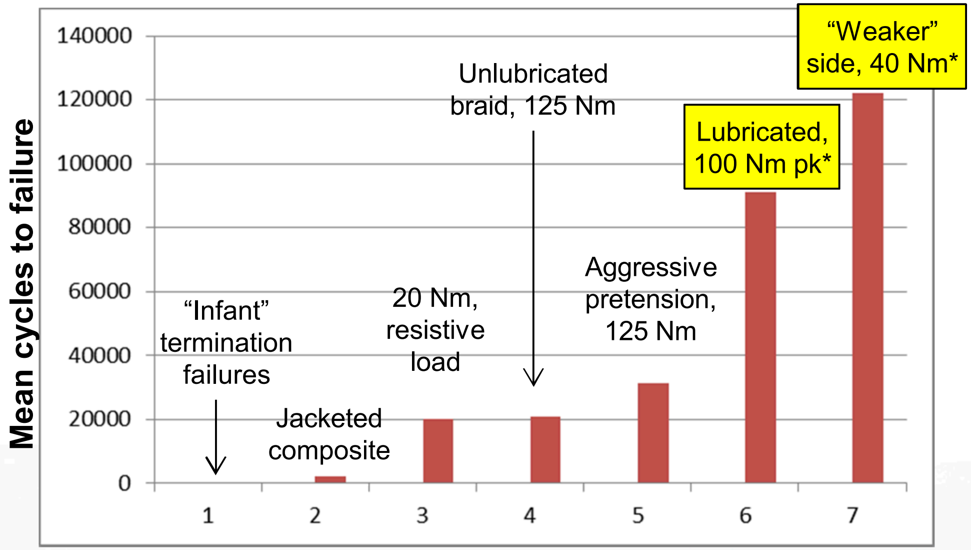
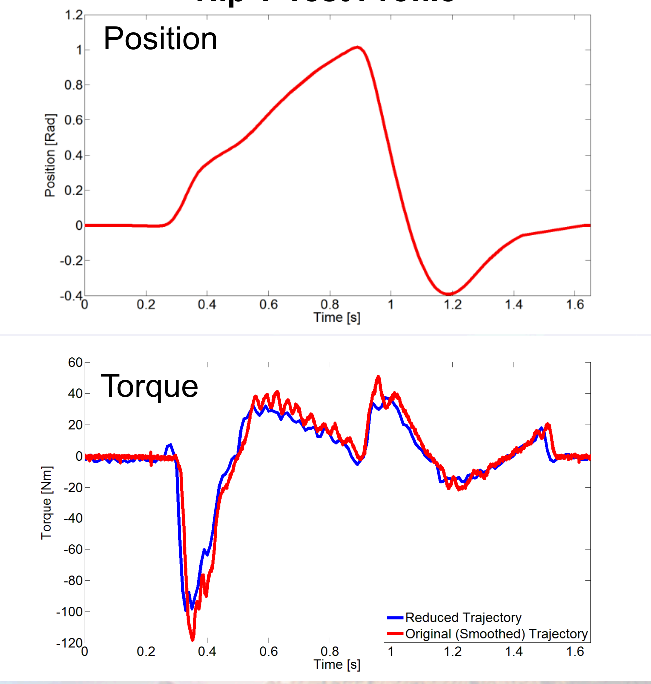
Rope Transmission Testing

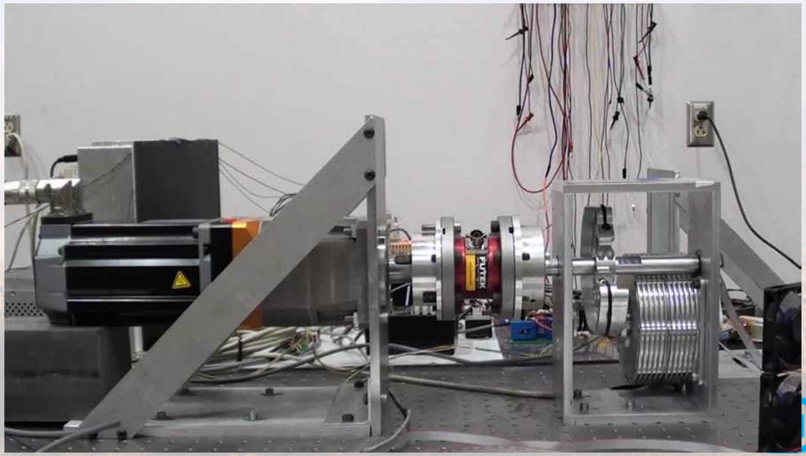
- Synthetic ropes
  - Lighter, stronger than steel, more efficient in small D/d ratios
  - Can we get adequate cycle life?

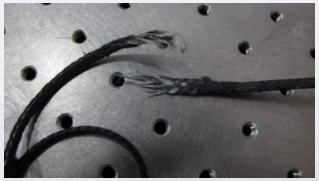


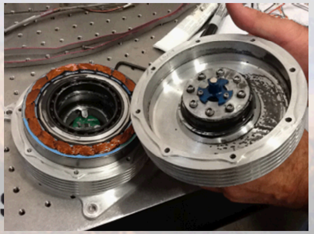
* - ropes intact, test stand failed

Hip Y Test Profile



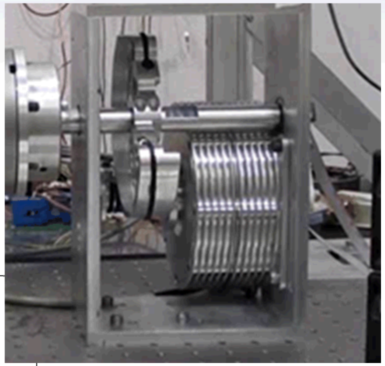


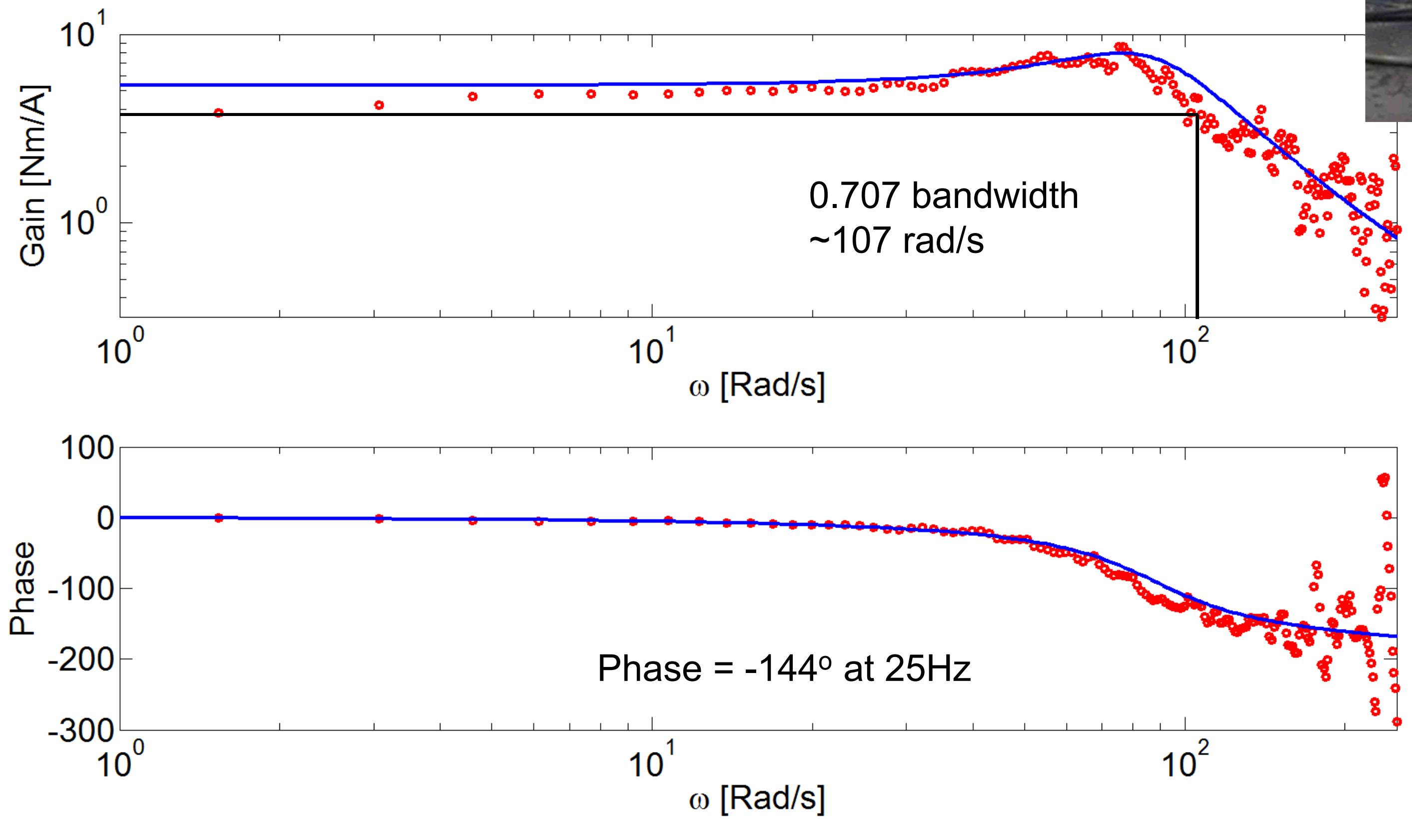




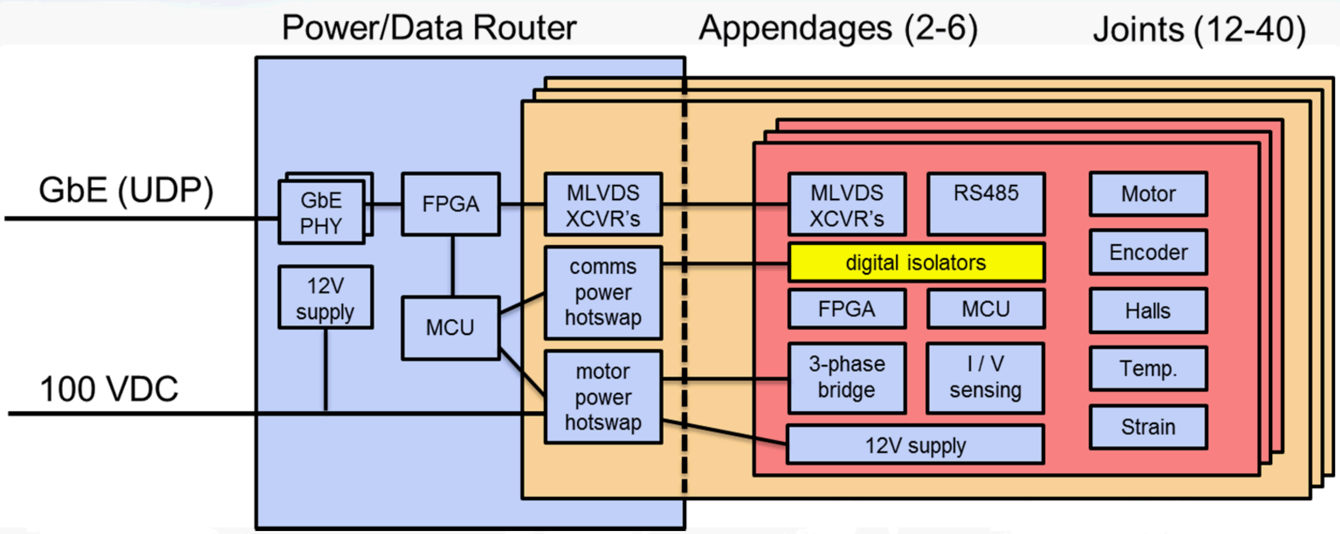
Torque Control Bandwidth

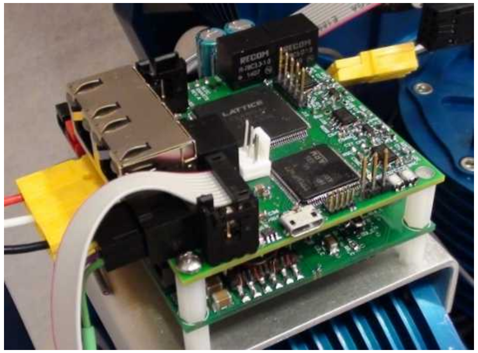
Input: Current Command
Output: Measured Torque





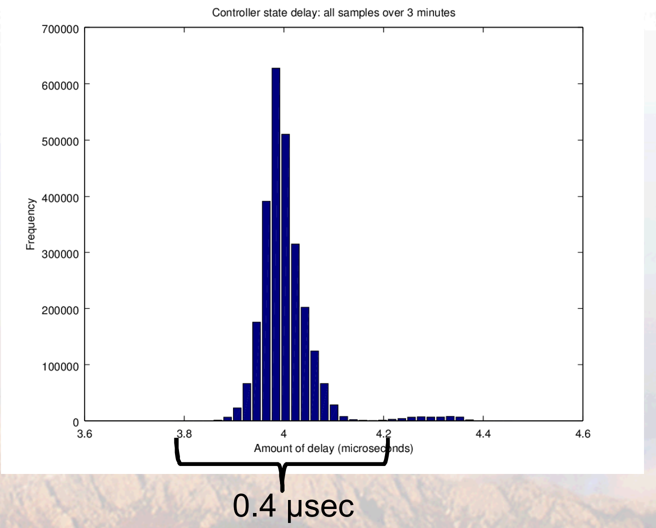
Electronics, Firmware and Comms





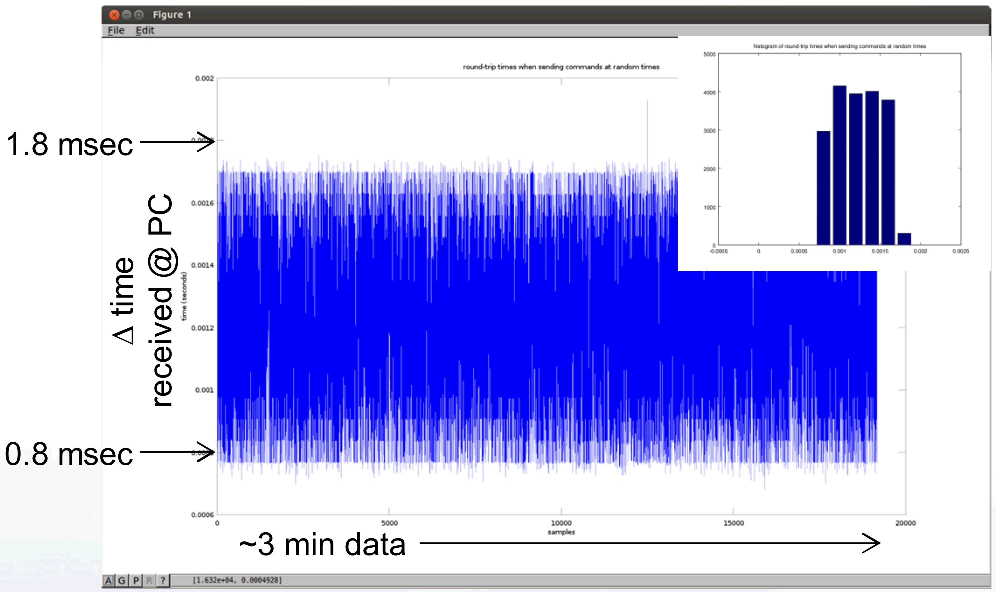
Joint Drive Electronics

- **Very low power m-LVDS comm backbone**
- **Local joint control at 10-30 kHz**
- **System UDP output at 1 kHz**
- **Delay locked loop synchronizes distributed timing for μsec scale jitter**



Comm & Power Performance

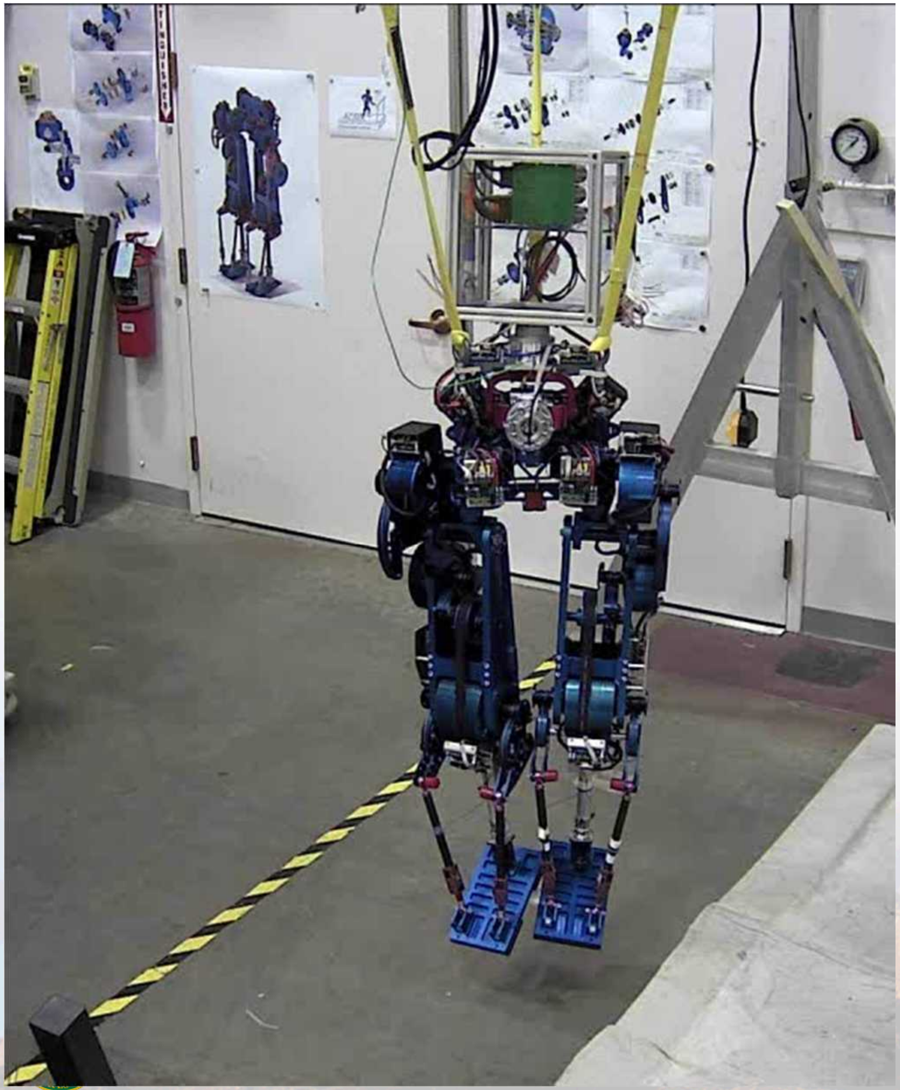
"Roundtrip" packet time from PC, packets sent at random times

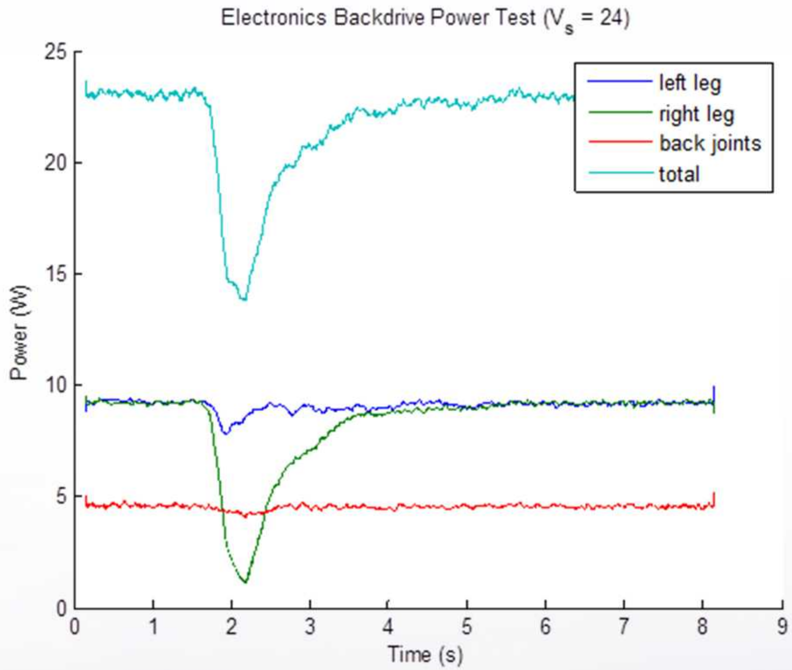


- **Packet roundtrip performance**
  - **Use ~0.7 msec to propagate & respond to packet**
  - **Roundtrip time variation entirely due to random variation in "request" times**
  - **No packets dropped under normal conditions**

- **Power for full system (router boards + 15x joint stacks)**
  - **No FET switching: 15 W**
  - **FETs switching, no current: ~50 W**
    - **~2 W per joint switching (room for improvement)**

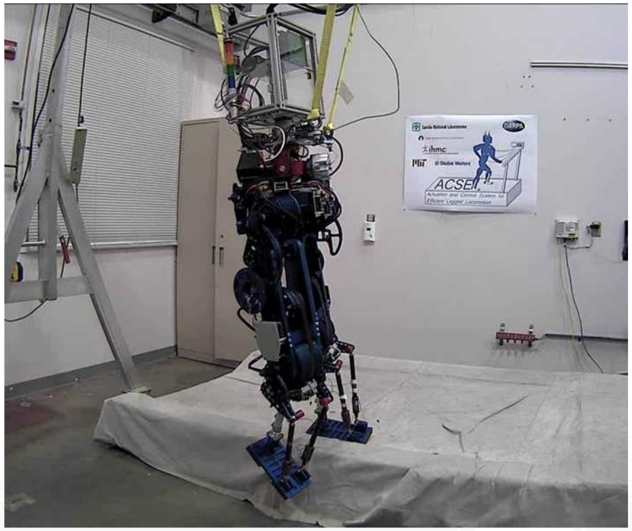
Backdrivability and Regeneration

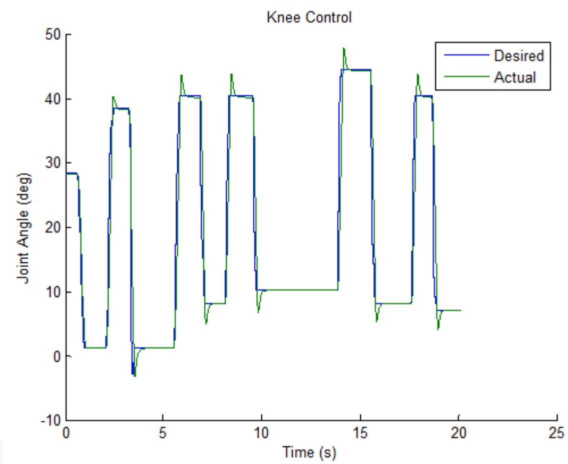


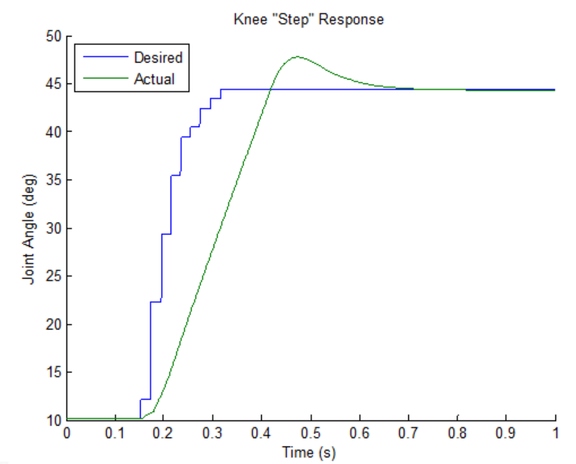


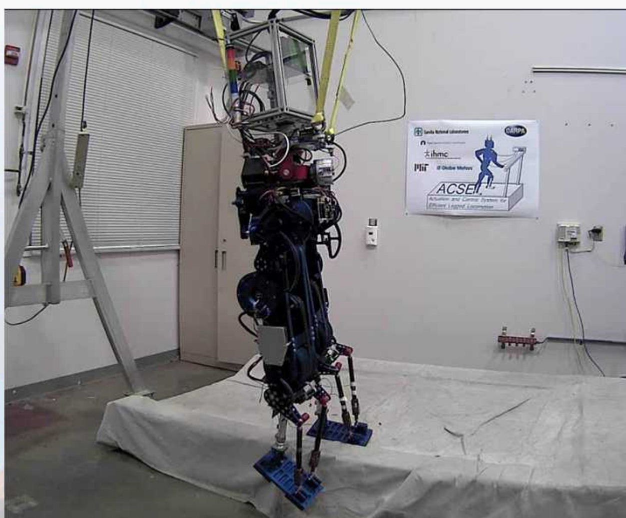
- **Regeneration demo**
  - **Raised leg to ~90^o and dropped**
  - **Input energy ~60 J (~18 kg @ 0.3 m)**
  - **9 J regenerated (reduced input power)**
  - **24 J dissipated in motors**

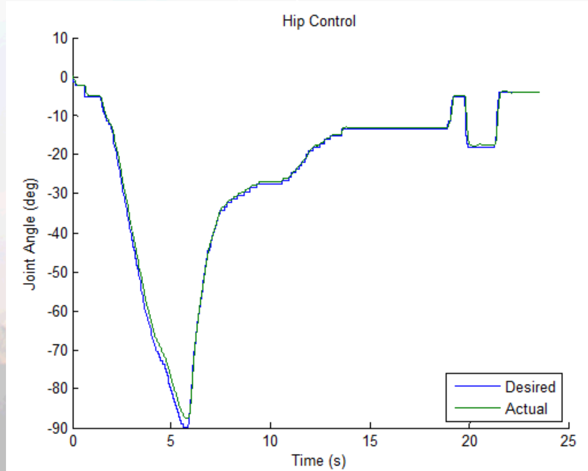
Joint Position Control

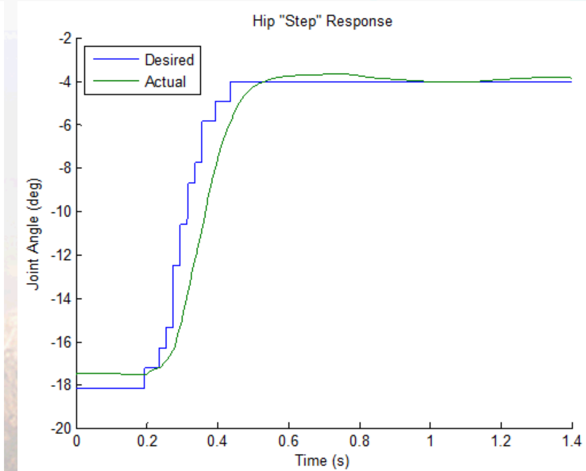




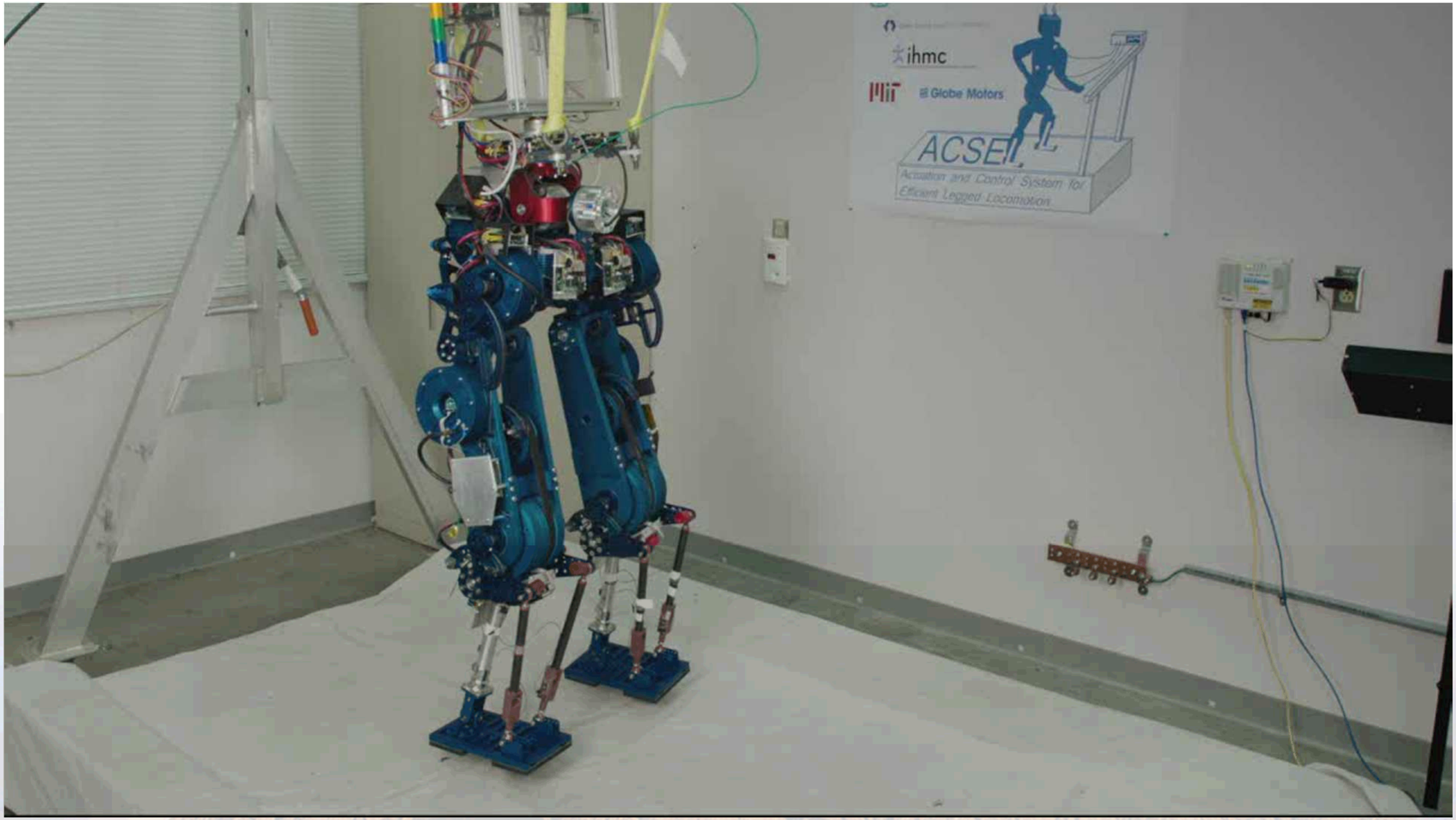




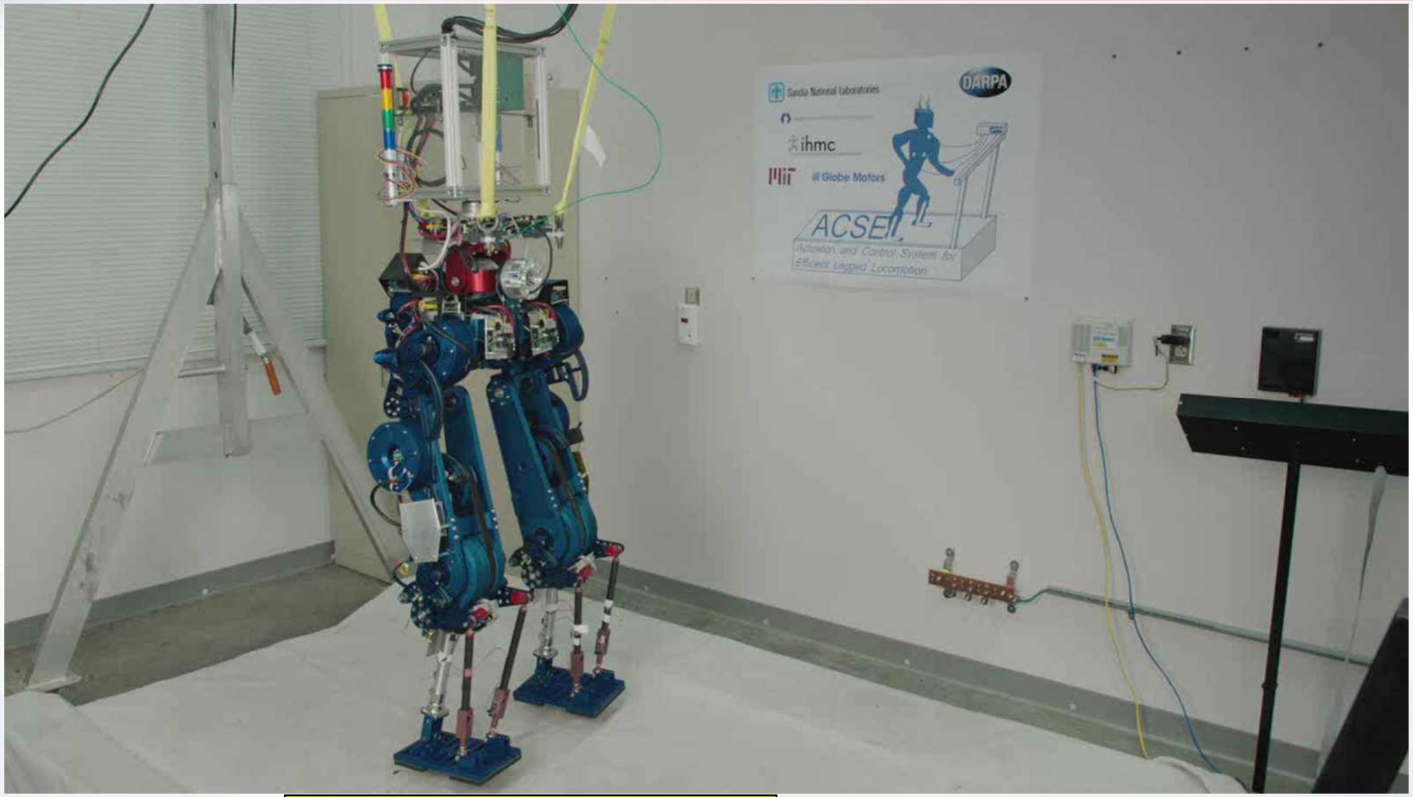




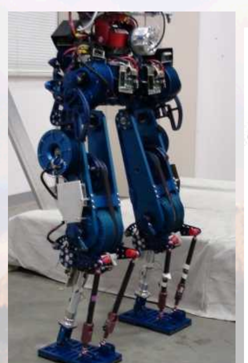
15 DOF Position Control

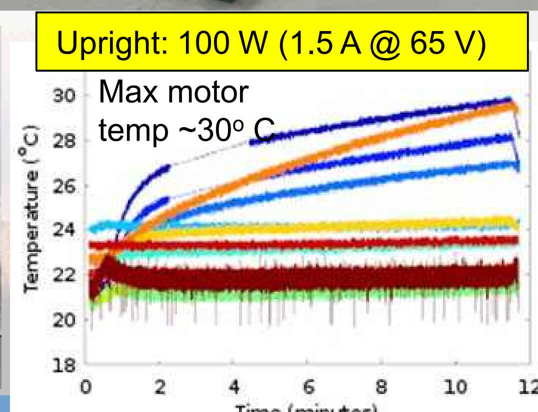


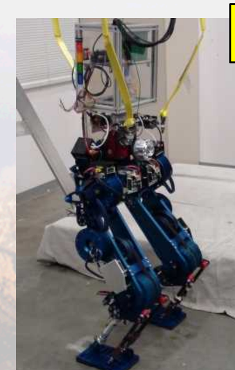
Standing (Position Controlled)

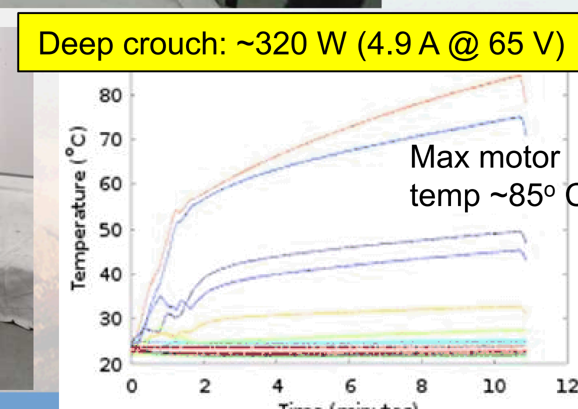


10 minute standing trials:

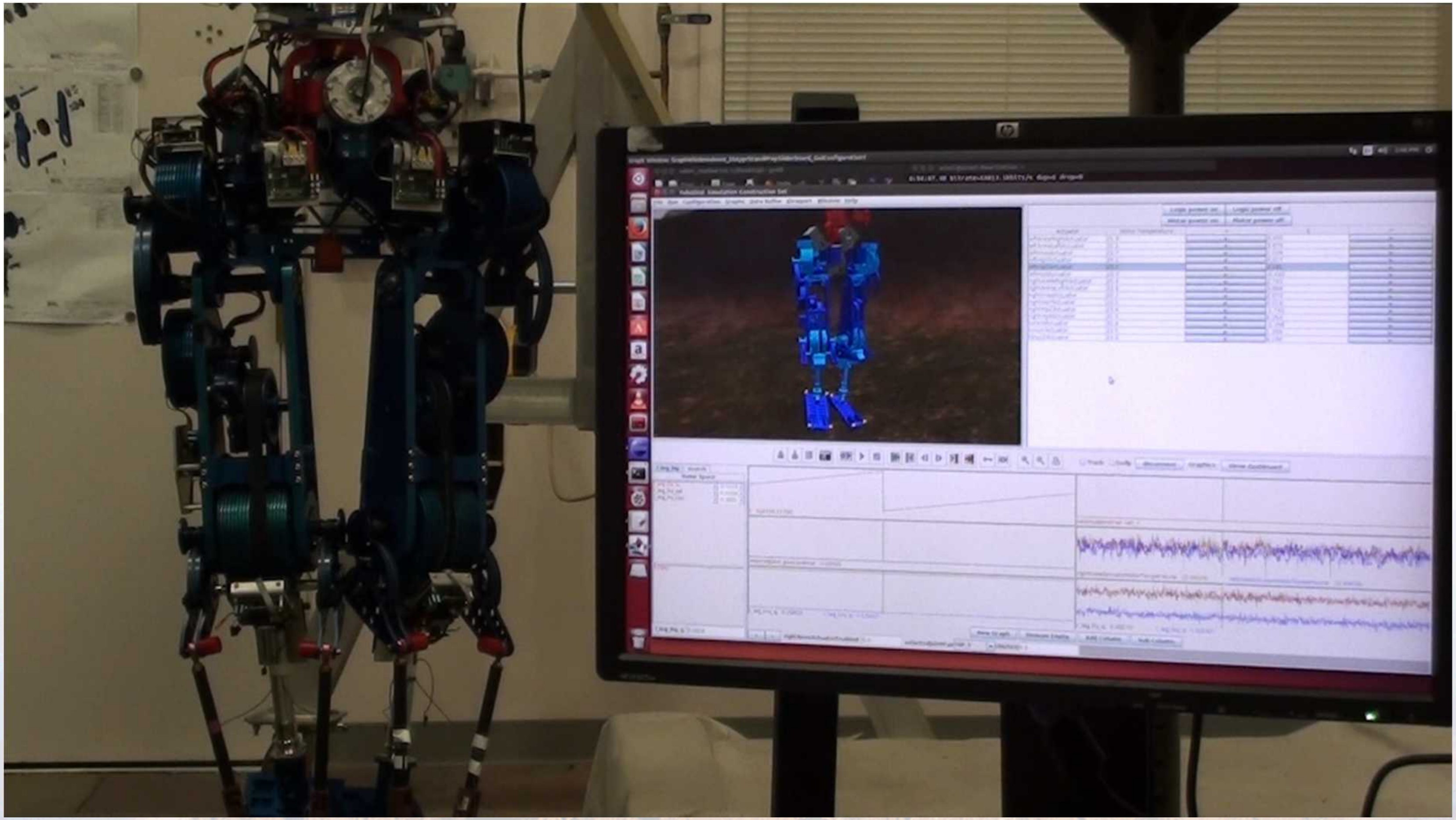




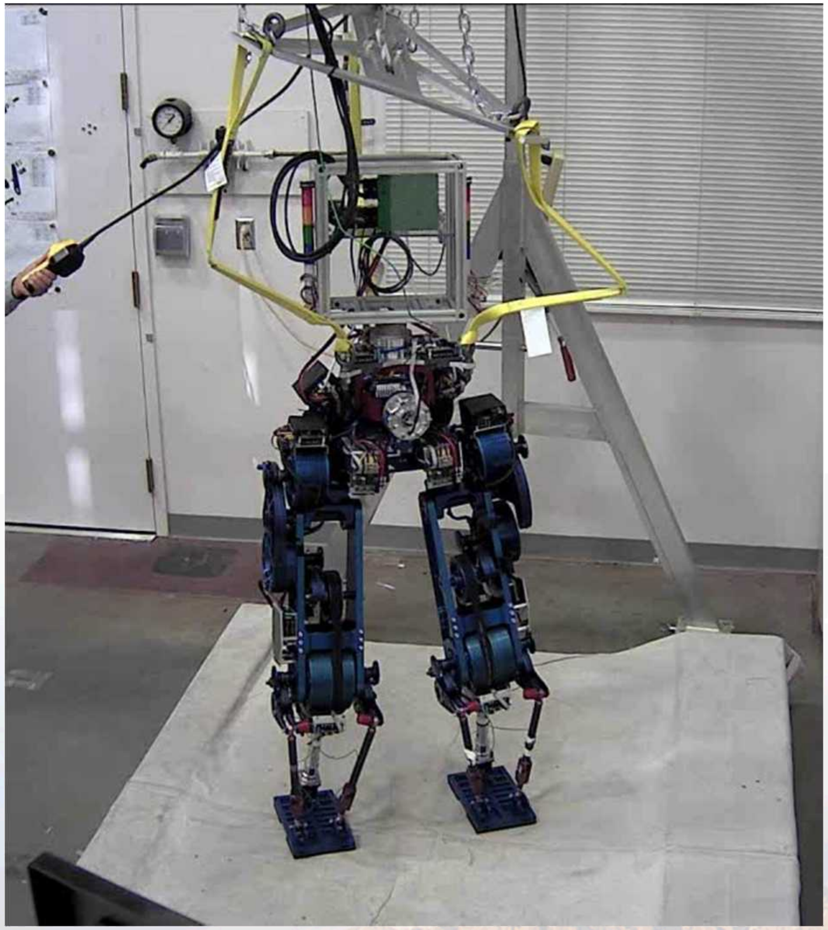


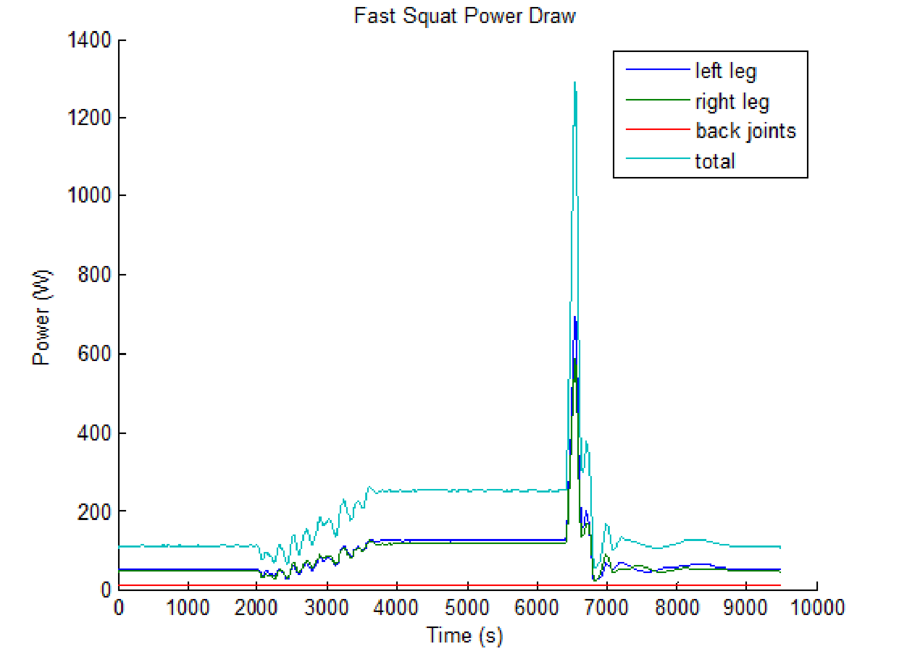


Integration with SCS



Squatting

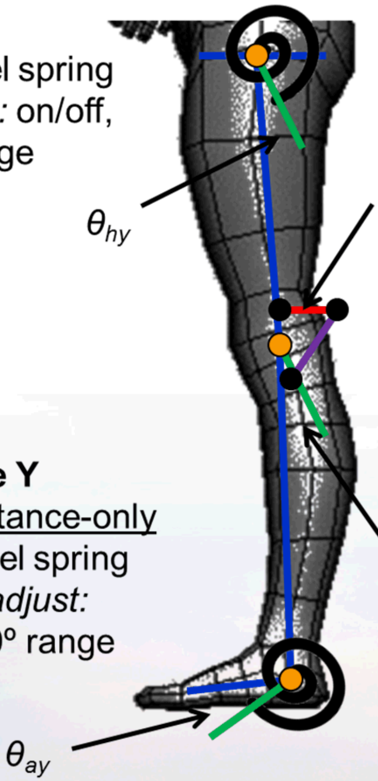



Fast Squat Power Draw
Power (W)
Time (s)
left leg
right leg
back joints
total
0
200
400
600
800
1000
1200
1400
0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000

Making STEPPR (More) Efficient

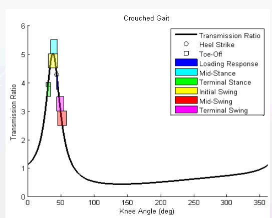
Passive mechanical “support elements” with simple adjustments used when changing gait

Hip Y
SE: parallel spring
Gait adjust: on/off,
θ_{hy} 38º range



Hip X
SE: parallel spring, partial range: adduction only
Gait adjust: none

Knee
SE: PDT 4-bar *
Gait adjust:
θ_k 78º range



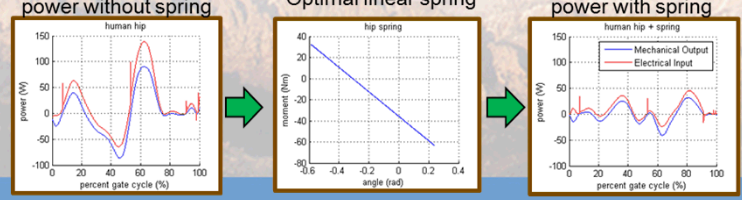
Ankle Y
SE: stance-only parallel spring
Gait adjust:
θ_{ay} 50º range

Gait	∆ECOT
Atlas Stance Sim (GFE Gazebo)	62%
Atlas Crouched Level Sim (GFE)	63%
Atlas Crouched Level Sim (IHMC)	79%
Atlas Humanlike Sim #1 (IHMC)	42%
Atlas Humanlike Sim #2 (IHMC)	32%
Atlas Humanlike Sim #3 (IHMC)	32%
Atlas Running Sim (IHMC)	10%
Atlas Rocks Sim (IHMC)	81%
Atlas Slopes Sim (IHMC)	63%
Atlas 2x4 Real Data (IHMC)	85%
STEPPR Sim #1 (IHMC)	45%
STEPPR Sim #2 (IHMC)	70%
Human Level (Schache)	50%
Human Level (Silder)	44%
Human Stairs (Silder)	7%

Predict average 51% reduction in ECOT across 15 gaits

Designed via Data-Based Optimizations

Hip motor mech & elec power without spring | Optimal linear spring | Hip motor mech & elec power with spring



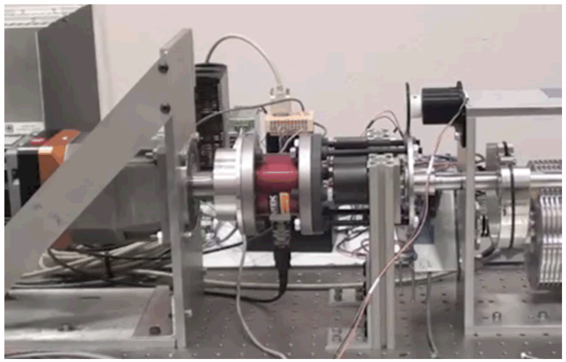
* - PDT = Pose Dependent Transmission

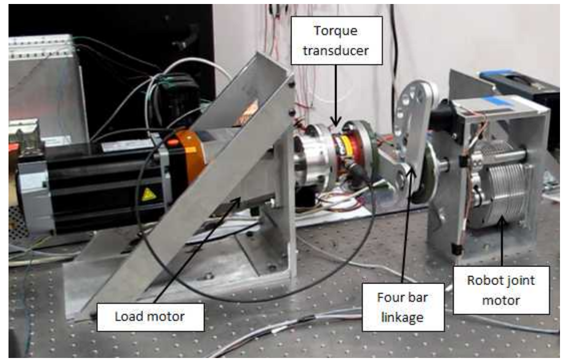
Support Element Validation

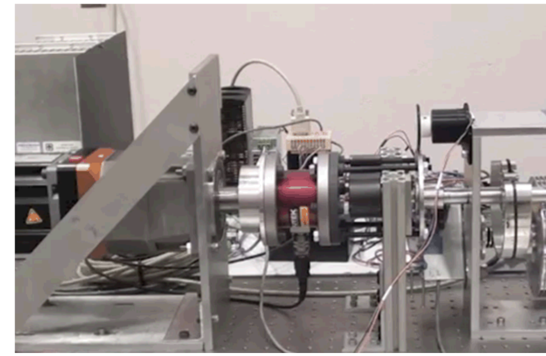
Hip Adduction Spring

Knee PDT (Four-Bar)

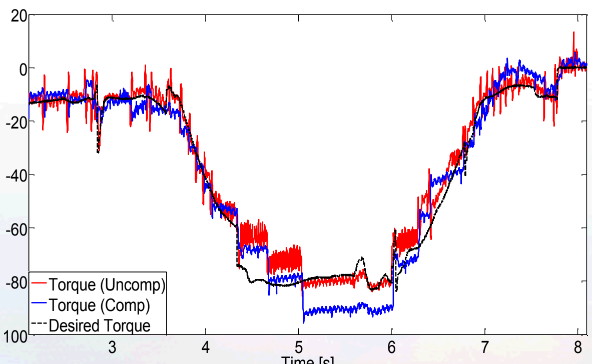
Ankle Spring (1/2 stiffness)

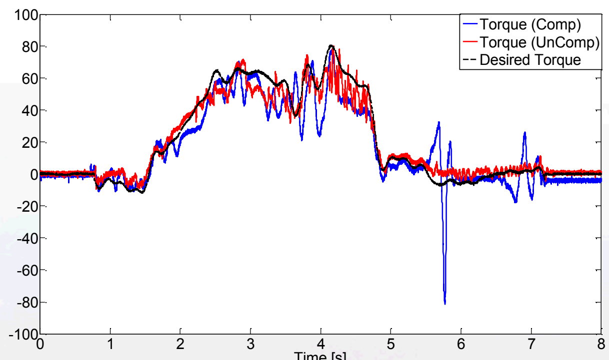


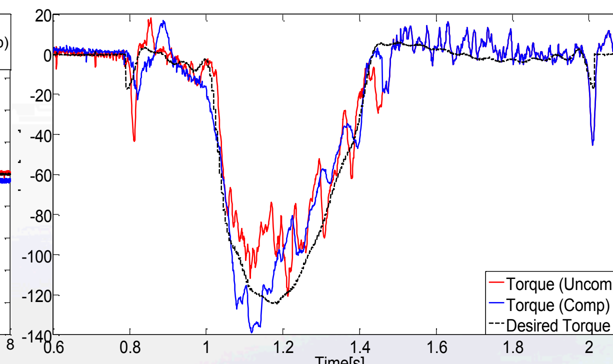




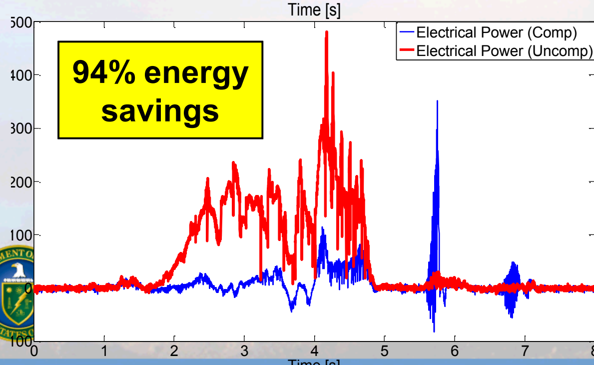
Torque

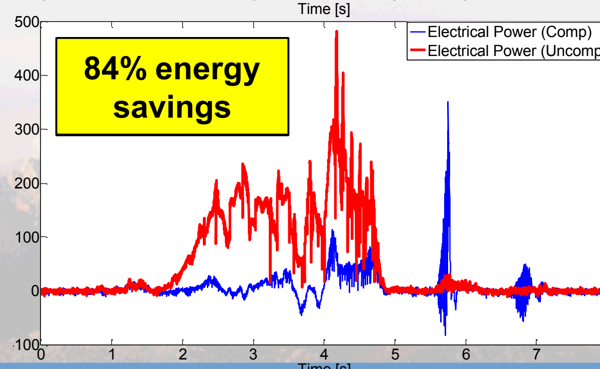


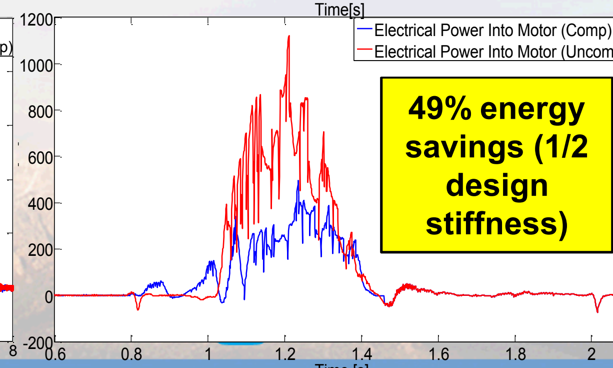




Power



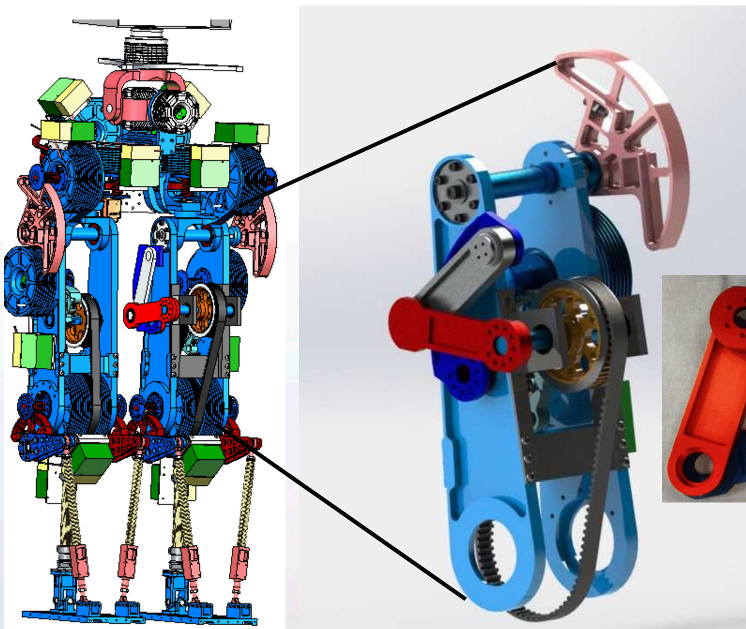




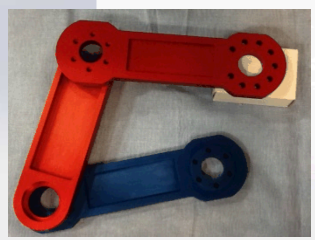
STEPPR 2.0 Retrofit Kit

- Designed to allow STEPPR retrofit in ~1-2 days
- Status: Some parts received, rest in fabrication (expected ~10/10)

Knee Four-bar Linkage

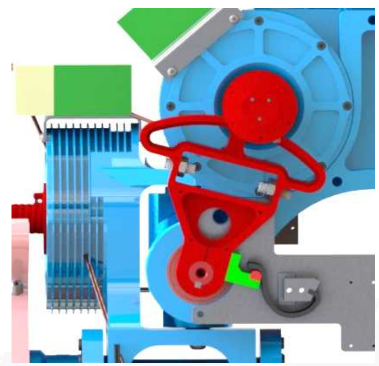


Design Rendering

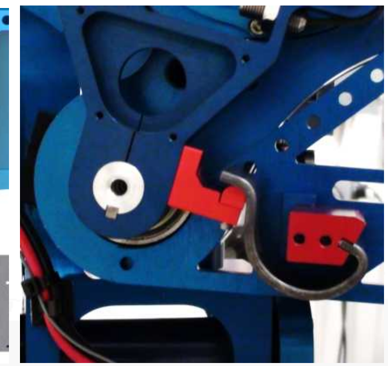


Kit Parts

Hip X (Roll) Spring



Design Rendering

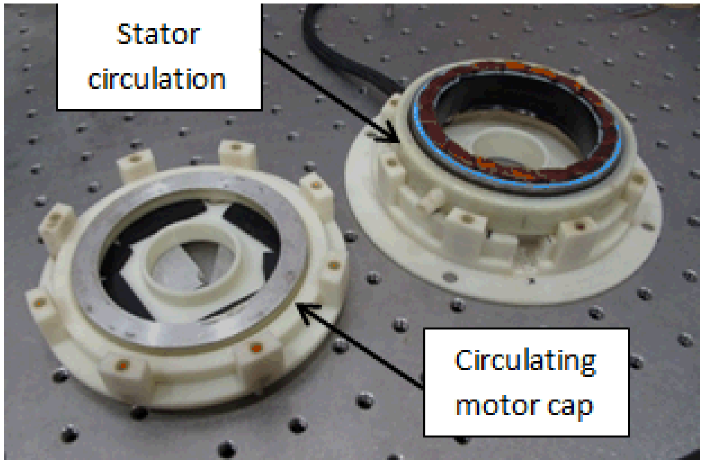


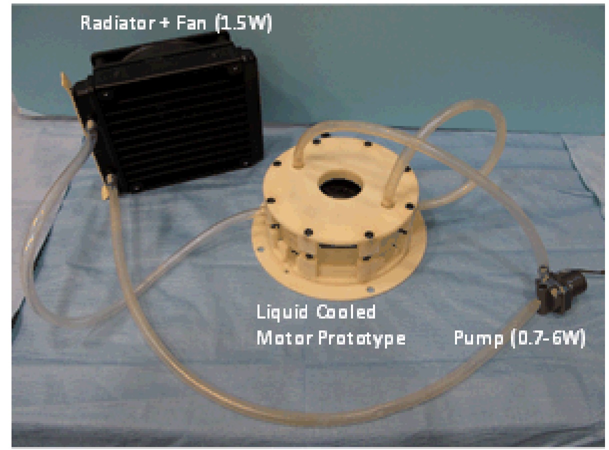
Parts In Place on STEPPR

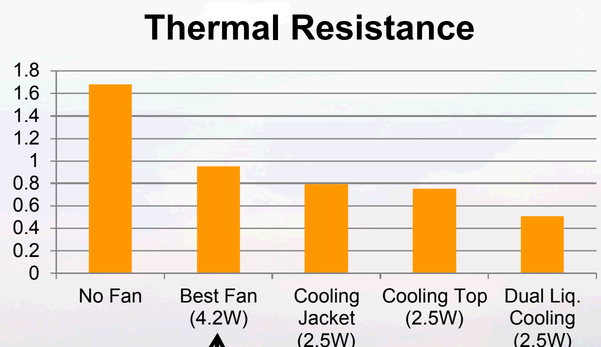
Stance-only Ankle Spring

Design Rendering

Liquid Motor Cooling

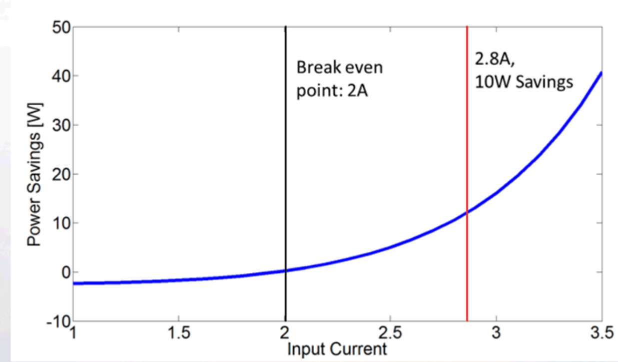






Air cooling: 32% increase in cont. T with 4.2 W

Liquid cooling: 80% increase in cont. T with 2.5 W



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WANDERER

Walking Anthropomorphic Novelly Driven Efficient Robot for Emergency Response

- **Preserve core drive features of STEPPR, but improve:**
  - **Self- adjusting, integrated support elements**
  - **Better packaging, protection & aesthetics; reduce mass**
  - **Limited, targeted design risks**
- **Downsize motors?**
  - **Support elements significantly unload motors for normal behaviors**
  - **Smaller motors help packaging & system mass, but….**
  - **We predict shifting to smaller motors would *increase* COT by ~5-10%**
- **Why?**

$$P_{elec} \cong \sum_{joints} (i^2 R + \tau\omega)$$

Mechanical term decreases with motor size

i^2R *increases* as motor size decreases, unless full robot mass scales proportional to motors

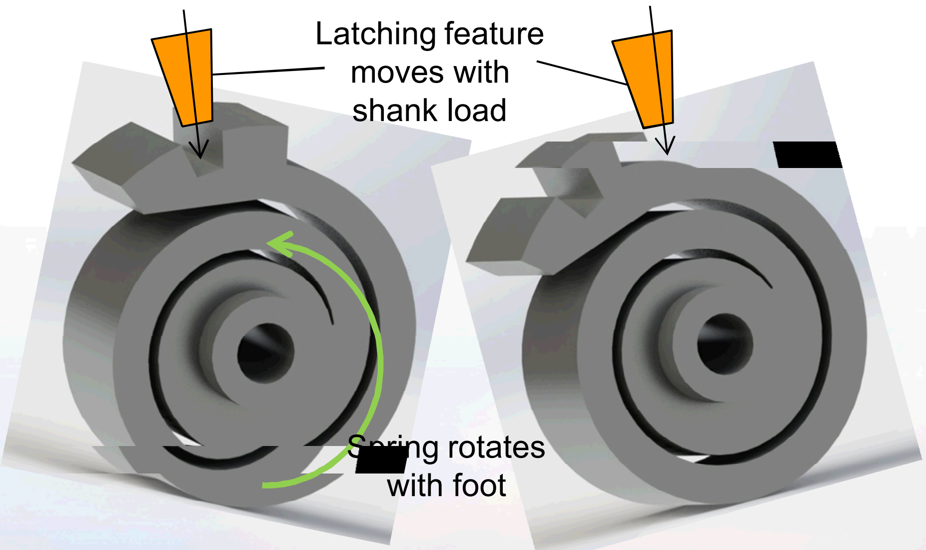
Conditions under which decreasing motor size improves efficiency:

- Full robot mass scales strongly with motors
- Most electrical power goes to mechanical work

Adjustable Support Element Concepts

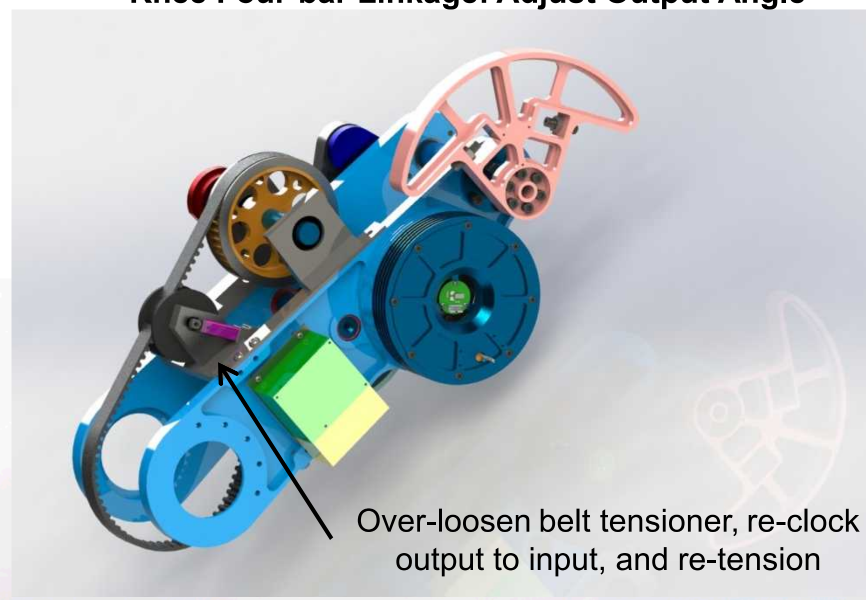
Minimize adjustment actuators and keep out of load path

Stance-only Ankle Spring: Adjust Spring Equilibrium Angle



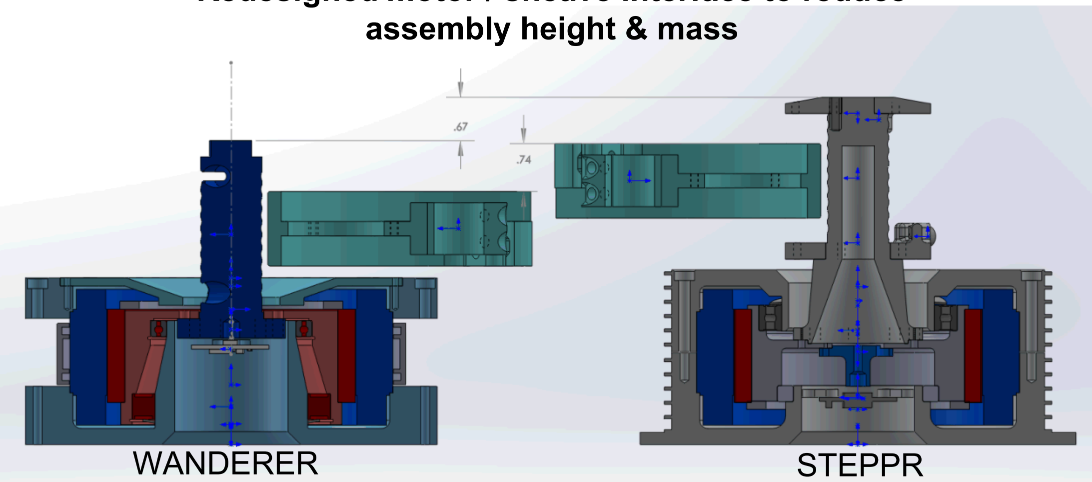
Equilibrium position determined by ankle angle at heel strike (unactuated adjustment)

Knee Four-bar Linkage: Adjust Output Angle

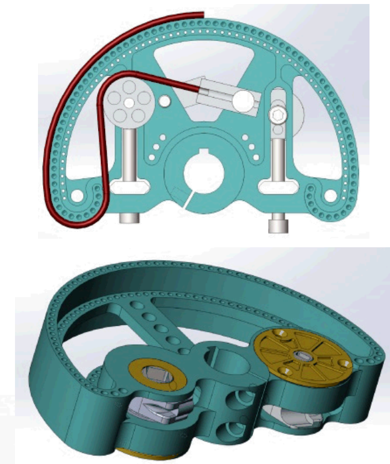


WANDERER Drivetrain

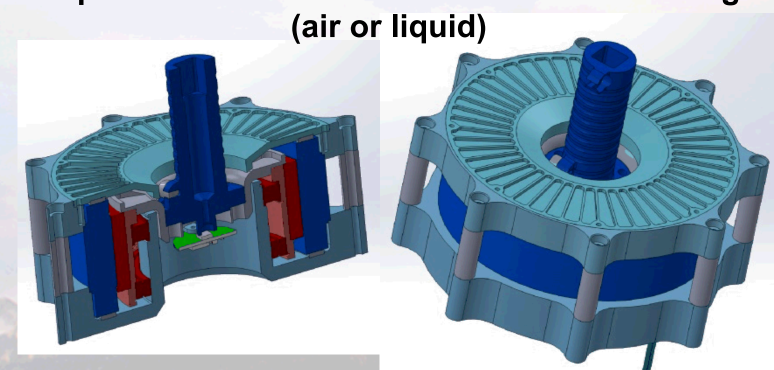
Redesigned motor / sheave interface to reduce assembly height & mass



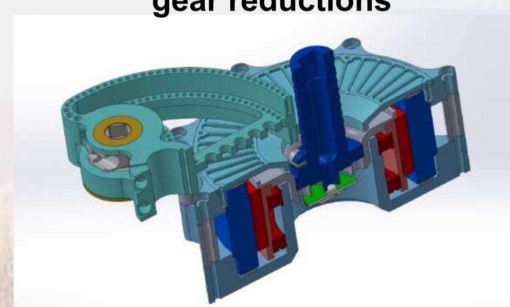
Pulley concepts improve rope installation & maintenance



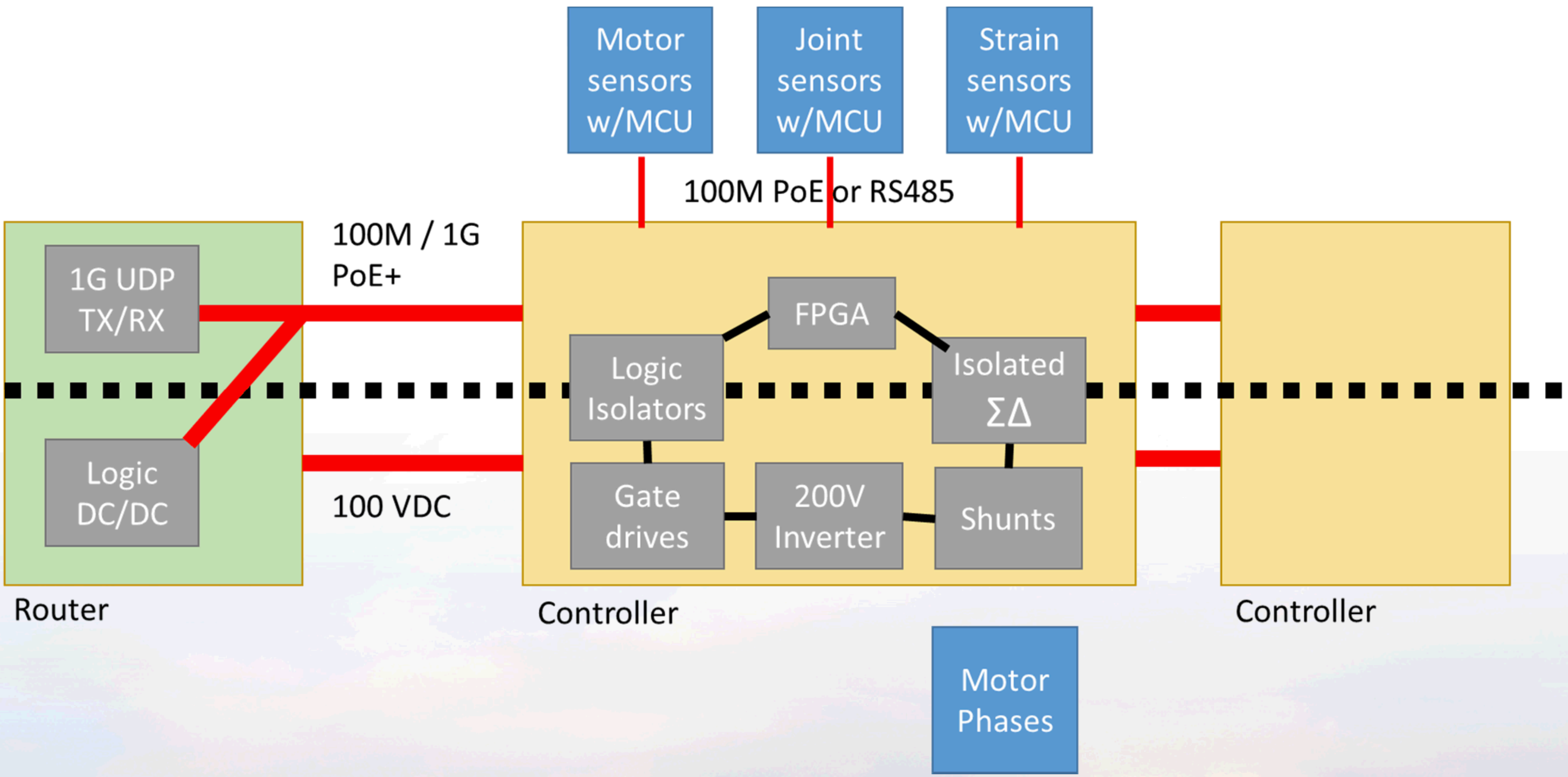
Expose stator outer circumference for cooling (air or liquid)



Experiment with slightly larger gear reductions



WANDERER Electrical Architecture



Spend some more idle power in exchange for better isolation and comms reliability at all voltages

Backdrivability and Gearing Optimization (Preview)

- Simplified analysis suggests gearing is a painless way to increase efficiency

$$P_{elec} \cong \sum_{joints} (i^2 R + \tau\omega)$$

Electrical power decreases ~N^2

Mechanical power unchanged by idealized gearing

- Limits to gearing
  - Motor speed limits (& speed-related losses)
  - Implementation issues (inefficiencies, mass of multi-stage transmissions)
  - Loss of "intrinsic backdrivability"

- How to define sufficient backdrivability? Ideas:
  - Critical: Avoid binding conditions
  - Load-tuned: Some fraction of load impedance profile (if known)
  - ★ Data-based: % deviation from desired joint τ due to drive inertia / friction
    - Aligns well with ACSELL design methodology

More to come on this

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Next Steps

- **STEPPR**
  - **Minor tweaks based on IHMC feedback**
  - **Ship to IHMC late October**
  - **Ready for whole-body control**

- **STEPPR 2.0**
  - **Kit finished in October**
  - **Ready for installation after STEPPR is walking**

- **WANDERER**
  - **SNL & OSRF shift greater focus to WANDERER**
  - **New layout complete & initial parts on order early November**
  - **All parts ordered by December**

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Team

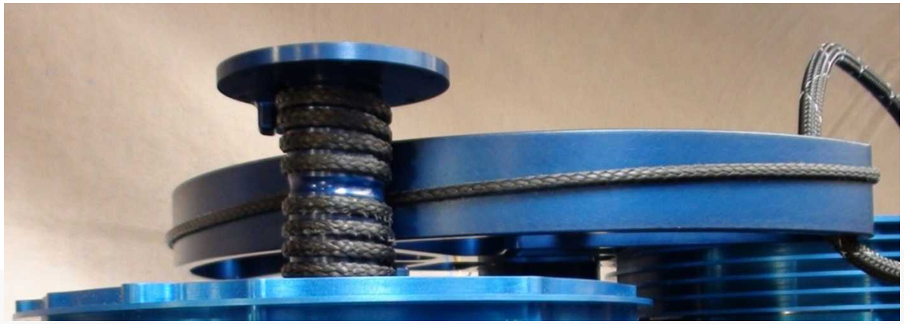
- **Sandia**
  - Clint Hobart
  - Jon Salton
  - Joshua Love
  - Steve Spencer
  - Ani Mazumdar
  - Tim Blada
  - Mike Kuehl
  - Greg Brunson
  - Nadia Coleman
- **IHMC**
  - Jerry Pratt
  - Peter Neuhaus
  - Sylvain Bertrand
  - Jesper Smith
  - Doug Stephen
  - Others
- **OSRF**
  - Morgan Quigley
  - Gabby Merritt
  - Victor M. Vilches
- **MIT**
  - Neville Hogan
- **Globe Motors**
  - Roy Gosline
  - Gary Sutton
  - Syed Hossain

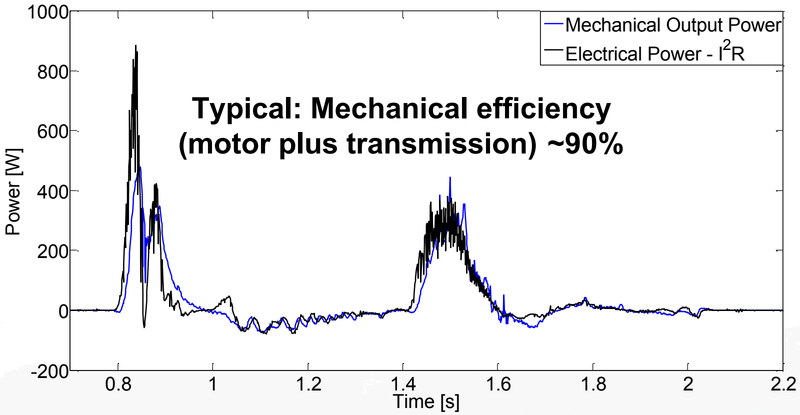
Questions?

Backups

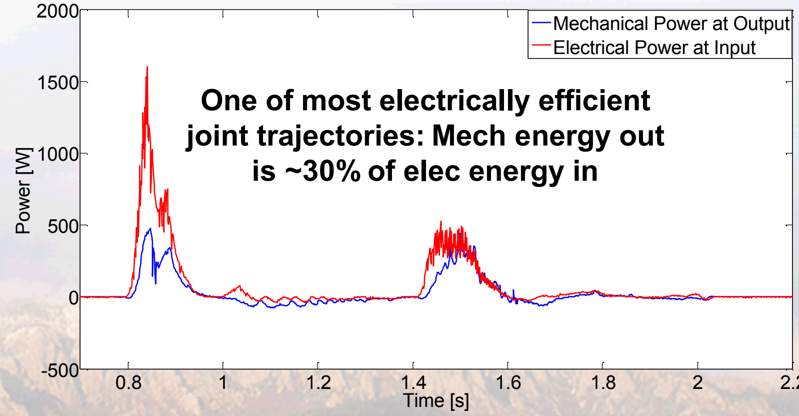
Drivetrain

- **Vectran rope transmissions**
  - **Terminations: Home-made to > 1200 lb (operate < 800 lb)**
  - **Tested loaded cycle life >25k**





- **Efficiency for relevant profiles**
  - **Ropes: mid-90s%**
  - **Mechanical (motor + trans): ~90%**
  - **Electrical to joint work: negative to ~30%**



<u>Crouched robot gait (planar):</u>
Avg Mechanical Power: 9W
Avg. Electrical Power: 245W

<u>Humanlike robot gait (planar):</u>
Avg Mechanical Power: 23W
Avg. Electrical Power: 417W

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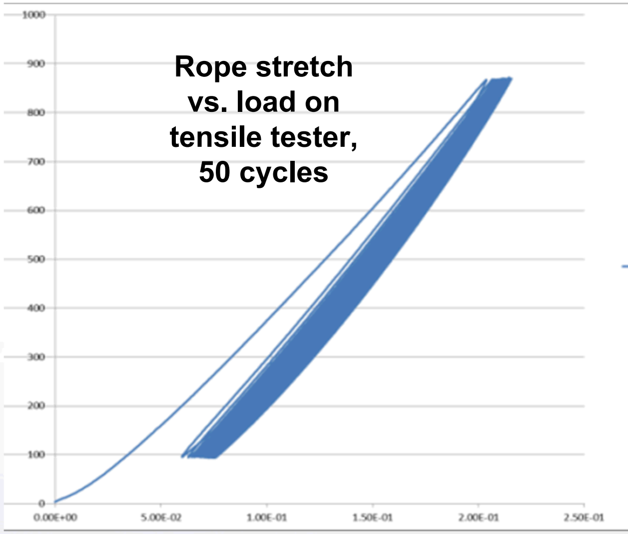
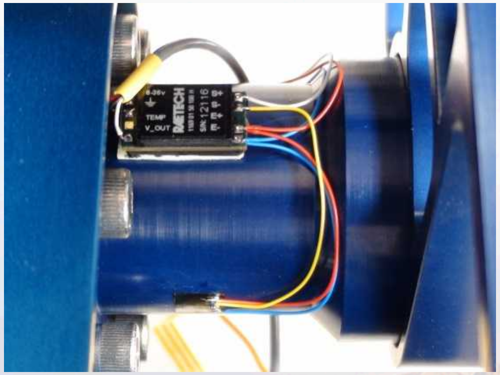
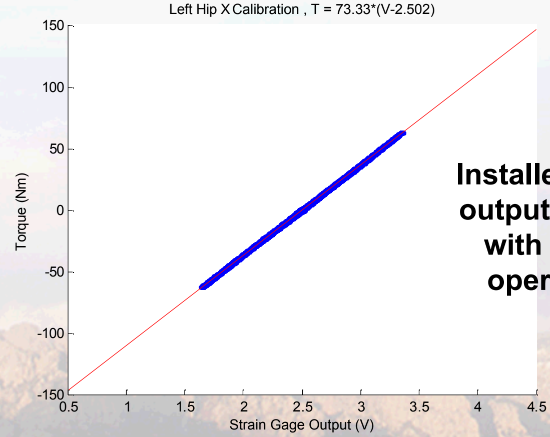
Drivetrain

- **Vectran rope transmissions**
  - **Terminations: Home-made to > 1200 lb (operate < 800 lb)**
  - **Tested loaded cycle life >25k**
  - **Efficiency mid-90s% for relevant profiles**



- **Strain**





Installed strain gage output is very linear with torque over operating range

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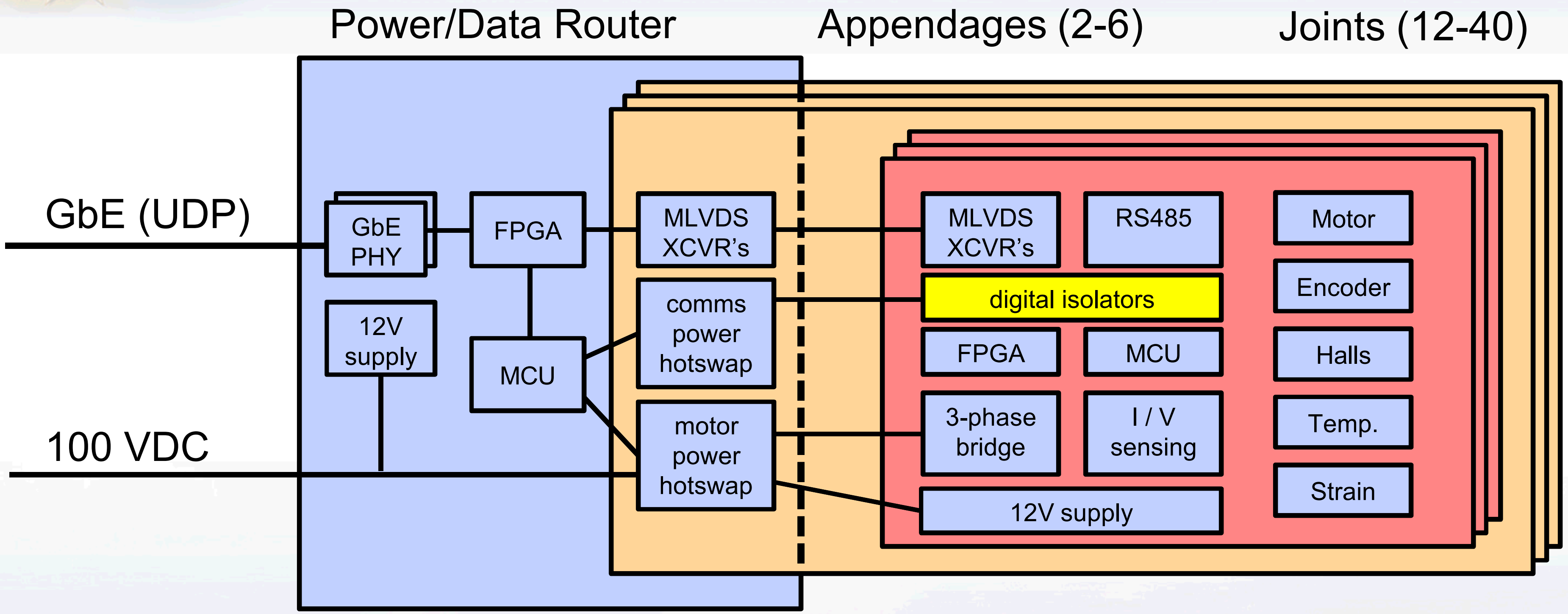
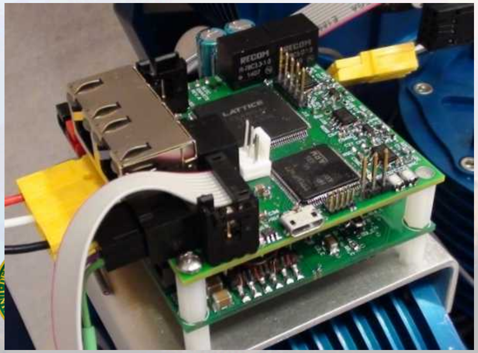
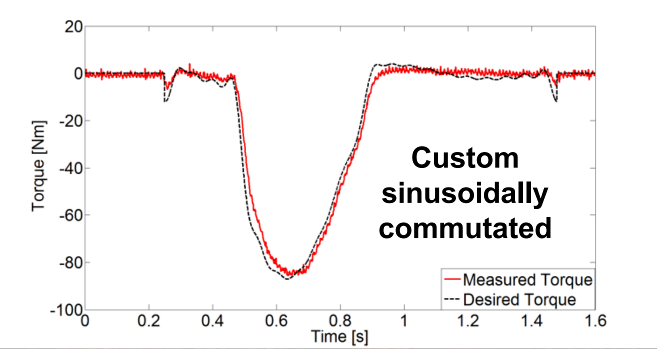
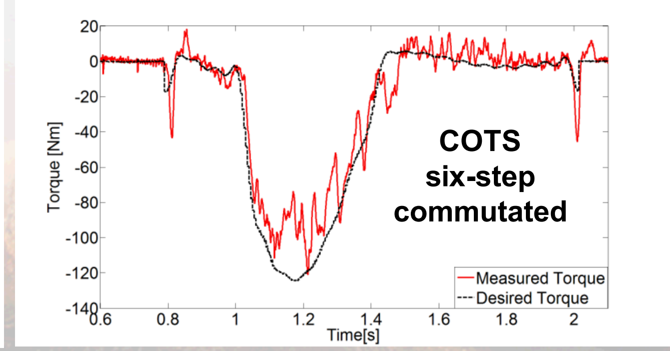
Electronics Architecture



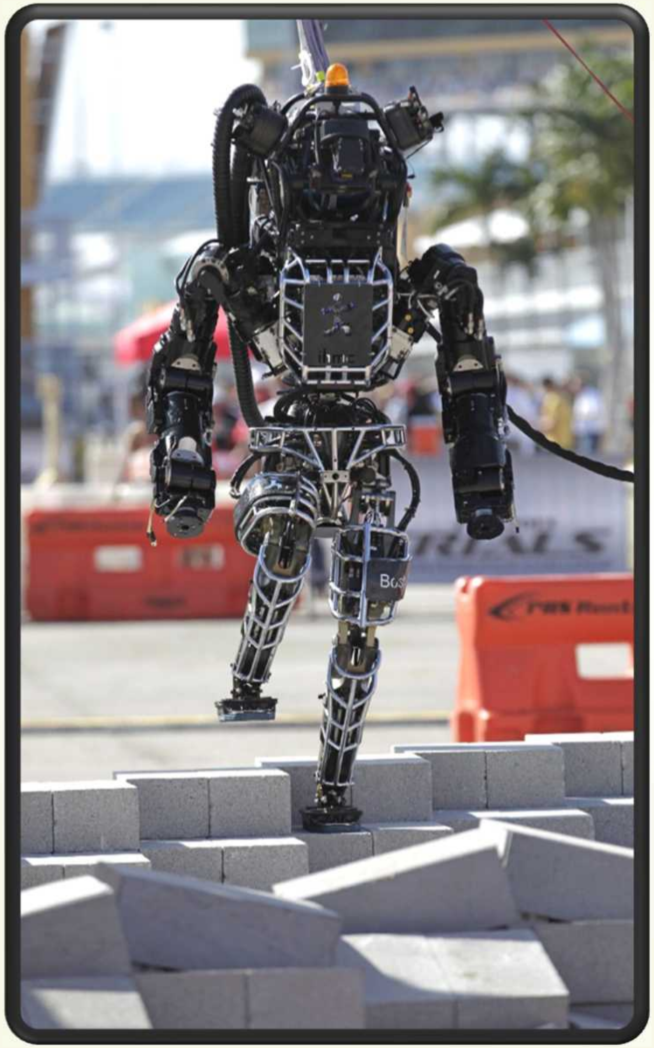
Sinusoidal commutation wins at low speed, high torque.

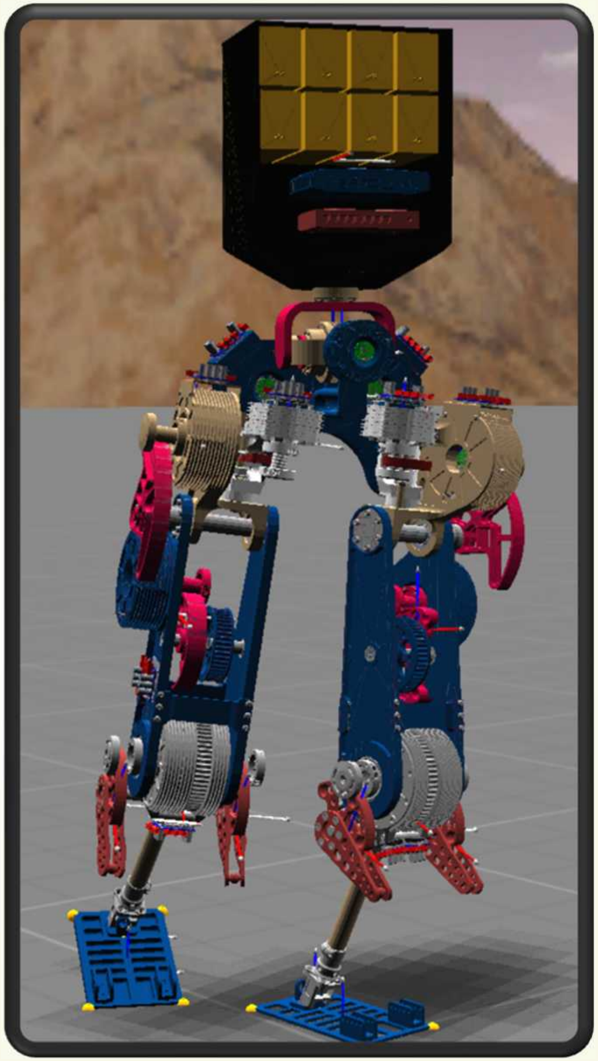




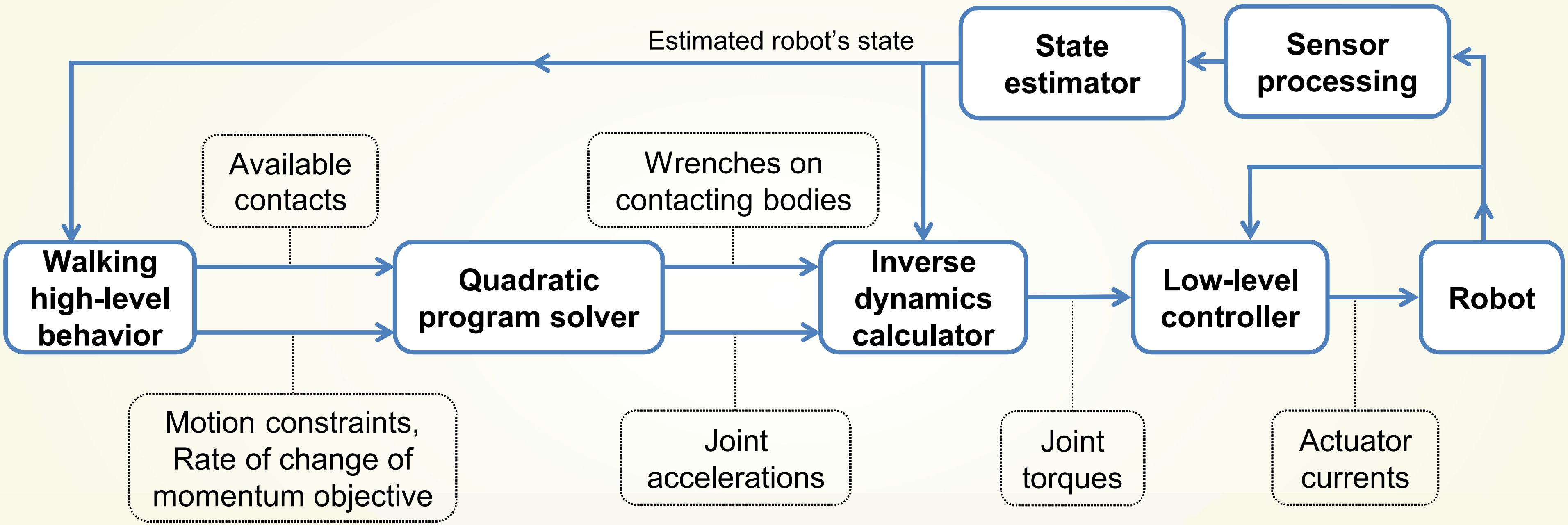


IHMC Walking Control Algorithm: From Atlas to STEPPR





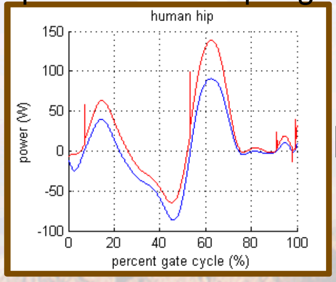
Control framework



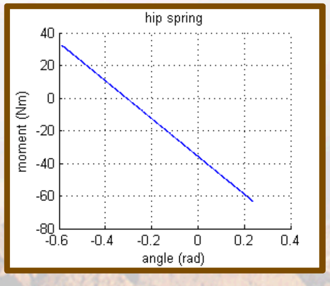
Final Robot: Support Elements

- **Support elements (SEs)**
  - **Unpowered / minimally powered during gait cycle**
  - **Change motor loading to reduce input energy for same output behavior**
  - **Make simple <u>adjustments</u> when gaits change**
- **Examples**
  - **Joint springs**
  - **Variable-ratio (e.g. pose dependent) transmissions**
  - **Multi-joint mechanisms**
- **Design process: optimization**

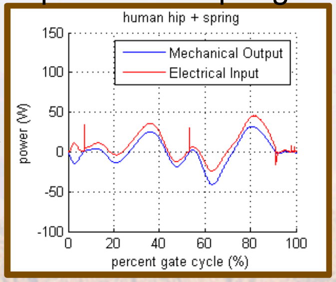
Hip motor mech & elec power without spring



Optimal linear spring



Hip motor mech & elec power with spring



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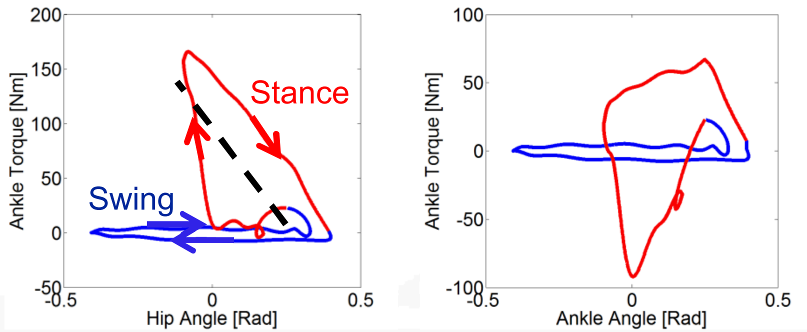
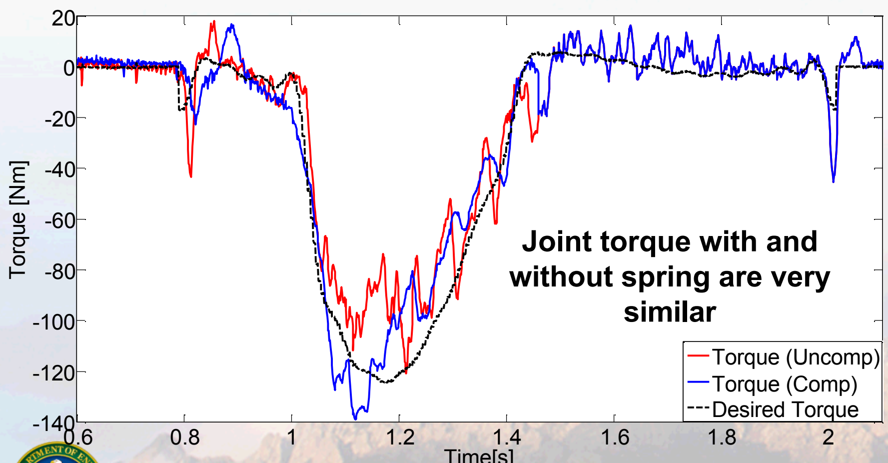
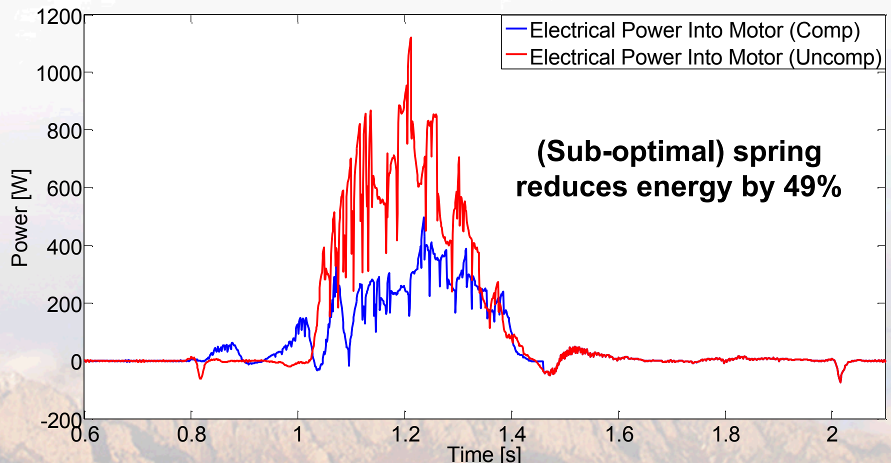
SE: Ankle Spring Testing

- **Stance-only ankle spring**
  - **Full torque, full speed, ½ spring constant**







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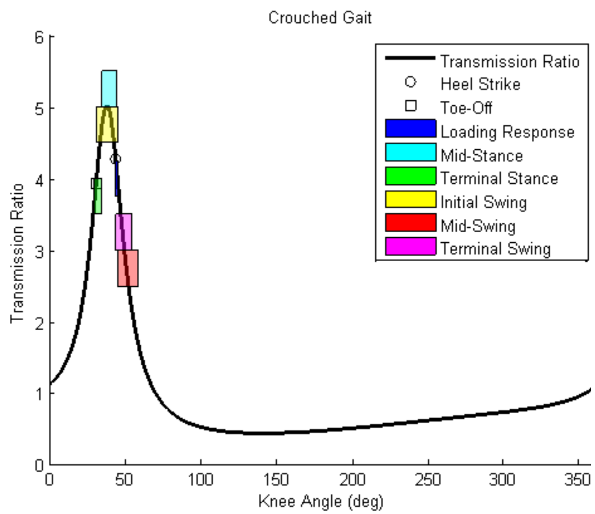
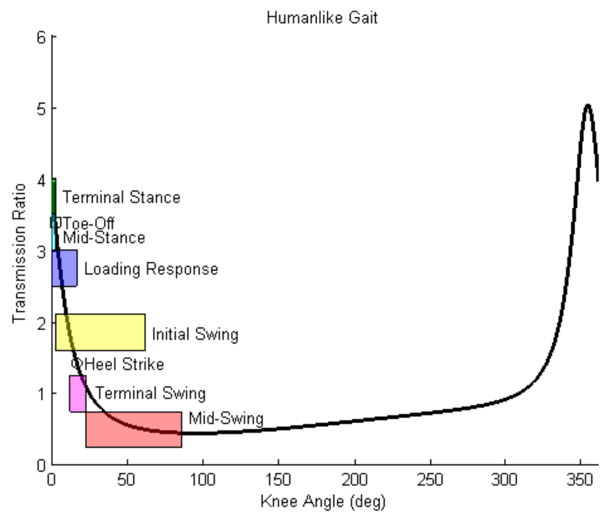
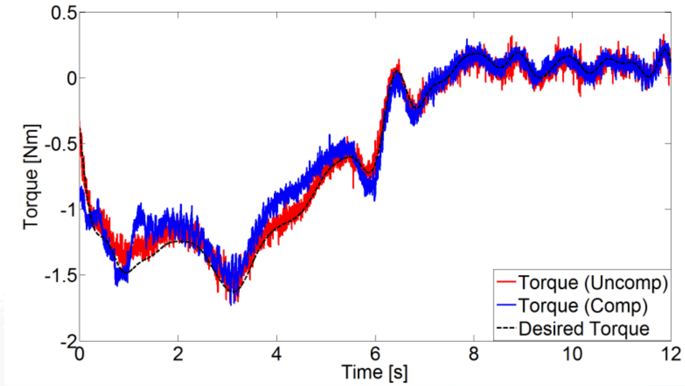
SE: Knee PDT Testing

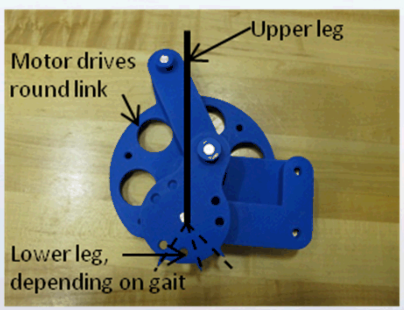
- **Adjustable PDT (four-bar mechanism) for knee**

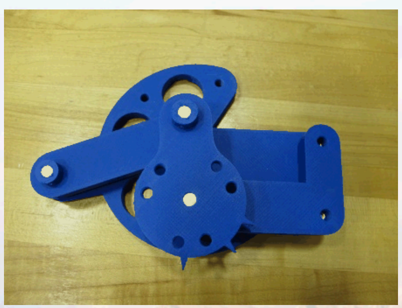


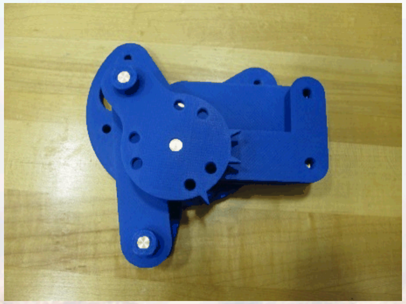


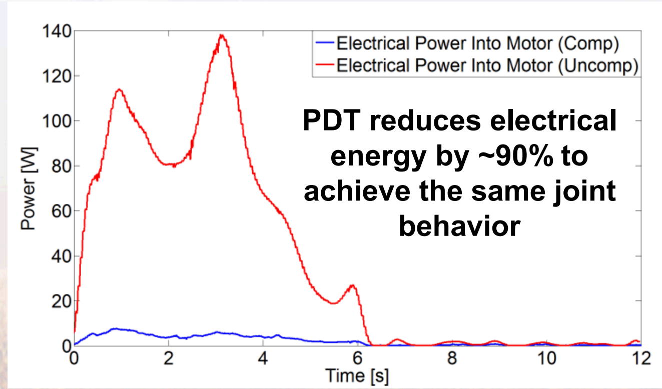
Joint torque with and without PDT are very similar











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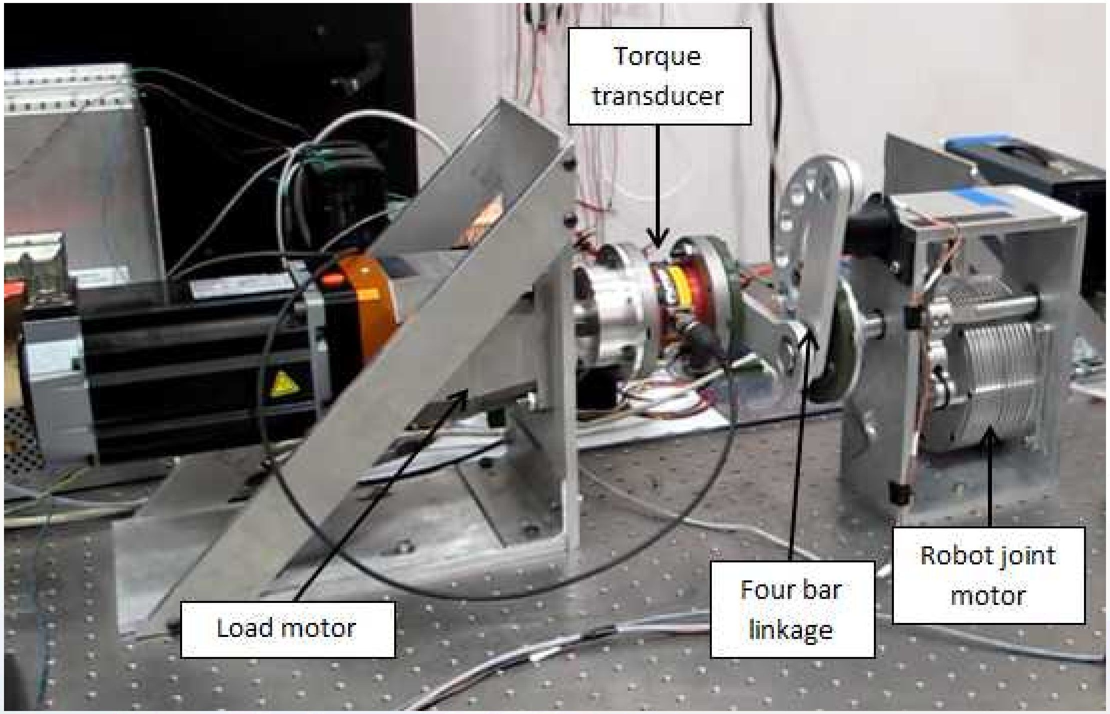
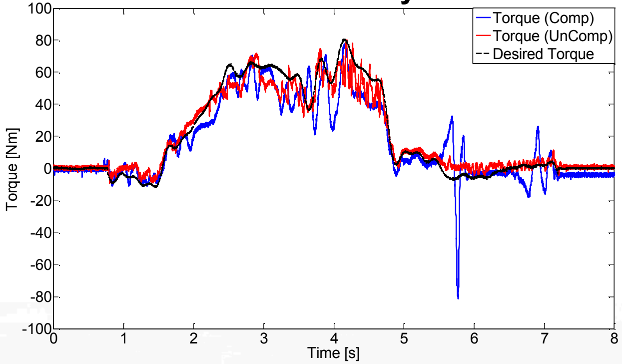
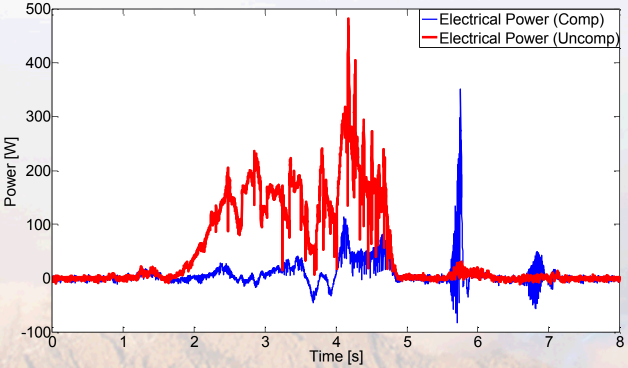
Full Scale Knee PDT Testing



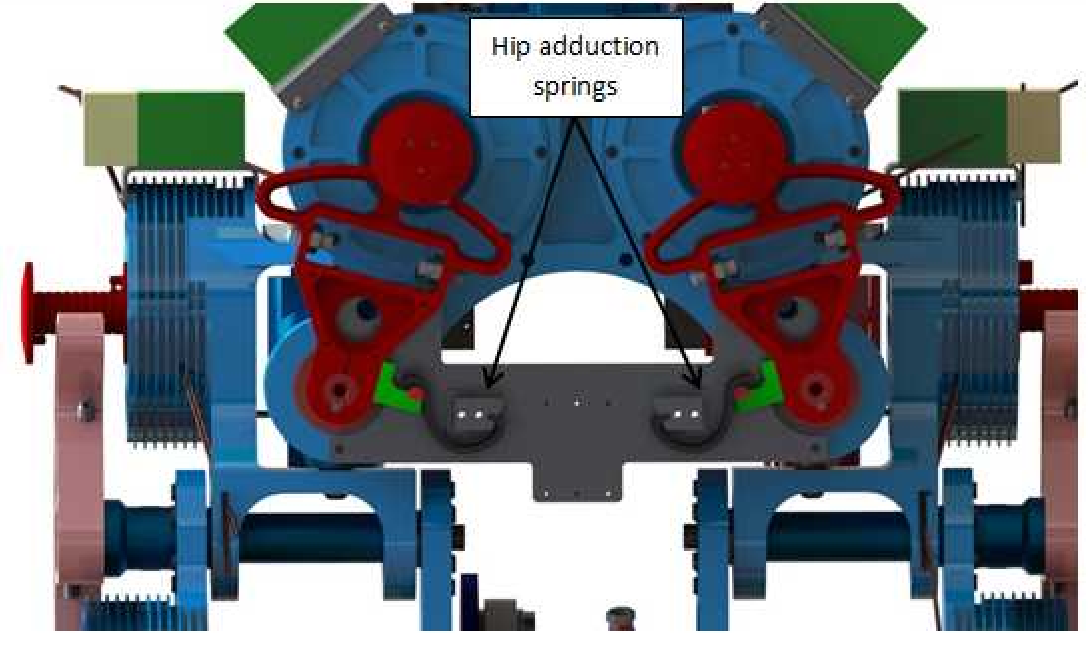
Joint torque with and without PDT track reasonably well



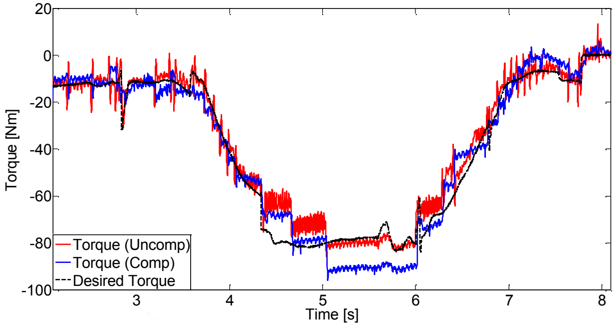


PDT reduces electrical energy by ~84% to achieve the same joint behavior

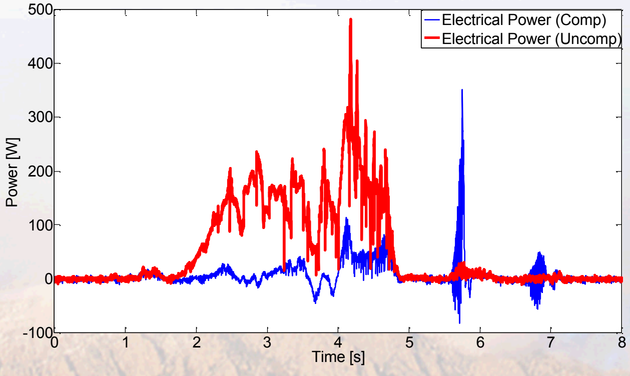
Hip Adduction Spring Validation



Joint torque with and without spring track reasonably well



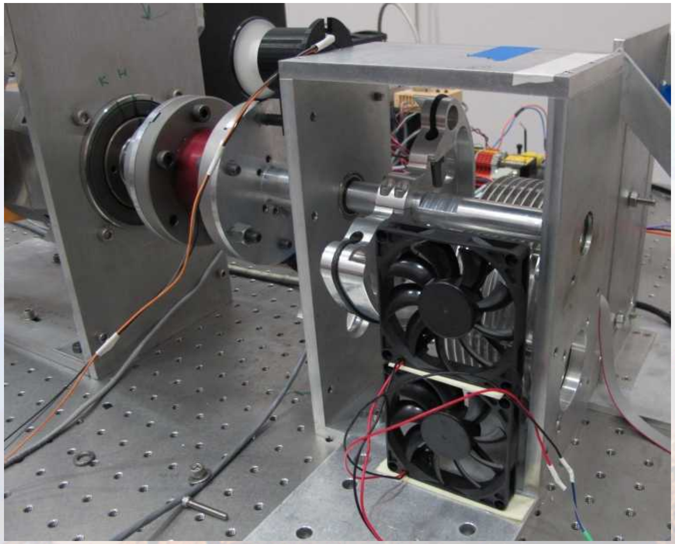
PDT reduces electrical energy by ~94% to achieve the same joint behavior

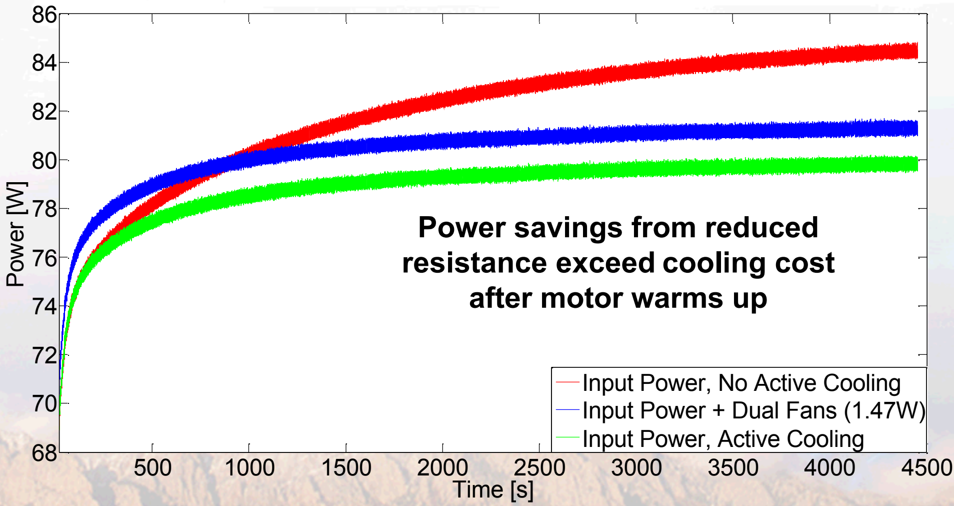


Forced Air Cooling

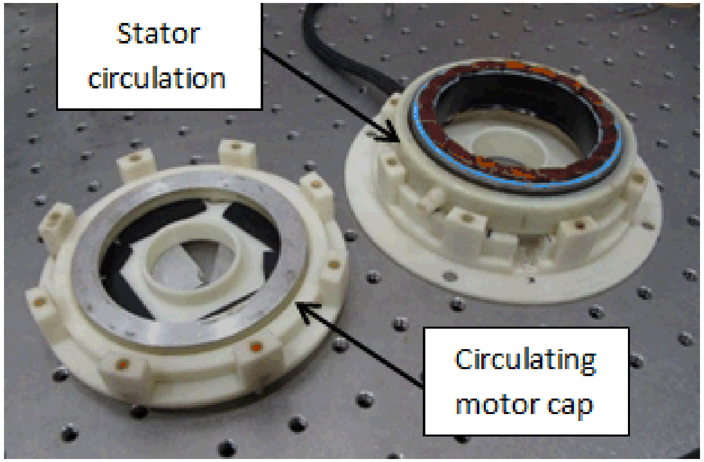
- **Potential benefits**
  - **Exceed rated motor torques**
    - **Transients**
    - **Continuous**
    - **Reduce motor mass, which saves energy**
      - **Energy savings vs. mass location?**
  - **Reduce I^2R**

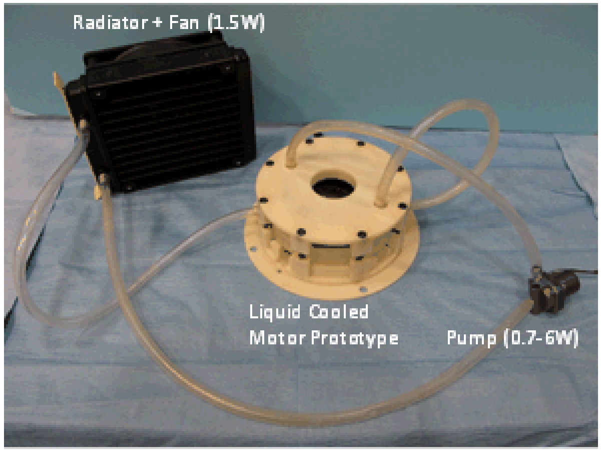
Type	Thermal Res.	Cont. Torque
Motor Spec.	1 K/W	6.55 Nm
Fins	0.87 K/W	7.02 Nm
1.4W Fan	0.65 K/W	8.12 Nm
2.6W Fan	0.63 K/W	8.25 Nm
4.2W Fan	0.62 K/W	8.32 Nm

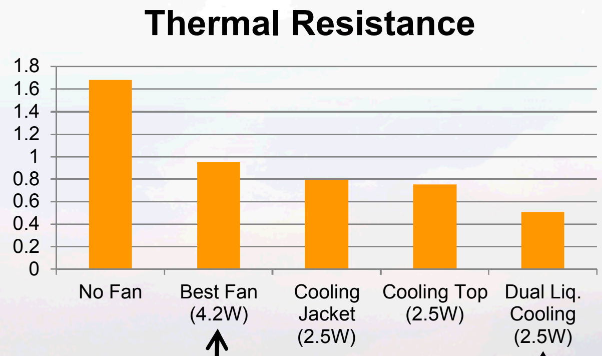


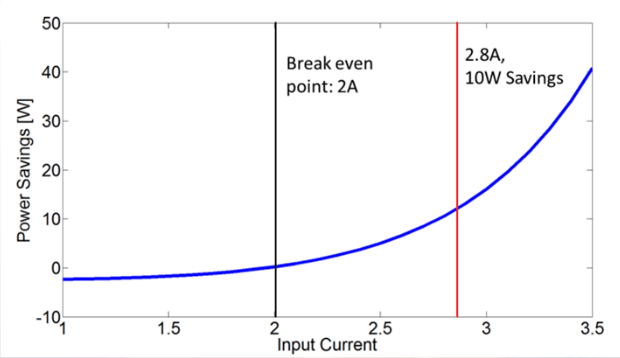


Liquid Motor Cooling









Air cooling: 32% increase in cont. T with 4.2 W

Liquid cooling: 80% increase in cont. T with 2.5 W

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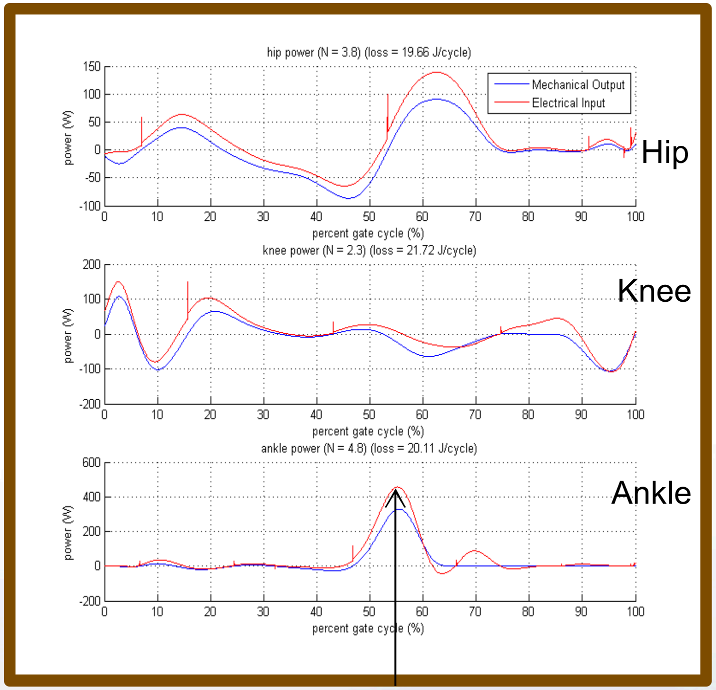
Data- and Model-Based Design & Analysis Method

- **Joint curves (motion, torque, power)**
  - **Literature: Human gaits**
  - **Simulations**
  - **Real robot data**

- **Analyze actuation energy**
  - **Assume modeled joint behavior is realized**
  - **Mechanical energy / COT ("output")**
    - **Calculate from joint curves**
  - **Electrical energy / COT ("input")**
    - **Apply an actuator loss model**

- **Actuation system design problem**
  - **Minimize elec energy to realize mech joint behavior**
  - **Other desirable characteristics (low impedance, low mass, etc.)**

Planar joint power, mechanical & electrical, human level walking



Space between the curves is instantaneous actuator loss

ECOT and Motor Scaling (1)

- **Assumptions:**

$$P_{elec} \cong \sum_{joints} (i^2 R + \tau\omega)$$

Joule heating dominates losses

$$\tau \sim m_{total} = (m_{motors} + m_{other})$$

ma & mgh

$$K_m = \frac{K_t}{\sqrt{R}} \sim m_{motors}$$

for given motor configuration

When m_{motors} is scaled by s_m, m_{other} is scaled by s_o

When $s_m \leq 1$, $s_m \leq s_o \leq 1$

When motor mass is reduced, mass of rest of robot scales proportionally or less

ECOT and Motor Scaling (2)

- **Scaling:**

τ scales by: $s_m \left(\frac{m_{motors} + \frac{s_o}{s_m} m_{other}}{m_{motors} + m_{other}} \right)$ [when $s_m \leq 1$, $s_m \leq s_o \leq 1$]

K_m scales by s_m

- **Impact on power:**

Electrical power equals: $\sum_{joints} \left(\frac{\tau^2}{{K_m}^2} + \tau\omega \right)$

Electrical term increases unless $s_o = s_m$

Mechanical term decreases if $s_m < 1$

- **Conditions under which reducing motor size increases efficiency:**
  - **Full robot mass scales strongly with motor mass, AND/OR**
  - **Most power goes to mechanical power (i.e. highly efficient)**

Note: Significant friction makes reducing motor size less likely to improve efficiency (τ scales more weakly with s_m)

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WANDERER Electrical Architecture

- Big picture: spend some more idle power in exchange for better isolation and comms reliability at all voltages.
- Fully isolated logic and motor power trees
- Logic power tree:
  - Power-over-Ethernet (PoE+) for minimal cabling
  - Switch 100M and 1Gbit on the fly: low power vs visibility
- Motor power tree:
  - Gate drives triggered through logic isolators
  - Current sensing via isolated sigma-delta modulators
- Controllers are "sensor hubs"
  - move A/D to site of sensing: strain gages, motor temps, etc.
  - sensors connect to controllers via 100M PoE or RS422
  - controller is just a semi-decent FPGA. No more MCU's.