SAND2015-1050PE

Robotic Mobility: Where Can it Take Us?

February, 2015

Steve Buerger, Ph.D. (sbuerge@sandia.gov, 505-284-3381)

Intelligent Systems, Robotics and Cybernetics Group
Sandia National Laboratories

Successful Robots Today

Robots that stay in one place

Robots that get around structured environments

Robots that move around your living room

Robots that go where cars / jeeps go

Where would we like to go?

Aggressive mountain terrain

Fukushima tsunami and reactor failure

Complex urban terrain

Sandia National Laboratories

Challenges

- Pure mobility
- Energy efficiency
- Navigation & control
- Effects

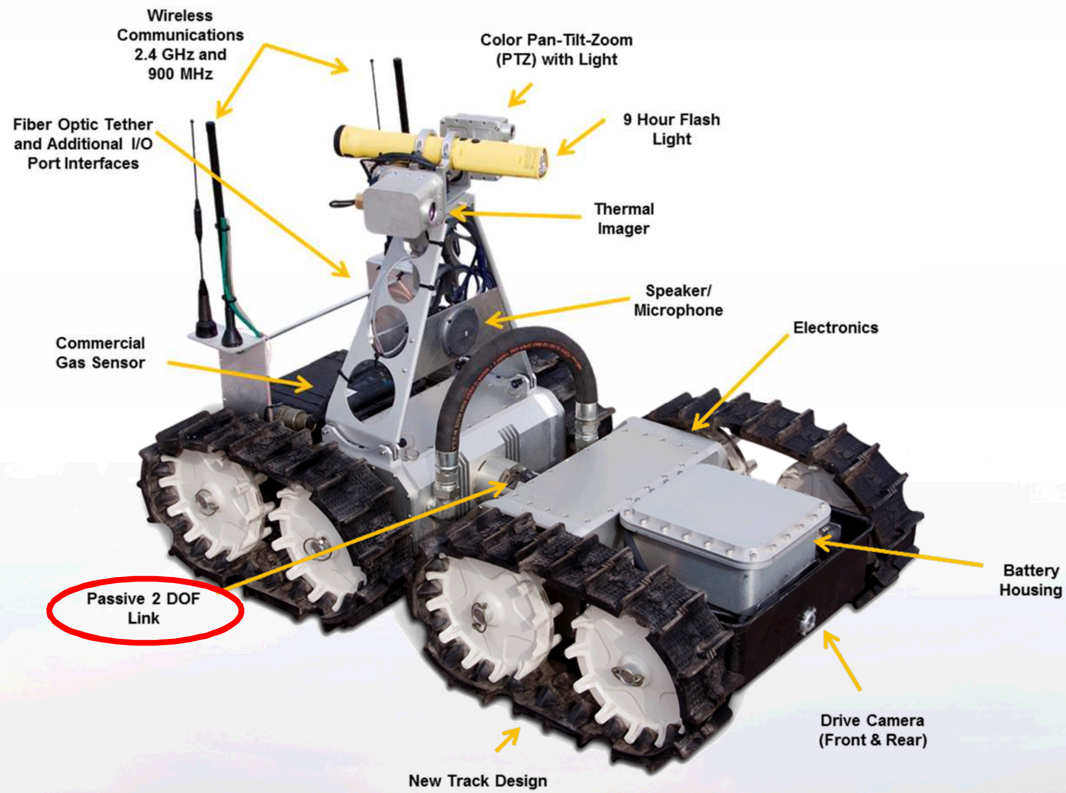
Extending tracked mobility

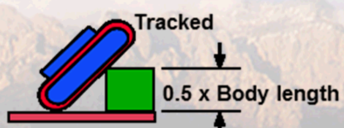
Link to UUR Gemini Scout “AUVSI” video

Pushing the limits of tracked mobility

Gemini: Design derived from mobility analysis for wheeled and tracked vehicles traversing obstacles

- **Dual body ideal for larger obstacles, unstructured terrain**
- **DOFs designed by optimization**
- **Established length/width ratios for ideal tracked vehicle skid steering capabilities**
- **Passive joint provides much better mobility than equivalent single body tracked vehicle**





Max obstacle size is limited to a fraction of body dimensions – always!

Sandia National Laboratories

… almost always

UUR Urban hopper video:
Link to SAND20115443P (UUR)

… almost always

#1 Google News "Top Story" (summer 2009) for 3 days, until….

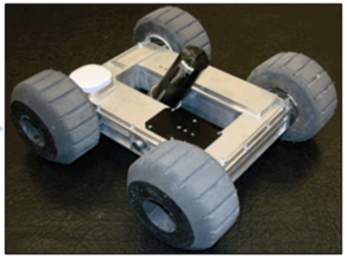
Hopping robots

- **History**

Collective Behavior and Hopping

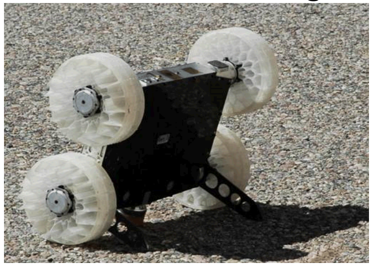
Intelligent Mobile Land Mine (2000)

Driving and Hopping



Sandia Tilt Actuator Hopper (2005)

Precision Landing



Boston Dynamics Tilt Body Hopper (2011)

- **Core technology challenges**
  - **Controlled fueling & combustion-powered hopping**
  - **Not breaking when you land**

Sand Flea video:
Link to SAND20115443P (UUR)

Energy to Hop vs. Hover

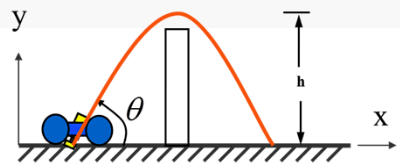
- **Energy efficiency comparison**
  - **Firm ground hop energy:** $E_{hop} \approx \varepsilon_{piston} M \cdot g \cdot h$

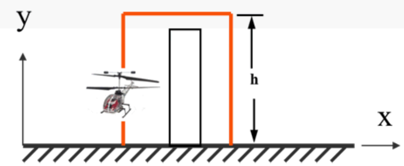
    Piston efficiency

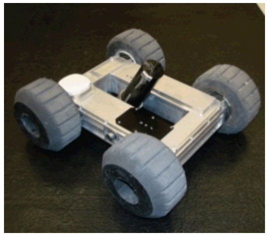
  - **Energy to hover:**

    $$E_{hover} = \frac{(1+\varepsilon_{prop})}{2} \cdot \sqrt{\frac{F}{A \cdot \rho}} \cdot \sqrt{\frac{2 \cdot M \cdot h}{\frac{1}{M \cdot g} - \frac{1}{F}}}$$

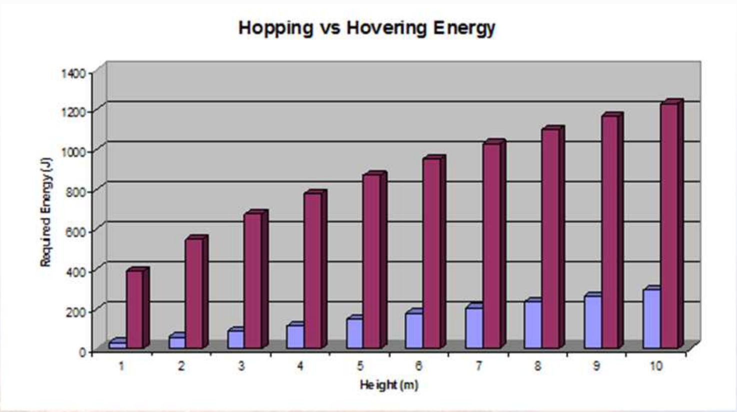
    Reduce energy by increasing propeller area







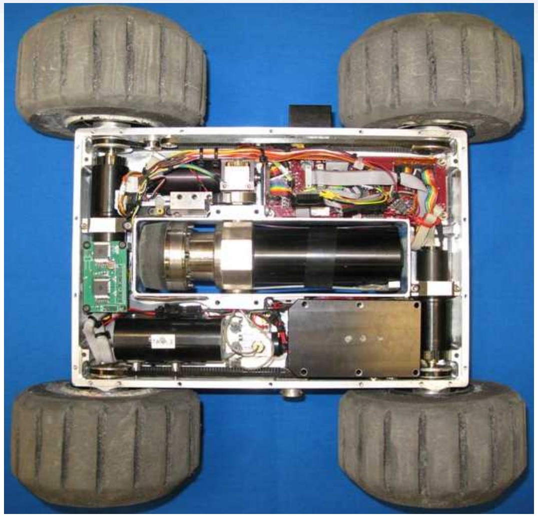
  - **Scaling with obstacle height:**
    - **Piston & prop efficiencies are similar**
    - **Efficiencies cross as height increases**
    - **Hopping is preferred for small obstacles, when ground is hard**



  - **Why?**
    - **Hovering uses (air) mass flow, which creates velocity dependence**

For small obstacles: "Drive when you can, hop when you have to"

ECE-specific issues



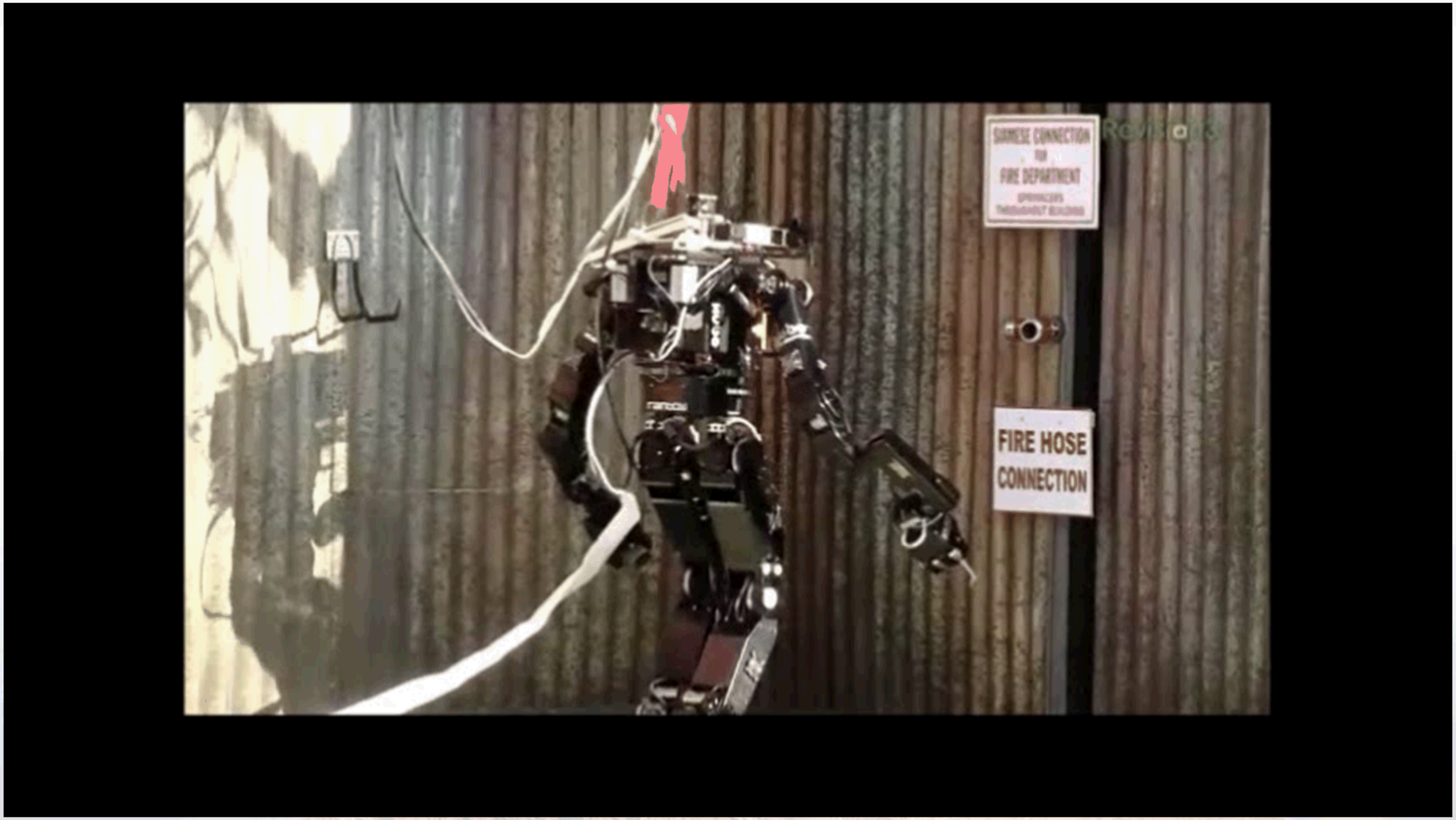
- Custom, shock-tolerant embedded electronics
  - Drive motors, servos
  - Valve system feedback control, ignition
  - Hop sequence control & failsafes
  - Custom Li-ion battery pack
  - Onboard Gumstix, 802.11 & 802.15 comms
- GPS navigation, path planning at “shoebox” scale, close to ground
- GPS-denied navigation
  - Sensor issues

GPS nav video:
Link to SAND20115443P (UUR)

Why not just do it how people do it?

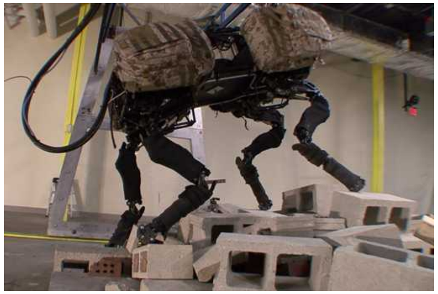
Much of the world is built for people; let's move how people move

Why not just do it how people do it?



Legged robots

- **Pros**
  - **Step over & onto obstacles**
  - **Mobility (somewhat) less dependent on terrain type**
  - **Balancing bipeds: high reach with small footprint**



BDI Big Dog

- **Cons**
  - **Walking control is (still) hard**
  - **Endurance**
    - **There is a reason we invented the wheel (bicycles, skateboards, etc.)**
    - **Cost of transport (dimensionless)**
      - **Bicyclist: >0.1**
      - **Horse: >0.2**
      - **Person: >0.3**
      - **Production car: >0.3**
      - **Airplane: >0.5**
      - **Dog: >0.7**
      - **Helicopter: >1.4**
      - **Legged robots: ~3-30?**

$$COT = \frac{E}{m \cdot g \cdot d}$$

BDI Atlas

Honda Asimo

Endurance is a big limiter for legged robots today

Improving legged robot endurance

- **Supply**
  - **Better batteries (specific energy, specific power)**
    - **Yes please!**
  - **Chemical energy (e.g. hydrocarbons)**
    - **Noisy, dirty**
    - **Relatively inefficient transduction to actuators – but high power!**
  - **Energy harvesting**
    - **Be conscious of power (how many solar panels to make a hp)**

LS3 – Boston Dynamics

- **Consumption**
  - **Gait quality: Maximize distance traveled per joint work**
    - **Active research area**
    - **Defining gaits limits what you can do**
  - **Drive efficiency: Minimize energy used per work done at joints**
    - **Do the right kinds of behaviors more efficiently**

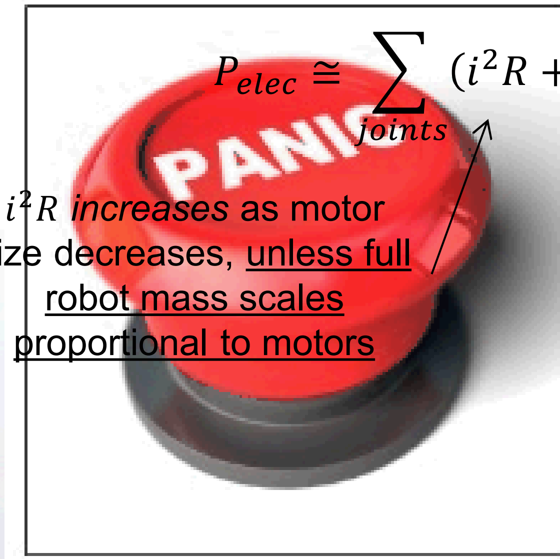
Cornell Ranger

Can drivetrain efficiency be improved?

Improving drivetrain efficiency (1)

- **DARPA's goal: 20x (!) improvement in endurance from battery power**

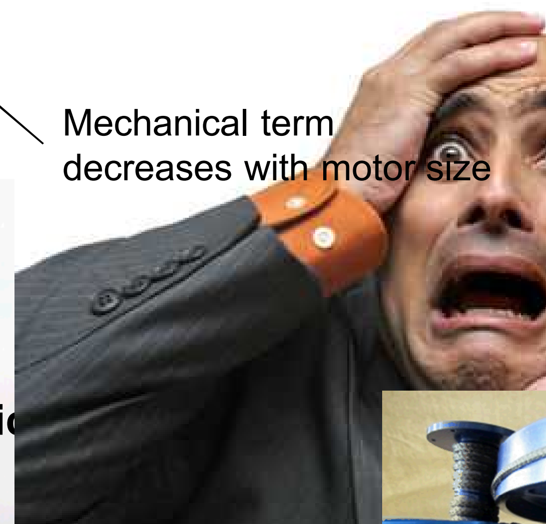
- **First:** / **Second: Start with a very efficient core drivetrain**
  - **Big motors: The bigger the better! Why?**



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

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

Mechanical term decreases with motor size

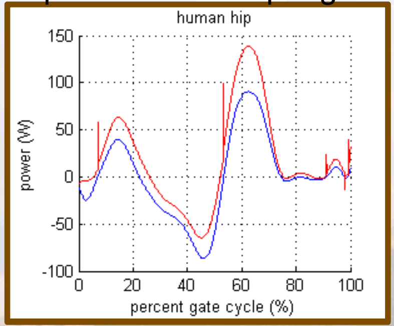


  - **... thetic**
    - **Avoid torque feedback**
      - **Keep gear reductions small (6:1 to 10:1)**

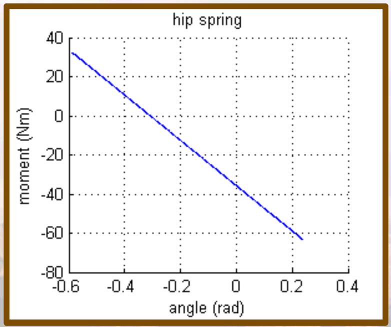
Improving drivetrain efficiency (2)

- **Third: Keep motors operating in "efficient" space as much as possible**
  - **Assume joint speed / torque profiles to achieve a wide range of biped gaits**
    - **Simulations, real robot data, literature**
    - **Provided by our partners at FL IHMC**
  - **Use passive mechanical elements to "warp" those profiles to draw energy more efficiently from motors**
    - **Parallel springs**
    - **Variable transmissions**
  - **Apply optimization across _all_ gaits to look for common features**
    - **Decide which parameters are "adjustable," which are not**

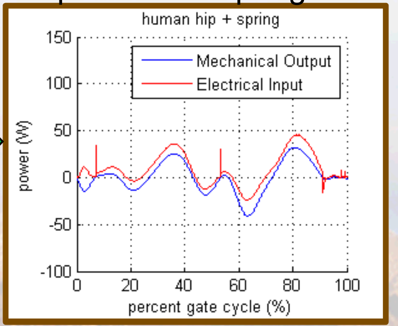
Hip motor mech & elec power without spring



Optimal linear spring



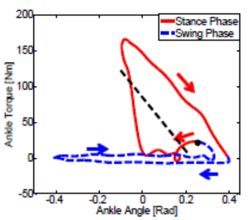
Hip motor mech & elec power with spring

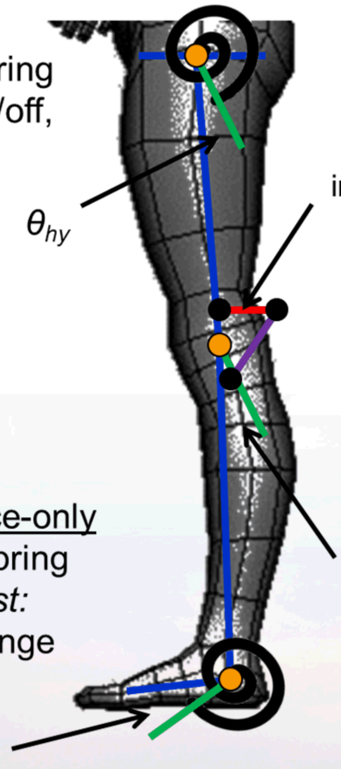


Improving drivetrain efficiency (3)

Passive mechanical "support elements" with simple adjustments used when changing gait

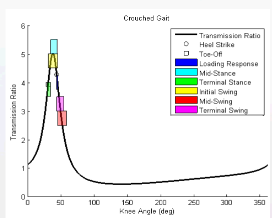
Hip Y
SE: parallel spring
Gait adjust: on/off,
θ_{hy} 38º range





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

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

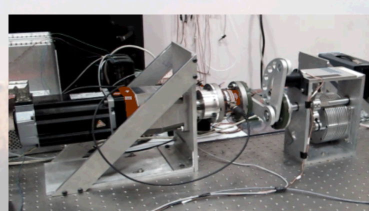


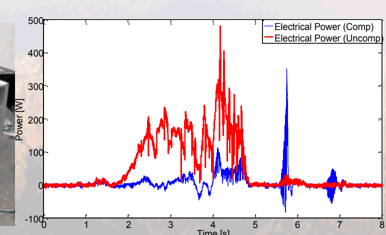
Hip X
SE: parallel spring, partial range: adduction only
Gait adjust: none

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

* - PDT = Pose Dependent Transmission



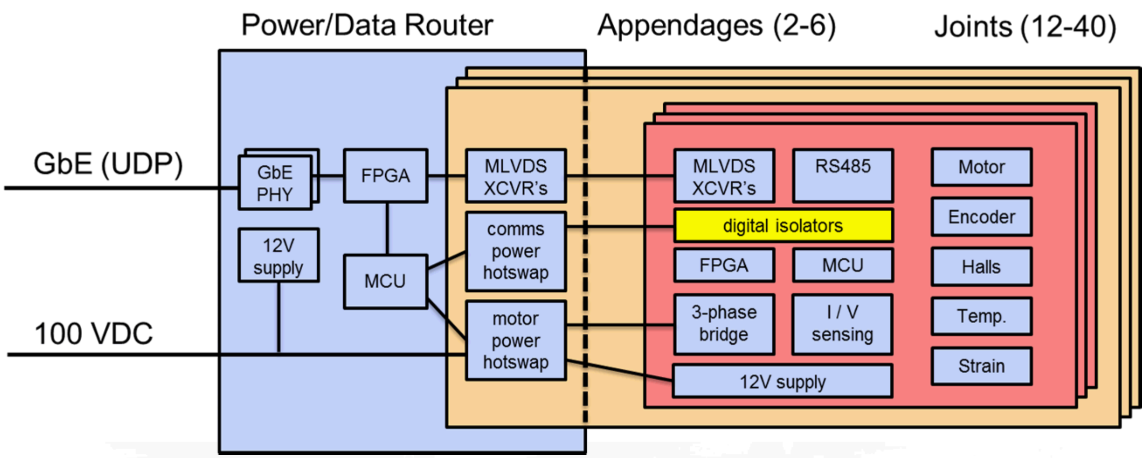


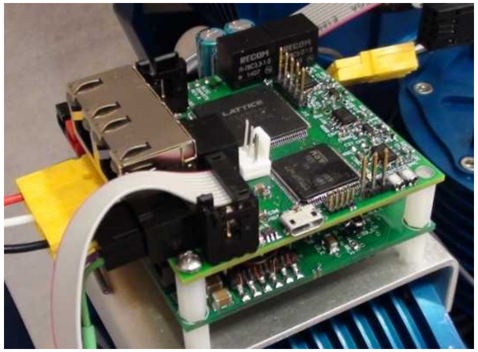
Joint Energy Savings Validated on Bench

Sandia National Laboratories

Improving drivetrain efficiency (4)

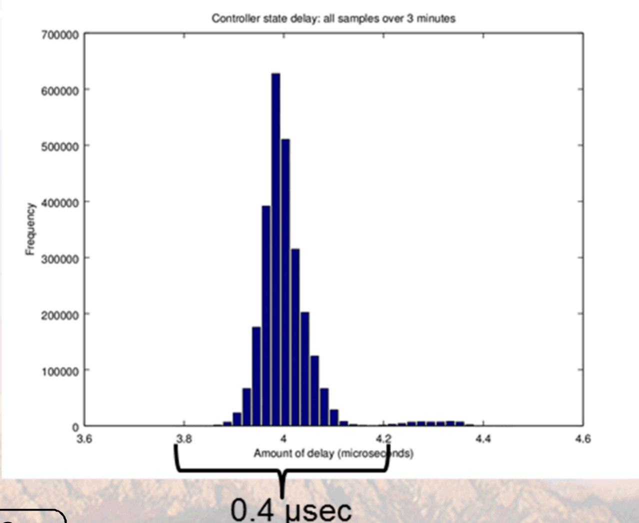
- **Fourth: Reduce parasitics to near zero**





Joint Control Stack

- **Very low power m-LVDS comm backbone**
- **Local joint control at 10-30 kHz**
- **System UDP output at 1 kHz**
- **Delay locked loop synchs distr. clocks for µs jitter**
- **System power (router boards + 15x joint stacks)**
  - **No FET switching: 15 W**
  - **FETs switching, no current: ~50 W**
    - **~2 W per joint switching (room for improvement)**

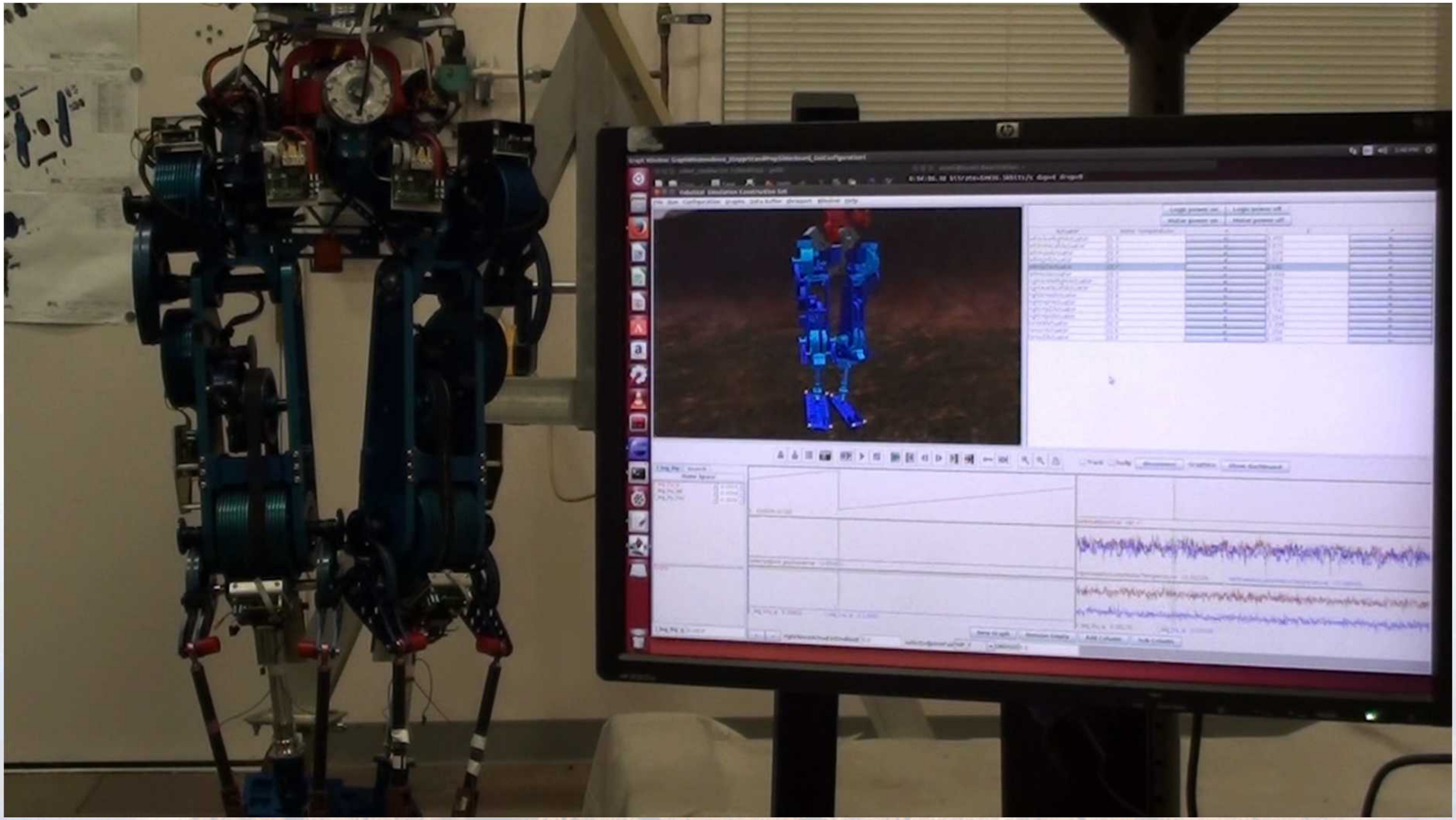


Electronics & firmware designs available open source through OSRFoundation.org

Sandia National Laboratories

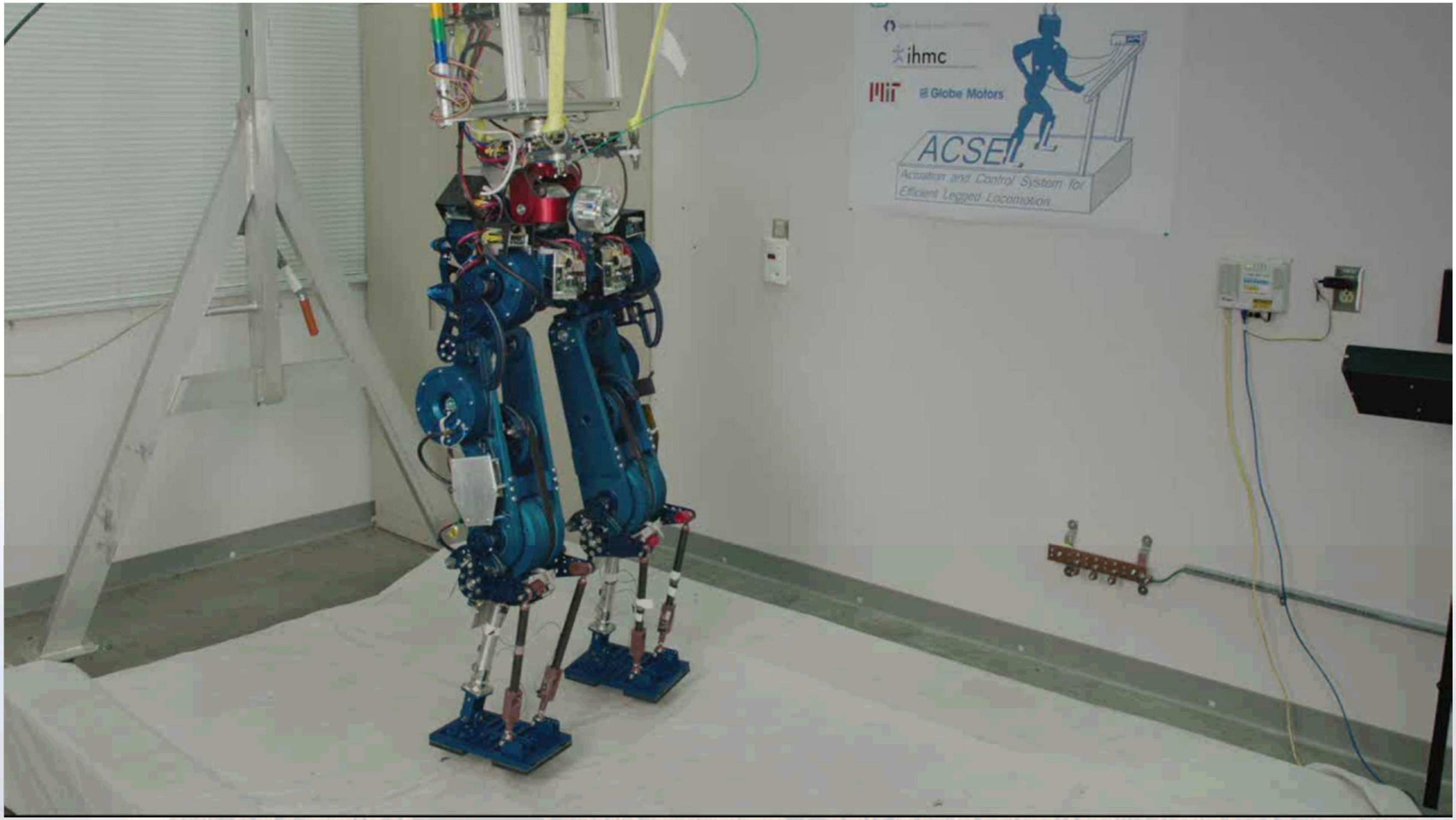
STEPPR

(Sandia Transmission Efficient Prototype Promoting Research)



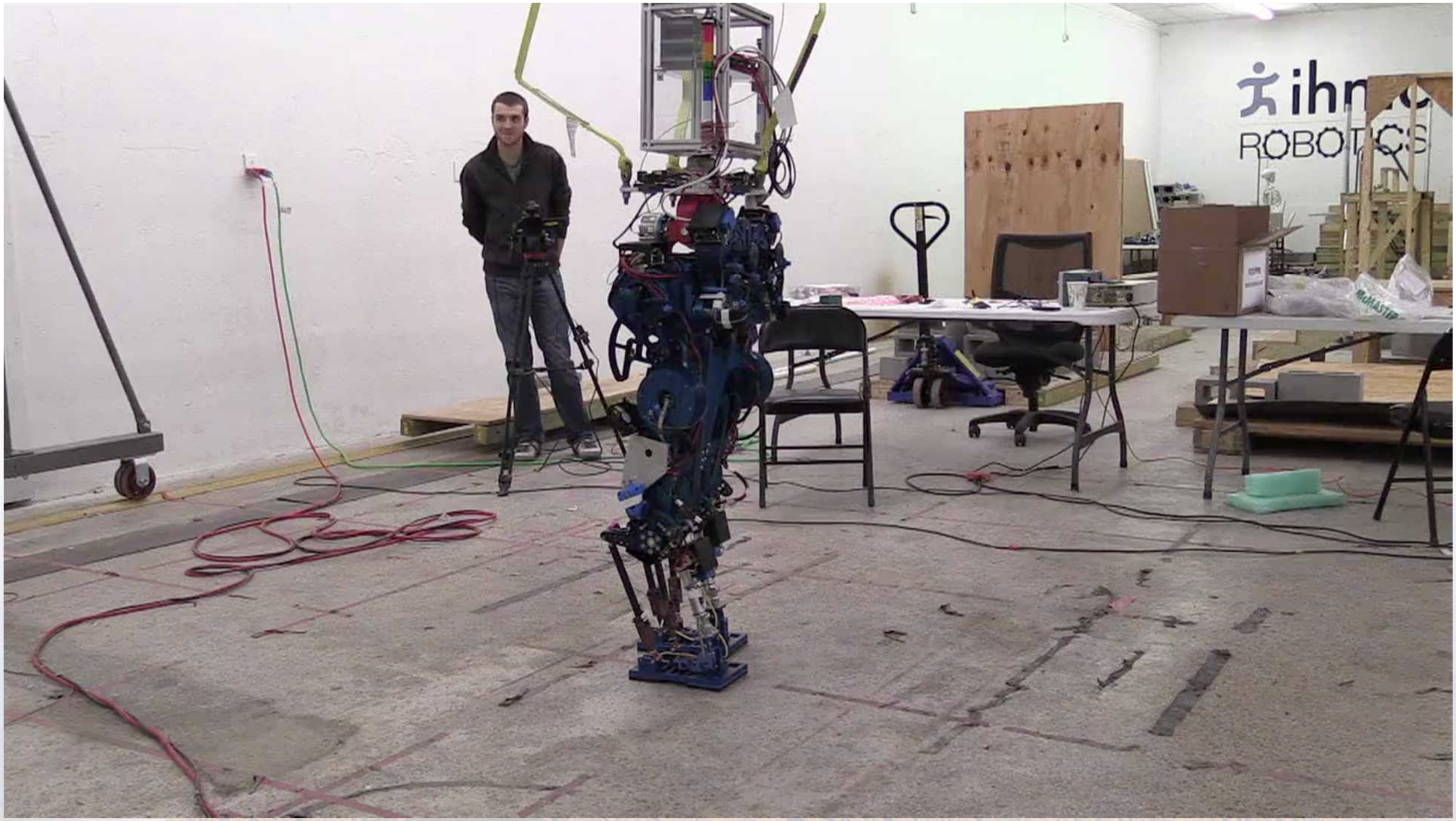
STEPPR

(Sandia Transmission Efficient Prototype Promoting Research)



STEPPR

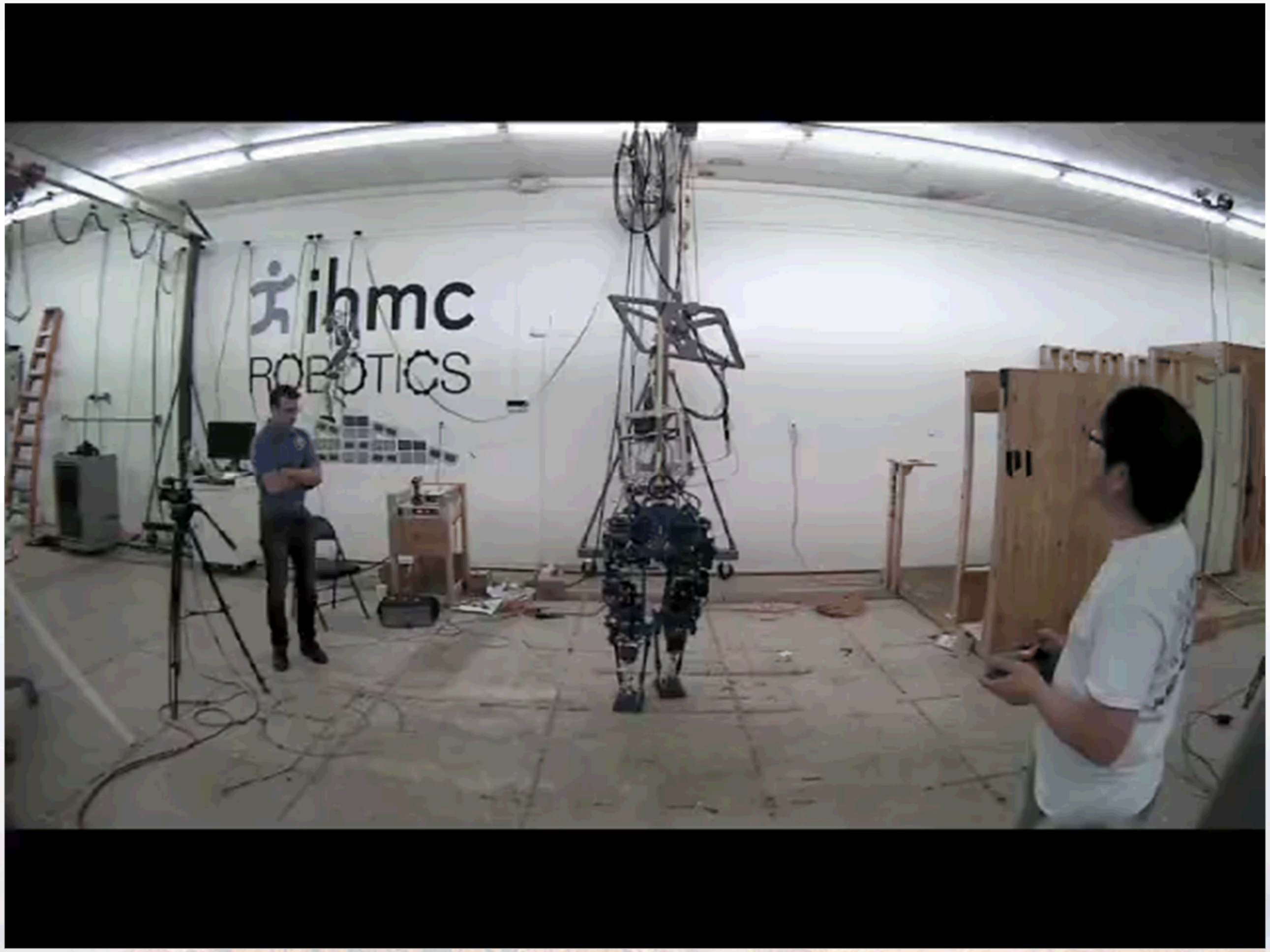
(Sandia Transmission Efficient Prototype Promoting Research)



Sandia National Laboratories

STEPPR

(Sandia Transmission Efficient Prototype Promoting Research)

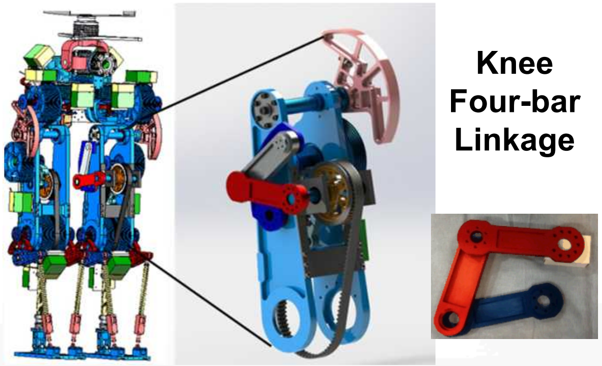


STEPPR

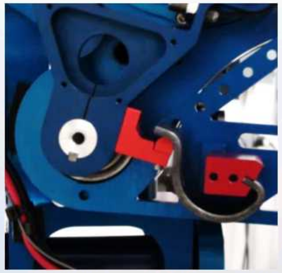
(Sandia Transmission Efficient Prototype Promoting Research)

Next "STEPs"…

- Long duration walking
- Implement support elements



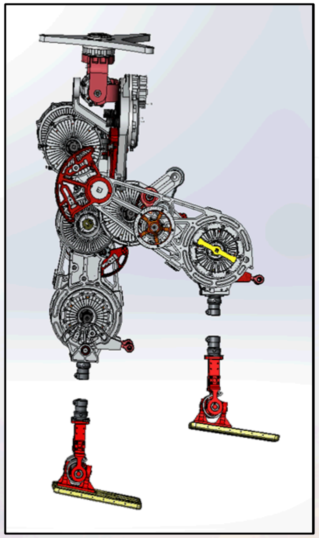
Knee Four-bar Linkage

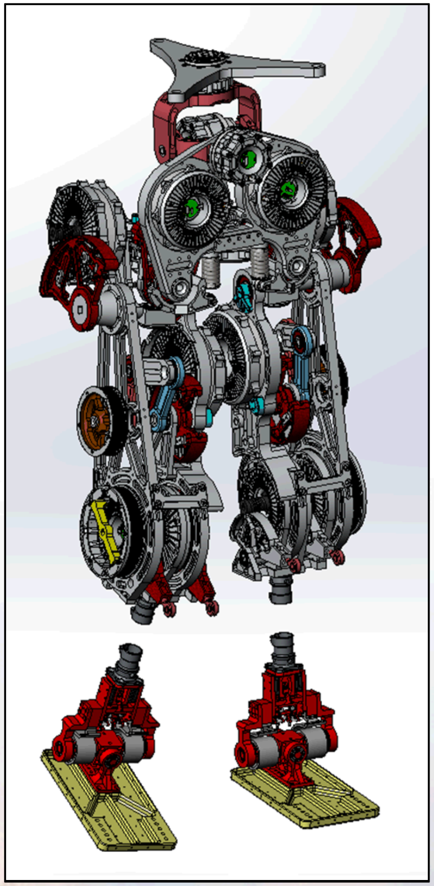


Hip X (Roll) Spring

Stance-only Ankle Spring

- WANDERER (Walking Anthropomorphic Novelly Driven Efficient Robot for Emergency Response)





So far we are pretty efficient, but there is a ways to go

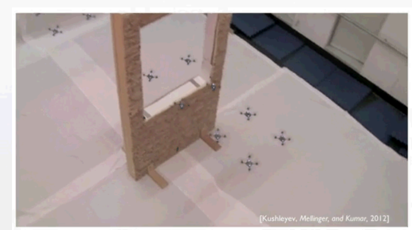
Multi-modal mobility

Link to UUR Volant video

Does mobility make robots useful?

- **Handling terrain is only a part of the story**
  - **How do we make robots do what we want?**

- **Single-vehicle, real-time control**
  - **Limited by comm bandwidth**
  - **Limited operator response**
- **Collaborative control with higher objectives (e.g. swarms)**
  - **Usually homogeneous, single-functional vehicles**
  - **Usually single objective**
  - **Output behavior is usually vehicle motion**



V. Kumar
TED talk

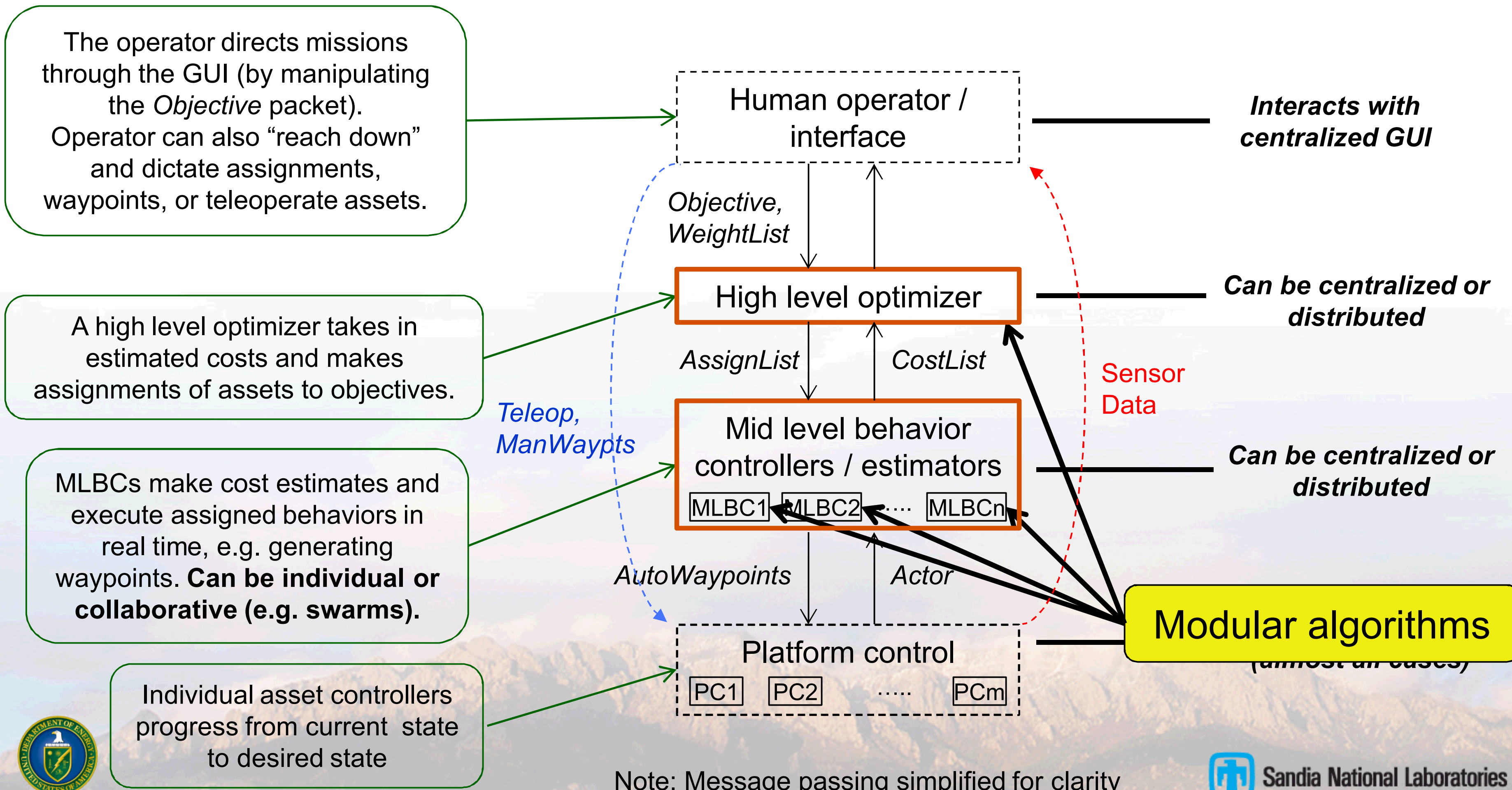
- **Heterogeneous collaboration, with shared man / machine intelligence**
  - **Automate the easy stuff (& let an operator fix what breaks)**
  - **Make system responsive to operator's real-time command intent**

"One controlling many"

Link to UUR OCM video
SAND2014-15882 V

Layered Assignment and Control Architecture

- **Command & control is layered, modular, and distributed across multiple entities within the system**



Sandia National Laboratories

Conclusions

Mobility – Energy efficiency – Navigation & Control - Effects

- **Mobility problem is about making robots useful**
- **Lots of room to improve pure mobility**
- **Much more (than mobility) is required to make robots useful**

? Questions ?

- Sponsors
  - DARPA
  - JIEDDO
  - SNL LDRD
  - NIOSH
- Partners
  - OSRF
  - IHMC
  - Boston Dynamics
- Team members
  - {too many to list}