Sustainable Human-Centered Robots

Luis Sentis
Associate Prof. Aerospace Eng. and Eng. Mechanics
Co-Founder of Apptronik Systems

International Winter School on Humanoid Robot Programming
7 February 2018

The WEF proposes a measure of its own, dubbed the "inclusive development index." While it takes into account growth, as measured using GDP per capita, employment, and productivity, it also incorporates several other metrics, including gauges of poverty, life expectancy, public debt, median income, wealth inequality and carbon intensity. The index also considers investments in human capital, the depletion of natural resources, and damage caused by pollution.

GDP vs. Inclusive Development Index

Unlabeled picture from exoskeleton search

Human Centered Robotics:
The study of **sustainable** machines and robotic systems…

… with high mobility and sensing to assist, augment, or represent humans…

… in any way that will increase **productivity**, security, health and social comfort.

NASA Technical Memorandum 86856

Human Factors in Space Station Architecture II

EVA Access Facility: A Comparative Analysis of Four Concepts for On-Orbit Space Suit Servicing

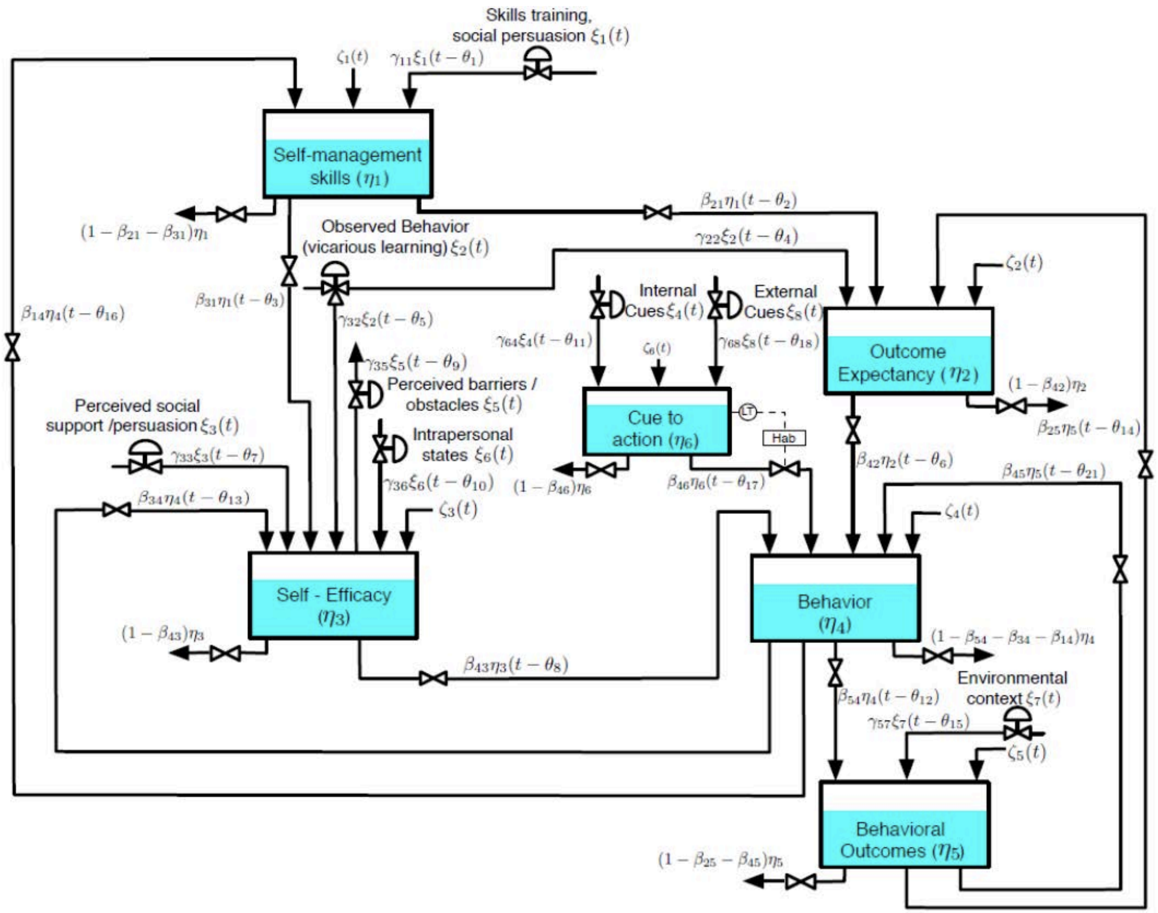
Marc M. Cohen
Ames Research Center

the Skylab mission (ref. 2).

Since 1982, the Space Transportation System (STS) places increasing emphasis upon the regular use of EVA for in-flight development, recovery, and repair of space systems. This trend is expected to continue on the Space Station. The dexterity of the human operator in EVA is transmitted through the human/machine interface imposed by the protective envelope of the suit; hence, significant advances in EVA capability are due primarily to improvements in the design of the space suit. The primary goal of space suit design is to reduce losses in human dexterity and in mobility to the

*Massachusetts Institute of Technology, Cambridge, MA.

Exploring Socio Cognitive Theory



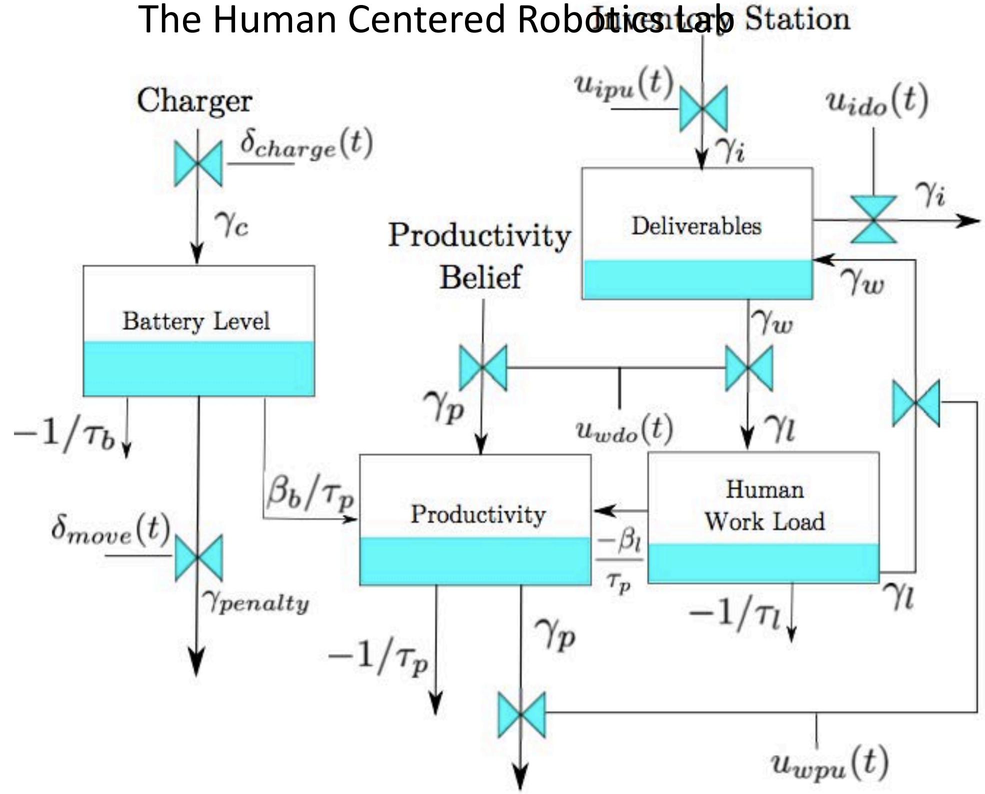
W. T. Riley, D. E. Rivera, A. A. Autienza, W. Nilsen, S. Allison, and R. Mermelstein, Health behavior models in the age of mobile interventions: are our theories up to the task? *Translational Behavioral Medicine: Practice,* 2011

A. Martin, D. E. Rivera, W. T. Riley, E. B. Hekler, M. P. Buman, M. A. Adams, and A. C. King. A Dynamical Systems Model of Social Cognitive Theory, *American Control Conference*, 2014.

Inspired by these Models: Productivity "Brain"

Disney Co.

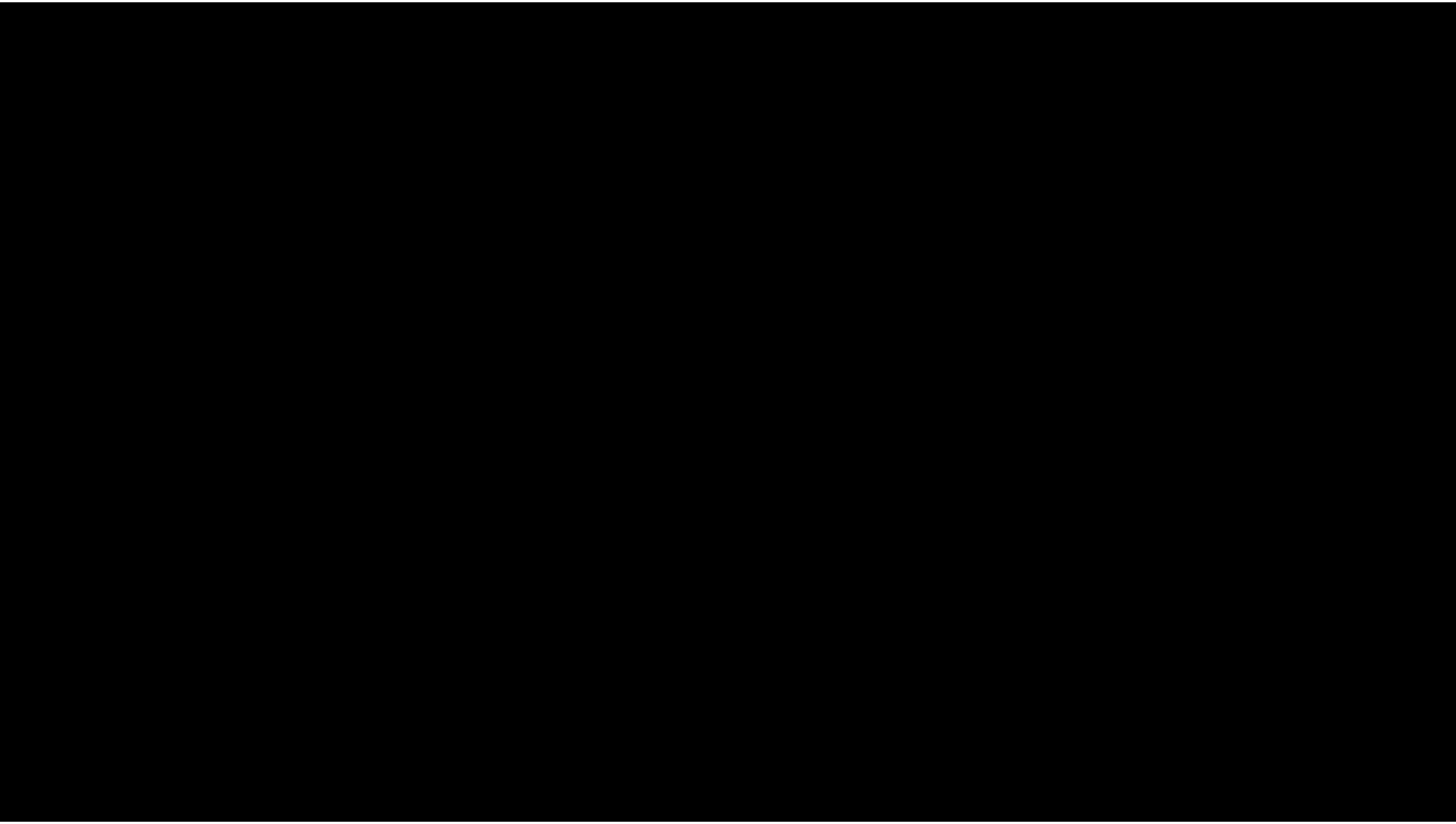
The Human Centered Robotics Lab



Jorgensen et al, Exploring Model Predictive Control to Generate Optimal Control Policies for HRI Dynamical Systems, **arXiv**, 2017

Dreamer the Disagreeable Robot

Is it okay to stop a robot from injuring a human?



Kim, Intelligent Collision Management in Dynamic Environments for Human-Centered Robots, **PhD Thesis**, 2017

Source images from ShutterStock.com. Composite image by ZP Graphic

Larger Vision

Trends in safety for ground robots

Kim et al., Full-Body Collision Detection and Reaction with Omnidirectional Mobile Platforms, **Autonomous Robots**, 2016

Human-centered interactions for ground robots

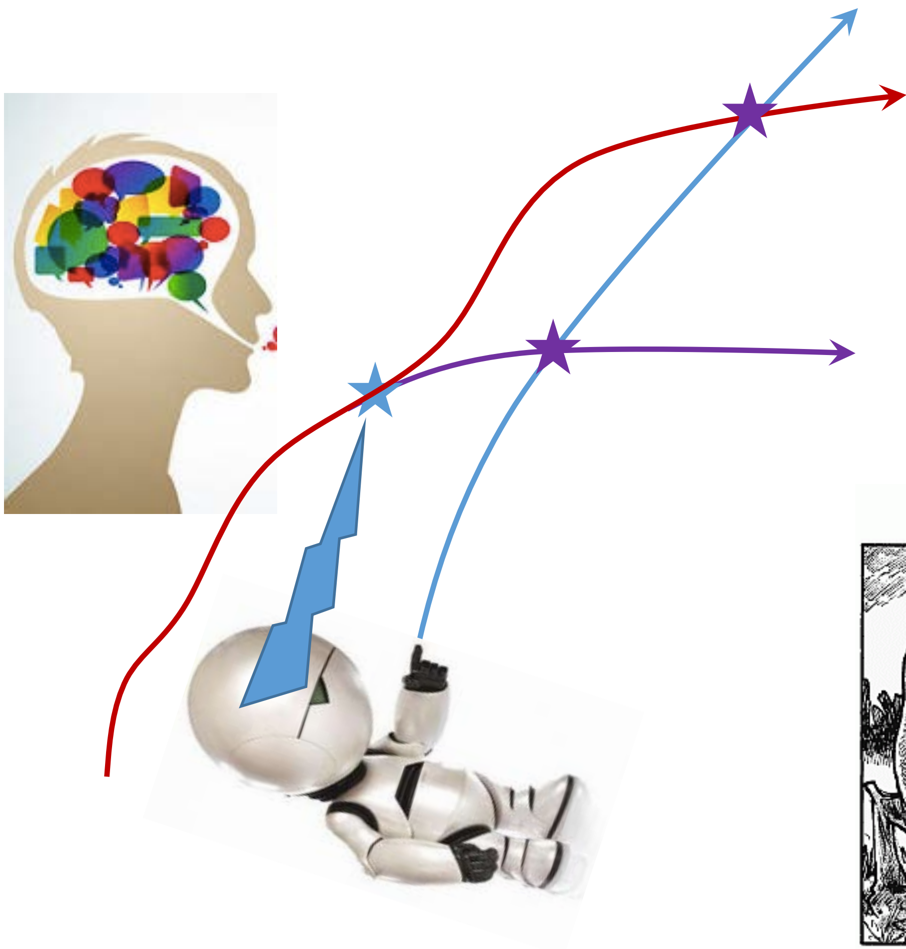
Human Body Part Multicontact Recognition and Detection Methodology

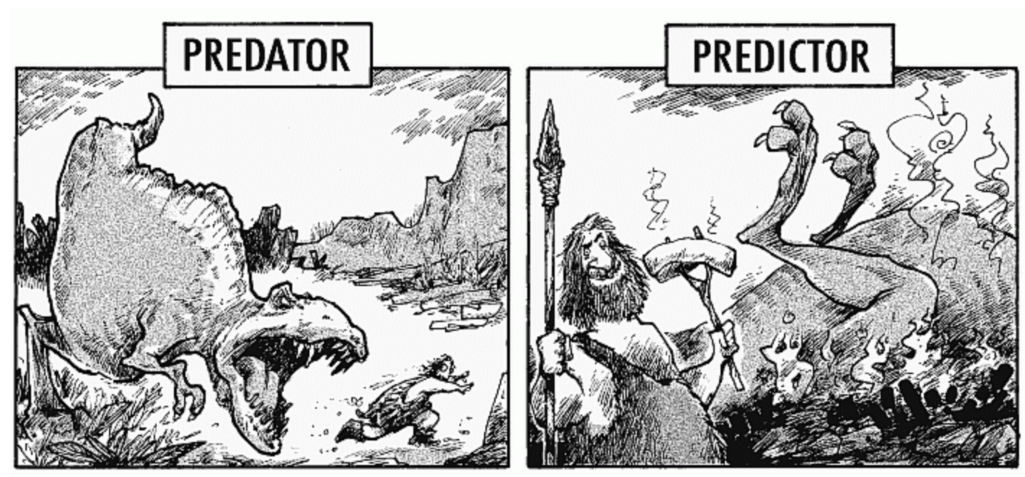
Kwan Suk Kim, Luis Sentis
The unversity of Texas at Austin

ICRA 2017

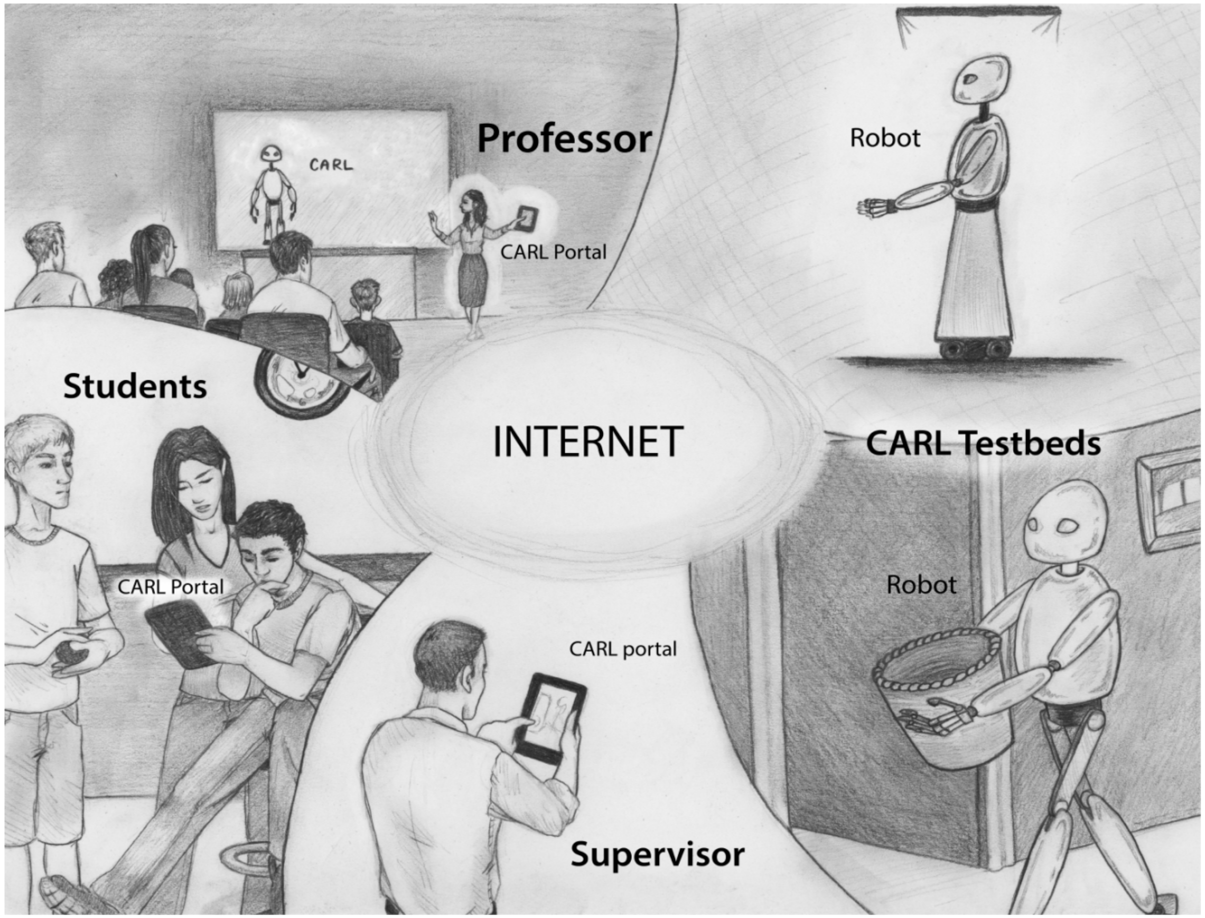
Kim and Sentis, Human Body Part Multicontact Recognition and Detection Methodology, **IEEE ICRA**, 2017

Productivity over a time horizon:
Activity Prediction and Intervention

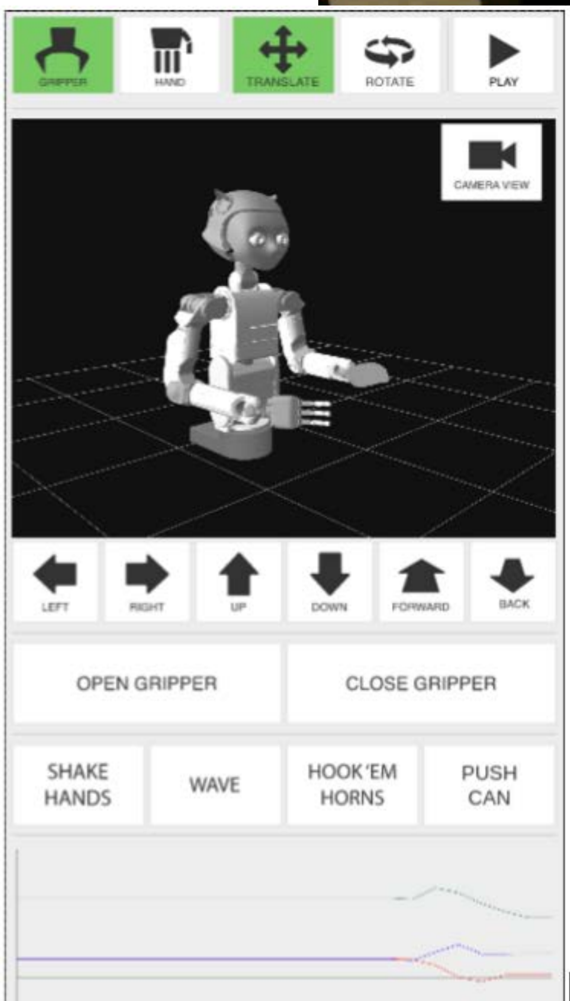




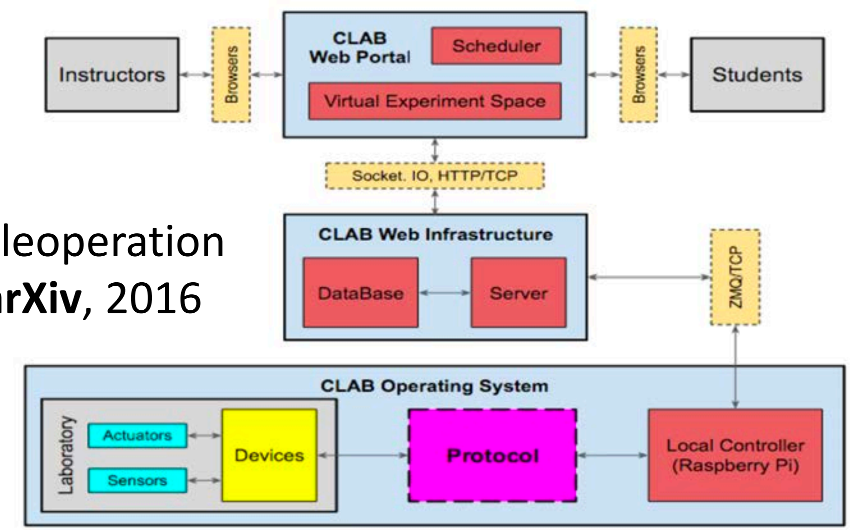
Early Concept on Shared Equipment

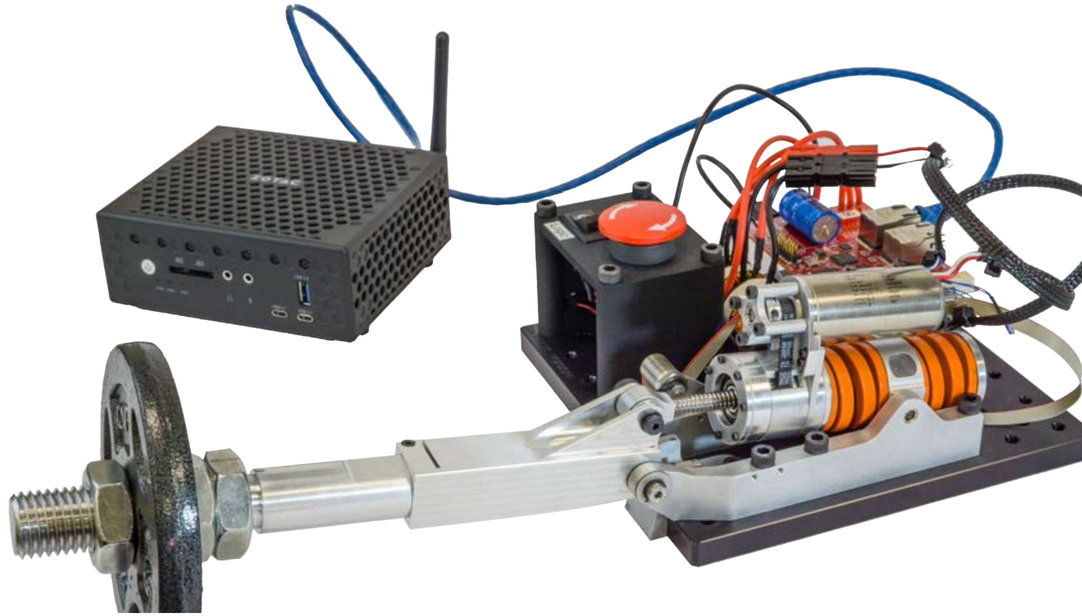


Fok et al, Web Based Teleoperation of a Humanoid Robot, **arXiv**, 2015

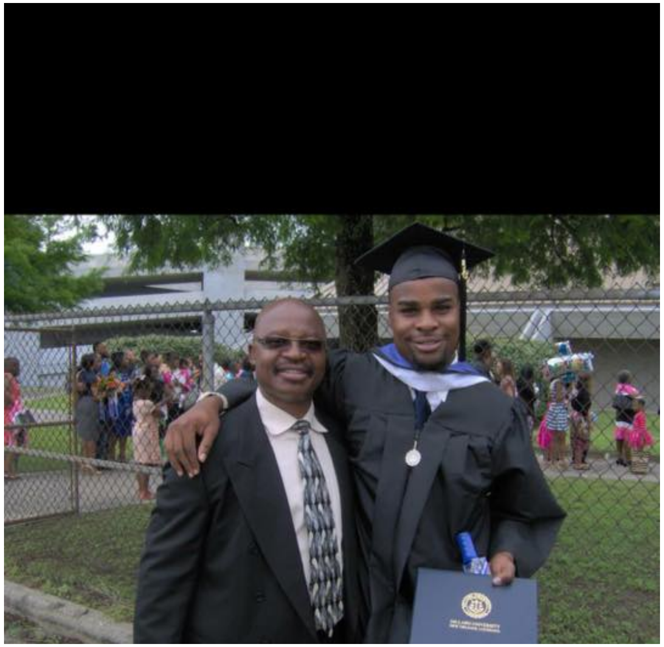


Fok et al, Web Based Teleoperation of a Humanoid Robot, **arXiv**, 2016

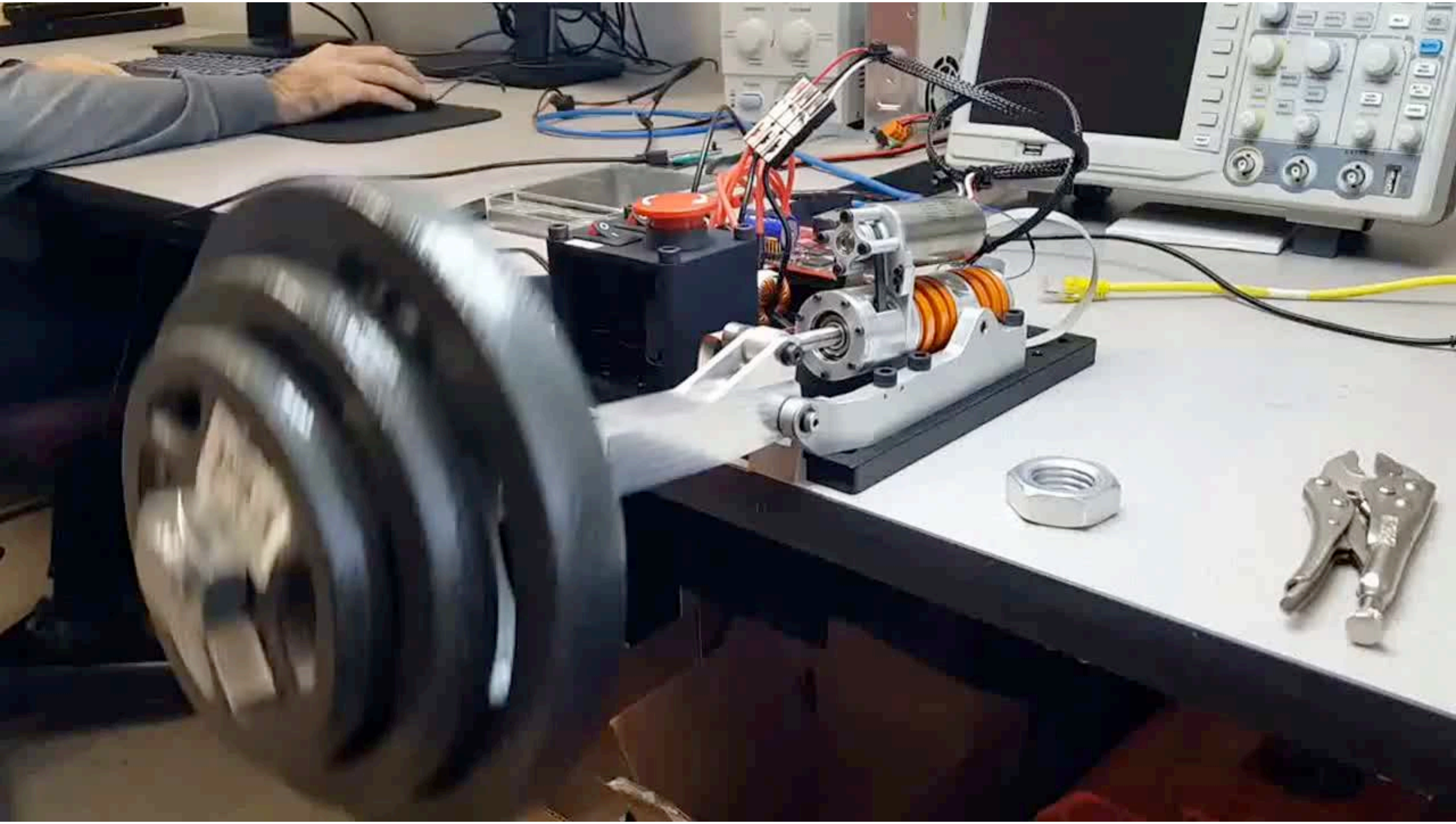




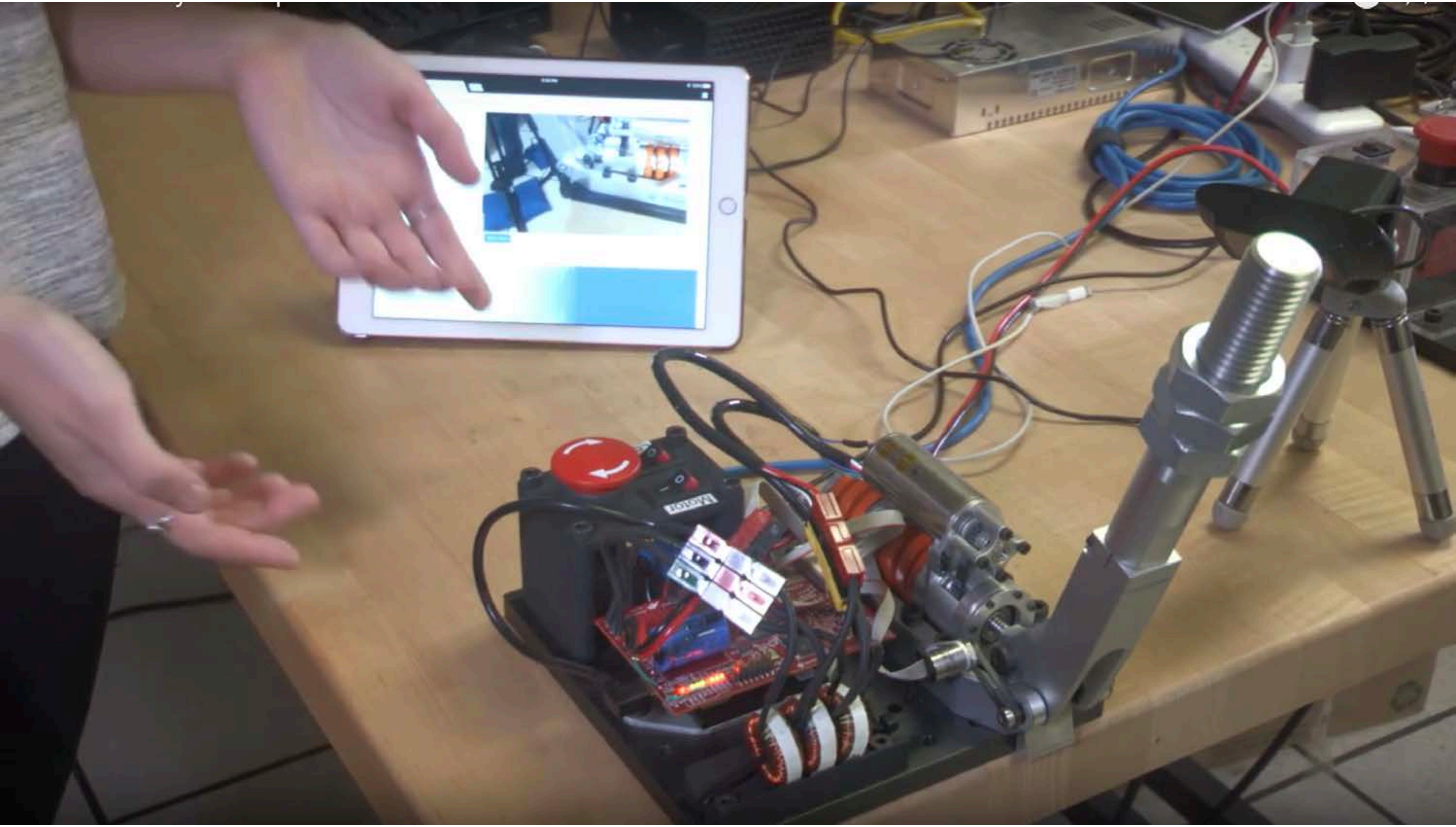
Trends on Education
From NASA to the Classroom



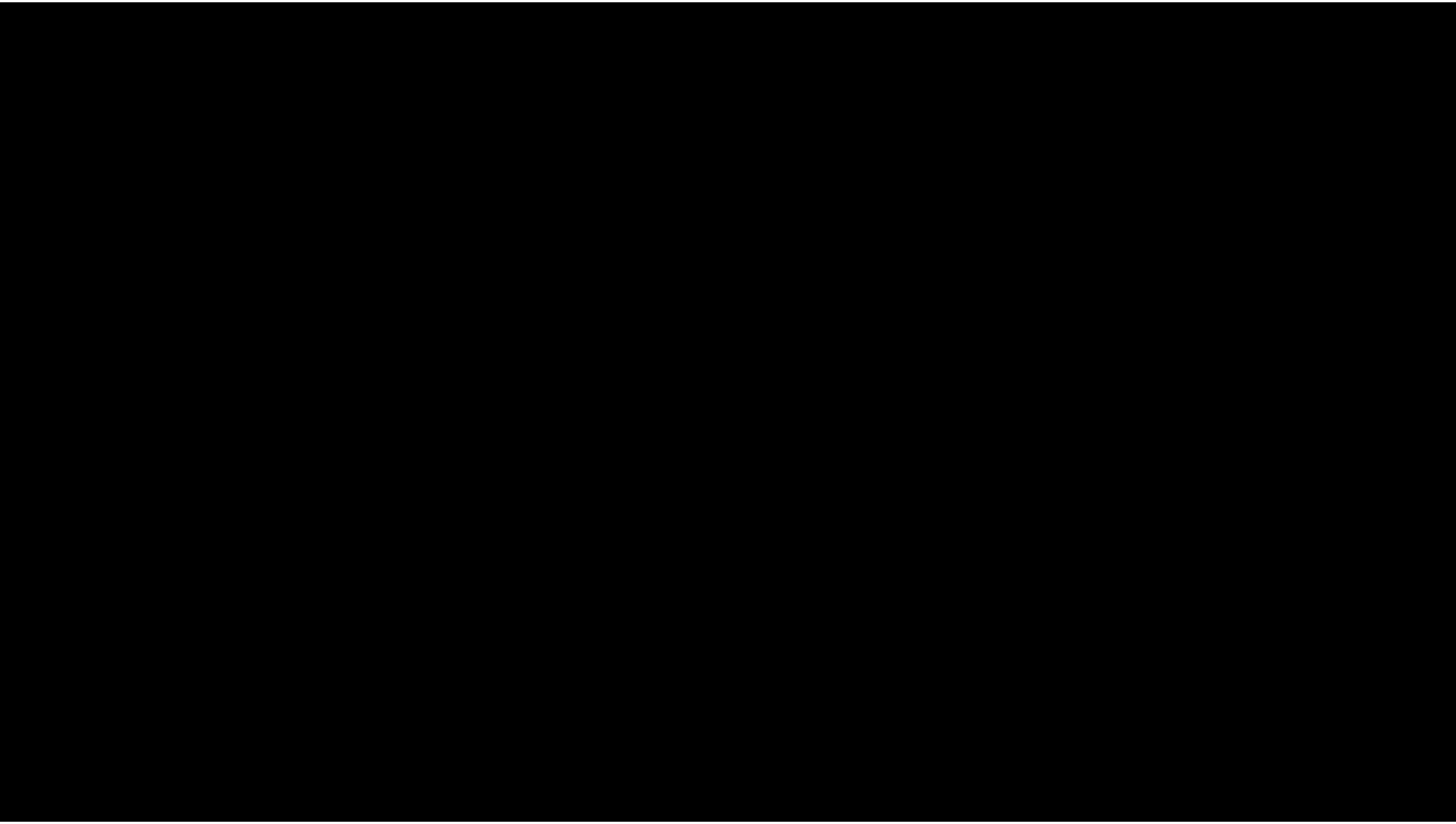
Case Study: From NASA to HBCU



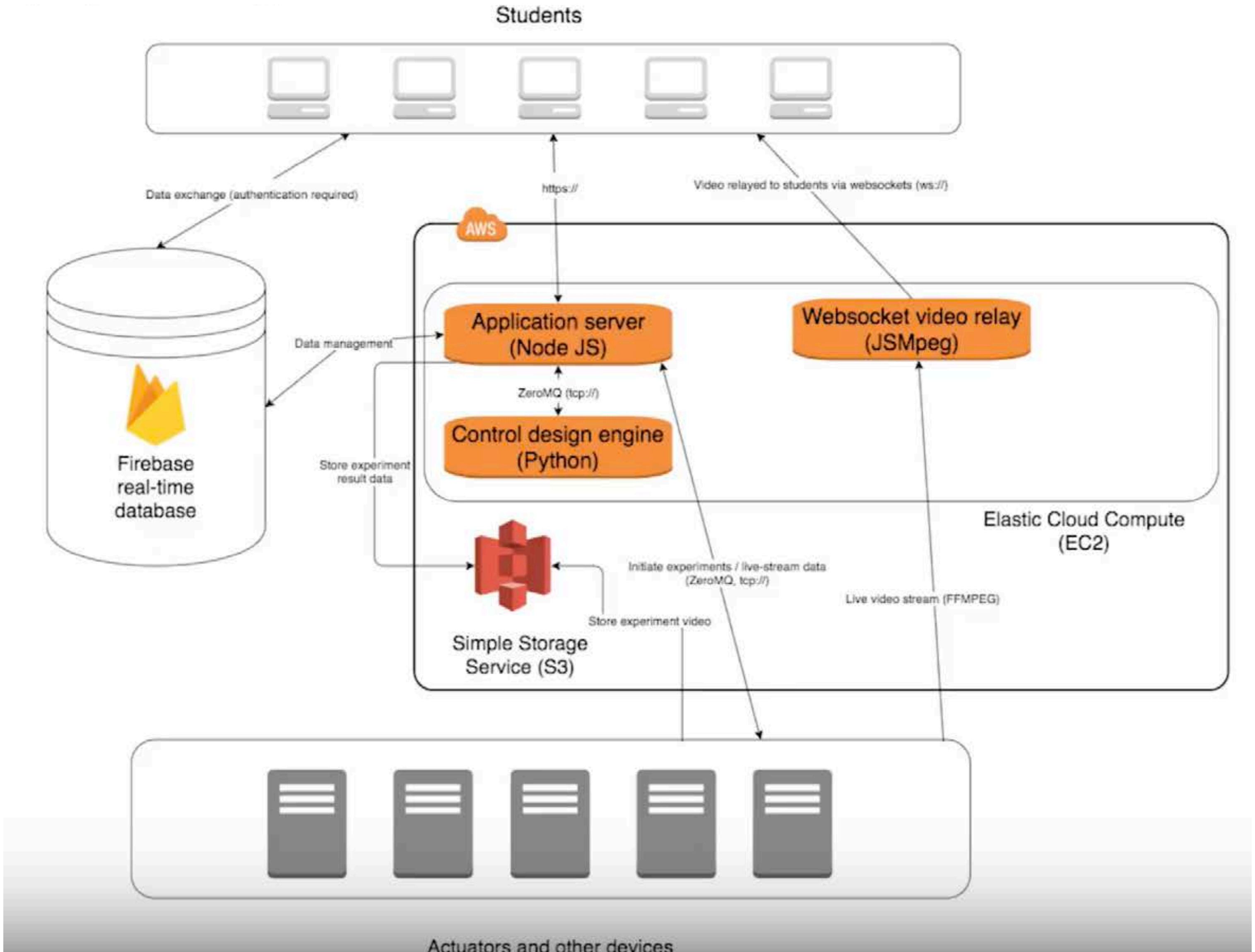
UT Shared Laboratory Initiative



UT Shared Laboratory Initiative



Cloud Architecture



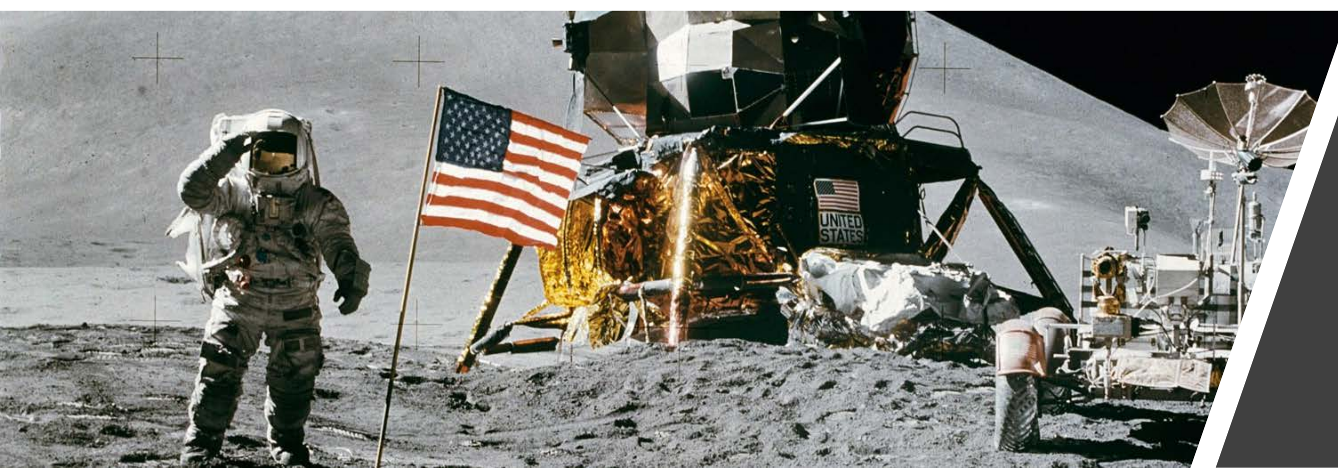
Decision and Control of Human-Centered Robots (2016)

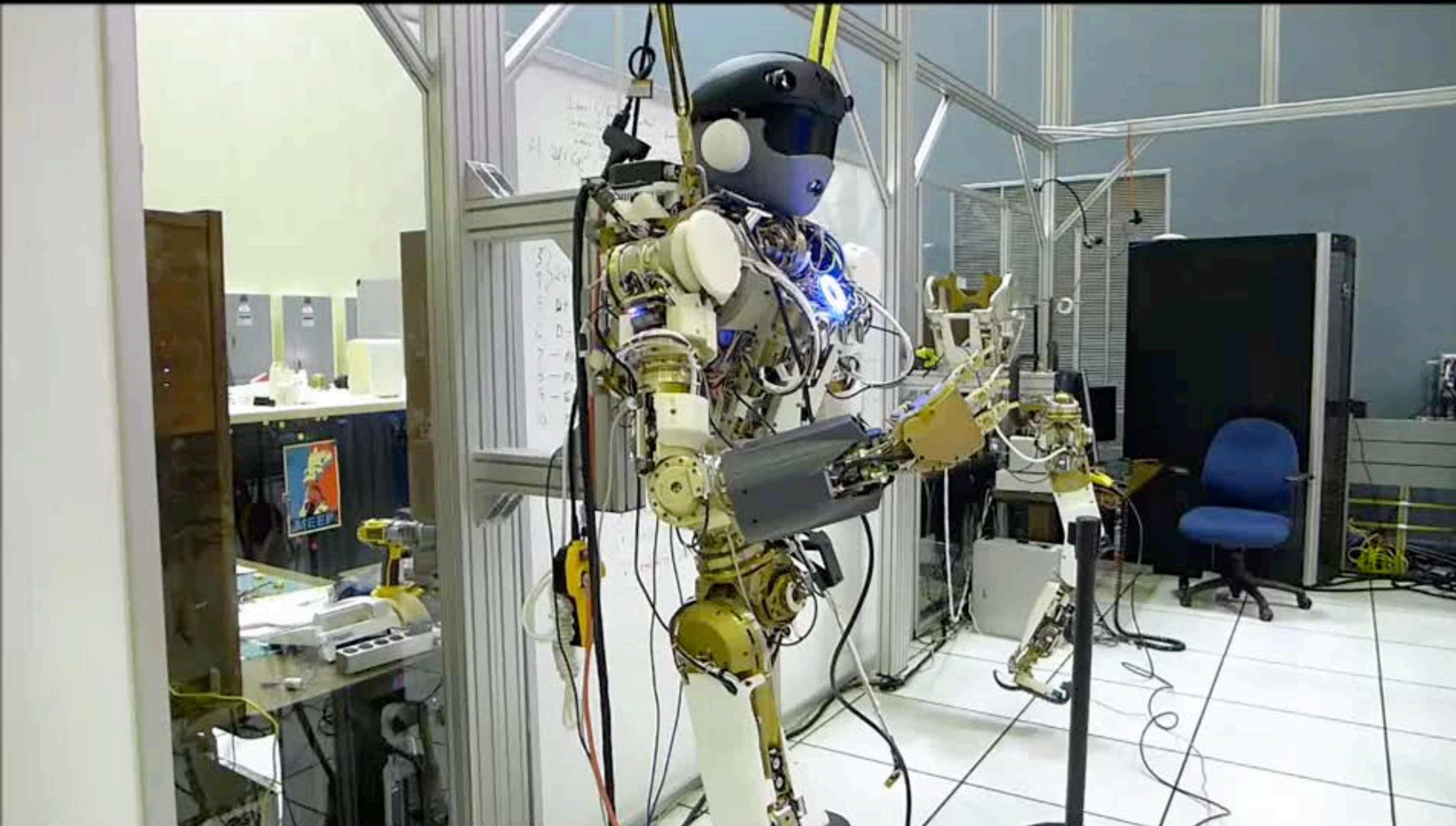
WEEK	TOPIC
Th 8/25	Syllabus / Background / Introductions / Project Teaming
Week 8/30	Intro Autonomous Systems, Socio Cognitive Modeling of Human Activity
Week 9/6	Unconstrained and constrained optimization, 1st and 2nd Order Solvers, Lagrangian Multipliers, Optimal Control, Model Predictive Control (MPC)
Week 9/13	Socio-Cognitive Behavior Intervention via MPC, Mixed Integer Programming
Week 9/20	Case Study: Behavior Interventions on Exercising Activity
Week 9/27	Introduction to Sequential Composition, LQR-Trees Theory
Week 10/4	LQR-based Linearization along Trajectories, Regions of Attraction via SOS Tools, Case Study: Nonlinear Underactuated System Stabilization
Week 10/11	Intro to Motion Planning with LTL Specifications, Lifted Graphs, Admissible Paths, Intro to Linear Temporal Logic
Week 10/18	Transition Systems Incorporating Geometric and Temporal States, Mission Compliant Paths, Intro Automata Theory
Week 10/25	Nonlinear Controller Synthesis and Automatic Workspace Partitioning for Reactive High-Level Behaviors
Week 11/1	Intelligent Collision Management in Human-Centered Robots
Week 11/8	Provably Safe Obstacle Avoidance for Autonomous Robotic Ground Vehicles
Week 11/15	Stabilizing Series-Elastic Point-Foot Bipeds Using Whole-Body Operational Space Control, Integrated Task and Motion Planning
Week 11/22	Details ONR MURI Autonomous Systems, Thanksgiving Holiday
Week 11/29	**Final Project Presentations**

Embodied Cognitive Control (2017)

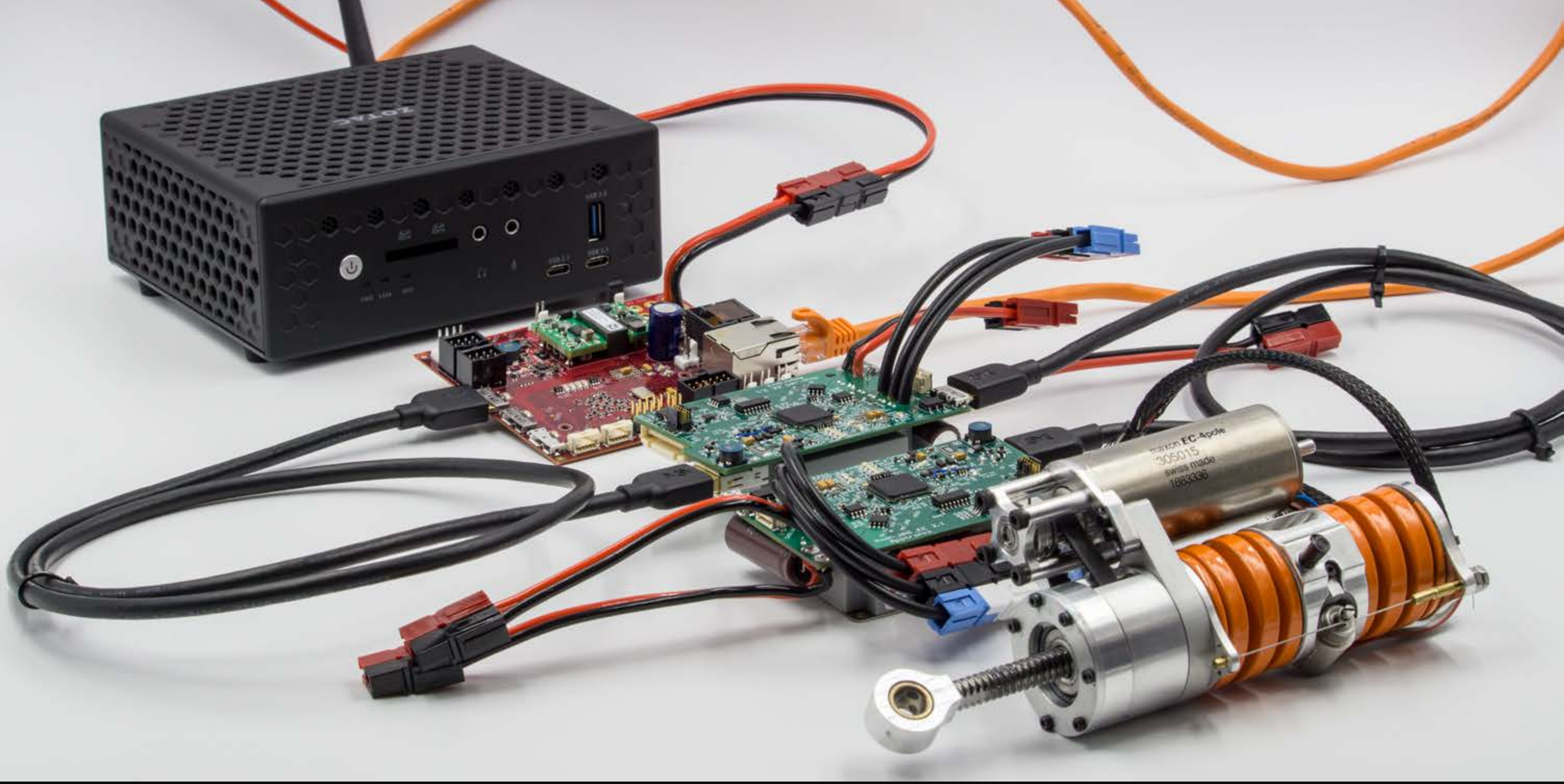
WEEK	TOPIC
Th 8/31	Syllabus / Background / Introductions / Project Logistics
Week 9/5	Embodied cognitive systems: Intersection between control systems theory and cognitive agents. What is cognition? Increasing system productivity with cognition and embodiment. Review of UT Austin Villa RoboCup@Home 2017 robotics cognitive software. Review of ACT-R cognitive architecture.
Week 9/12	Intelligent agents: Rationality. Computational goal of cognitive systems. Vacuum cleaner world - STRIPS language. Engineering intelligence.
Week 9/19	Rational robotic agent. Morality issues in interventional agents. Examples of rational agents using the humanoid robot Dreamer and the mobile robot Trikey.
Week 9/26	Paradigms of cognitive science. Cybernetics. Cognitivism. The birth of AI. The physical symbol system hypothesis. The heuristic search hypothesis. Turing complete machines. Church-Turing test.
Week 10/3	Learning agents. Types of agents: model-based, goal-based, utility-based, learning-based. Overview of reinforcement learning. Markov decision process. Value iteration. Actor-critic learning process.
Week 10/10	Knowledge-based agents. Logic inference. Propositional logic. First order logic. Example, Wumpus World.
Week 10/17	Knowledge representation. Introduction to ProLog. Defeasible reasoning. Non-monotonic logics. Negation as failure. Review of SOAR cognitive architecture.
Week 10/24	Knowledge engineering. Ontologies. Web Ontology Language. Knowledge classification. Taxonomies. Historical perspective. Description logic. RDF schema. Architecture of a knowledge base.
Week 10/31	Semantic Reasoning. Review of KnowRob architecture. Case study: IBM Watson.
Week 11/7	Midterm Project Presentations
Week 11/14	Embodiment and mission specifications. Safety controllers. Barrier certificates. Control barrier functions. Control lawas for CBF. Quadratic barrier pair. Linear matrix inequality. Signal temporal logic. Mixed integer programming. LTLC syntax.
Week 11/28	Synthesis of symbolic controllers. Symbolic regression. Achieving parsimonious hybrid dynamical models. Hybrid automata. Closing remarks.
Week 12/5	Final Project Presentations

Embodiment

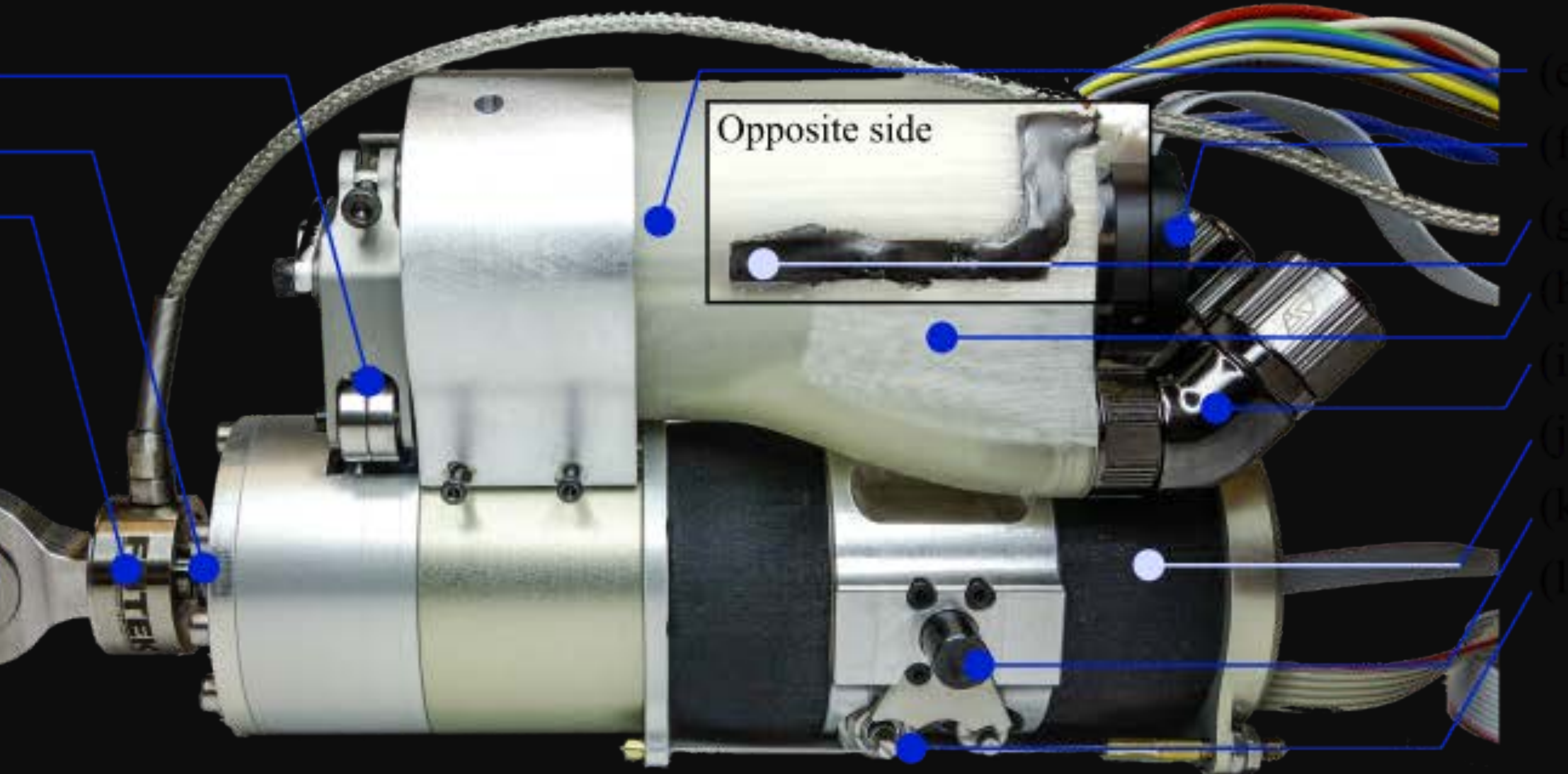



MEEP

Sustainability



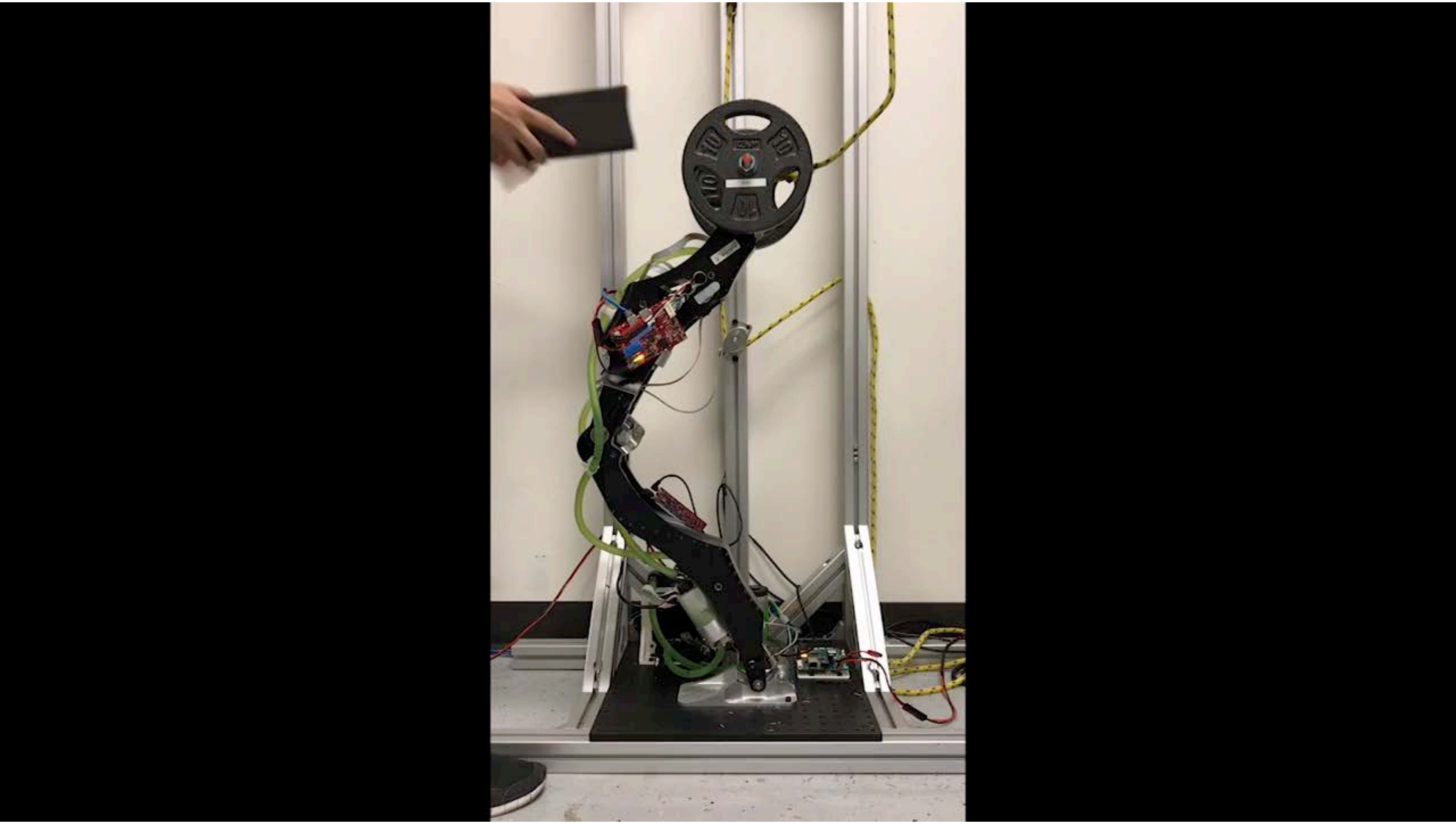
Embedded Nervous System and Muscle



Viscoelastic Liquid Cooled Actuation

Kim et al, Investigations of Viscoelastic Liquid Cooled Actuators Applied for Dynamic Motion Control of Legged Systems, **IEEE Humanoids, 2017**

Prototype Compliant Legged System



Kim, et al, Investigations of a Robotic Testbed with Viscoelastic Liquid Cooled Actuators, **arXiv**, 2017

P170 Orion

- Small compact design ➢ Fits into small design envelopes
- 4kN/kg force density ➢ Minimizes mass and inertial effects while maximizing power
- Impact Tolerance ➢ Shock absorption and robustness vs. rigid drivetrains
- Ball screw drive train ➢ High mechanical efficiency, quiet operation
- Maxon brushless DC motor ➢ Smaller, more efficient and optimized for torque and power
- High Fidelity Force feedback ➢ Reactive and adaptive to the environment.

Specifications:

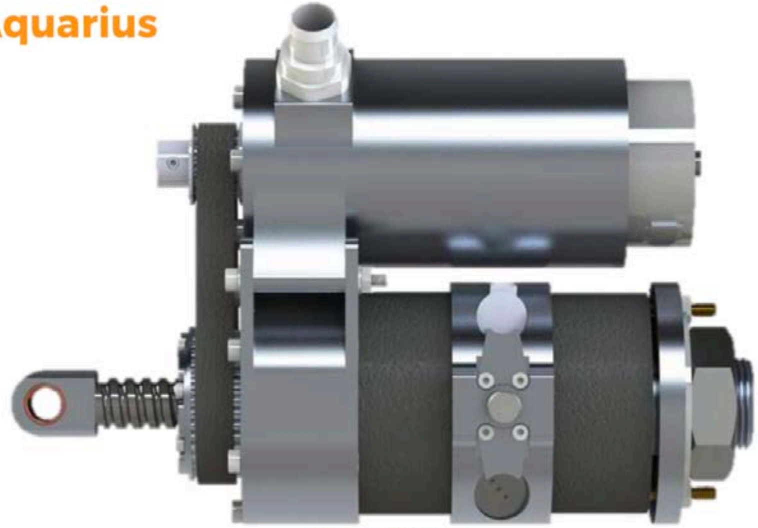
Rated power output	170W
Continuous force	847N [190lbs]
Peak force	3200N [719lbs]
Max speed	27.7cm/s [10.9in/s]
Stroke	6.47cm [2.55in]
Voltage	48-60V
Mass	786g [1.73lbs]
Max efficiency	80% (load-dependent)
Current Draw	5A continuous, 20A peak

Applications:

- Human interactive robotic systems
- Wearable robotics
- Dynamic robotic systems
- Precision agriculture
- Aerospace
- Industrial automation
- Any other application that demands force precision

Apptronik™ *Empowering the Next Generation of Robotics*

PL-360 Aquarius



Features:

- Compact and modular design
- Liquid cooling
- Lightweight
- Series compliance
- Ball screw primary drive

Benefits:

- Integrates well into space-constrained designs
- Continuous support of heavy loads
- Integrates well into mass-constrained designs
- Force control with improved positioning capability
- High mechanical efficiency, high backdrivability, zero backlash, quiet operation, prismatic motion

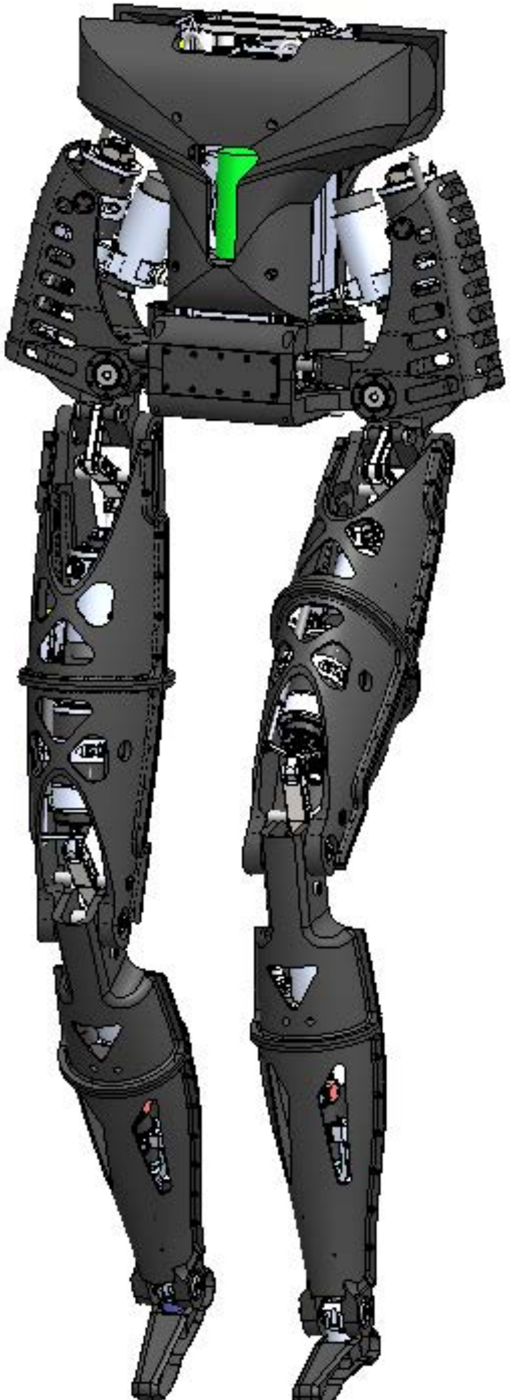
Specifications:

Rated power output	360W
Continuous force	1977N [445lbs]
Peak force	6236N [1600lbs]
Max speed	40.4cm/s [15.9in/s]
Stroke	8.3cm [3.26in]
Voltage	48-60V
Mass	1.6kg [2.58lbs]
Max efficiency	81% (load-dependent)
Current Draw	5A continuous, 20A peak

Applications:

- Human interactive robotic systems
- Wearable robotics
- Dynamic robotic systems
- Aerospace
- Industrial automation
- *Any other application that demands force precision*

Larger vision

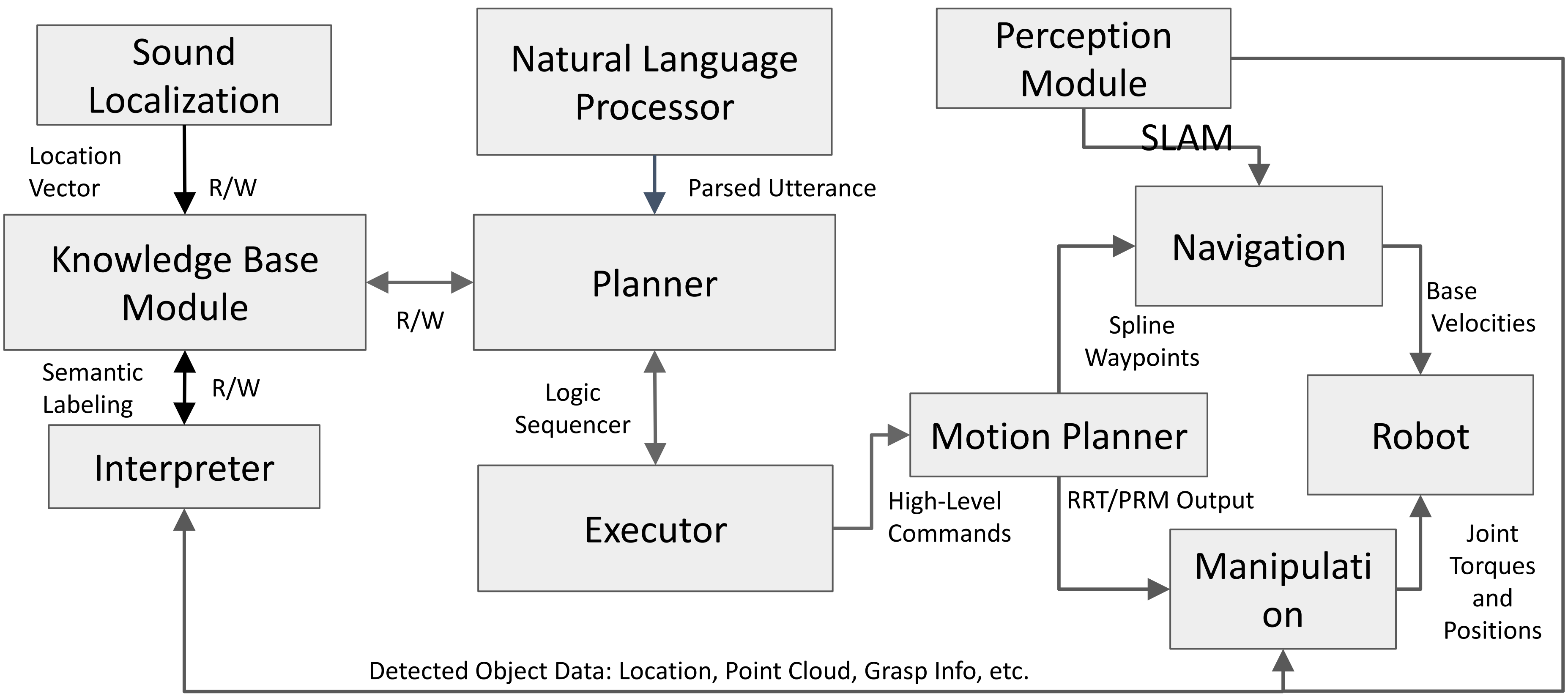


Draco Humanoid 2018

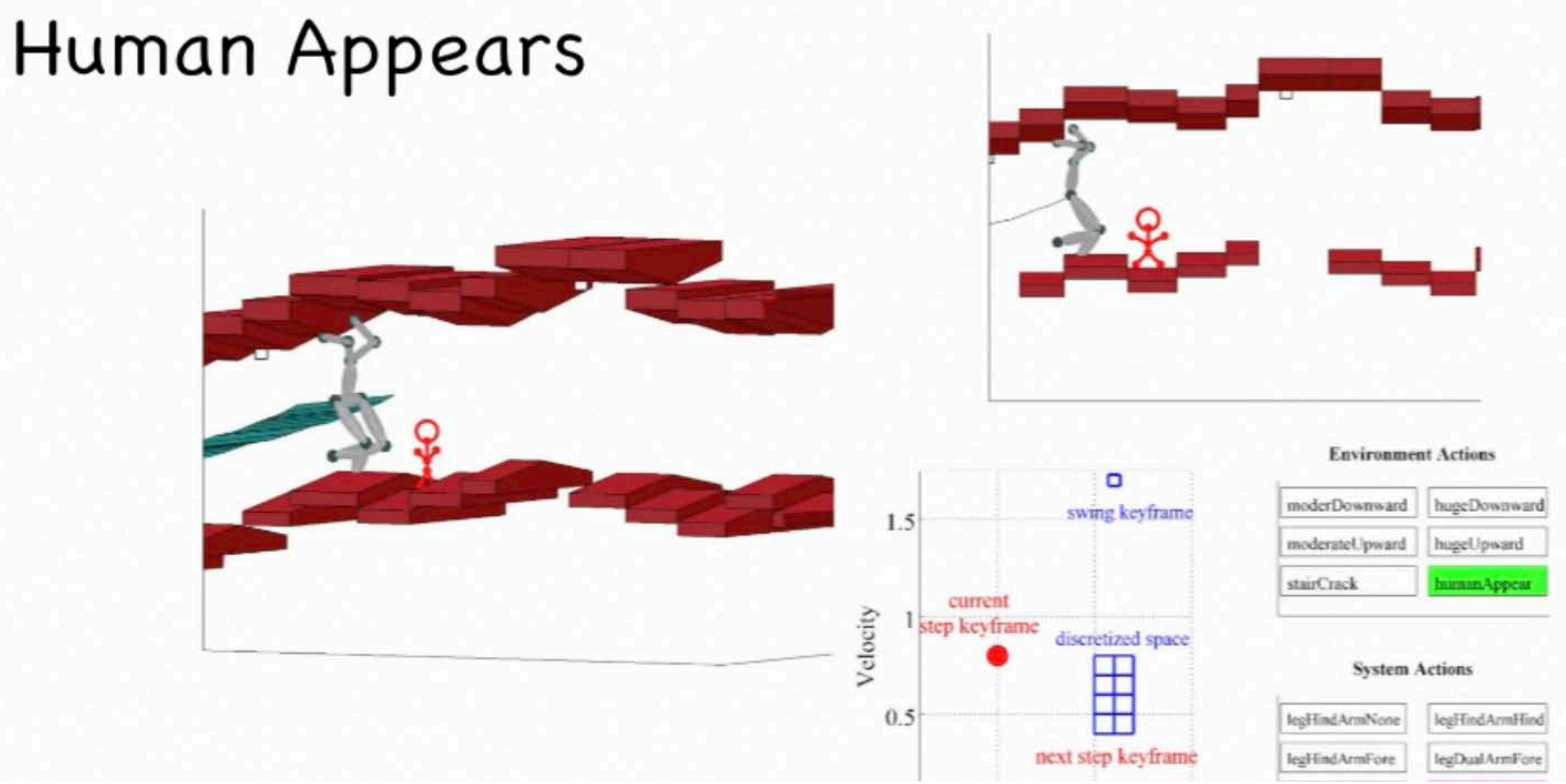
RoboCup@Humanoids

3rd Prize RoboCup@Home 2017

Cognitive Architecture RoboCup@Home 2017



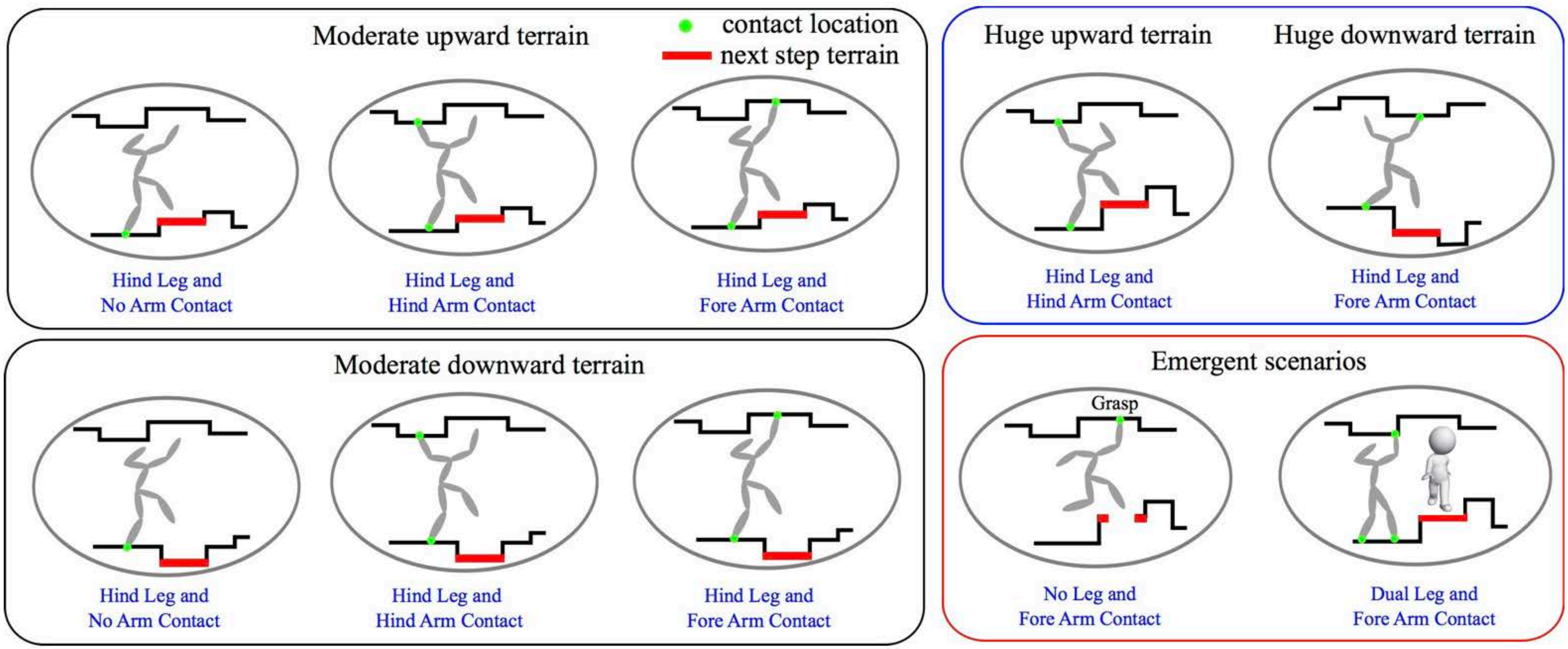
Competition Nagoya



Mission specifications

Zhao and Sentis, High-Level Planner Synthesis for Whole-Body Locomotion in Unstructured Environments, **IEEE CDC**, 2016

Action Model for Variable Environments



Solve this Problem as a Formal Decision Process - LTL Specifications

- Environment actions are represented by stair height

$$\mathcal{E} := \{e_{md}, e_{hd}, e_{mu}, e_{hu}, e_{sc}, e_{ha}\}$$

- System actions are abstracted as contact configurations

$$\mathcal{S} := \{a_{li\text{-}aj},\ \forall (i,j) \in \mathcal{A}_{\text{index}}\}$$

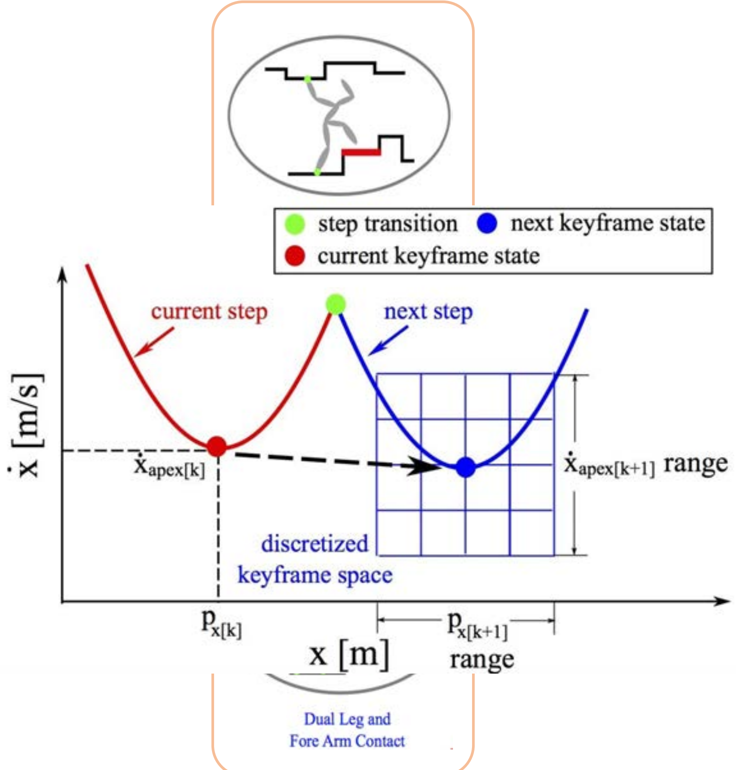
- System keyframe states are represented by

$$\mathcal{Q} := \{q_{i\text{-}j},\ \forall (i,j) \in \mathcal{Q}_{\text{index}}\} \bigcup \{q_{\text{swing}}, q_{\text{stop}}\}$$

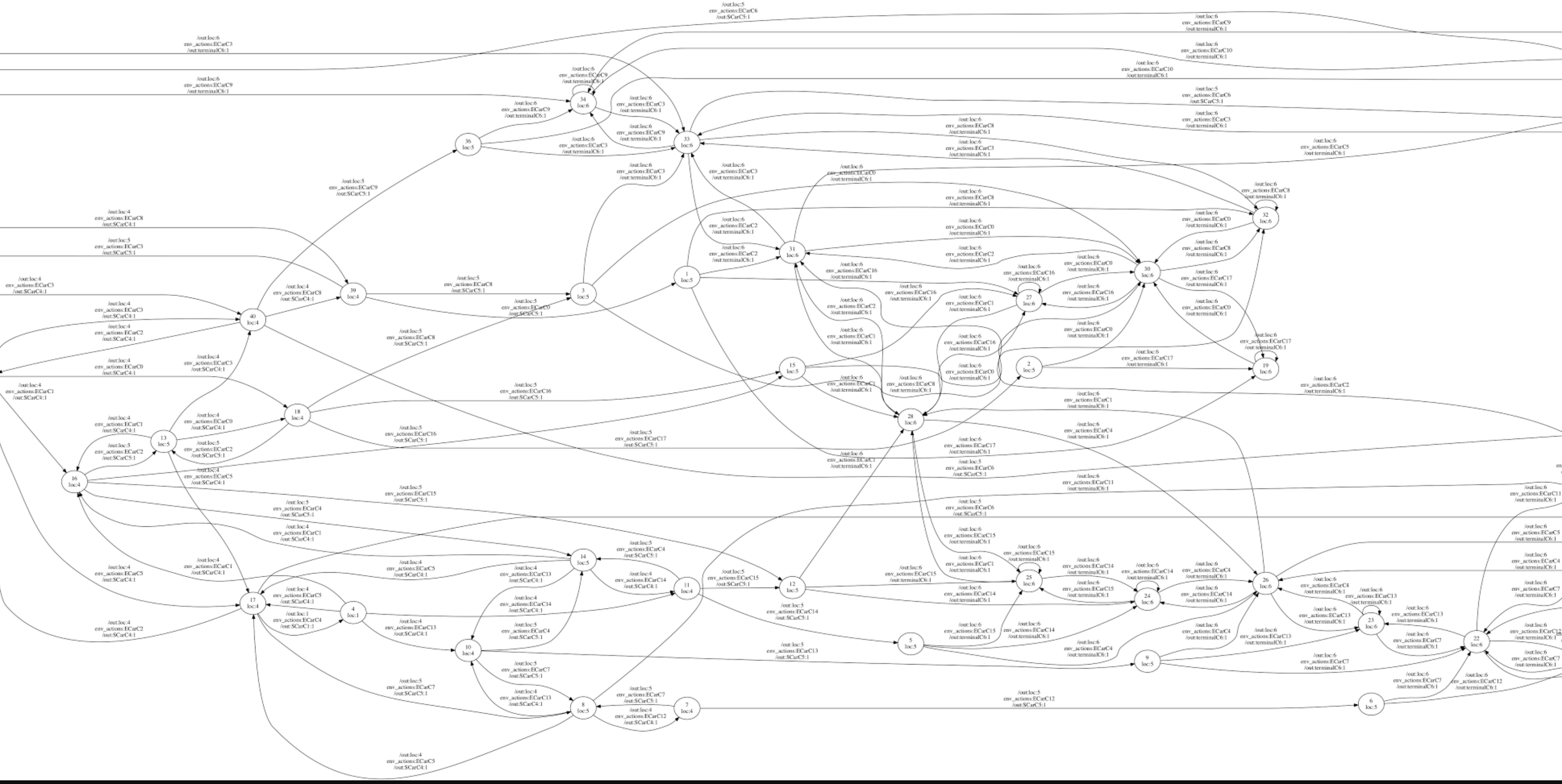
- **LTL Examples**

$$\square\left(e_{ha} \Rightarrow (a_{ld\text{-}ah} \vee a_{ld\text{-}af})\right)$$

$$\square\left((q_{s\text{-}s} \wedge \bigcirc e_{md}) \Rightarrow \bigcirc(q_{s\text{-}s} \vee q_{s\text{-}n} \vee q_{n\text{-}s})\right)$$



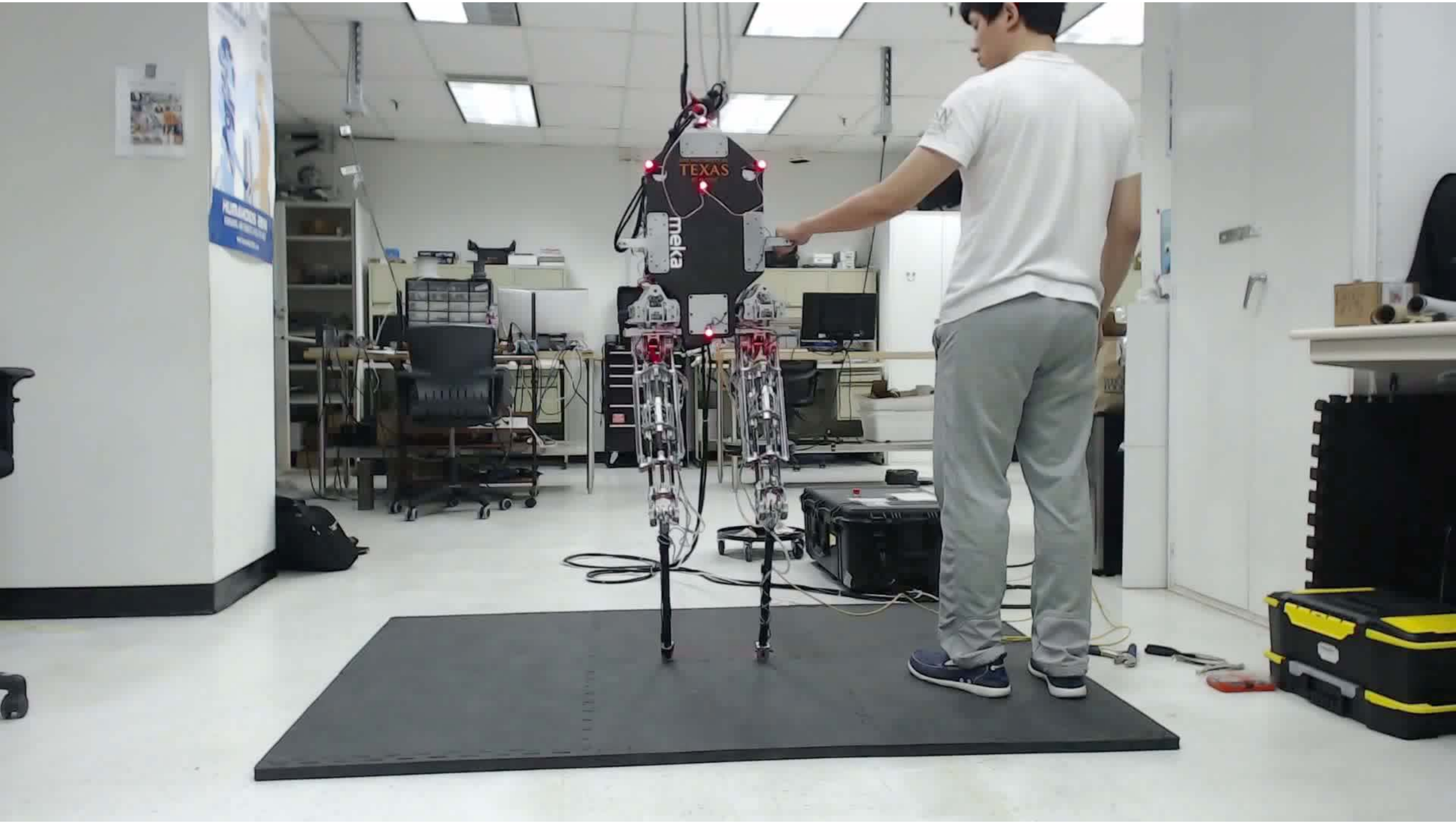
- Zhao and Sentis, High-Level Planner Synthesis for Whole-Body Locomotion in Unstructured Environments, **IEEE CDC**, 2016
- Zhao et al, Robust Optimal Planning and Control of Non-Periodic Bipedal Locomotion with A Centroidal Momentum Model, **IJRR** 2017



Manually Creating the Automaton Would Be Challenging…

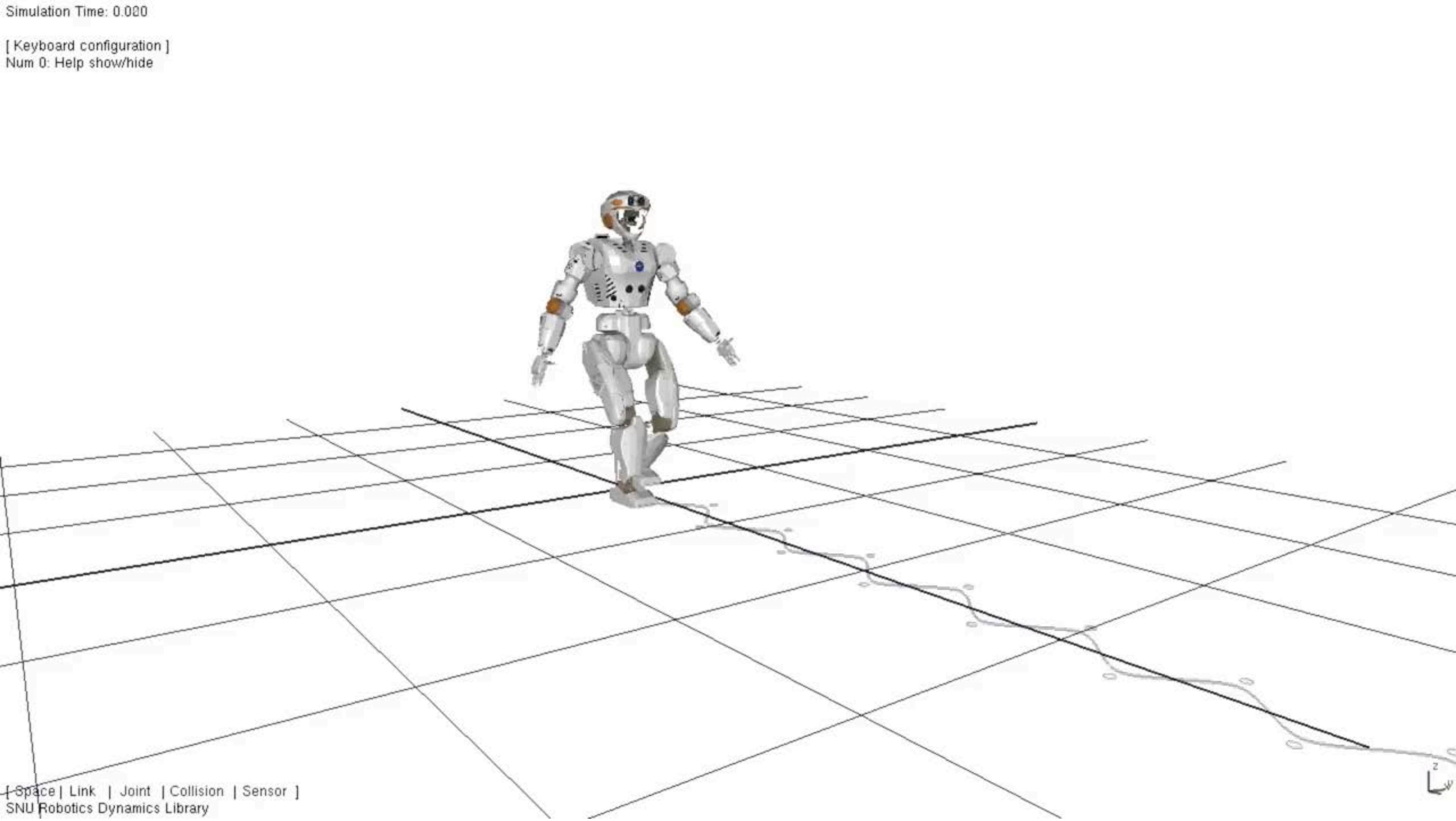
Video: Integrated Task and Motion Locomotion Planner

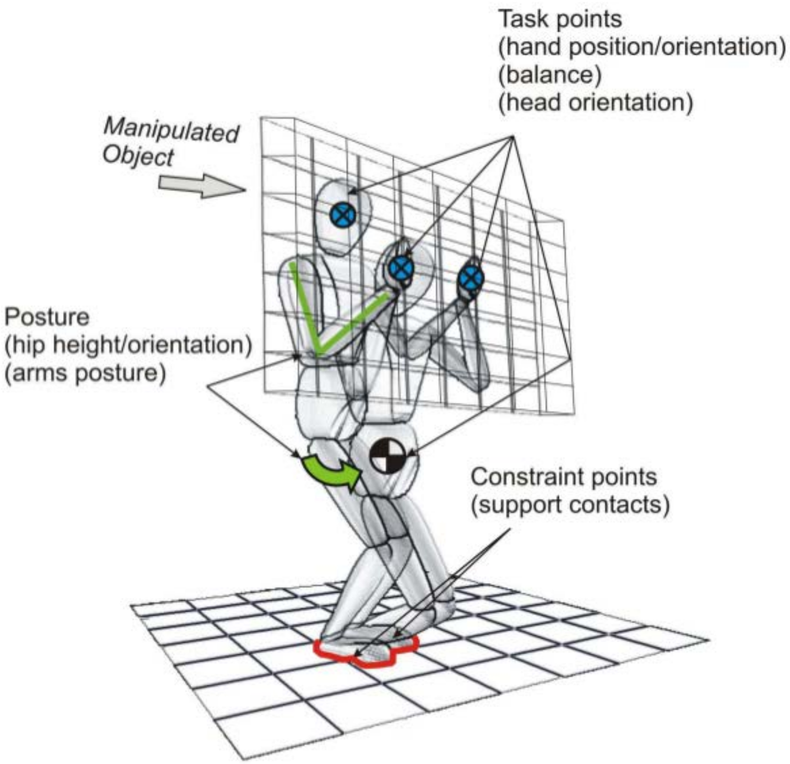
Unsupported Point Foot Walking



Kim et al, Stabilizing Series-Elastic Point-Foot Bipeds using Whole-Body Operational Space Control, **IEEE TRO**, 2016

RL Disturbance Adaptation





$$
\begin{array}{ll}
\multicolumn{2}{l}{A_1 \leftarrow A \quad \text{and} \quad b_1 \leftarrow b} \\
\multicolumn{2}{l}{\text{for } i = 1 : n \text{ do}} \\
\quad \underset{\mathcal{X}}{\text{minimize}} & \pi_i = ||E_i \mathcal{X} - u_i||^2 \\
\quad \text{subject to} & A_i \mathcal{X} = b_i \\
 & G \mathcal{X} \preceq h \\
 & A_{i+1} \leftarrow [A_i^T \; E_i^T]^T \\
 & b_{i+1} \leftarrow [b_i^T \, E_i \mathcal{X}^T]^T \\
\multicolumn{2}{l}{\text{end}}
\end{array}
$$

WBC as Prioritized Optimization

Sentis et al, Compliant Control of Multi-Contact and Center of Mass Behaviors in Humanoid Robots, **IEEE TRO**, 2010

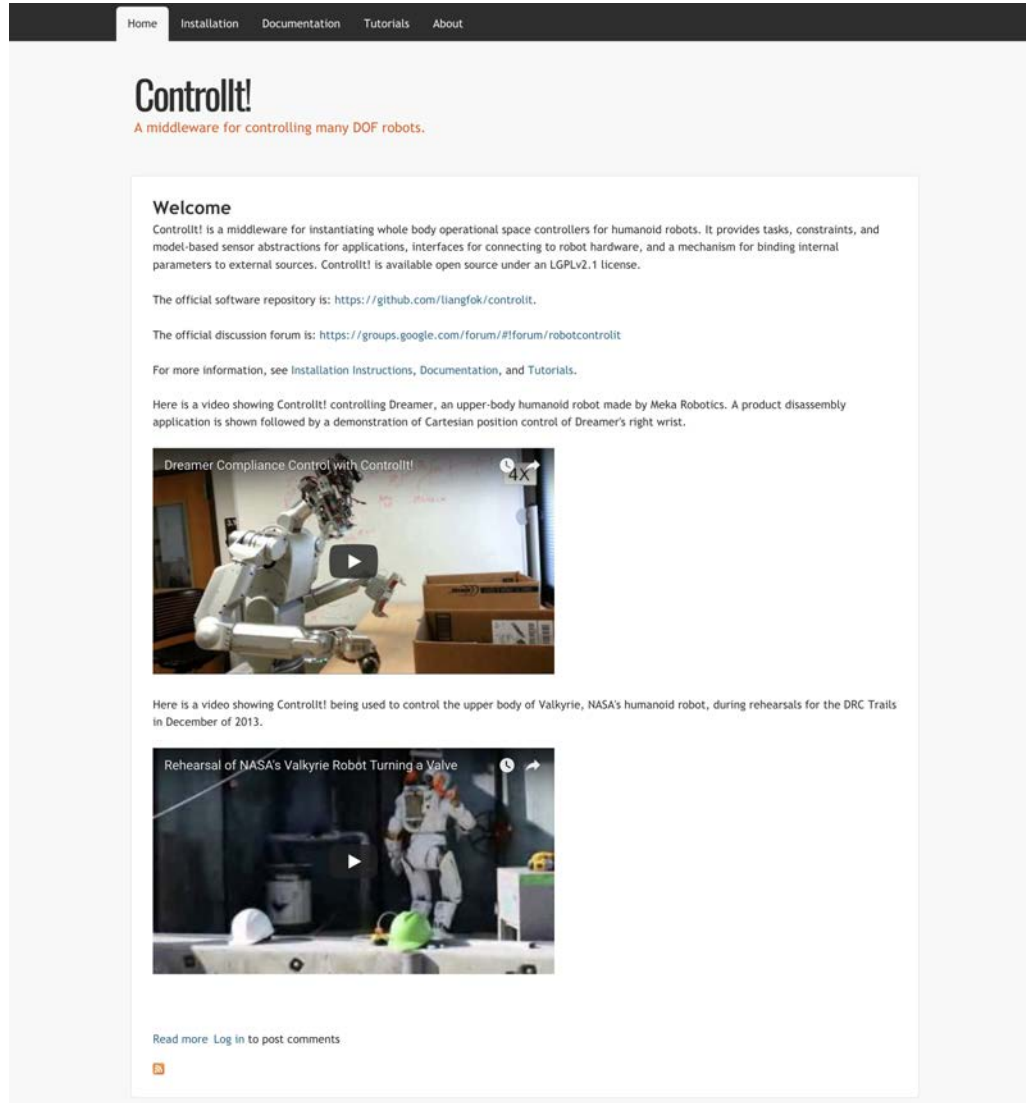
Inspired by bilevel optimization

$$\begin{aligned} \min_x \quad & F(x, y(x)) \\ \text{subject to} \quad & g(x, y(x)) \leq 0 \end{aligned}$$

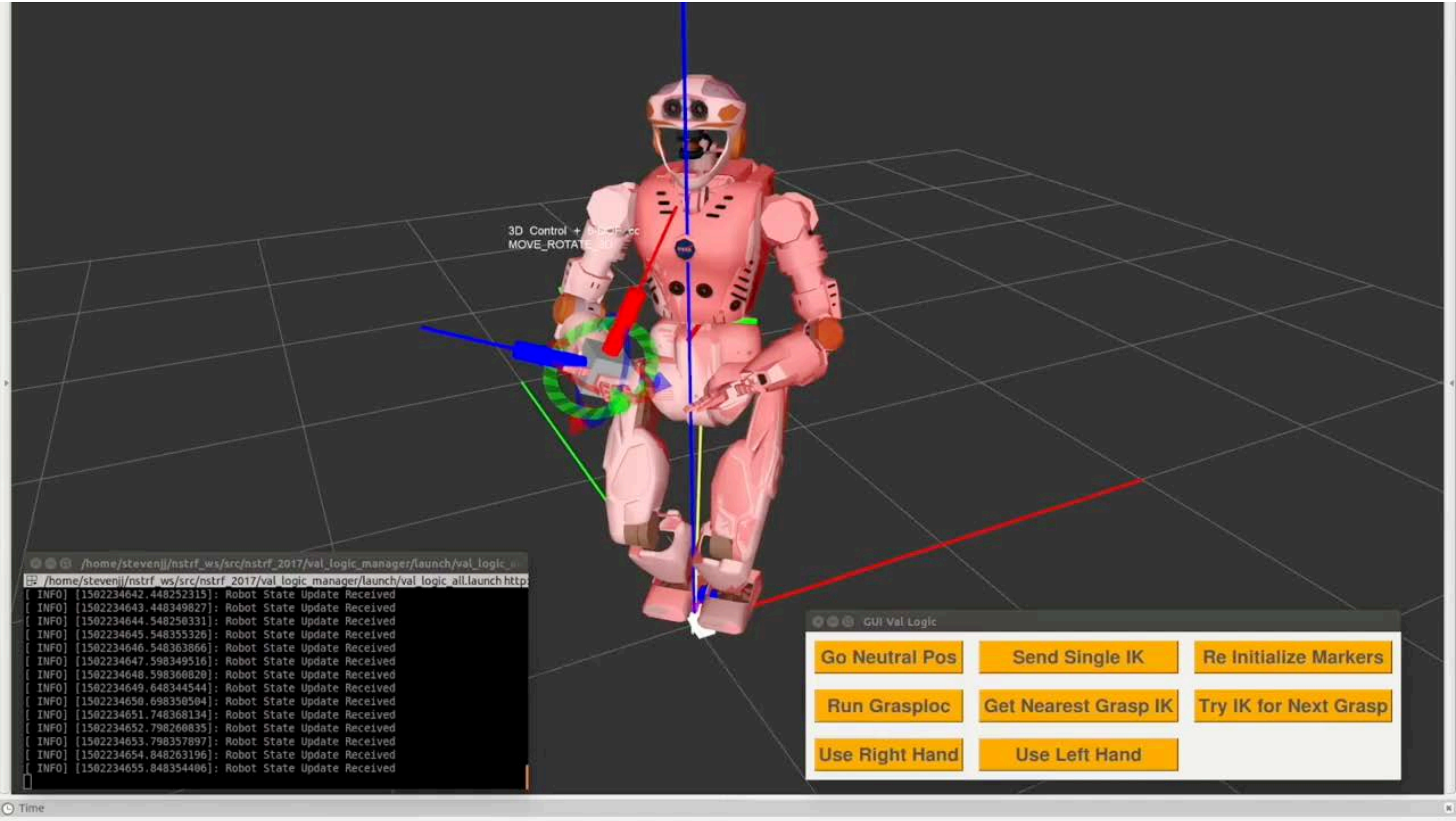
$$\begin{aligned} \min_y \quad & f(x, y) \\ \text{subject to} \quad & h(x, y) \leq 0 \end{aligned}$$

LN Vicente, PH Calamai, “Bilevel and multilevel programming: A bibliography review”, Journal of Global optimization, 1994 - Springer

ControlIt!


Home
Installation
Documentation
Tutorials
About
ControlIt!
A middleware for controlling many DOF robots.
Welcome
ControlIt! is a middleware for instantiating whole body operational space controllers for humanoid robots. It provides tasks, constraints, and model-based sensor abstractions for applications, interfaces for connecting to robot hardware, and a mechanism for binding internal parameters to external sources. ControlIt! is available open source under an LGPLv2.1 license.
The official software repository is: https://github.com/liangfok/controlit.
The official discussion forum is: https://groups.google.com/forum/#!forum/robotcontrolit
For more information, see Installation Instructions, Documentation, and Tutorials.
Here is a video showing ControlIt! controlling Dreamer, an upper-body humanoid robot made by Meka Robotics. A product disassembly application is shown followed by a demonstration of Cartesian position control of Dreamer's right wrist.
Dreamer Compliance Control with ControlIt!
4X
Here is a video showing ControlIt! being used to control the upper body of Valkyrie, NASA's humanoid robot, during rehearsals for the DRC Trails in December of 2013.
Rehearsal of NASA's Valkyrie Robot Turning a Valve
Read more Log in to post comments

Whole-Body Motion Planning



E E

N **N** E E

D N N

E E **D**

N N

D