Shared Autonomy for Robotics
Closing the Loop

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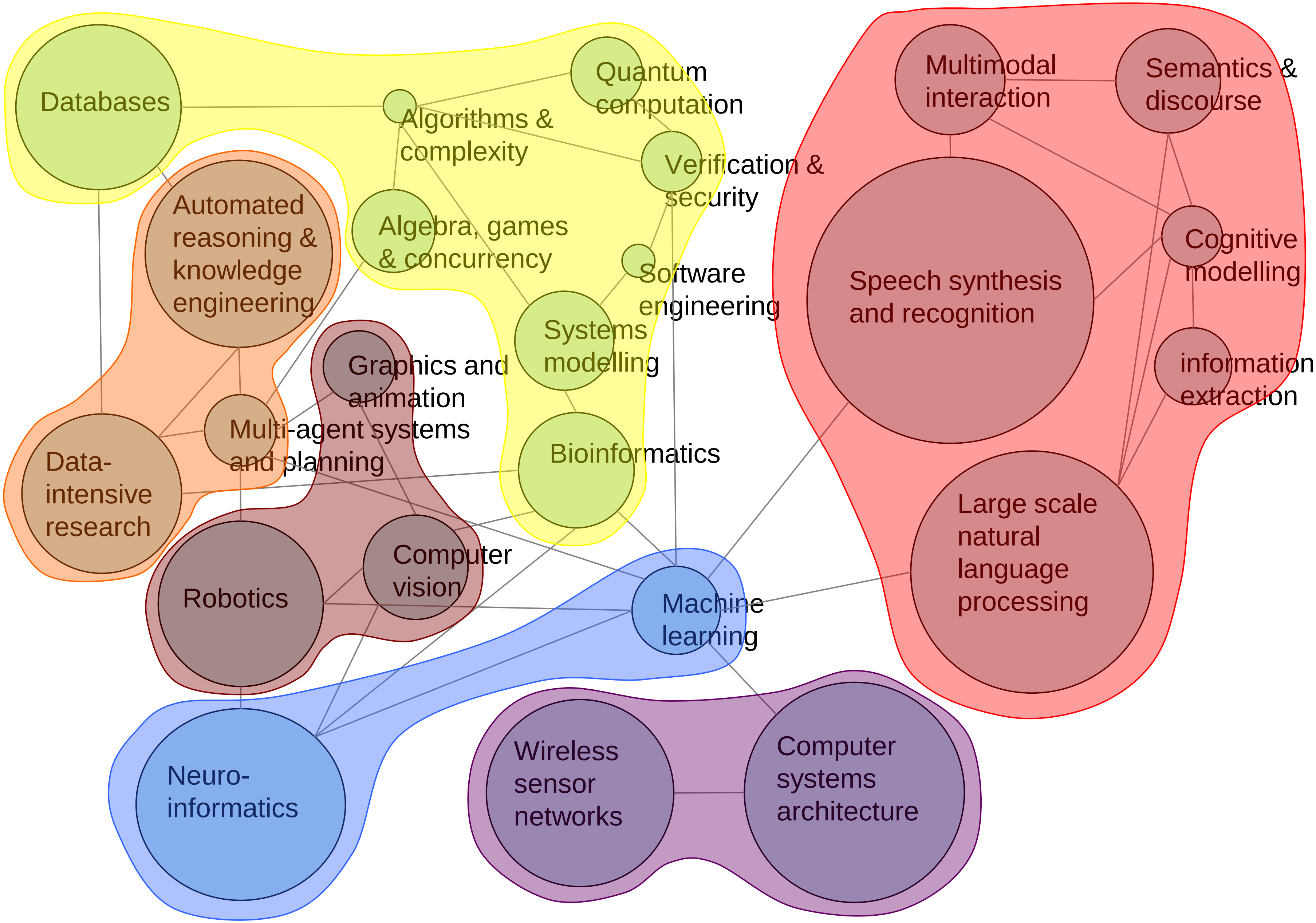
ROBOTICS AND COMPUTER VISION

Institute of Perception, Action and Behaviour (IPAB)

Director: Sethu Vijayakumar

Our research landscape



EDINBURGH CENTRE FOR
ROBOTICS
Innovation Ready

Valkyrie Humanoid

Flagship **Robotarium Platform:**
UoE-NASA Valkyrie Humanoid
UK Hub for Humanoids Research
Space Robotics Challenge

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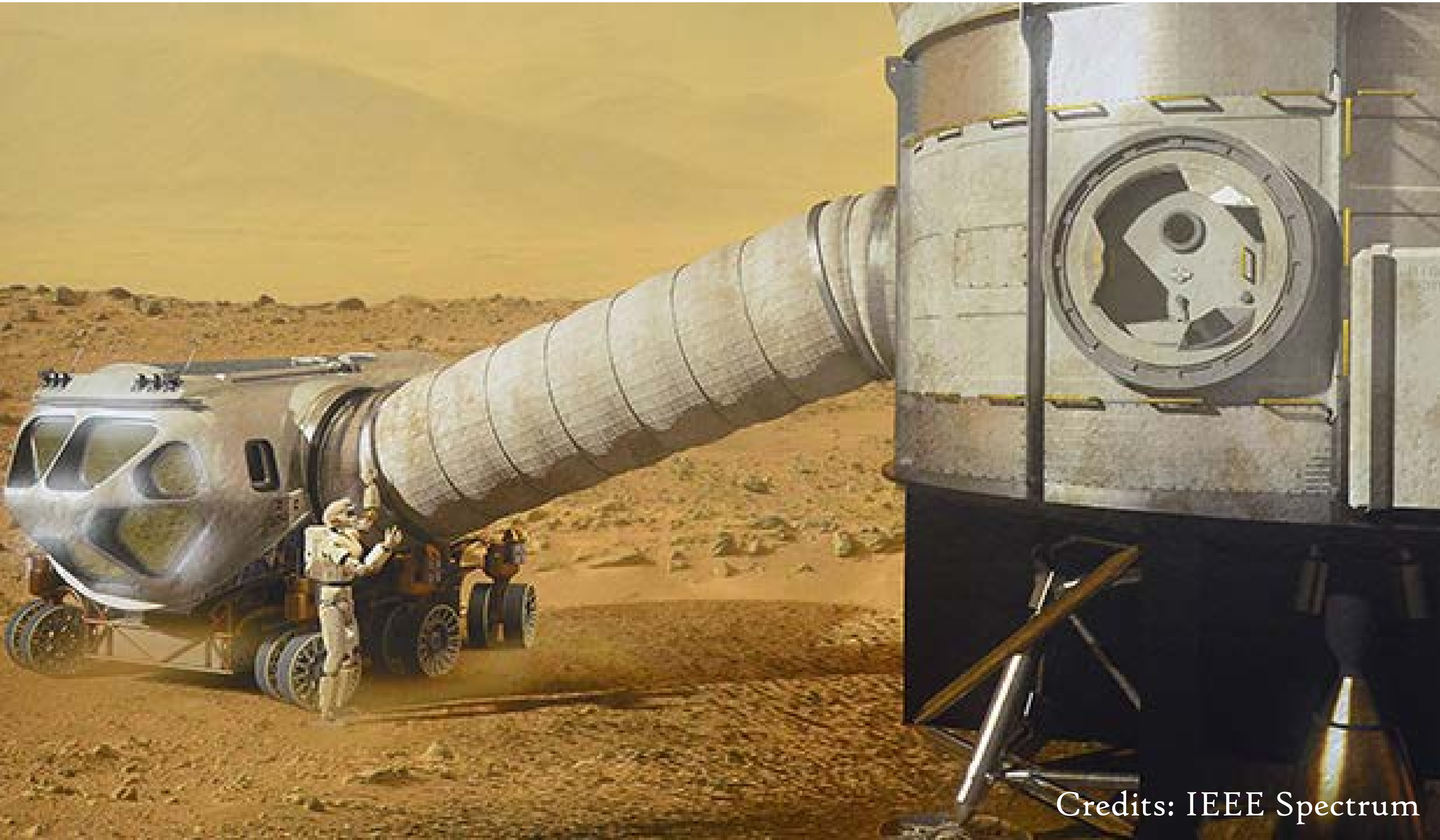
NASA

NASA Space Robotics Challenge

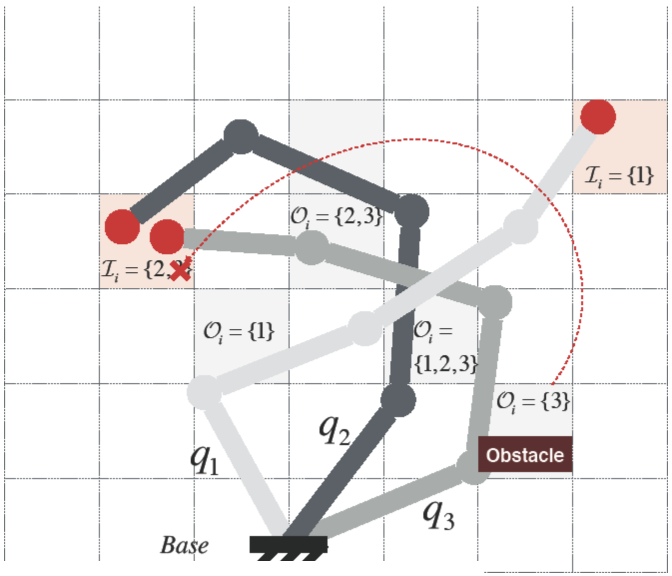
Credits: IEEE Spectrum

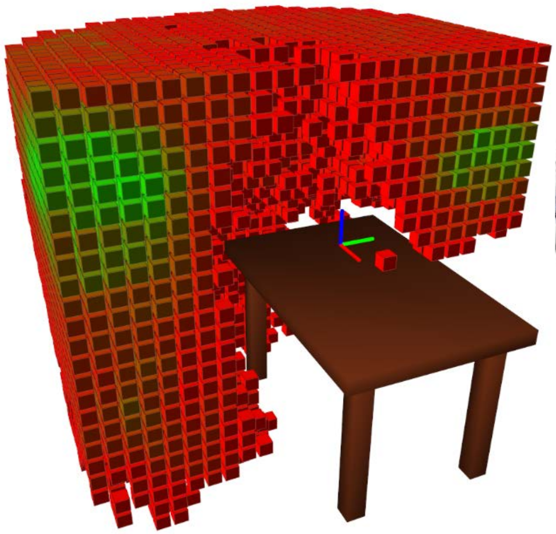
NASA Space Robotics Challenge

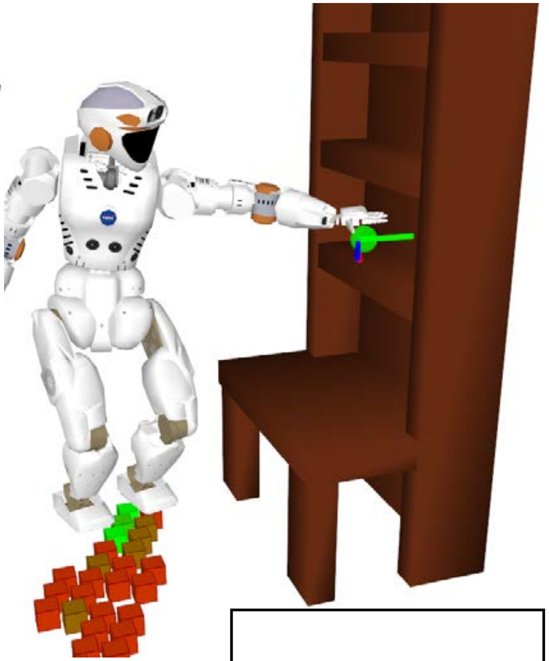
NASA Space Robotics Challenge

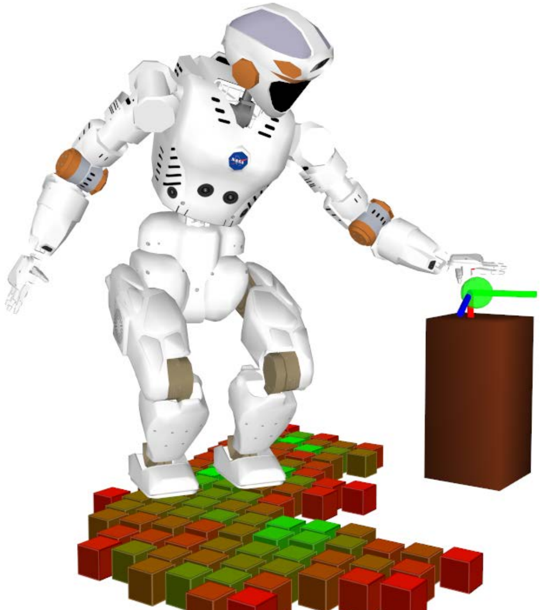


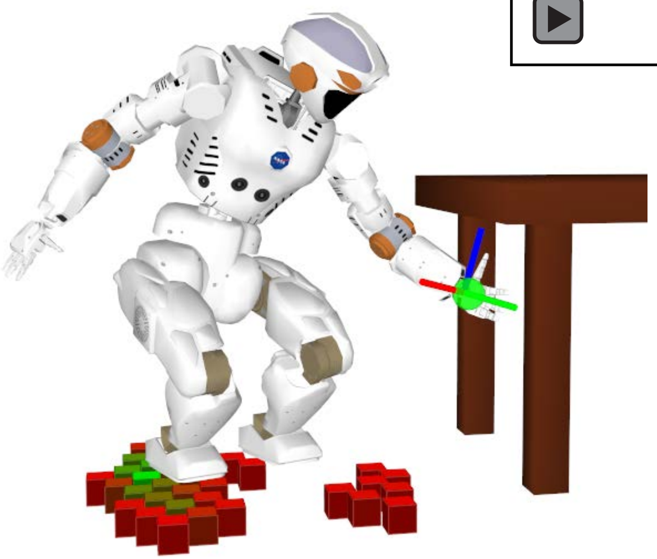
Advanced Whole Body Motion Planning

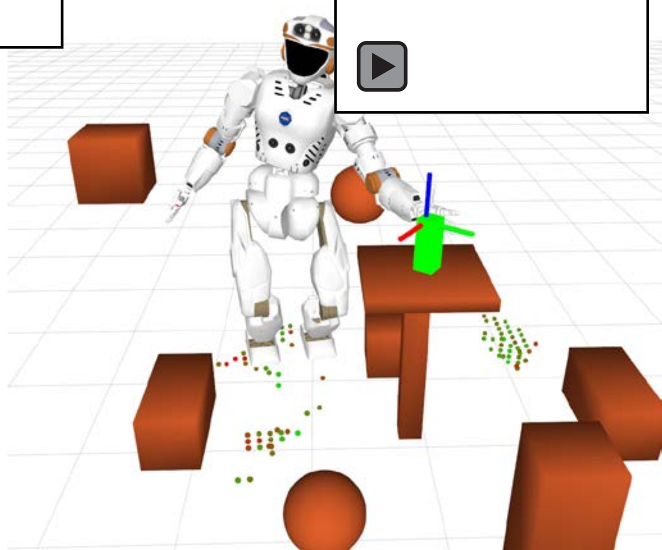








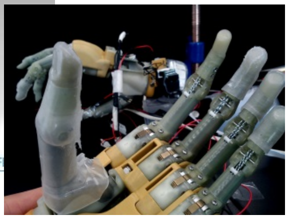




Robots That Interact

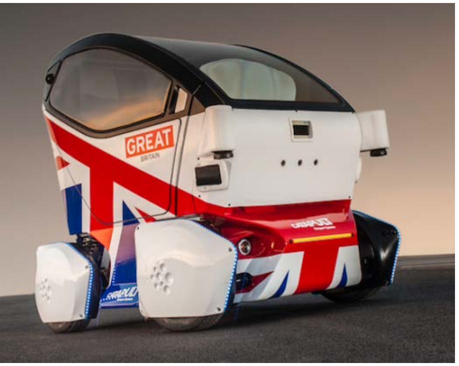
Full-autonomy challenges due to:

1. Close interaction with multiple objects
2. Noisy sensing with ambiguity
3. Hard to model dynamics
4. Guarantees for safe operations
5. Highly constrained environment
6. Un-modelled user intentions



Prosthetics, Exoskeletons

Humanoids



Self Driving Cars

Nuclear Decommissioning

Field Robots (Marine)

Medical Robotics

Service Robots

Industrial/ Manufacturing

1: **Understanding** and **Representing** the world around you

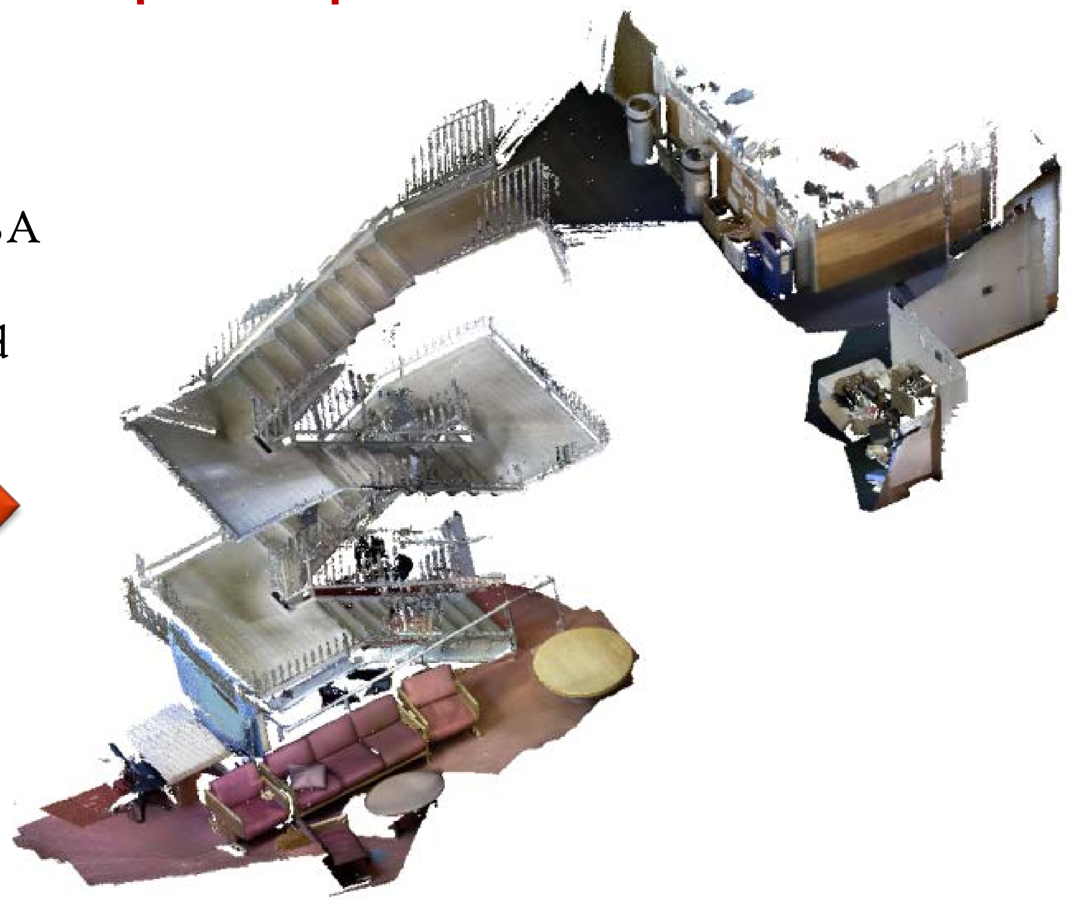
(Tracking and Localisation)

Toyota's Human Support Robot (HSR)

1: **Understanding** and **Representing** the world around you

State Estimation: unified percept of the world

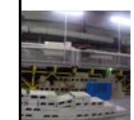
UoE-NASA
Valkyrie
Humanoid
Platform



Fa… al. Dense Ma… Locomotion on uneven terrain, Best Paper Award, Humanoids 2015

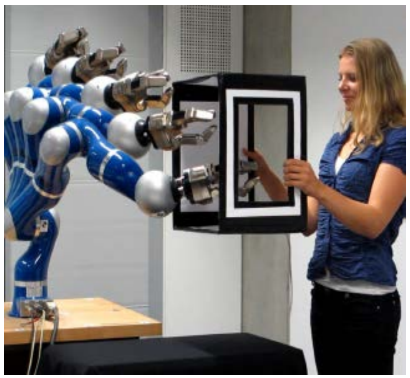
1: Understanding and **Representing** the world around you

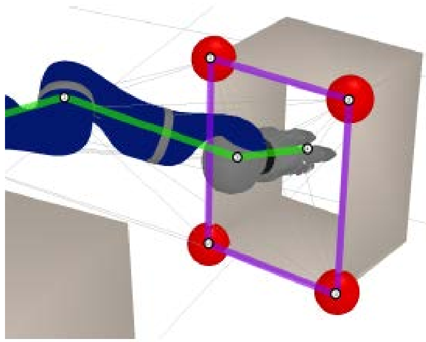
(Closed Loop Sensing and Manipulation)



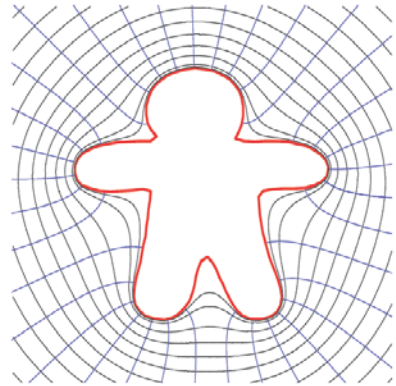
2: **Understanding** and **Representing** the world around you

Bridging Representations

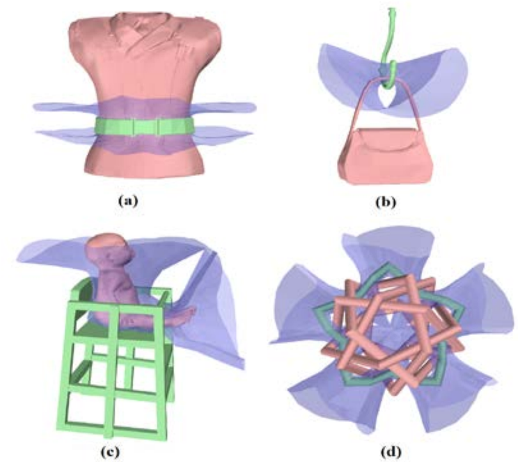




Interaction Mesh based Relational Descriptors



Harmonic Electric Fields



Relational tangent planes

- Interaction with dynamic, articulated and flexible bodies
- Departure from purely metric spaces -- focus on relational metrics between active robot parts and objects/environment
- Enables use of simple motion priors to express complex motion

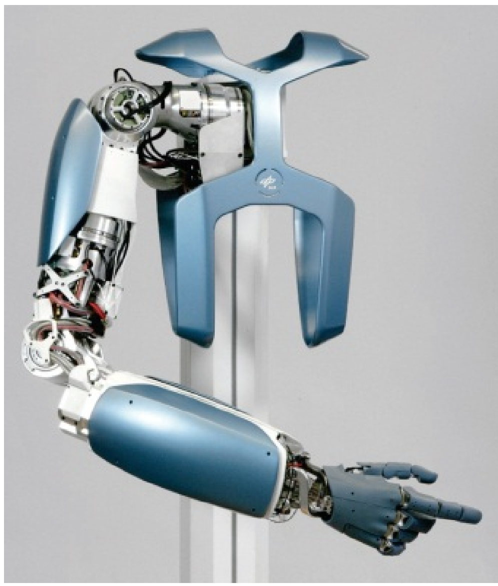
Ivan V, Zarubin D, Toussaint M, Komura T, Vijayakumar S. Topology-based Representations for Motion Planning and Generalisation in Dynamic Environments with Interactions. IJRR. 2013

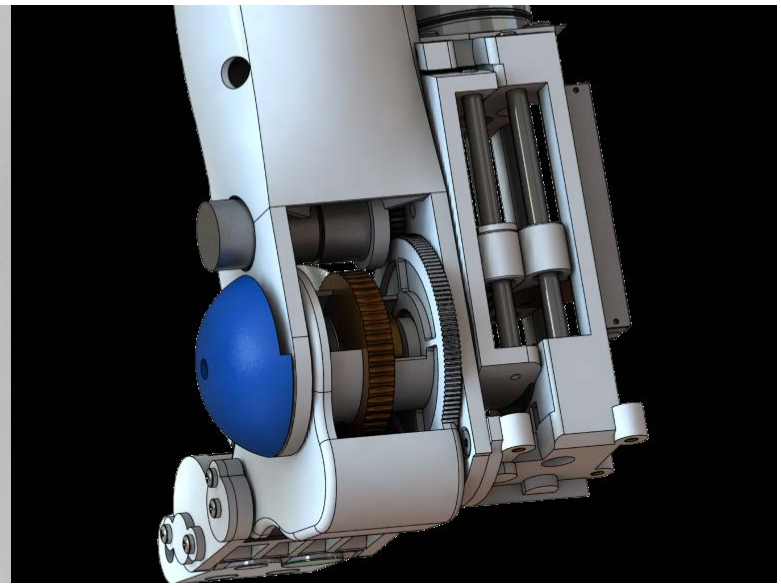
Robots for Confined Spaces

Courtesy: OC Robotics Ltd.

3:Dealing with **Uncertainty**

- through Compliant Actuation

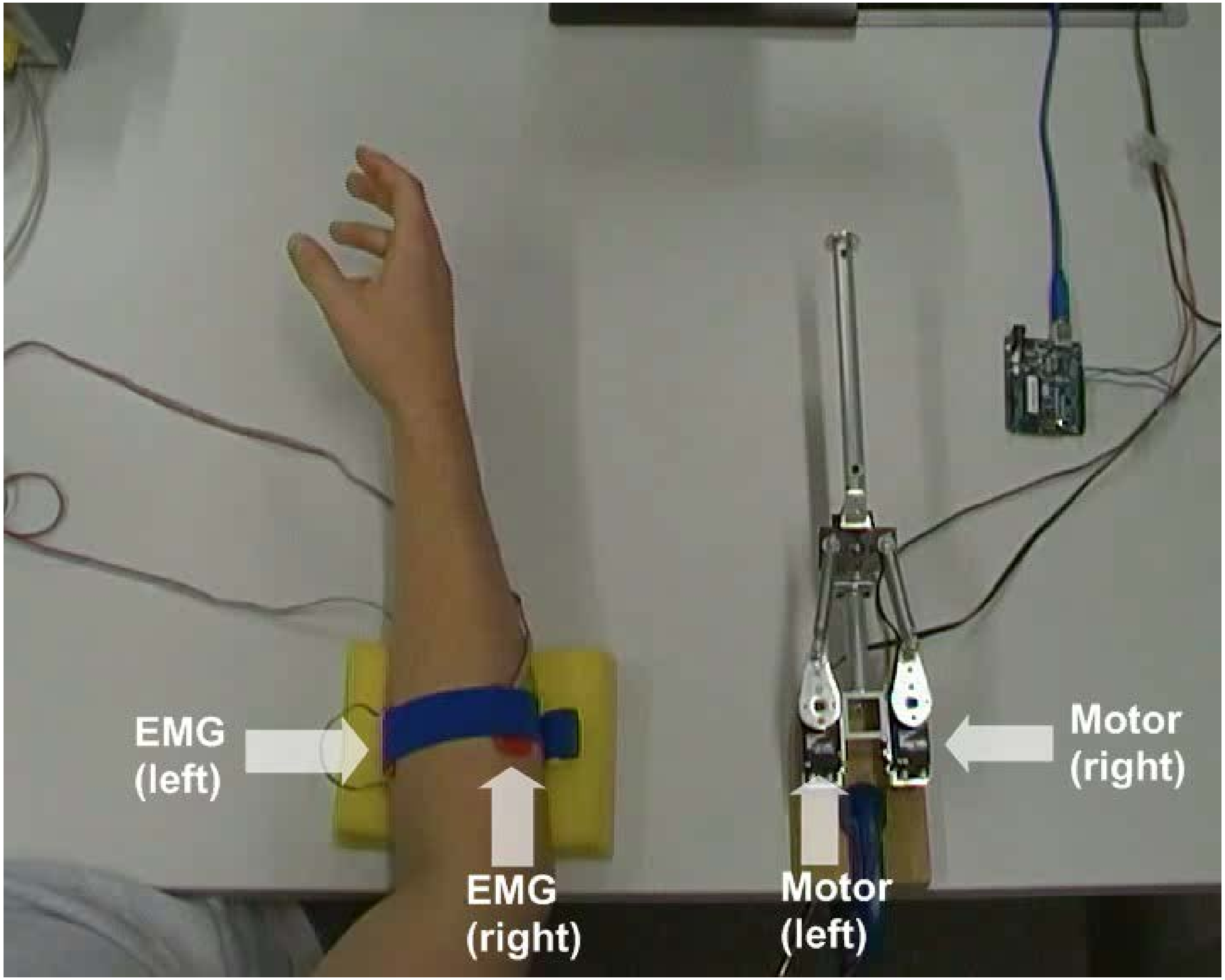


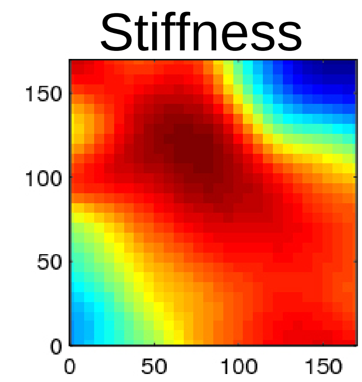


HASy (DLR); BLUE and miniBLUE compliant bipeds @ University of Edinburgh

Braun, Vijayakumar, et. al., Robots Driven by Compliant Actuators: Optimal Control under Actuation Constraints, *IEEE T-RO*), 29(5) (2013). [*IEEE Transactions on Robotics Best Paper Award*]

Variable Stiffness Actuation





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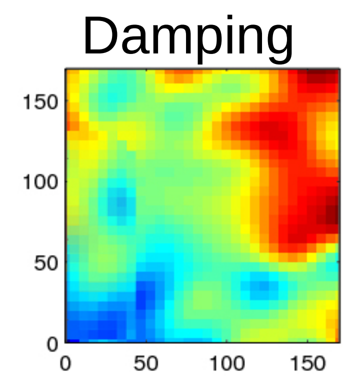
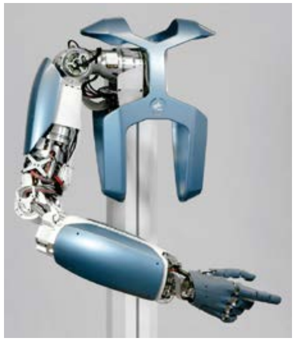


Impedance

Compliant Actuators

- VARIABLE JOINT STIFFNESS

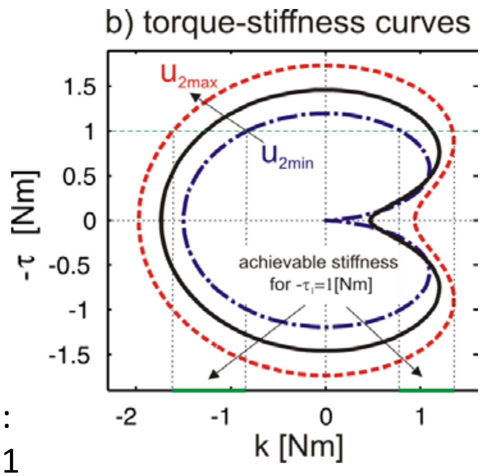
MACCEPA:
Van Ham et.al, 2007



DLR Hand Arm System:
Grebenstein et.al., 2011

$$\boldsymbol{\tau} = \boldsymbol{\tau}(\mathbf{q}, \mathbf{u})$$

$$\mathbf{K} = \mathbf{K}(\mathbf{q}, \mathbf{u})$$



Torque/Stiffness Opt.

- Model of the system dynamics:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}) \quad \mathbf{u} \in \Omega$$

- Control objective:

$$J = -d + w\frac{1}{2}\int_0^T \|\mathbf{F}\|^2 dt \rightarrow \min.$$

- Optimal control solution:

$$\mathbf{u}(t, \mathbf{x}) = \mathbf{u}^*(t) + \mathbf{L}^*(t)(\mathbf{x} - \mathbf{x}^*(t))$$

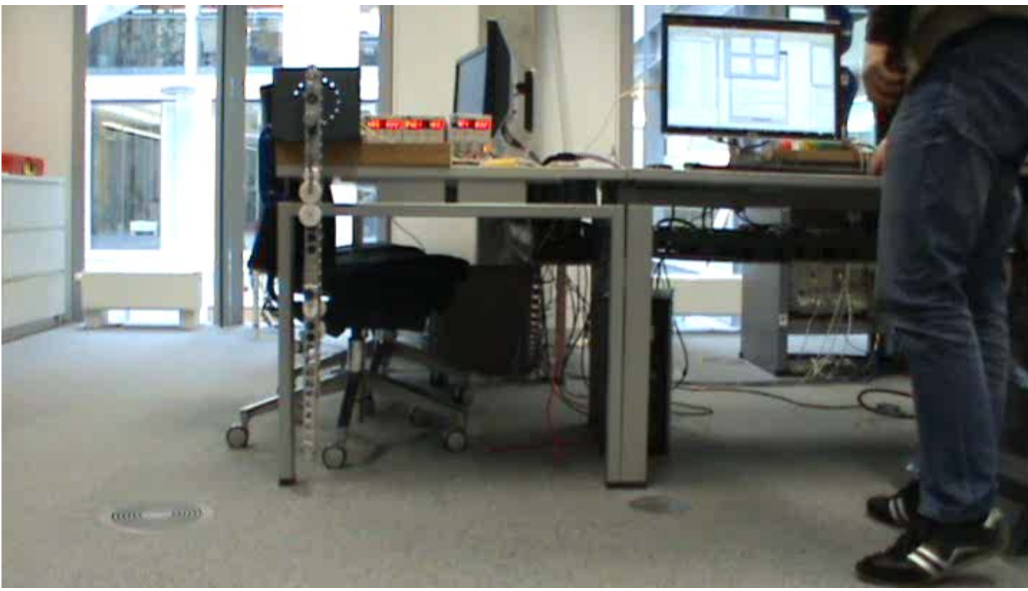
iLQG: Li & Todorov 2007
DDP: Jacobson & Mayne 1970

David Braun, Matthew Howard and Sethu Vijayakumar, Exploiting Variable Stiffness for Explosive Movement Tasks, *Proc. Robotics: Science and Systems (R:SS), Los Angeles* (2011)

THE UNIVERSITY of EDINBURGH informatics

ipab Institute of Perception, Action and Behaviour

Highly **dynamic** tasks, explosive movements



Optimising and Planning with Redundancy: **Stiffness** and **Movement** Parameters

Scale to High Dimensional Problems

David Braun, Matthew Howard and Sethu Vijayakumar, Exploiting Variable Stiffness for Explosive Movement Tasks, *Proc. Robotics: Science and Systems (R:SS), Los Angeles* (2011)

Multi-phase Movement Optimization

- Task encoding of movement with multi-phases

$$J = \phi(\mathbf{x}(\underbrace{T_f}_{(3)})) + \sum_{j=1}^{K} \psi^j(\mathbf{x}(\underbrace{T_j^-}_{(2)})) + \int_{T_0}^{\overset{(3)}{\underline{T_f}}} h(\mathbf{x}, \underbrace{\mathbf{u}}_{(1)})dt$$

Terminal cost Via-point cost Running cost

- cf. individual cost J_i for each phase $T_{j-1} \leq t < T_j$
- total cost by sequential optimization could be suboptimal

Optimization problem

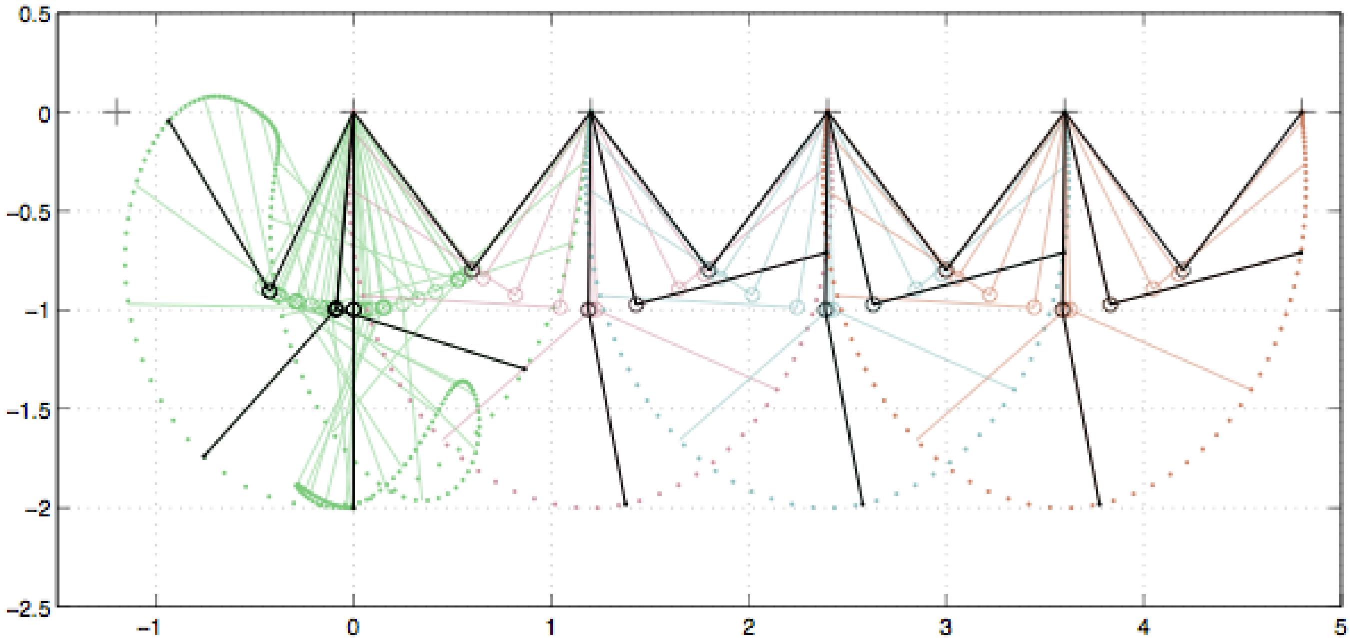
(1) optimal feedback control law $\mathbf{u} = \mathbf{u}(\mathbf{x}, t)$ to minimize J

(2) switching instances $T_1, \cdots, T_k$

(3) final time (total movement duration) T_f

Optimized Brachiating Manoeuvre

Swing-up and locomotion



Additionally optimize for Movement Time

4:Learning to **Predict** and **Adapt**

- Predicting Consequences
- Predicting Task Goals and Intentions

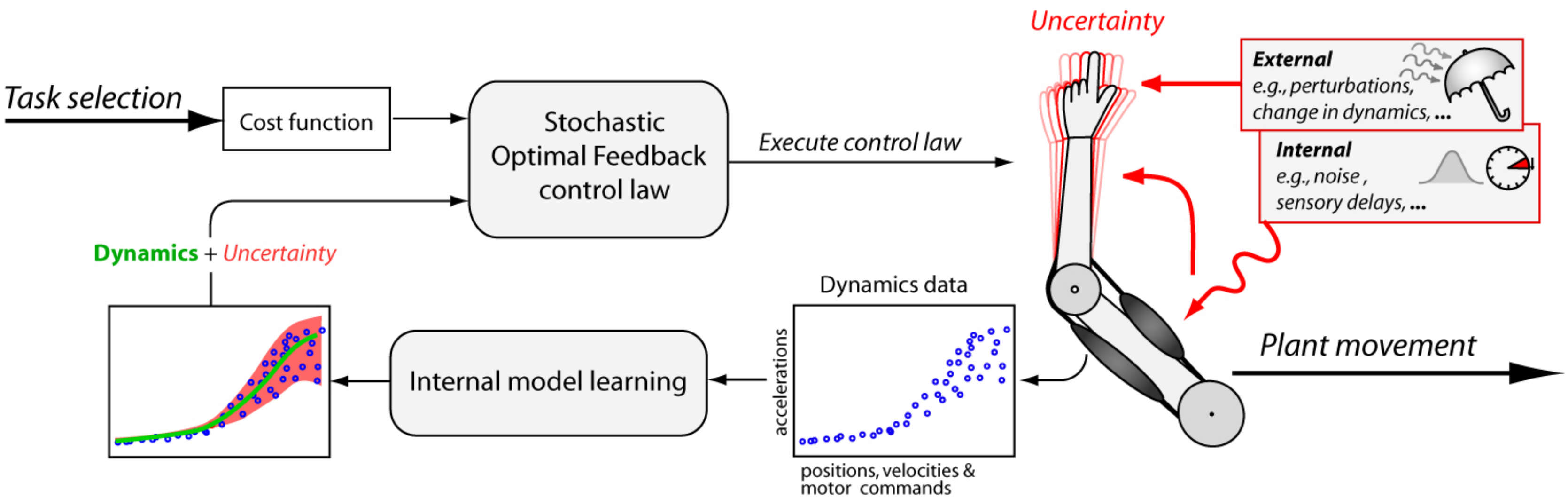
Learning the Internal Dynamics

Learning the Task Dynamics

Stefan Klanke, Sethu Vijayakumar and Stefan Schaal, A Library for Locally Weighted Projection Regression, *Journal of Machine Learning Research (JMLR),* vol. 9. pp. 623--626 (2008).

http://www.ipab.inf.ed.ac.uk/slmc/software/lwpr

On-the-fly adaptation at Any Scale



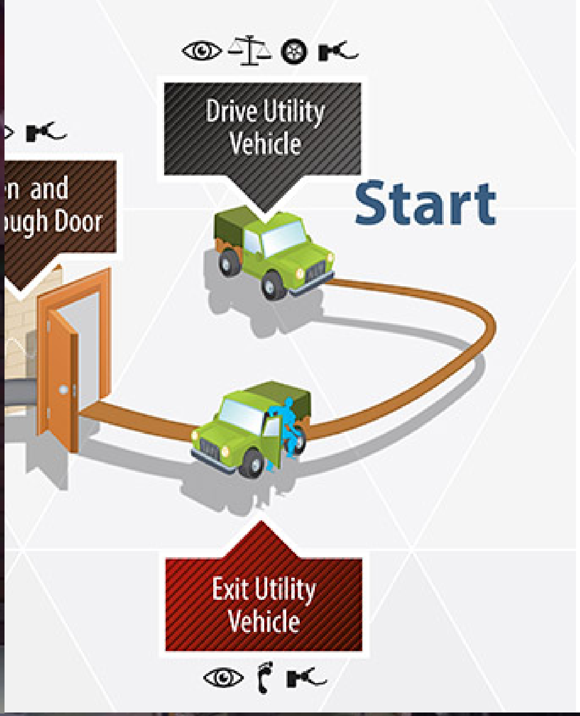
- Fast dynamics online learning for adaptation
- Fast (re) planning methods that incorporate dynamics adaptation
- Efficient Any Scale (embedded, cloud, tethered) implementation

EPSRC Grant: Anyscale Applications (EP/L000725/1): 2013-2017

Putting it all together:
Adaptive, Human-in-the Loop Behaviour

This capability is crucial for **safe, yet precise** human robot interactions as well as applications as diverse as **wearable exoskeletons**.


DANGER
HIGH
VOLTAGE

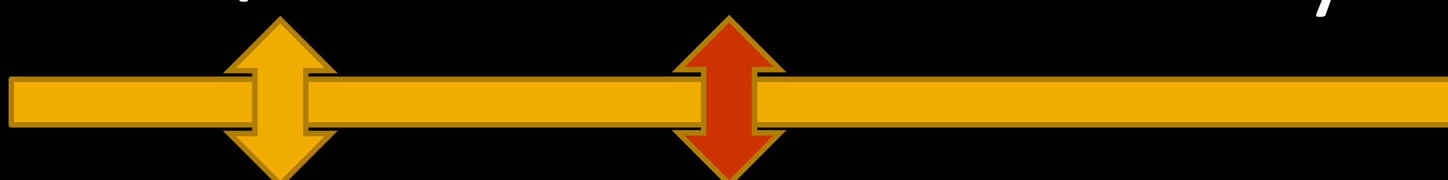

Drive Utility
Vehicle
Start
n and
ugh Door
Exit Utility
Vehicle


Rubble: Clear Debr
or Walk on Rough
Terrain
End
DARPA
DARPA
ROBOTICS
CHALLENGE
FINALS 2015
Climb Stairs


01

Teleoperation

Autonomy



Shared Autonomy

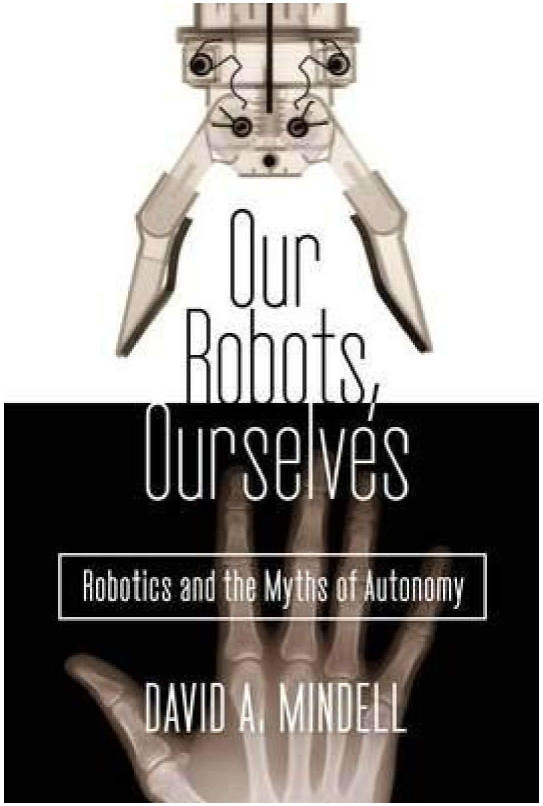
Shared Autonomy

"Full autonomy is a 20th century rhetoric"

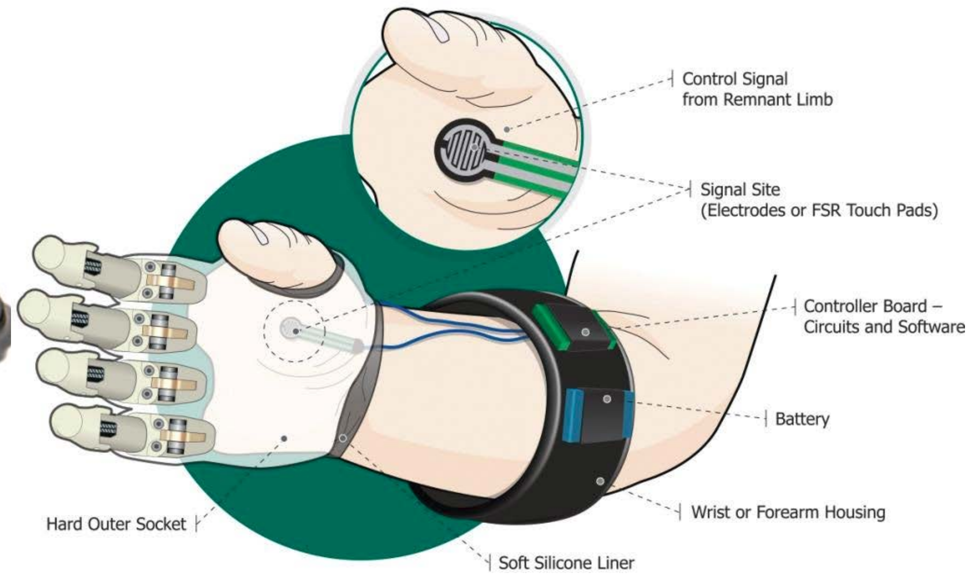
"The real frontier is collaboration, which includes autonomy but **different levels of autonomy at different moments** under the control of a human operator."

"Such systems should have the ability to turn on autonomy when it can be helpful. Autonomy can reduce human workload and fatigue, but humans should still be present in the loop."

- IEEE Spectrum, David Mindell (MIT)



Shared Autonomy: An Example



touch
bionics

UoE contact: Professor Sethu Vijayakumar (CDT Director)
sethu.vijayakumar@ed.ac.uk

EPSRC CDT-RAS

The EPSRC Center for Doctoral Training in Robotics & Autonomous Systems

- Multidisciplinary ecosystem – 65 PhD graduates over 8.5 years, 50 PIs across Engineering and Informatics disciplines

  Control, actuation, Machine learning, AI, neural computation, photonics, decision making, language cognition, human-robot interaction, image processing, manufacture research, ocean systems …

- Technical focus – ‘Interaction’ in Robotic Systems

  Environment: Multi-Robot: People: Self: Enablers

- ‘Innovation Ready’ postgraduates

  Populate the innovation pipeline. Create new businesses and models.

- Cross sector exploitation

  Offshore energy, search & rescue, medical, rehabilitation, ageing, manufacturing, space, nuclear, defence, aerospace, environment monitoring, transport, education, entertainment ..

- Total Award Value (> £14M): CDT £7M, Robotarium £7.1M

  38 company sponsors, £2M cash, £6.5M in-kind (so far ..)

  Schlumberger, Baker Hughes,, Renishaw, Honda, Network Rail, Selex, Thales, BAe, BP, Pelamis, Aquamarine Power, SciSys, Shadow Robot, SeeByte, Touch Bionics, Marza, OC Robotics, KUKA, Dyson, Agilent …

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ROBOTICS

ROBOTARIUM

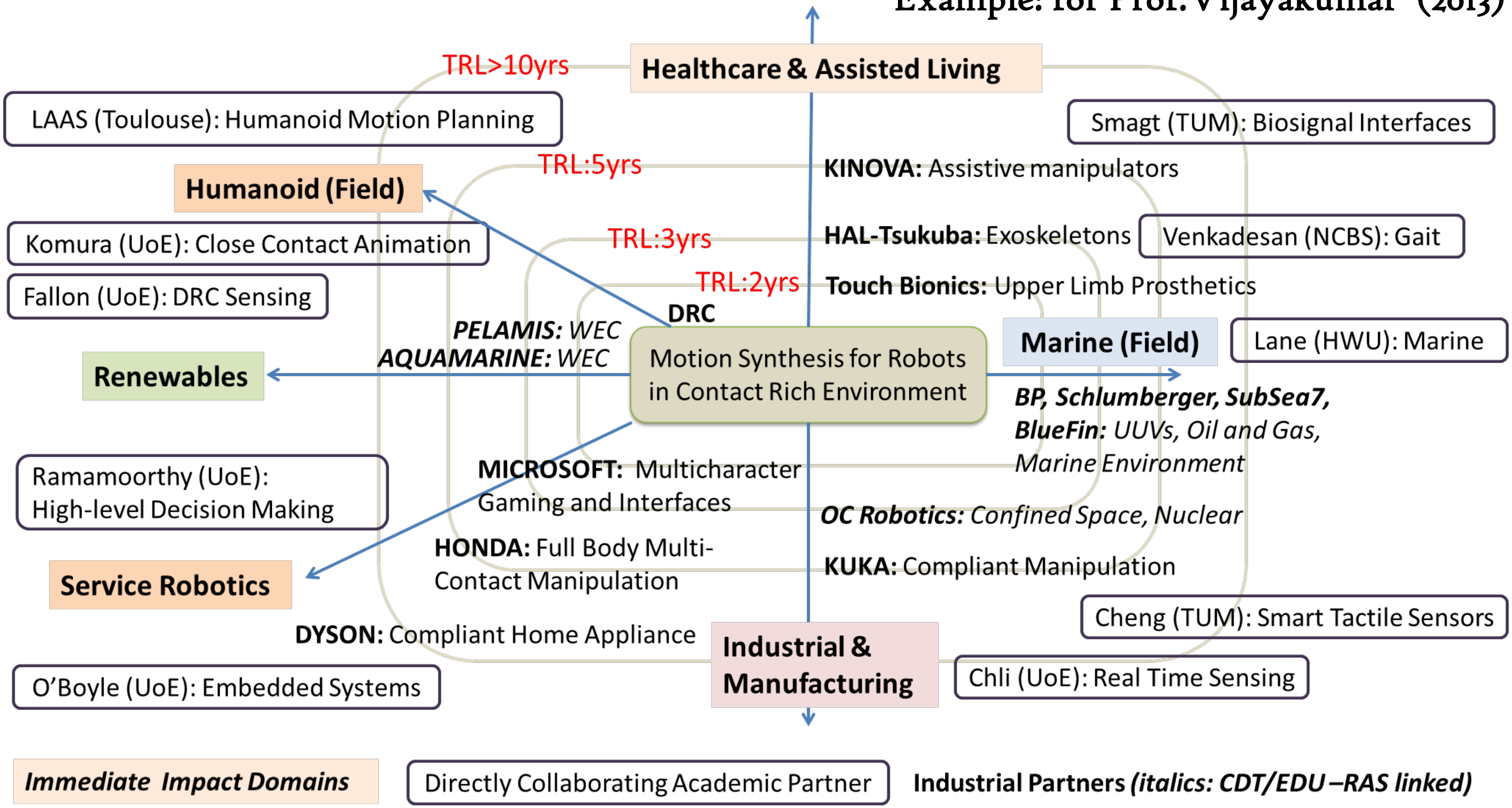
A National UK Facility for Research into the Interactions amongst Robots, Environments, People and Autonomous Systems

www.edinburgh-robotics.org

EPSRC

Translation and Impact

Example: for Prof. Vijayakumar (2013)



- Translation through Industrial & Scientific Collaborations and Skilled People

“we tend to overestimate technology
in the short term and
underestimate technology
in the long term”

Arthur C. Clarke

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$\overbrace{\text{Shared Autonomy for Robotics}}^{\text{interactive}}$

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ROYAL ACADEMY OF ENGINEERING

Microsoft Research