The Alan Turing Institute

THE UNIVERSITY OF EDINBURGH

EDINBURGH CENTRE FOR ROBOTICS

Shared Autonomy
The Future of Interactive Robotics

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EPSRC
Engineering and Physical Sciences Research Council

Robotics is becoming ubiquitous

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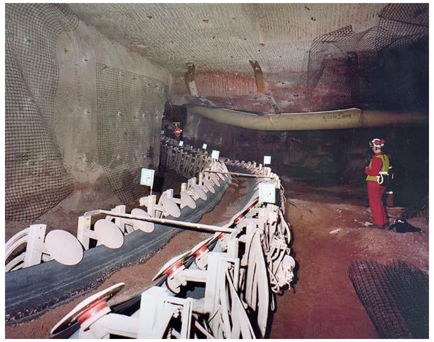
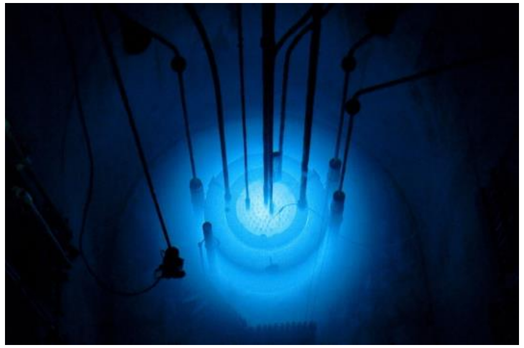
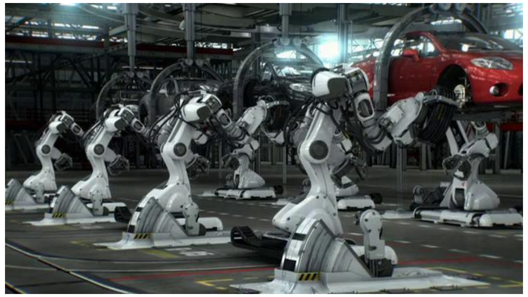
Affecting Everything That Moves

The real world

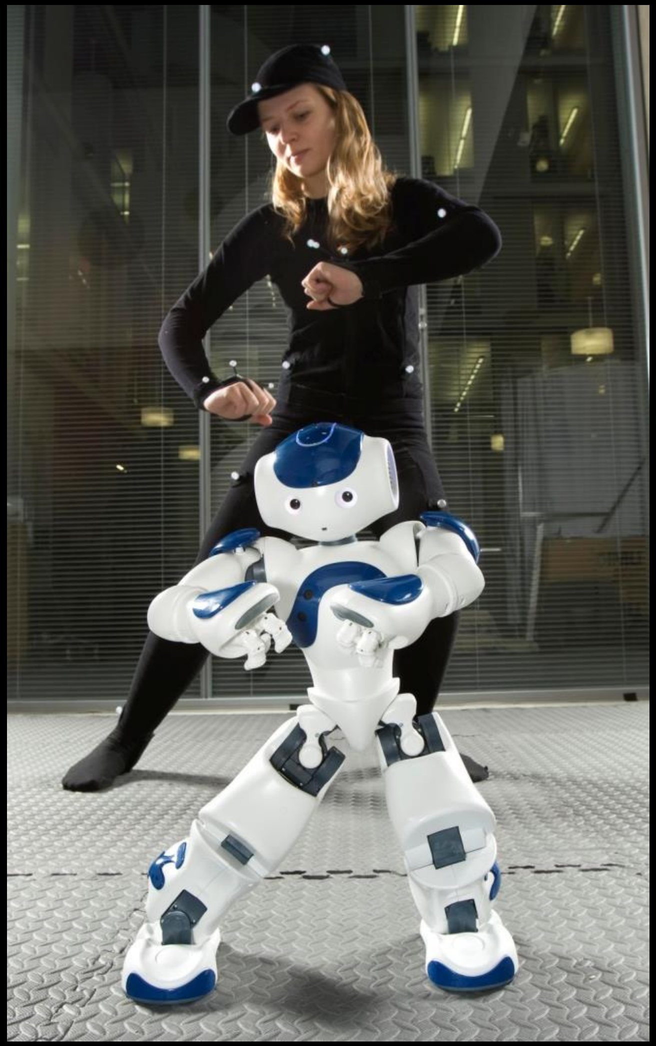






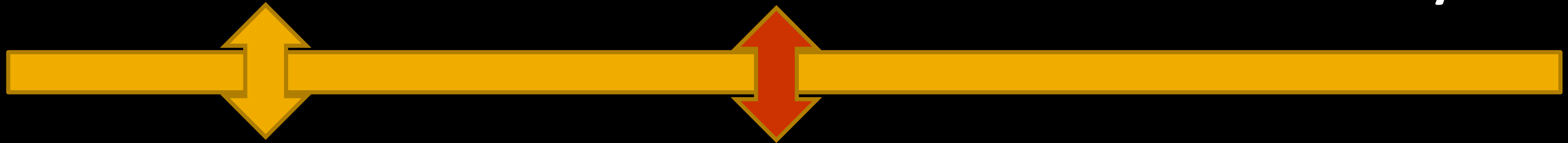




Teleoperation

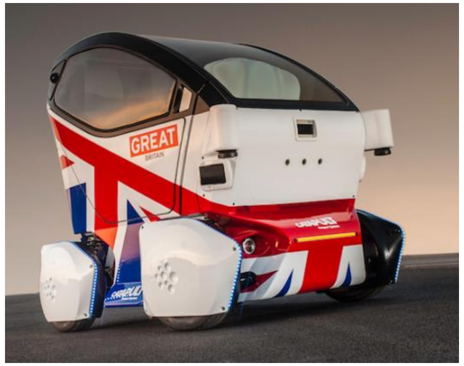
Autonomy



Shared Autonomy

Robots That Interact

Prosthetics, Exoskeletons

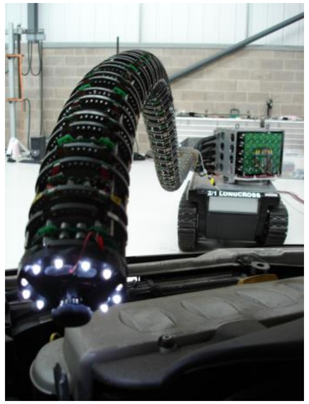


Self Driving Cars

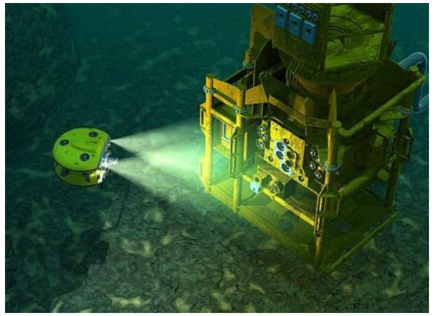
Full-autonomy challenges due to:

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

Humanoids



Nuclear Decommissioning



Field Robots (Marine)

Inspection and Integrity

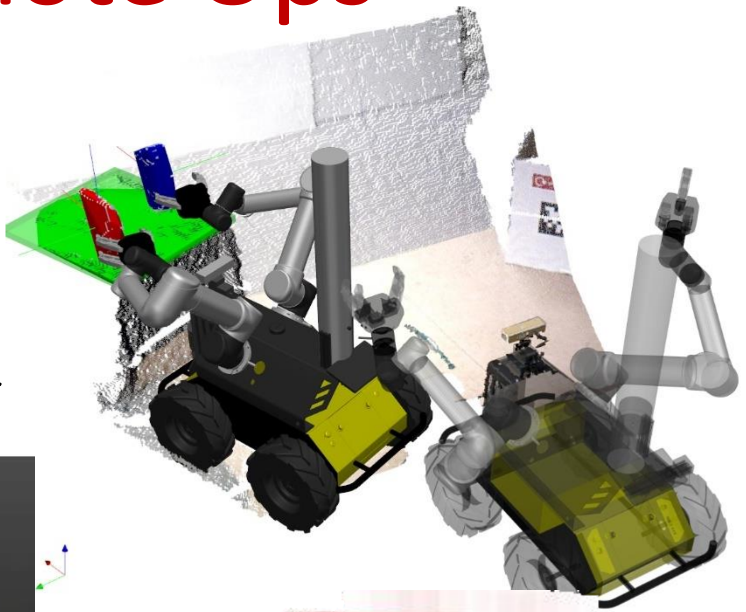
Medical Robotics

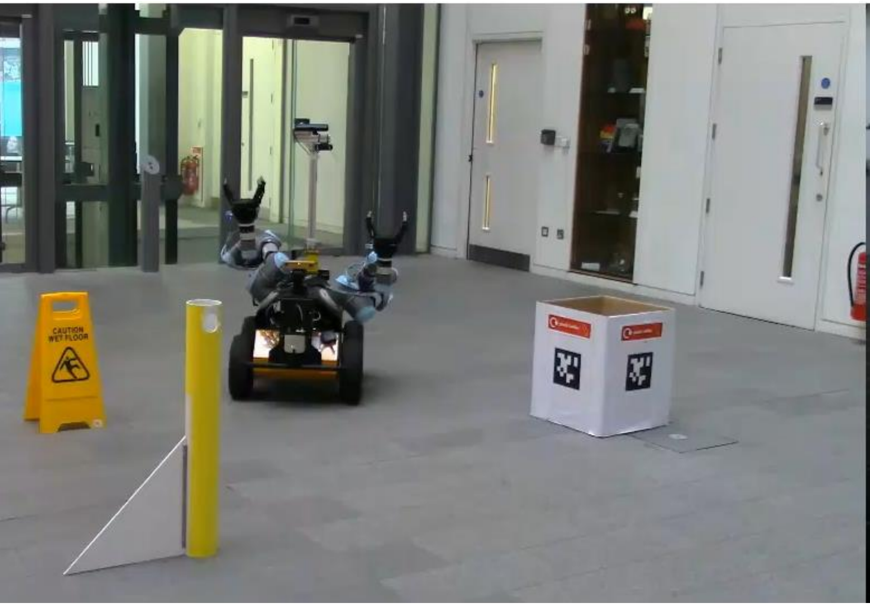
Service Robots

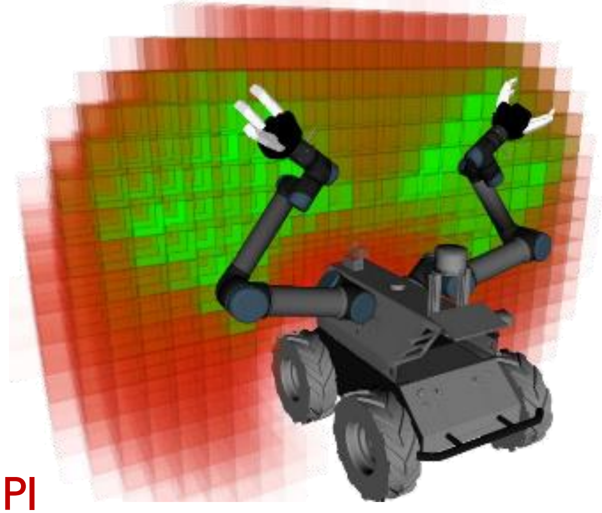
Industrial/ Manufacturing

Project 1: Shared Autonomy for Remote Ops

1. Shared autonomy or remote operation with **assisted teleoperation** and **autonomous behaviours**
2. **No line of sight** – depth sensing, laser, situational awareness cameras
3. **High performance compression and networking** with **fail safety**



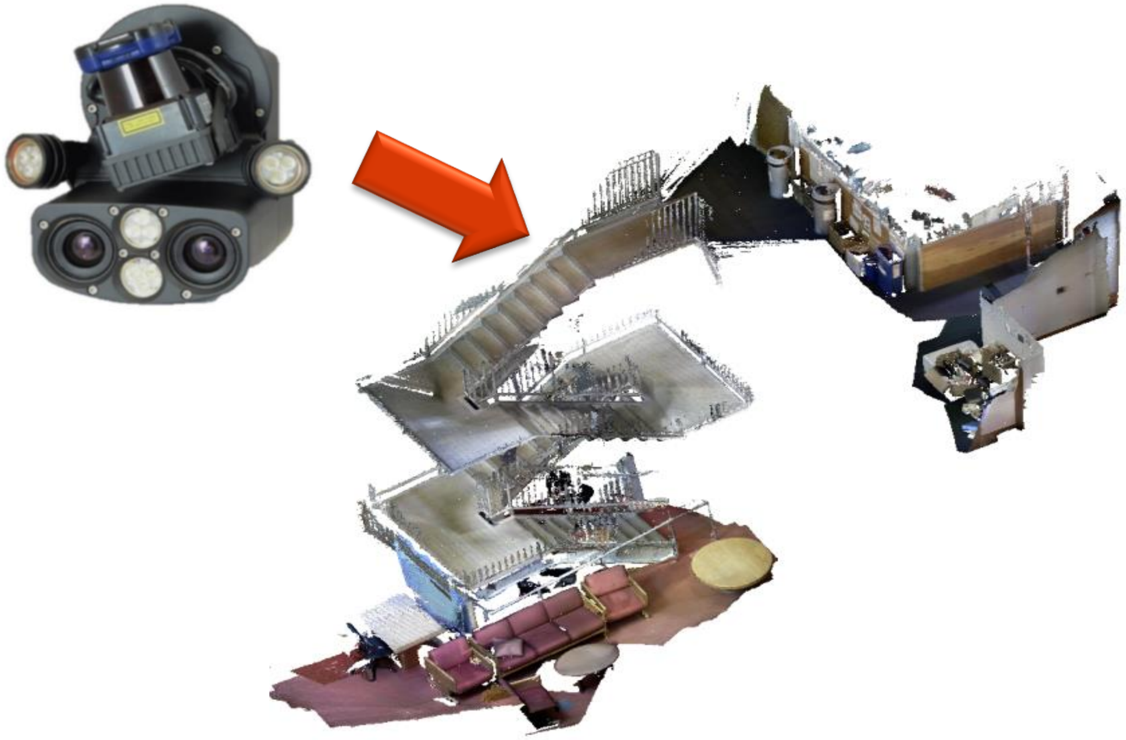




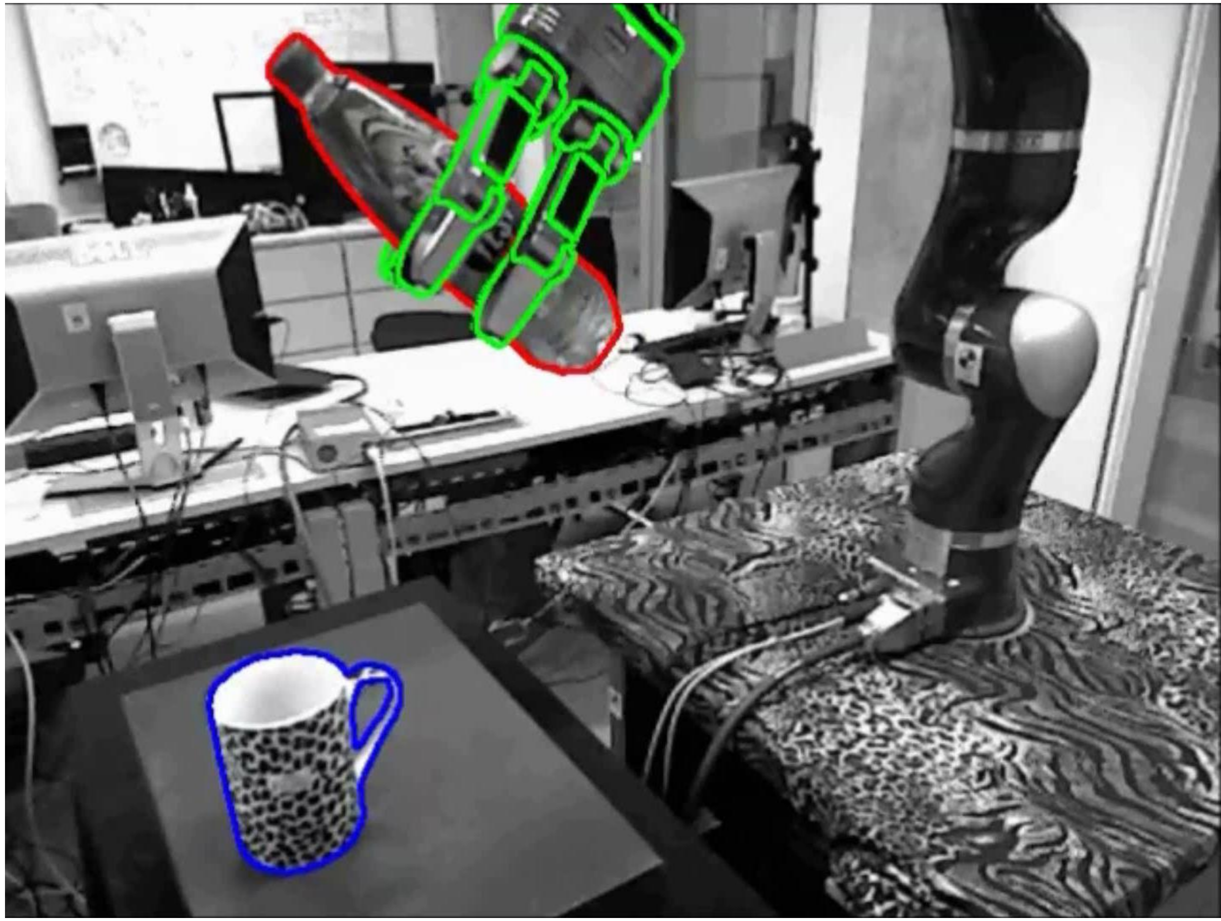
[2018-2022] **EPSRC** co-funded National Centre for Nuclear Robotics (NCNR): **£11.3M:** Mistry PI

W. Merkt, S. Vijayakumar et. al, Robust Shared Autonomy for Mobile Manipulation with Continuous Scene Monitoring, *Proc. 13th IEEE Conference on Automation Science and Engineering*, Xian, China (2017)

Real-time Sensing and Acting with Feedback

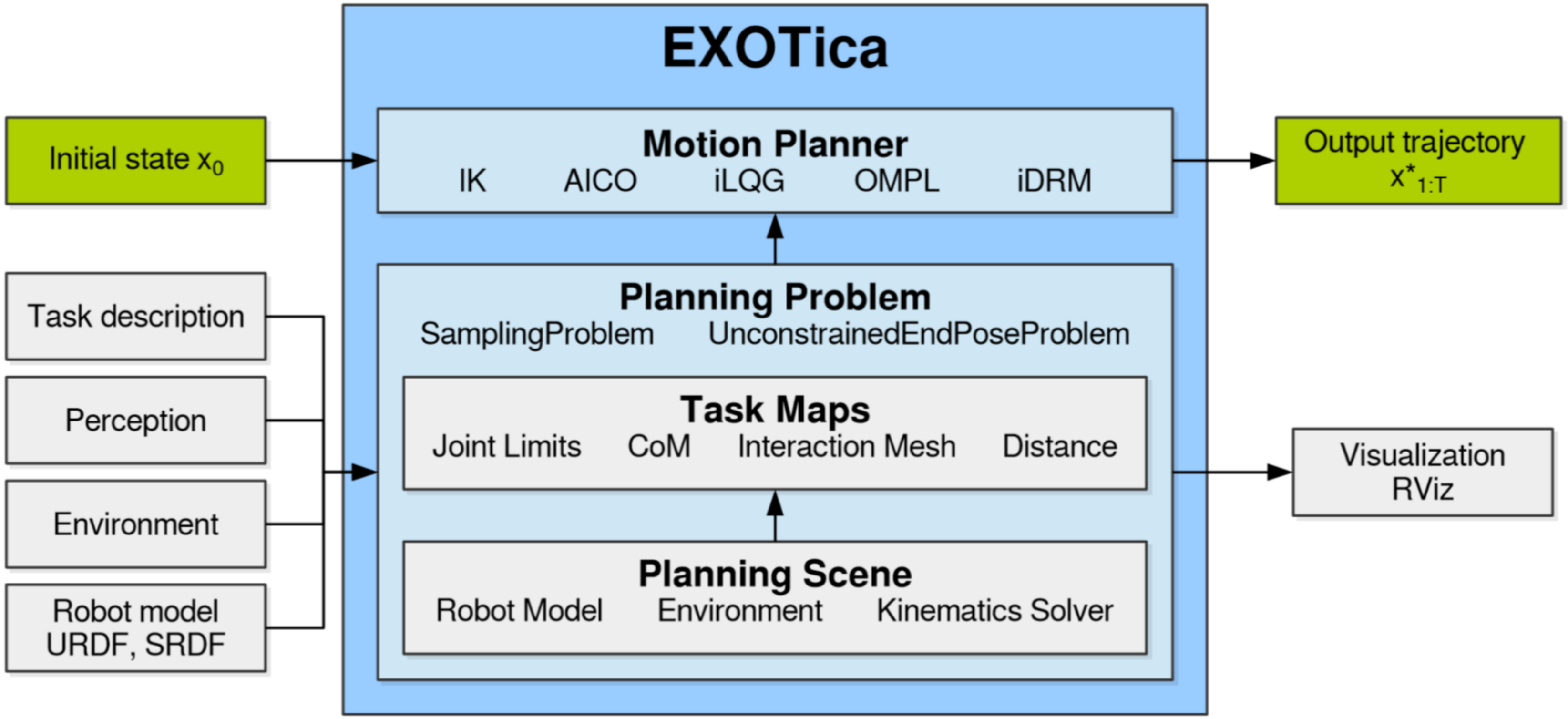


T. Whelan, M. Kaess, H. Johannsson, M. F. Fallon, J. J. Leonard, and J. B. McDonald, “Real-time Large Scale Dense RGB-D SLAM with Volumetric Fusion,” *Intl. J. of Robotics Research*, vol. 34, iss. 4-5, pp. 598-626, 2015.



K. Pauwels, V. Ivan, E. Ros and S. Vijayakumar, **Real-time object pose recognition and tracking with an imprecisely calibrated moving RGB-D camera,** *Proc. IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems* (IROS), Chicago (2014).

Integrated Motion Planner for Shared Autonomy



Code: https://github.com/ipab-slmc/exotica
Documentation: https://ipab-slmc.github.io/exotica

Vladimir Ivan, Yiming Yang, Wolfgang Merkt, Michael P. Camilleri, Sethu Vijayakumar, **EXOTica: An Extensible Optimization Toolset for Prototyping and Benchmarking Motion Planning and Control**, *In: Koubaa A. (eds) Robot Operating System (ROS). Studies in Computational Intelligence, Springer*, vol. 778, pp. 211-240 (2019)

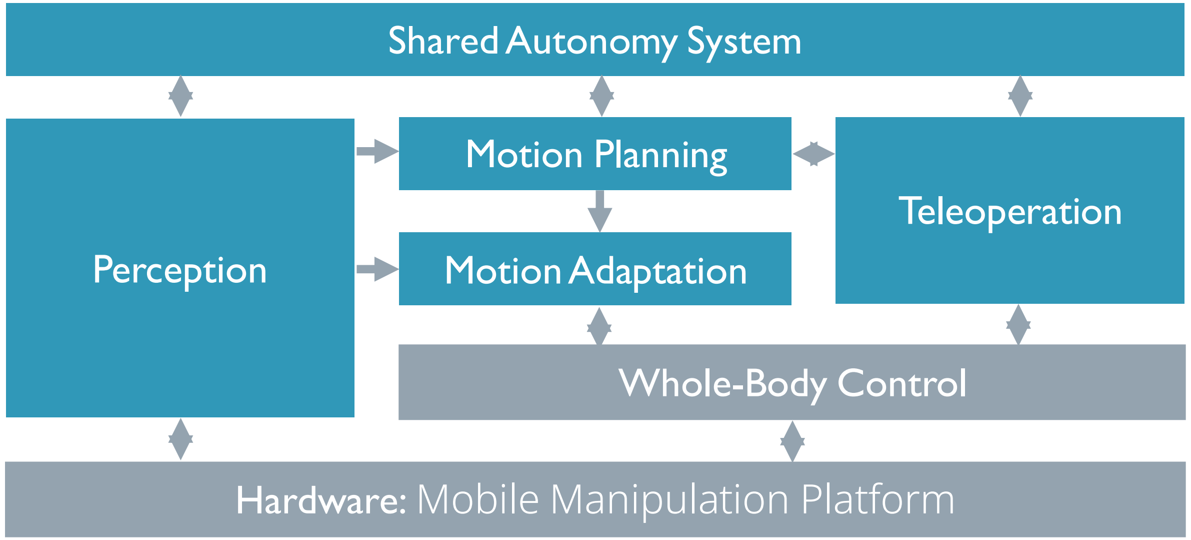
ORCA HUB
Offshore Robotics for Certification of Assets
Remote Safety and Integrity

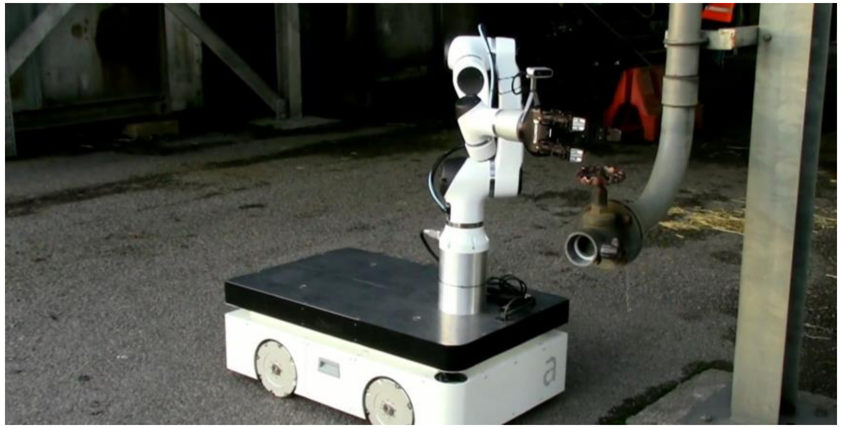
Manipulation in Dynamic Environments

- **Target:** Manipulating moving obstacles (enclosed) in complex, non-static environments

➔ Continuous, non-stop motion with fast, reactive planning desired

- Salient USPs:
    1. *Time-indexed bi-directional motion planning*
    2. Robust and modular, can be used for manipulators & mobile co-bots
    3. Scales to high DoF
    4. Efficient (< 100ms)
- Integration and demonstration Field Trials
- Uses 'Exotica' motion planner





Y. Yang, W. Merkt, V. Ivan, S. Vijayakumar, **Planning in Time-Configuration Space for Efficient Pick-and-Place in Non-Static Environments with Temporal Constraints**, IEEE Humanoids 2018.

Current Project Portfolio in **Shared Autonomy**

Project 2: Robot Assisted Remote Inspection, Maintenance, Repair of Assets

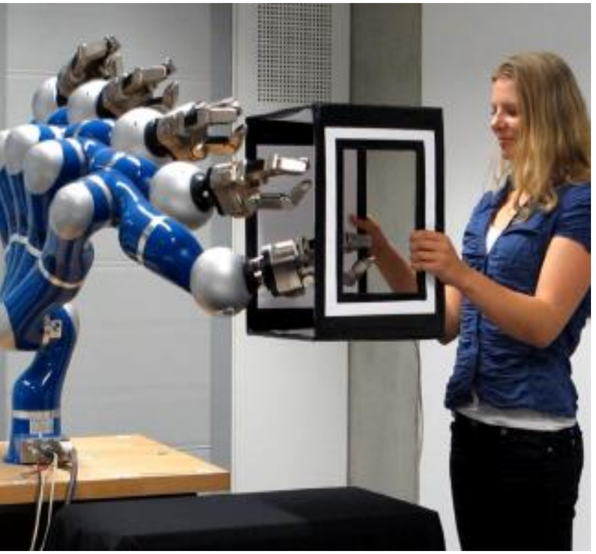
Legged Mobility and Contacts, Impedance Control

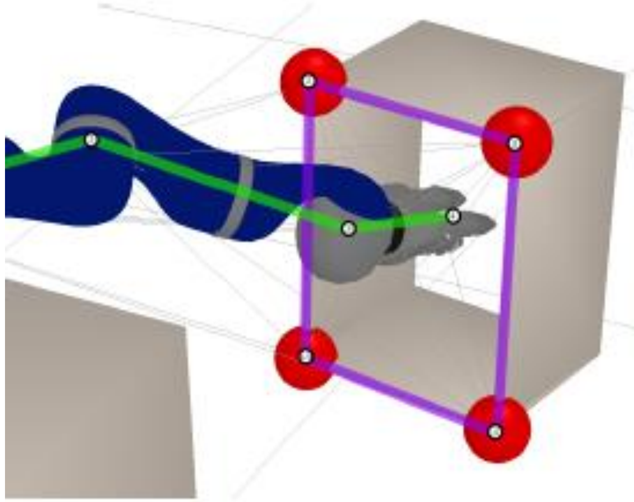
ORCA HUB
Offshore Robotics for Certification of Assets
Remote Safety and Integrity

[2018-2022] **EPSRC** co-funded **Robotics and AI (RAI) Hub** in Offshore Robotics for Certification of Assets (**ORCA**): **£15M**

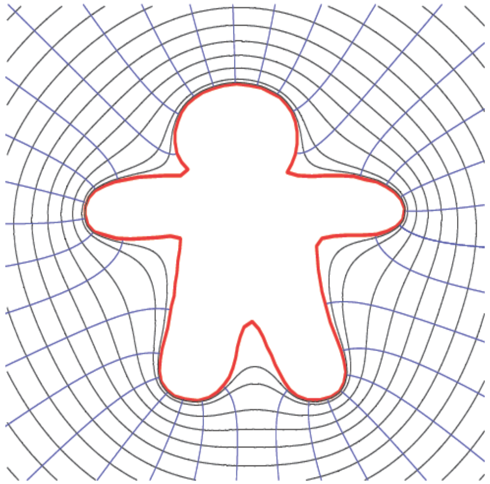
Jun Nakanishi, Andreea Radulescu, David Braun and Sethu Vijayakumar, Spatio-temporal Stiffness Optimization with Switching Dynamics, Autonomous Robots, vol. 41(2), pp. 273-291 (2017).

Bridging **Representations** with **Topology**

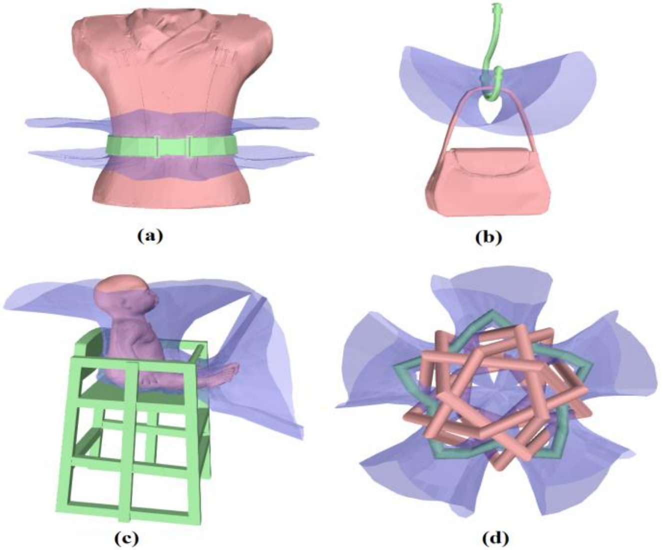




Interaction Mesh based Relational Descriptors



Harmonic Electric Fields



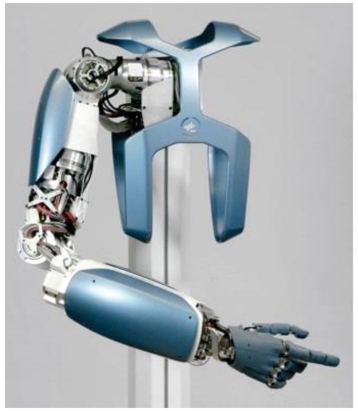
Relational tangent planes

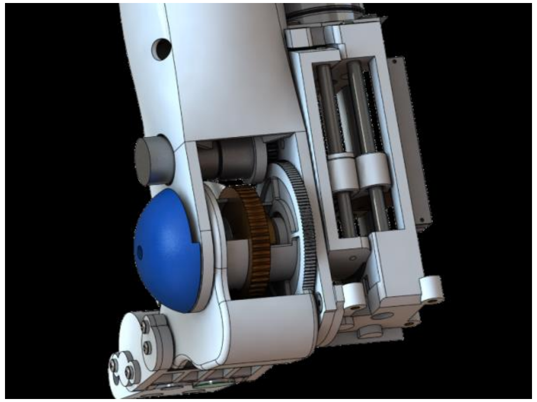
[redacted]th dynamic, articulated and flexible bodies
[redacted]n purely metric spaces -- focus on relational metrics between
[redacted]arts and objects/environment
[redacted] simple motion priors to express complex motion [redacted]

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

Dealing with **Uncertainty**

Compliant Actuation Design & Stiffness Control





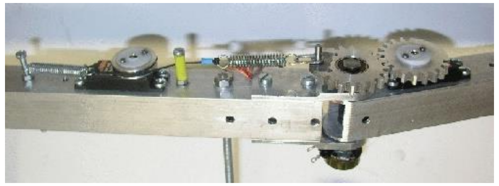
- Design of novel passive compliant mechanism to deal with unexpected disturbances and uncertainty in general
- Algorithmically treat stiffness control under real world constraints
- Exploit natural dynamics by modulating variable impedance
- **Benefits:** Efficiency, Safety and Robustness

D. Braun, F. Petit, F. Huber, S. Haddadin, P. van der Smagt, A. Albu-Schffer and S.Vijayakumar, **Robots Driven by Compliant Actuators: Optimal Control under Actuation Constraints**, *IEEE Transactions on Robotics* (*IEEE T-RO*), 29(5), pp. 1085-1101 (2013). [TRO Best Paper Award]

Compliant Actuation Design & Stiffness Control

Compliant Actuators

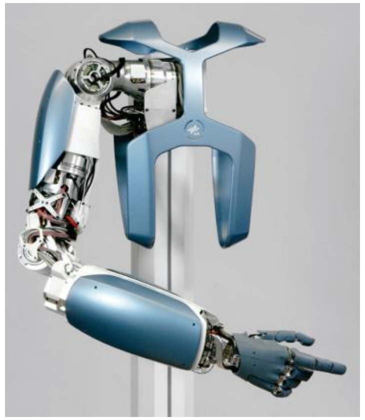
- VARIABLE JOINT STIFFNESS



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

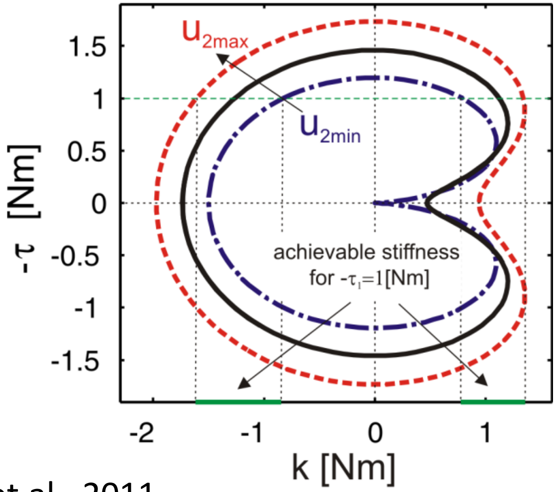
$$\mathbf{K} = \mathbf{K}(\mathbf{q},\mathbf{u})$$

MACCEPA: Van Ham et.al, 2007



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

b) torque-stiffness curves



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)

Graphical Model Representation

Given:

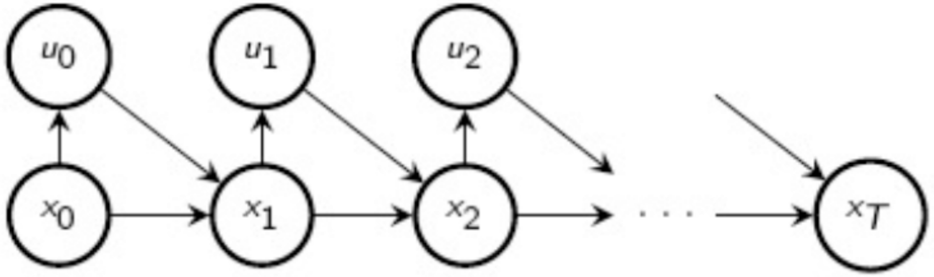
- Discrete time controlled stochastic process

State: $x_t \in \mathbb{X} = \mathbb{R}^n$

$\bar{x} = (x_0, \ldots, x_T)$

Control: $u_t \in \mathbb{U} = \mathbb{R}^m$

$\bar{u} = (u_0, \ldots, u_T)$



Transition Probability:

$P(x_{t+1}|x_t, u_t)$ (typically $P(x_{t+1}|x_t, u_t) = \mathcal{N}(x_{t+1}; f(x_t, u_t), \mathbf{Q})$)

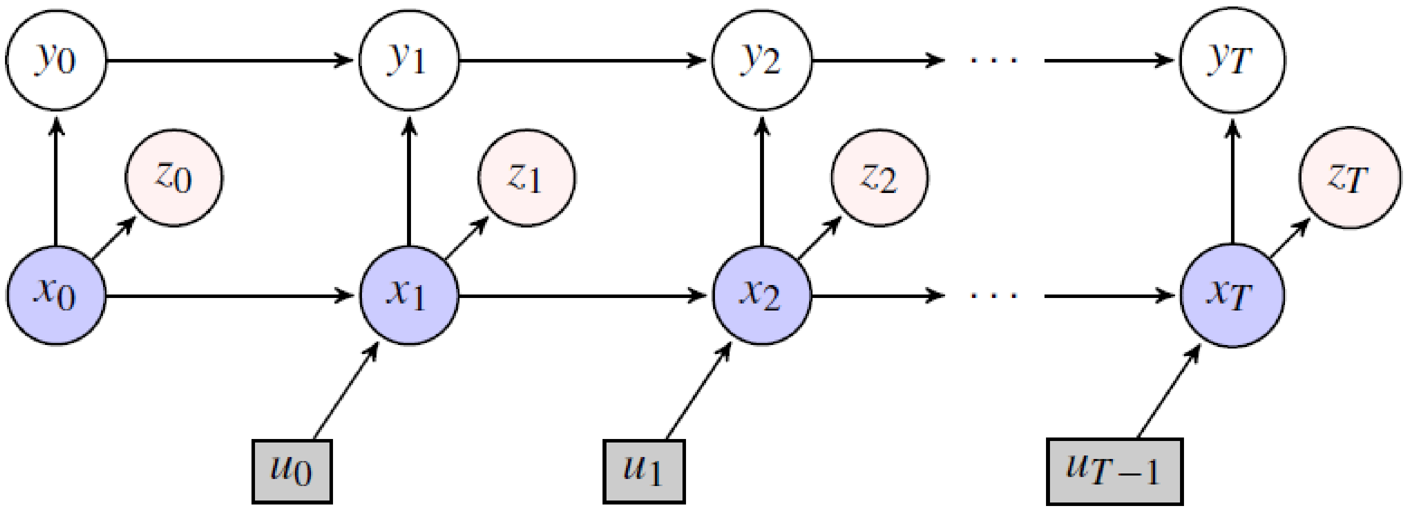
- Cost function

$$\mathcal{C}(\bar{x}, \bar{u}) = \sum_{t=0}^{T} \mathcal{C}_t(x_t, u_t) \qquad \mathcal{C}_t(\cdot, \cdot) \geq 0$$

Solve: $\pi^* = \operatorname{argmin}_\pi \langle \mathcal{C}(\bar{x}, \bar{u}) \rangle_{\bar{x}, \bar{u}|x_0, \pi}$

Konrad Rawlik, Marc Toussaint and Sethu Vijayakumar, On Stochastic Optimal Control and Reinforcement Learning by Approximate Inference, *Proc. Robotics: Science and Systems (R:SS 2012)*, Sydney, Australia (2012).

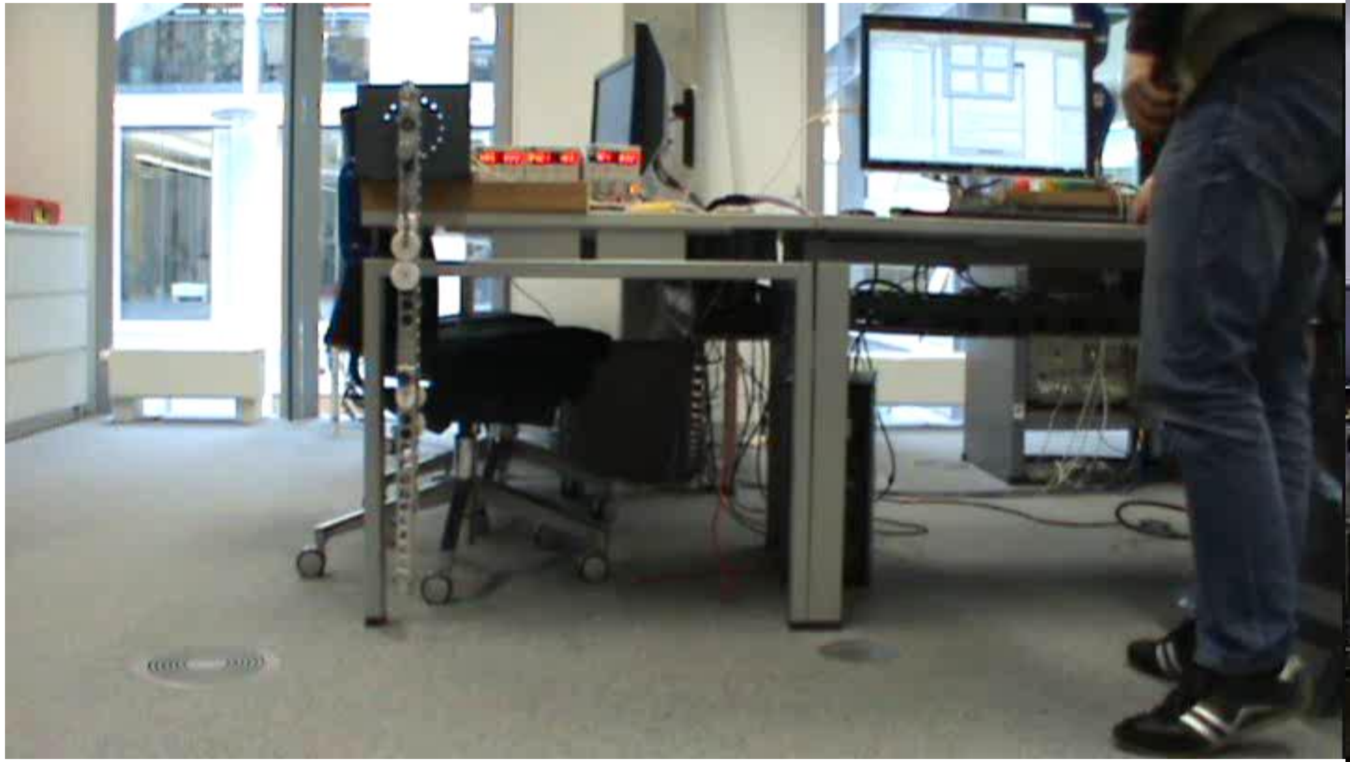
Multi-scale Planning by Inference



- Inference based techniques for working at multiple abstractions
- Planning that incorporates passive stiffness optimisation as well as virtual stiffness control induced by relational metrics
- Exploit novel (homotopy) equivalences in policy – to allow local remapping under dynamic changes
- Deal with contacts and context switching

J. Nakanishi, A. Radulescu and S. Vijayakumar, Spatiotemporal Optimisation of Multi-phase Movements: Dealing with Contacts and Switching Dynamics, *Proc. IROS,* Tokyo (2013).

Highly **dynamic** tasks, explosive movements

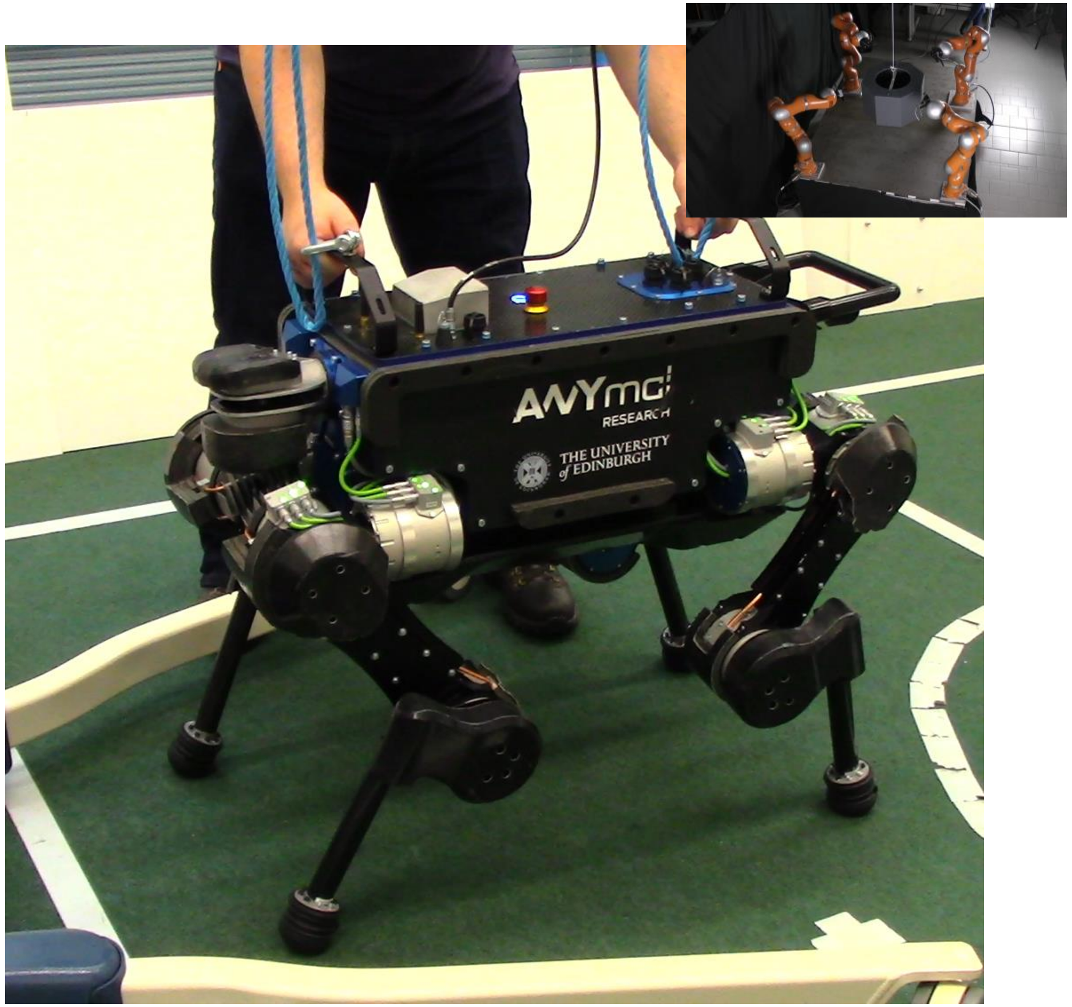


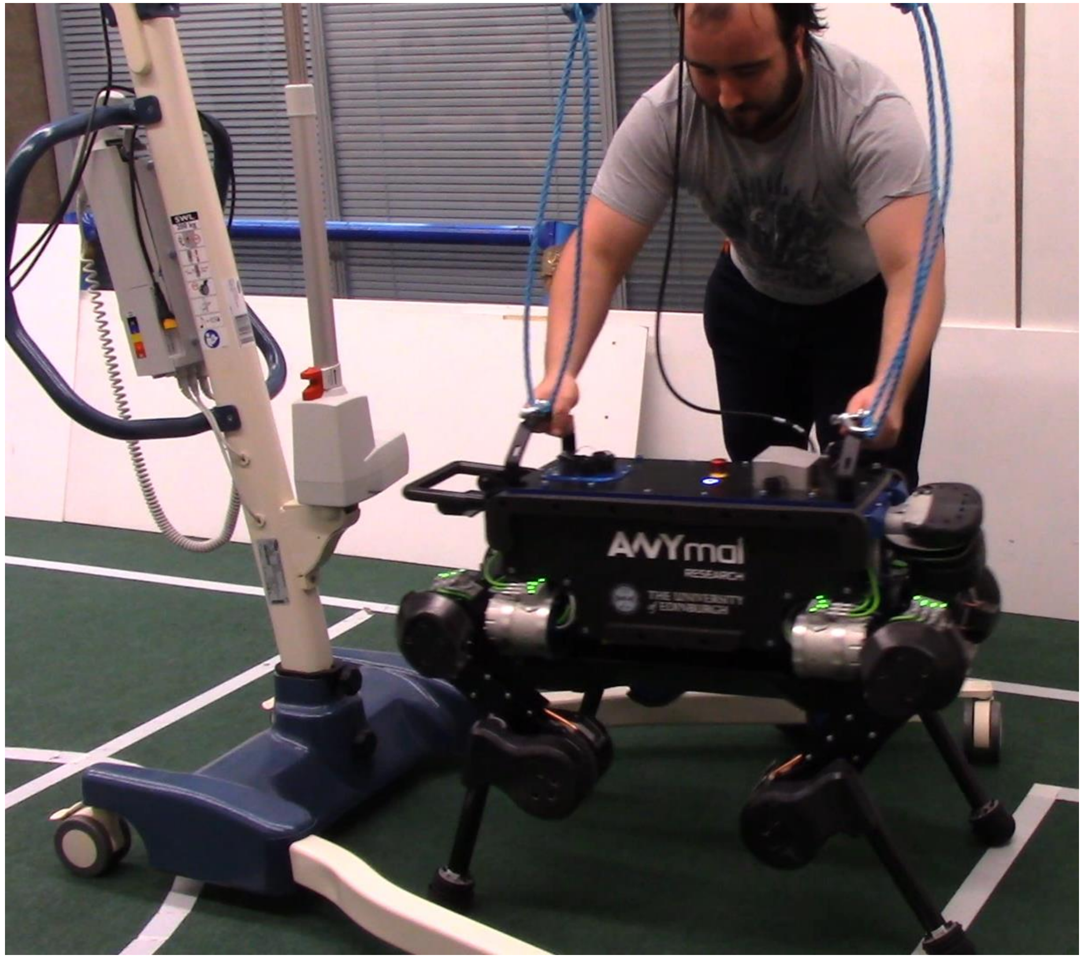
Optimising and Planning with Redundancy: **Stiffness** and **Movement** Parameters

Scale to High Dimensional Problems

D. Braun, F. Petit, F. Huber, S. Haddadin, P. van der Smagt, A. Albu-Schffer and S.Vijayakumar,
Robots Driven by Compliant Actuators: Optimal Control under Actuation Constraints, *IEEE Transactions on Robotics (IEEE T-RO)*, 29(5), pp. 1085-1101 (2013). [TRO Best Paper Award]

Impedance Modulation for Interactions: Arms & Legs

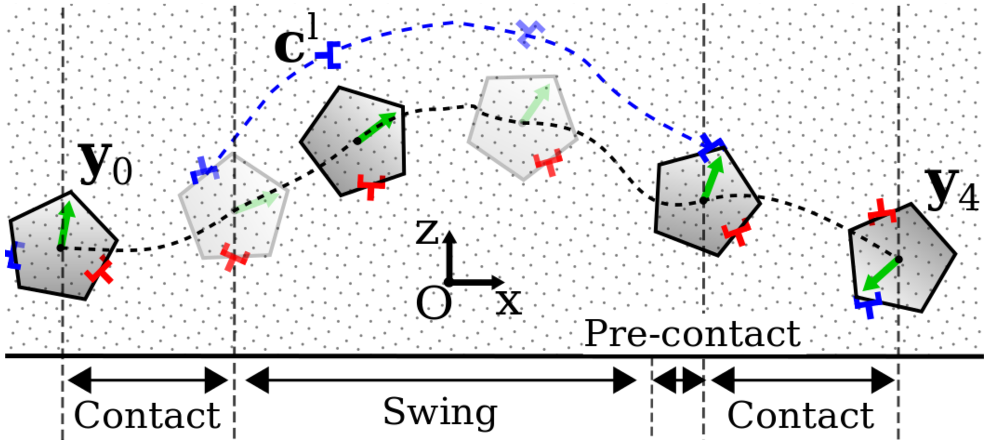




G Xin, HC Lin, J Smith, O Cebe, M Mistry, A Model-based Hierarchical Controller for Legged Systems subject to External Disturbances, *Proc. IEEE Intl. Conf. on Robotics and Automation* (ICRA)(2018)

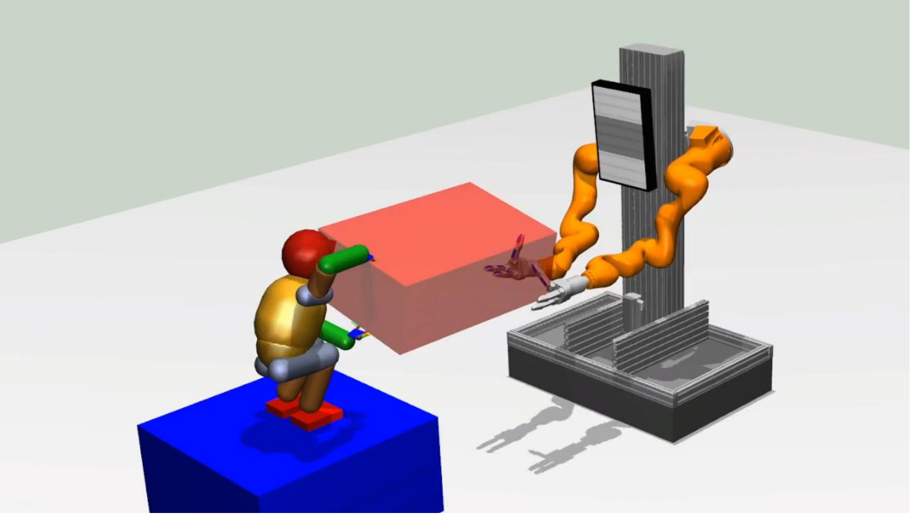
Dyadic collaborative Manipulation (DcM)

Honda Research Institute EU



Proposed **formalism** addressing **joint planning** in dyadic co-manipulation tasks.

A **hybrid trajectory optimization** for manipulation.



Stouraitis, T., Chatzinikolaidis, I., Gienger, M., Vijayakumar, S. *Dyadic collaborative Manipulation through Hybrid Trajectory Optimization*, Conference on Robot Learning (CoRL), 2018. [Best Paper Award Finalist]

Robots for the Aircraft Industry

Inspection, Repair, Certification, Assembly, Decommission

Traditional Manufacturing
- Fixed Base Platforms
- Large Jigs

Automating of Assembly Processes
- Humans and Robots work in different space and/or time

Human Robot Collaboration
- Sensing for accurate positioning
- Compliant Manipulation
- Collaborative Motion Plans

Increasing Flexibility, Shared Control with Humans in the Loop, Increasing Reliability

Project 3: UoE-NASA Valkyrie Humanoid

EDINBURGH CENTRE FOR ROBOTICS
Innovation Ready

Flagship **Robotarium Platform UK**
Hub for Humanoids Research
Space Robotics Challenge

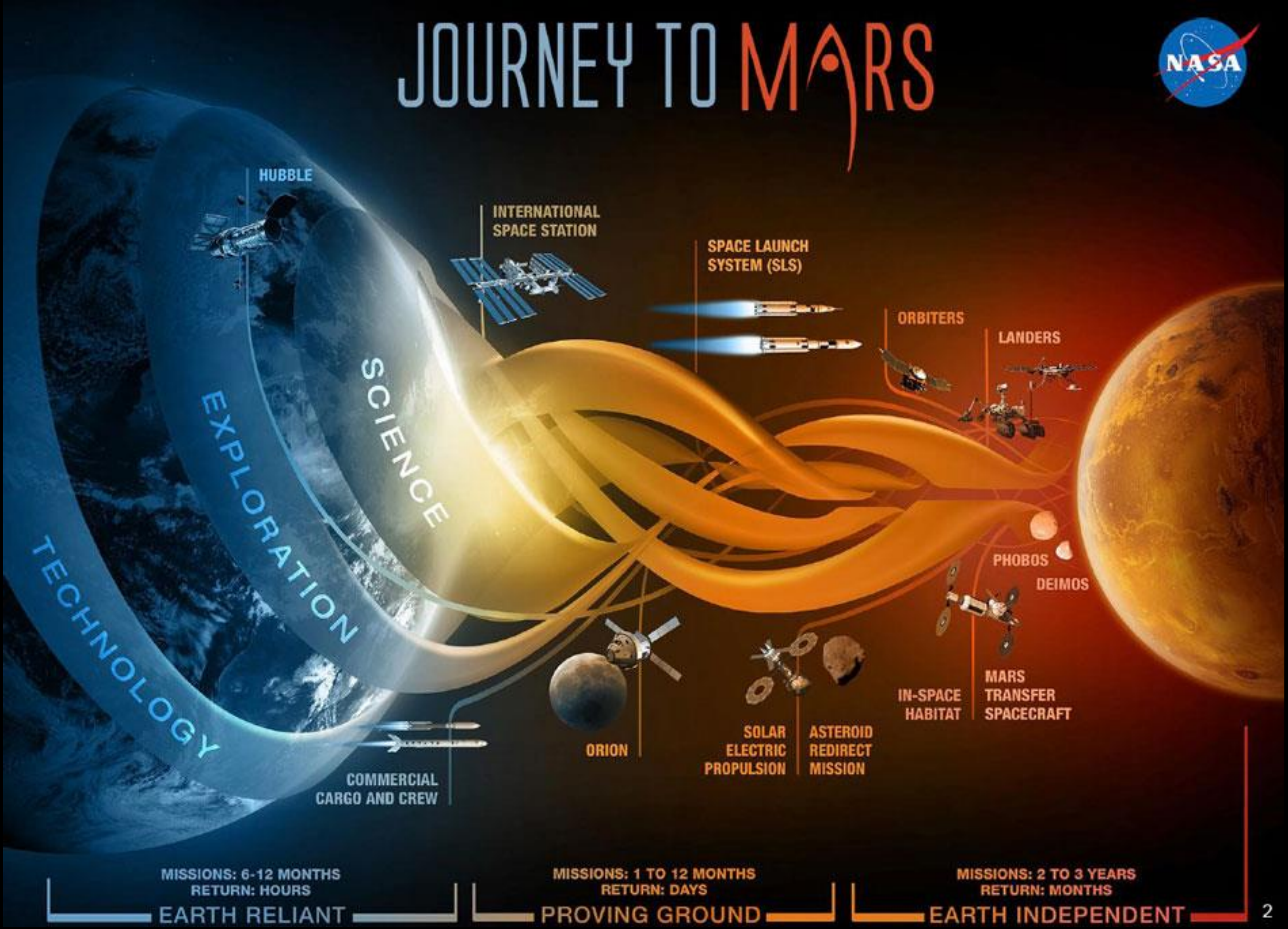
ROBOTARIUM
EDINBURGH CENTRE FOR ROBOTICS

THE UNIVERSITY OF EDINBURGH

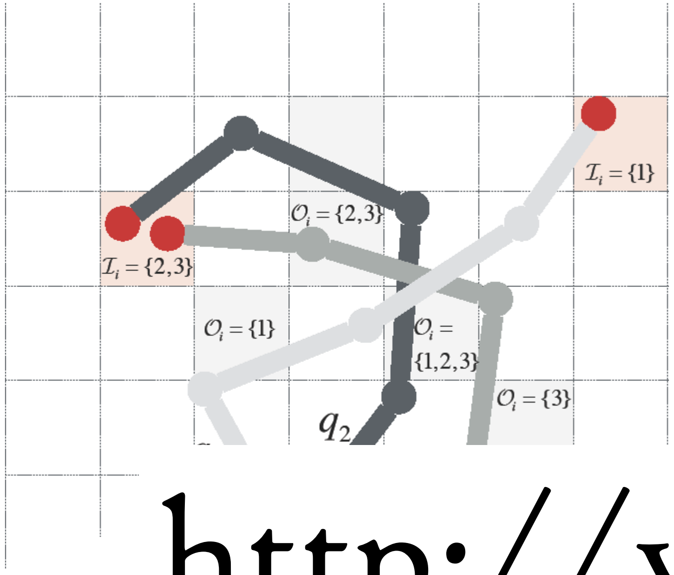
NASA

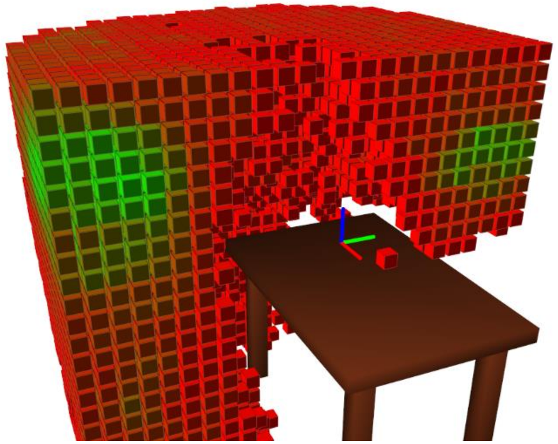
[2018-2022] **EPSRC** co-funded **hub** in Future AI and Robotics for Space **(FAIR-SPACE): £7M**

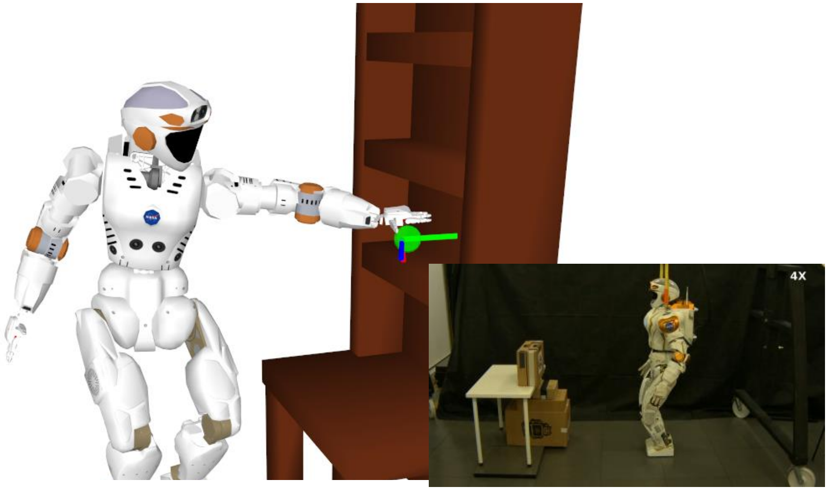
Y. Yang, W. Merkt, H. Ferrolho, V. Ivan and S.Vijayakumar, Efficient Humanoid Motion Planning on Uneven Terrain Using Paired Forward-Inverse Dynamic Reachability Maps, IEEE Robotics and Automation Letters, vol. 2(4), (2017)


JOURNEY TO MARS
NASA
HUBBLE
INTERNATIONAL SPACE STATION
SPACE LAUNCH SYSTEM (SLS)
ORBITERS
LANDERS
SCIENCE
EXPLORATION
TECHNOLOGY
PHOBOS
DEIMOS
ORION
SOLAR ELECTRIC PROPULSION
ASTEROID REDIRECT MISSION
IN-SPACE HABITAT
MARS TRANSFER SPACECRAFT
COMMERCIAL CARGO AND CREW
MISSIONS: 6-12 MONTHS
RETURN: HOURS
EARTH RELIANT
MISSIONS: 1 TO 12 MONTHS
RETURN: DAYS
PROVING GROUND
MISSIONS: 2 TO 3 YEARS
RETURN: MONTHS
EARTH INDEPENDENT

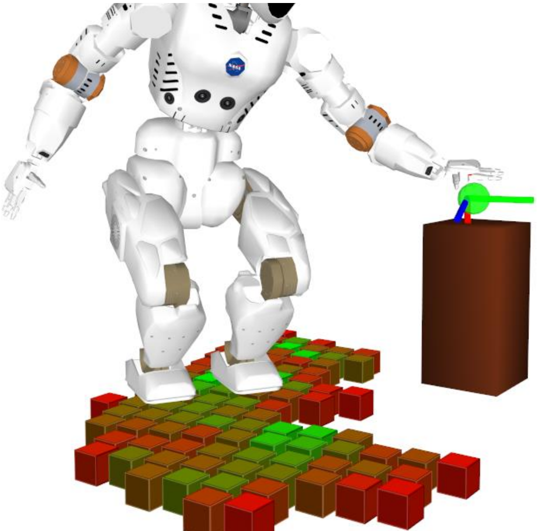
Full Body Dynamic Motion Planning

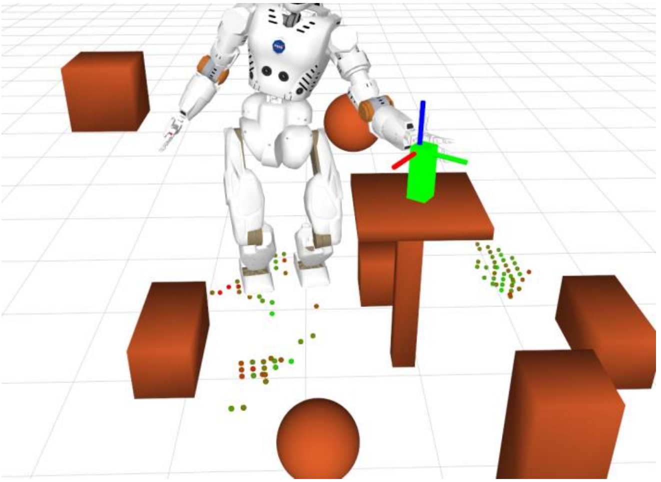


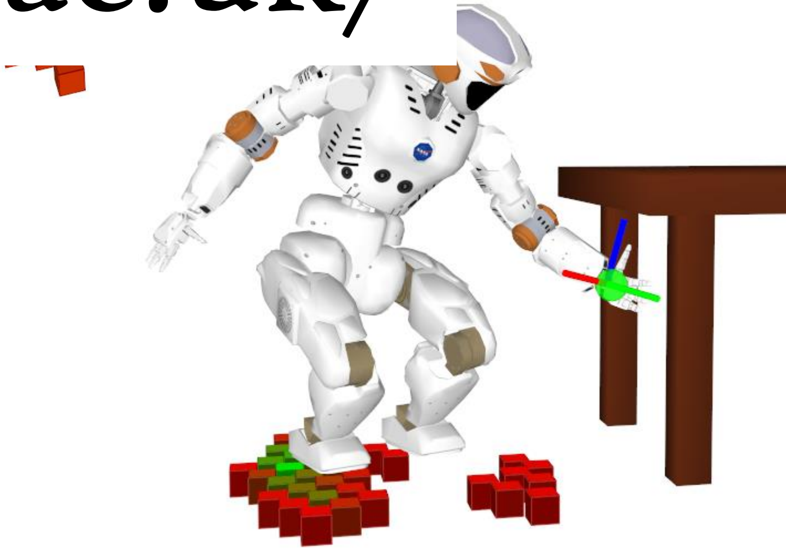




http://valkyrie.inf.ed.ac.uk/

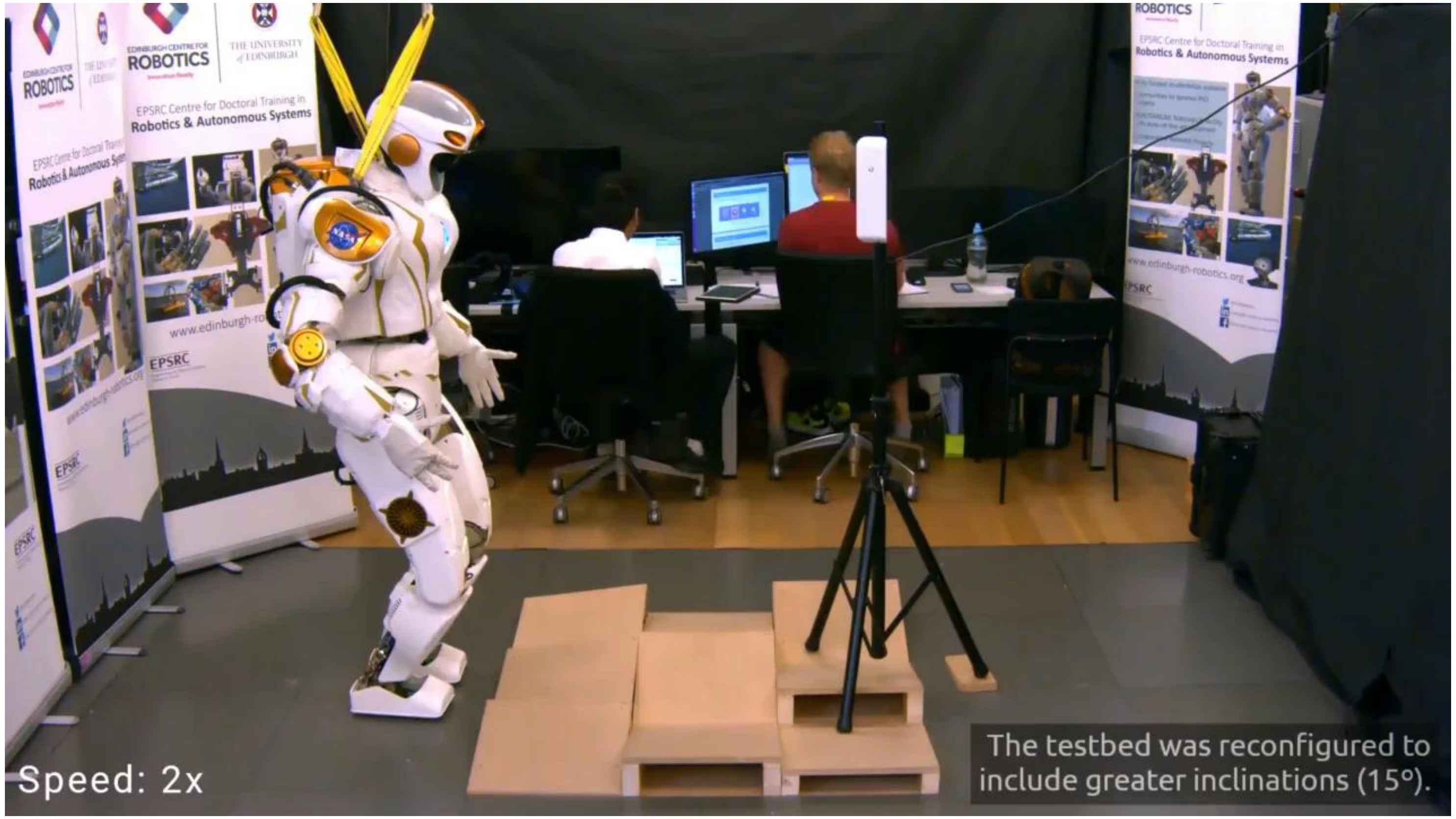






Whole-Body Motion Planning for NASA Valkyrie on Uneven Terrain in Complex Environments

Enabled planning of **collision-free** statically-balanced whole-body pre-grasp configurations with automatic **adaptation** to terrain regions of **arbitrary inclination**.

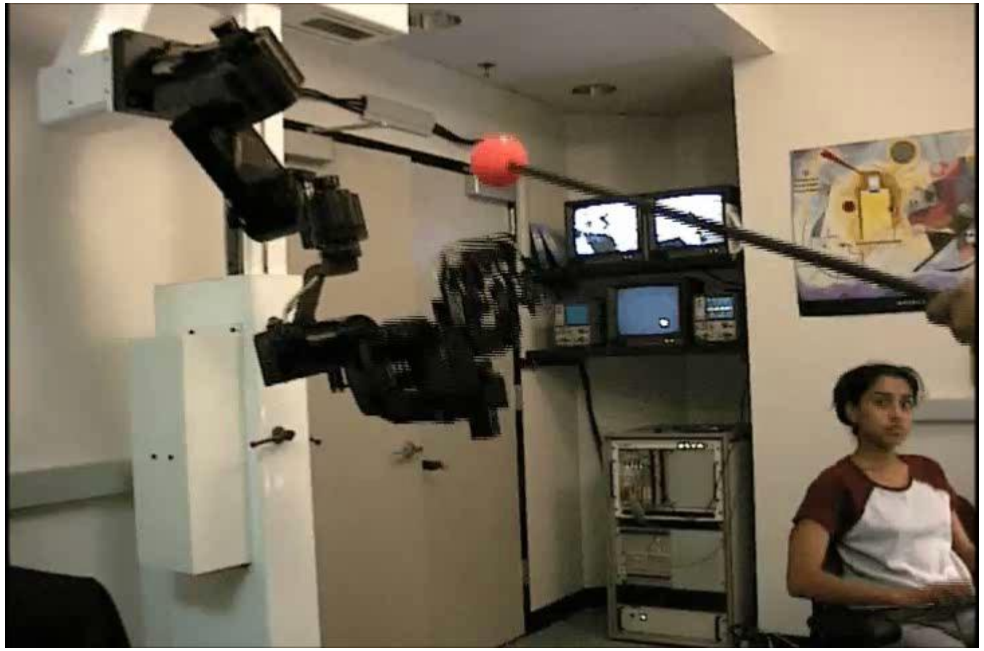


Henrique Ferrolho, Wolfgang Merkt, Yiming Yang, Vladimir Ivan, Sethu Vijayakumar. "Whole-Body End-Pose Planning for Legged Robots on Inclined Support Surfaces in Complex Environments," *IEEE Humanoids*, 2018.

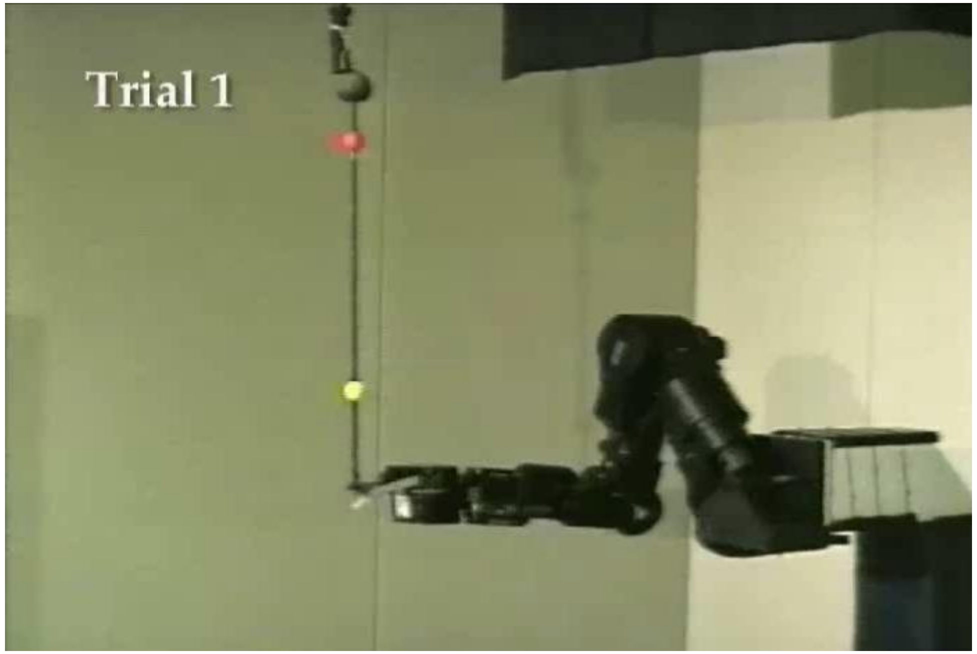
Learning to **Predict** and **Adapt**

- Predicting Consequences
- Predicting Task Goals and Intentions

Learning the Internal Dynamics



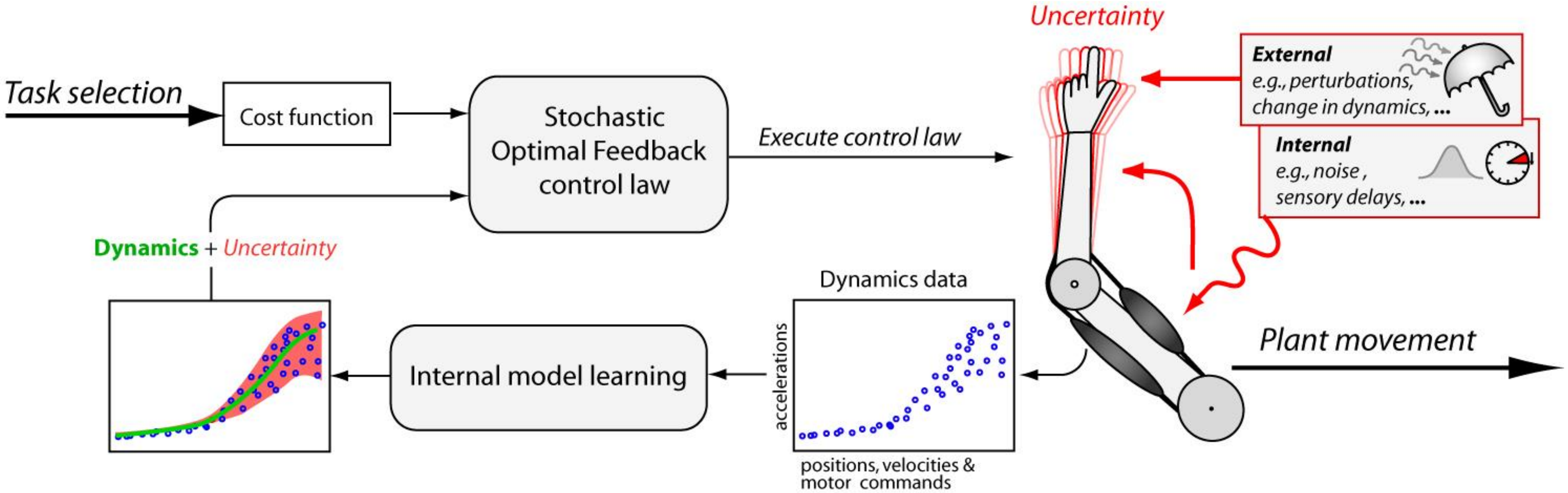
Learning the Task Dynamics



Sethu Vijayakumar, Aaron D'Souza and Stefan Schaal, Incremental Online Learning in High Dimensions, *Neural Computation*, vol. 17, no. 12, pp. 2602-2634 (2005).

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

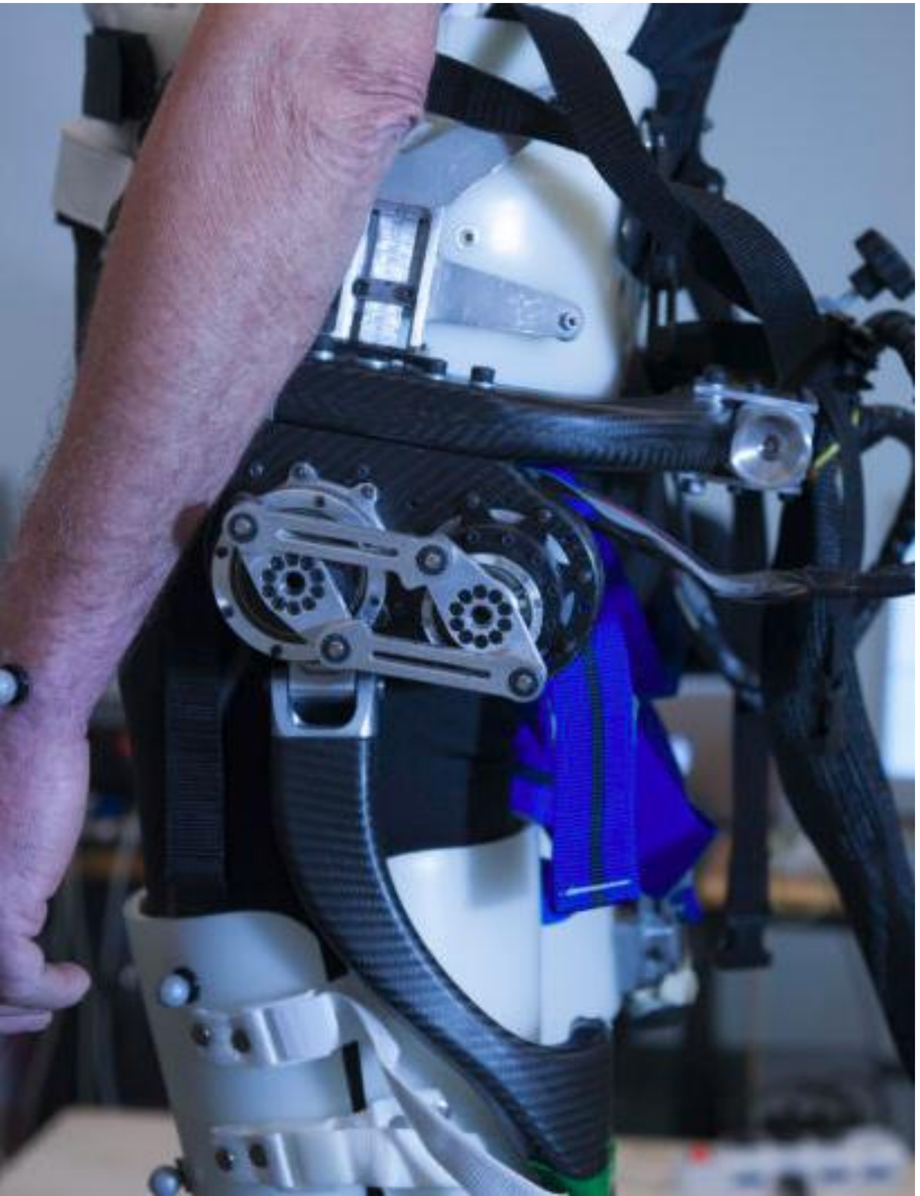
EPSRC Grant: Anyscale Applications (EP/L000725/1): 2013-2017

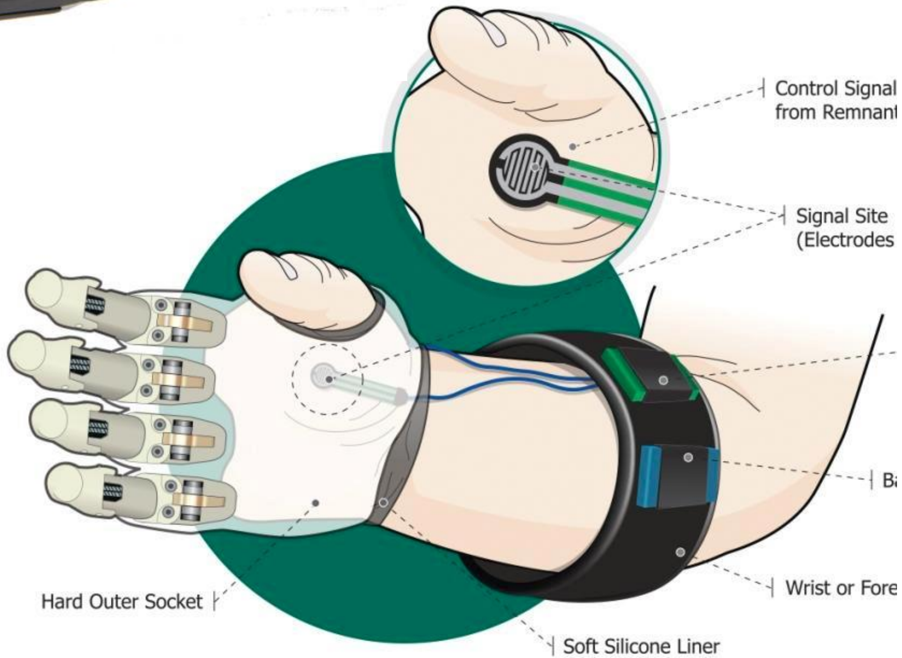
Andreea Radulescu, Jun Nakanishi, David Braun and Sethu Vijayakumar, **Optimal Control of Variable Stiffness Policies: Dealing with Switching Dynamics and Model Mismatch**, *J.-P. Laumond et al. (eds.), Geometric and Numerical Foundations of Movements*, Springer Tracts in Advanced Robotics 117, pp. 393-419 (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**.

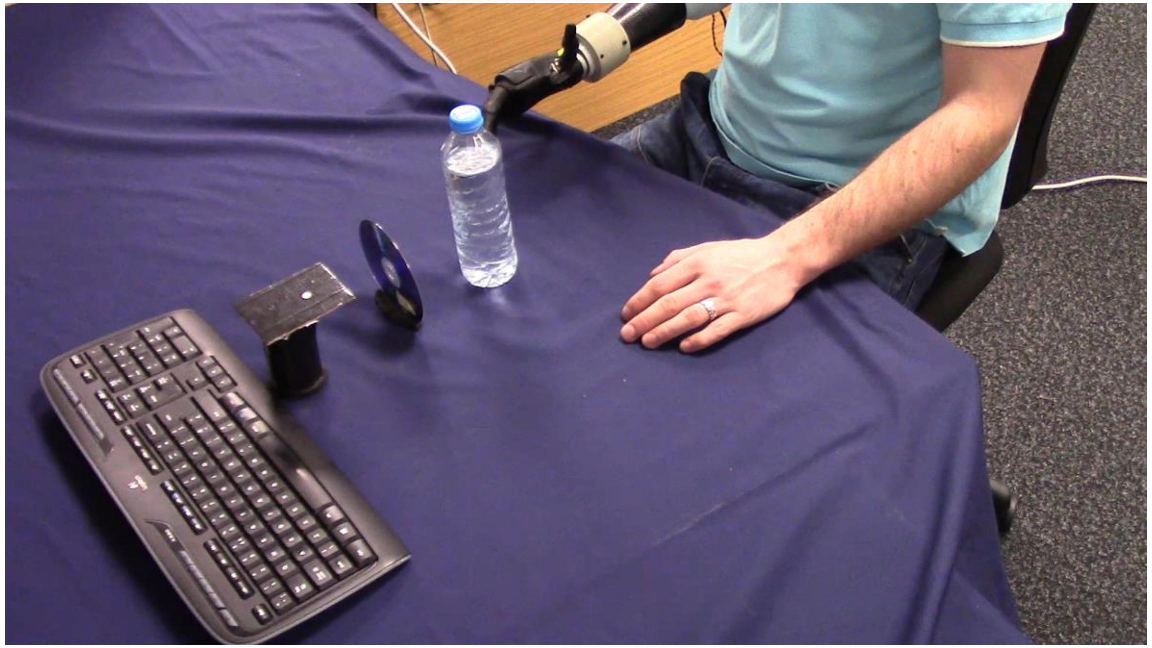
Project 4: Shared Autonomy in Healthcare

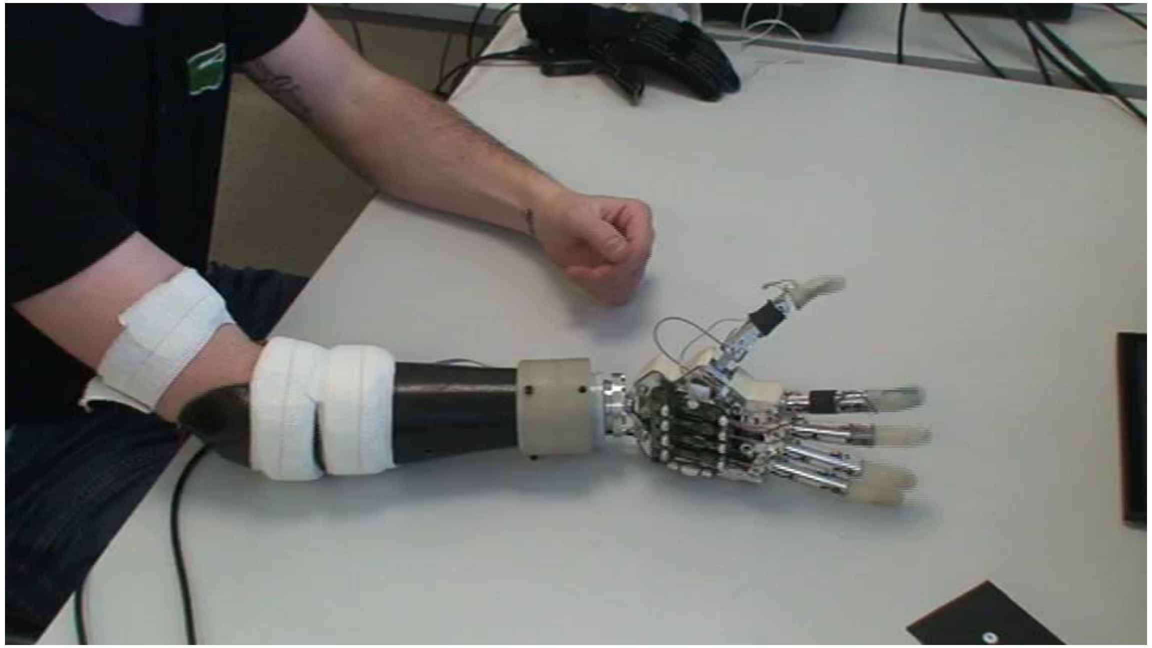




Prosthetics: Amputee Testing

EMG + IMU: Better real-time **pregrasp classification** and real-time **kinematic decoding** with **amputees**





A. A. Krasoulis, K. Nazarpour, and S. Vijayakumar, **Towards Low-Dimensionsal Proportional Myoelectric Control**, *Proc. Intl. Conf. IEEE Engineering in Medicine and Biology Society (EMBC'15)*, Milan, Italy (2015).

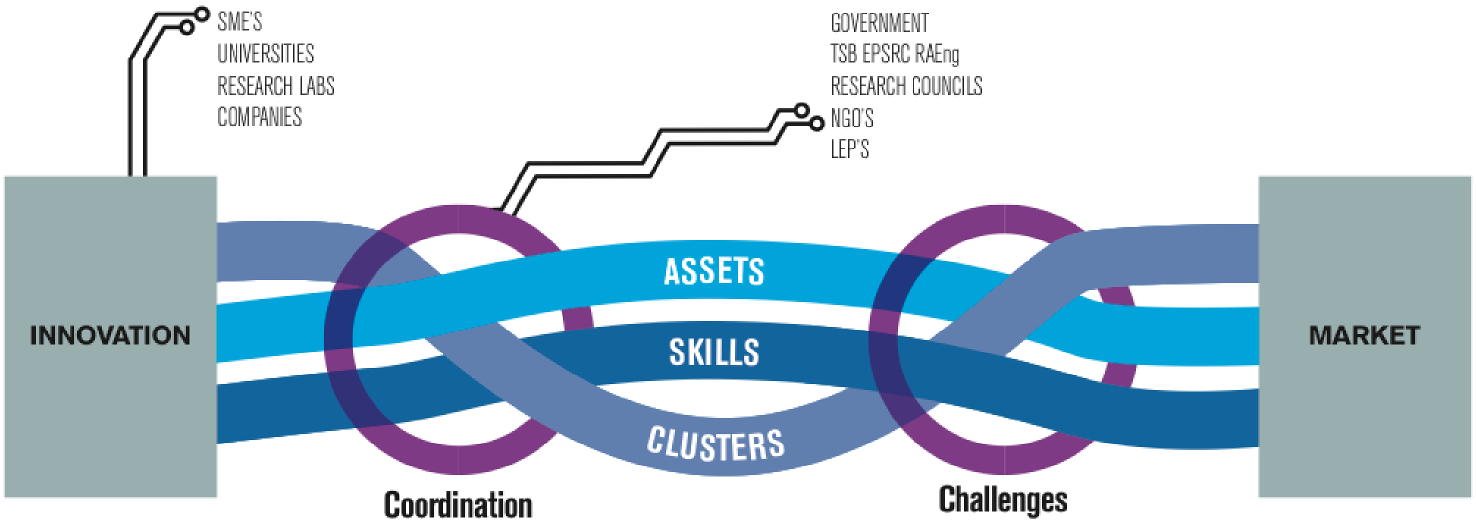
B. A. Krasoulis, S.Vijayakumar and K. Nazarpour, **Evaluation of Regression Methods for the Continuous Decoding of Finger Movement from Surface EMG and Accelerometry**, *Proc. Intl. Conf. IEEE EMBC Neural Engineering Conference (NER'15)*, Chicago (2015).

Exoskeletons for Assistance and Rehabilitation

Graham Henderson, Daniel Gordon and Sethu Vijayakumar, Identifying invariant gait stability metrics for exoskeleton assistance, *Proceedings IEEE International Conference on Robotics and Biomimetics (ROBIO '17),* Macau, China (2017)

Addressing Global Grand Challenges

Innovation to Market



EDINBURGH CENTRE FOR ROBOTICS

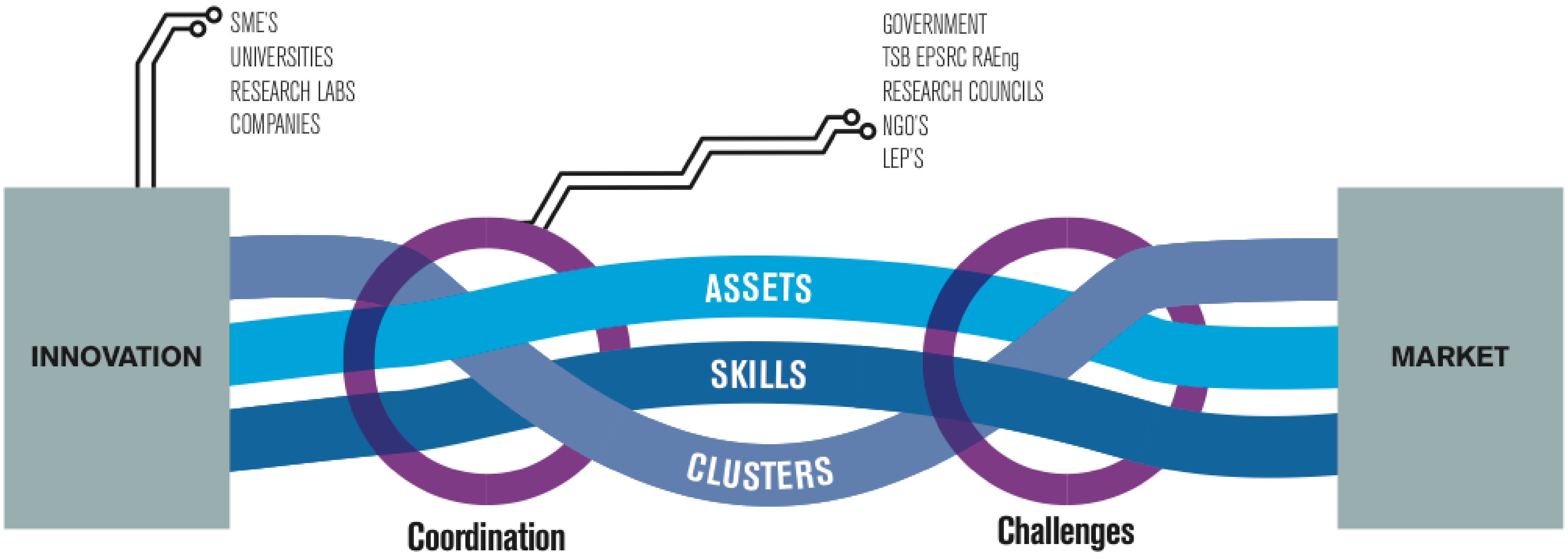
The Alan Turing Institute

Strategic Activity Pillars: Living Laboratories (Assets): Challenges: Skills: Clusters: Co-ordination

Edinburgh Centre for Robotics

A £100M Joint Venture between Edinburgh University and Heriot Watt University

Strategic Activity Pillars: Living Laboratories (Assets): Challenges: Skills: Clusters: Co-ordination (UK RAS2020 Strategy)



edinburgh-robotics.org sethu.vijayakumar@ed.ac.uk

UoE contact: Professor Sethu Vijayakumar (CDT Director)
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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 …

THE UNIVERSITY OF EDINBURGH

HERIOT WATT UNIVERSITY

EDINBURGH CENTRE FOR ROBOTICS

ROBOTARIUM

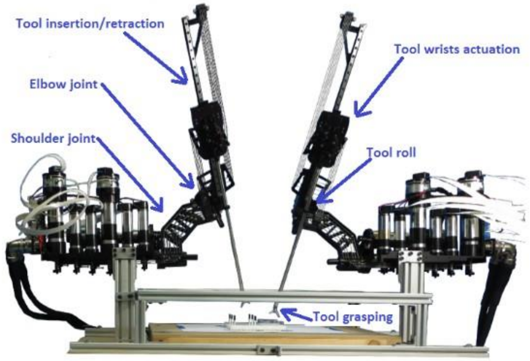
A National UK Facility for Research into the Interactions amongst Robots, Environments, People and Autonomous Systems

www.edinburgh-robotics.org

EPSRC

Shared Autonomy: Key Questions

- Moral / Ethical Decisions
- Security
- Responsibility
  - Causal Inference
- Transferring Control
  - When?
  - How fast?
  - How long?
- Learning Systems



World first hacking of a medical robot, UW (April 2015)

The trolley problem for Self Driving Cars

ATI
Robotics & Autonomous Systems Programme

The Alan Turing Institute

Vision

To create a world leading **scientific programme** of **data driven AI research** and **innovation** that addresses the unique challenges arising *from* and *towards* deployment of **Robotics and Autonomous Systems** (RAS) technology for solving socially relevant problems across domains.

Aims and Objectives

Develop and support a world leading portfolio of activities that lies at the intersection of data driven AI and machine learning, specifically targeted to the RAS domain. This will be achieved by:

1. building and funding a core research team investigating **'fundamental' algorithmic and computational** innovations under three key strands, with a research team lead heading each strand.
2. developing **Joint Industry Projects (JIPs)** through deep dive engagements with industry for technologies that are medium to high TRL levels – with between 50-75% of core funding coming from industry.
3. **de-risk deployment** through proof of concept implementations in several partner **'living labs'** that integrate hardware and data processing challenges

The Alan Turing RAS Programme

The Alan Turing Institute

Three research strands [that are crucial but are missing or under-represented elements in the current RAS and machine learning roadmap]:

a) Scalable algorithms under constraints

Real time inference requirements, computational constraints of embedded, untethered and mobile platforms, hardware limits (torque, joint) for guaranteeing safety, ML techniques such as approximate hierarchical inference for graceful performance degradation

b) Methods for efficient multi-agent computations

Intention detection and movement prediction, scalable multi-agent adversarial and collaborative policies, multimodal sensor aggregation for decision making

c) Verifiable, Robust and Explainable decision making for multimodal RAS assets

Enabling secure systems – communication, decision making; understanding and predicting failure modes, developing robustness and multiple failure recovery modes, fault and risk inference through probabilistic modelling

Each strand to be led by a Research Leads. 3-4 PDRAs per strand as seed.

JIPs to be developed with Industrial Partners. SME fund 50%, others 75%, Foreground IP owned by partners.

ATI/ECR Living Labs: Examples

Robots for Extreme Environments
- Oil and Gas Offshore
- Nuclear Decommissioning
- Space
- Asset inspection and maintenance

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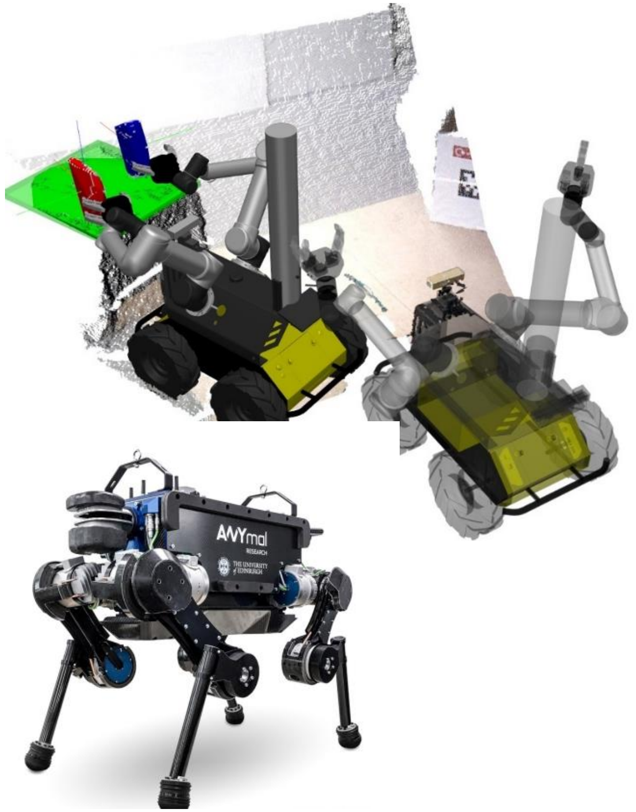
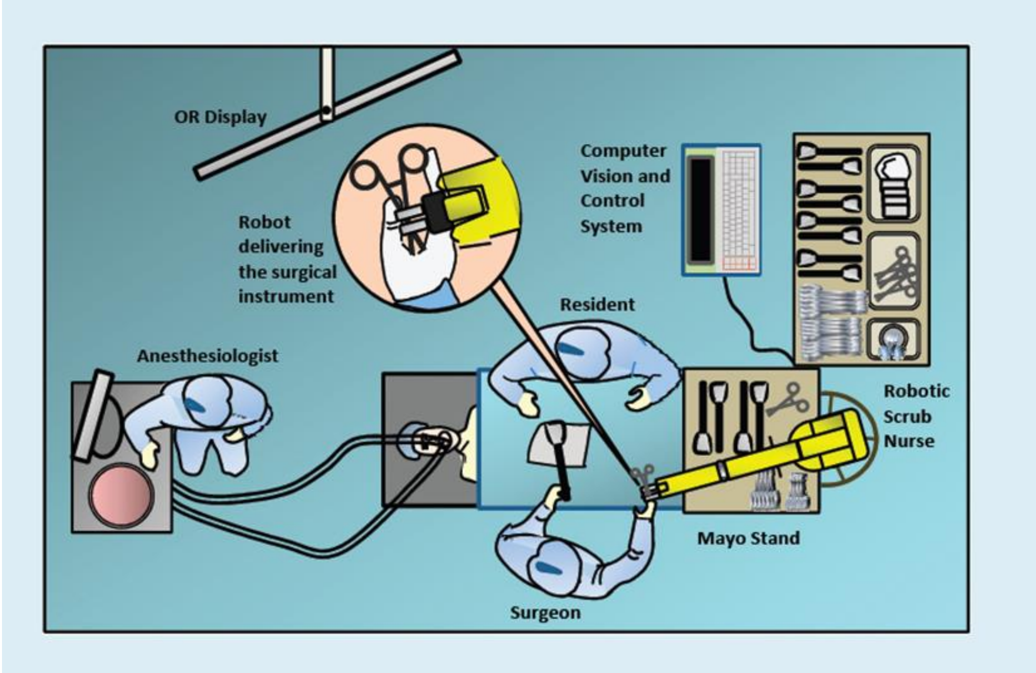
Robots in Healthcare and Assisted Living
- Hospital Surgery Mock-up
- Smart homes
- Exoskeleton and Prosthetic Device Testing

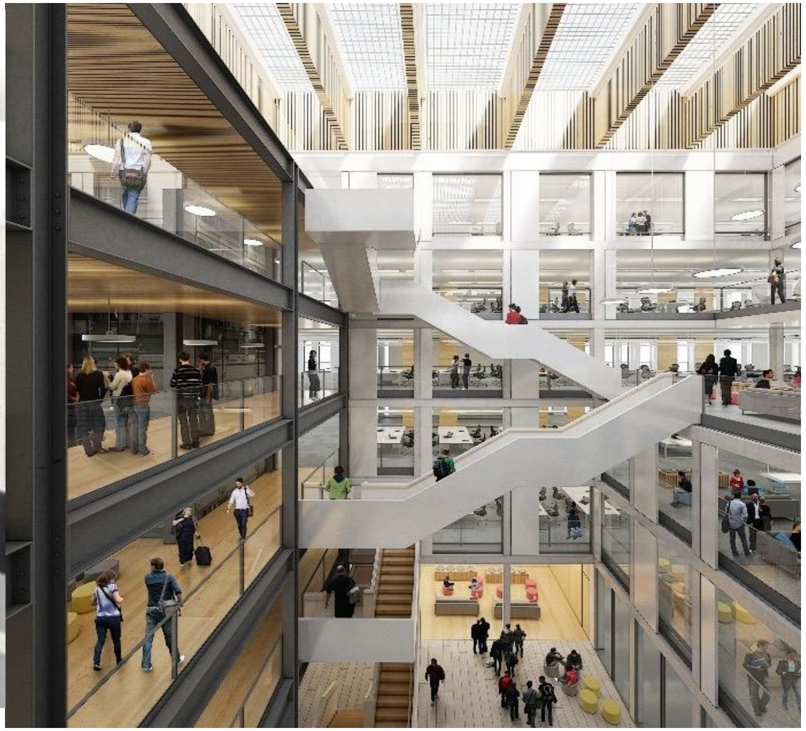
Address algorithmic and data challenges arising out of RAS deployment in realistic settings





Bayes Centre

THE UNIVERSITY *of* EDINBURGH



The Bayes Centre aims to excel in technology that powers **interaction** between **people**, **data** and **systems**, and create positive disruption from talent and ideas.

Bayes will bring together corporate R&D teams, researchers, start-ups and innovation groups and focus on:

- Generating and sharing ideas through research
- Attracting and developing talent through teaching
- Instigating and harnessing new disruptive innovation

http://www.bayes.ed.ac.uk/

The Alan Turing Institute

THE UNIVERSITY OF EDINBURGH

EDINBURGH CENTRE FOR ROBOTICS

Shared Autonomy
The Future of Interactive Robotics

Sethu Vijayakumar

RAEng Microsoft Chair in Robotics, **University of Edinburgh**, UK

Director, **Edinburgh Centre for Robotics**

Co-Programme Director, **The Alan Turing Institute**

www.edinburgh-robotics.org

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EPSRC
Engineering and Physical Sciences Research Council