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

@sethuwij  sethu-vijayakumar
Robotics is becoming ubiquitous

Affecting Everything That Moves

The real world
Teleoperation

Shared Autonomy

Autonomy
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
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

Real-time Sensing and Acting with Feedback


Integrated Motion Planner for Shared Autonomy

EXOTica

- Initial state $x_0$
- Task description
- Perception
- Environment
- Robot model URDF, SRDF

Motion Planner
- IK
- AICO
- iLQG
- OMPL
- iDRM

Planning Problem
- SamplingProblem
- UnconstrainedEndPoseProblem

Task Maps
- Joint Limits
- CoM
- Interaction Mesh
- Distance

Planning Scene
- Robot Model
- Environment
- Kinematics Solver

Output trajectory $x^*_{1:T}$

Visualization RViz

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

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

Current Project Portfolio in Shared Autonomy

Nuclear/Offshore Decommissioning

Disaster Recovery

Collaborative Manufacturing

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

Legged Mobility and Contacts, Impedance Control


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

Interaction Mesh based Relational Descriptors

Harmonic Electric Fields

Relational tangent planes

Interaction with dynamic, articulated and flexible bodies

in purely metric spaces -- focus on **relational metrics** between parts and objects/environment

**simple motion priors** to express complex motion

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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

Compliant Actuation Design & Stiffness Control

Compliant Actuators

- VARIABLE JOINT STIFFNESS

\[ \tau = \tau(q, u) \]
\[ K = K(q, u) \]

Model of the system dynamics:

\[ \dot{x} = f(x, u) \quad u \in \Omega \]

Control objective:

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

Optimal control solution:

\[ u(t, x) = u^*(t) + L^*(t)(x - x^*(t)) \]

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

Torque/Stiffness Opt.

MACCEPA: Van Ham et al, 2007

DLR Hand Arm System: Grebenstein et al., 2011
Graphical Model Representation

Given:

- **Discrete time controlled stochastic process**
  
  - **State:** $x_t \in \mathbf{X} = \mathbb{R}^n$
  
  - $\bar{x} = (x_0, \ldots, x_T)$

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

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

  - **Transition Probability:** $P(x_{t+1} | x_t, u_t)$ (typically $P(x_{t+1} | x_t, u_t) = \mathcal{N}(x_{t+1}; f(x_t, u_t), Q)$)

- **Cost function**

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

Solve:

$$\pi^* = \arg\min_\pi \langle C(\bar{x}, \bar{u}) \rangle_{\bar{x}, \bar{u} | x_0, \pi}$$

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

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-Schaffer and S. Vijayakumar,

Impedance Modulation for Interactions: Arms & Legs

Dyadic collaborative Manipulation (DcM)

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

Flagship Robotarium Platform UK Hub for Humanoids Research Space Robotics Challenge


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**.

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

- Predicting **Consequences**
- Predicting **Task Goals and Intentions**

Learning the Internal Dynamics  
Learning the Task Dynamics


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


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


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

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

www.edinburgh-robotics.org
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
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

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.

edinburgh-robotics.org  sethu.vijayakumar@ed.ac.uk
ATI/ECR Living Labs: Examples

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

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
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/
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