Robots that Learn
Old Dreams and New Tools

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One of the world’s top 20 Universities
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What does it take to control a robot?

PLAN

Controller

Estimator

Biomechanical Plant

Sensory Apparatus

Motor Command

Estimated State

Efference Copy

Sensory Data

State

Noise
Robots That Interact

Key challenges due to
1. Close *interaction* with multiple objects
2. Multiple *contacts*
3. Hard to model *non-linear dynamics*
4. Guarantees for *safe operations*
5. Highly *constrained* environment
6. Under significant *autonomy*
7. Noisy *sensing* with occlusions

...classical methods do not scale!
Innovation 1

Making **sense** of the world around you
(Real-time pose estimation under **camera motion** and severe **occlusion**)

Real-time Object Pose Recognition and Tracking with an Imprecisely Calibrated Moving RGB-D Camera

Karl Pauwels*, Vladimir Ivan+, Eduardo Ros*, Sethu Vijayakumar+

*CITIC, University of Granada, Spain
+School of Informatics, University of Edinburgh, UK

IROS 2014
Innovation 1

Making **sense** of the world around you

(Tracking and Localisation)

UEDIN-NASA
Valkyrie
Humanoid
Platform -2015

Wheelan, Fallon et.al, Kintinuous, IJRR 2014 (MIT DRC perception lead)
Innovation 2

Scalable Context Aware Representations

- 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
- Generalize
- Scale and Re-plan
- Deal with Dynamic Constraints

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
Real-time Adaptation using Relational Descriptors

Real-Time Motion Adaptation using Relative Distance Space Representation

Yiming Yang, Vladimir Ivan, Sethu Vijayakumar
School of Informatics, University of Edinburgh

International Conference on Advanced Robotics
2015
Robots for Confined Spaces

Courtesy: OC Robotics Ltd.
Innovation 3

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
Given:
- Start & end states,
- fixed-time horizon $T$ and
- system dynamics $dx = f(x,u)dt + F(x,u)d\omega$

And assuming some cost function:

$$v^\pi(t, x) \equiv E \left[ h(x(T)) + \int_t^T l(\tau, x(\tau), \pi(\tau, x(\tau)))d\tau \right]$$

Apply Statistical Optimization techniques to find optimal control commands

**Aim:** find control law $\pi^*$ that minimizes $v^\pi(0, x_0)$. 
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 \( P(x_{t+1}|x_t, u_t) = \mathcal{N}(x_{t+1}; f(x_t, u_t), Q) \))

- **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:

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

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Innovation 4

Novel 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

This capability is crucial for **safe, yet precise** human robot interactions and **wearable exoskeletons**.

**HAL Exoskeleton, Cyberdyne Inc., Japan**

**KUKA 7 DOF arm with Schunk 7 DOF hand @ Univ. of Edinburgh**
Variable Stiffness Actuation

EMG (left) → EMG (right) → Motor (left) → Motor (right)
Compliant Actuators

- VARIABLE JOINT STIFFNESS

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

MACCEPA: Van Ham et.al, 2007

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

Torque/Stiffness Opt.

- Model of the system dynamics:

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

- Control objective:

\[ J = -d + \omega \frac{1}{2} \int_{0}^{T} \| F \|^2 dt \to \min. \]

- Optimal control solution:

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

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

Optimizing **Spatiotemporal Impedance Profiles**

**Plant dynamics**
\[ \dot{x} = f(x, u) \]

**Reference trajectory**
\[ y(t) = r \psi^T(\phi)\theta + y_{\text{offset}} \]
\[ \dot{\phi} = \omega \]

**Optimization criterion**
\[ J = \Phi(x_0, x_T) + \int_0^T r(x, u, t) \, dt \]

**Optimal feedback controller**
\[ u^*(x, t) = \text{argmin}_u J \]

**Temporal optimization**
\[ t' = \int_0^t \frac{1}{\beta(s)} \, ds : \text{time scaling} \]

- optimize \( \beta \) to yield optimal \( T \) or \( \omega \)

Note: Here ‘u’ refers to motor dynamics of passive VIA elements
Highly **dynamic** tasks, explosive movements

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

**Scale to High Dimensional Problems**

Multi Contact, Multi Dynamics, Time Optimal

- Development of a systematic methodology for spatio-temporal optimization for movements including
  - multiple phases
  - switching dynamics
  - contacts/impacts
- Simultaneous optimization of stiffness, control commands, and movement duration
- Application to multiple swings of brachiation, hopping
Multi Contact, Multi Dynamics, Time Optimal

Plant dynamics
\[ \dot{x} = f_i(x, u) \ (i = 1, 2) \]
(asymmetric configuration)

Discrete state transition
\[ x^+ = \Gamma(x^-) \]
(switching at handhold)

- Hybrid dynamics modeling of swing dynamics and transition at handhold
- Composite cost for task representation
- Simultaneous stiffness and temporal optimization

Identification of Physical Parameters

- estimate moment of inertia parameters and center of mass location of each element from CAD
- added mass at the elbow joint to have desirable mass distribution between two links

Link parameters

Link 1 (w/o gripper, magnet)

\[ m_1 = 0.279, \quad I_{c1} = 0.0018 \]
\[ l_{c1} = 0.1737, \quad l_1 = 0.290 \]

Link 2 (incl. gripper, magnet, add. mass)

\[ m_2 = 1.311, \quad I_{c2} = 0.0203 \]
\[ l_{c2} = 0.0774, \quad l_2 = 0.290 \]

Servo motor dynamics parameter

\[ \ddot{q}_m + 2\alpha \dot{q}_m + \alpha^2 (q_m - u) = 0 \]
\[ \alpha \approx 25 \text{ with maximum range } -\frac{\pi}{2} \leq q_m \leq \frac{\pi}{2} \]

Additional mass (0.756kg)
Multi-phase Movement Optimization

• Task encoding of movement with multi-phases

\[ J = \phi(x(T_f)) + \sum_{j=1}^{K} \psi^j(x(T_i^-)) + \int_{T_0}^{T_f} h(x, u) dt \]

Terminal cost \hspace{1cm} Via-point cost \hspace{1cm} 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 \( u = u(x, t) \) to minimize \( J \)
(2) switching instances \( T_1, \cdots, T_k \)
(3) final time (total movement duration) \( T_f \)
Brachiation with Stiffness Modulation
Variable Impedance Bipeds: Towards Smart Lower Limb Prosthetics

Robust Bipedal Walking with Variable Impedance
- To make robots more energy efficient
- To develop robots that can adapt to the terrain
- To develop advanced lower limb prosthetics
Innovation 5

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

Online Adaptive Machine Learning

Learning the Internal Dynamics

Learning the Task Dynamics


http://www.ipab.inf.ed.ac.uk/slmc/software/lwpr
Haptic Feedback + Shared (EMG) Autonomous Control for Prosthetics
Touch Bionics – U.Edinburgh Partnership
Translation and Impact

Example: for Prof. Vijayakumar (2013)

- Translation through Industrial & Scientific Collaborations and Skilled People

Immediate Impact Domains

- Healthcare & Assisted Living
- Marine (Field)
- Service Robotics
- Renewables

Innovations and Collins Collaborations:

- LAAS (Toulouse): Humanoid Motion Planning
- Komura (UoE): Close Contact Animation
- Fallon (UoE): DRC Sensing
- Ramamoorthy (UoE): High-level Decision Making
- O’Boyle (UoE): Embedded Systems
- Microsoft: Multicharacter Gaming and Interfaces
- Honda: Full Body Multi-Contact Manipulation
- PELAMIS: WEC
- AQUAMARINE: WEC
- DRC
- TRL: 10 yrs
- TRL: 3 yrs
- TRL: 2 yrs
- KINova: Assistive manipulators
- HAL-Tsukuba: Exoskeletons
- Touch Bionics: Upper Limb Prosthetics
- Venkadesan (NCBS): Gait
- Lane (HWU): Marine
- BP, Schlumberger, SubSea7, BlueFin: UUVs, Oil and Gas, Marine Environment
- OC Robotics: Confined Space, Nuclear
- KUKA: Compliant Manipulation
- Cheng (TUM): Smart Tactile Sensors
- Chli (UoE): Real Time Sensing
- Smagt (TUM): Biosignal Interfaces
- Directly Collaborating Academic Partner
- Industrial Partners (italics: CDT/EDU – RAS linked)
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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CDT Structure

- MRes in the first year
- PhD starting in Year 2 after Project Proposal approval
- Yearly reports and reviews
- Thesis submission
ROBOTARIUM
A National UK Facility for Research into the Interactions amongst Robots, Environments, People and Autonomous Systems

www.edinburgh-robotics.org
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- Royal Society
- ATR International
- HONDA Research Institute
- RIKEN Brain Science Institute
- Touch Bionics
- DLR
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Thank You!