The Art of Robotics:
Toward a Holistic Approach

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Master of Science in Robotics
Thesis Defense
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Talk Agenda

1. Background — The BFD; how I ended up here
2. The Big Picture — Cover the central themes of this talk.
3. A Unifying Framework — An old framework, revived.
4. Conclusions — Review key points and propose some future work.
5. Acknowledgments & Questions — *“Please clap...”*

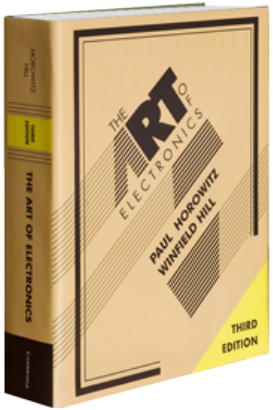
Background

The BFD

- **End Game:** Develop a Unified Framework for Understanding Robotics
  - **Thesis Purpose:** Reflect on and organize *my* understanding of robotics
    - **Talk Purpose:** Provide an overview of my thesis dissertation for the committee

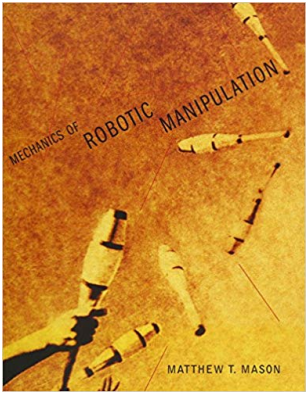
Talk Title Etymology I

- "The Art of Electronics", by *Horowitz & Hill*
  - Literally the electrical engineering bible
  - Incredibly thorough
  - Perfect balance of practicality and rigor



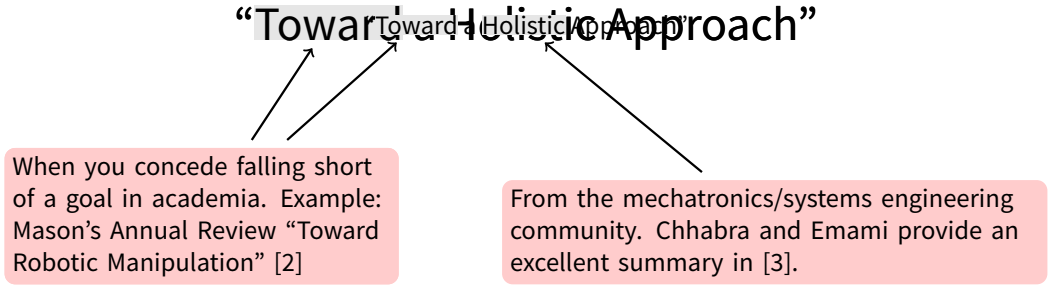
Talk Title Etymology II

- "Mechanics of Robotic Manipulation", by *Mason*[1] [1]
  - "Manipulation is an art…" (p.1)



[1] Matt, I'll take my referral payments by mail.

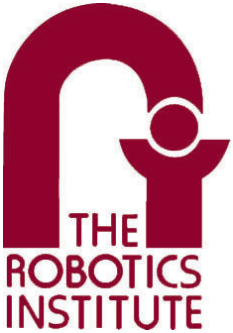
Talk (Sub)Title Etymology III



How I Ended Up Here (Some Context) I

- **Hobby robotics** ⇒ self-taught basic electronics, programming, CAD
  - “Keep it cheap”
  - “Keep it open-source”
  - “Keep it useful (or, at least, artistic)”
- **Cornell Undergrad** ⇒ ECE major, ME/CS minors
  - **ECE:**
    - “Everything is an impedance (or an admittance)”
    - “What’s the system bandwidth?”
  - **ME:**
    - “At the end of the day, everything is mechanical”
    - “Everything is a model, and every model is wrong”
  - **CS:**
    - “90% of solving a problem is finding the right representation”
    - “Everything breaks at the interfaces”

How I Ended Up Here (Some Context) II



“Time to become a robotics master...”

How I Ended Up Here (Some Context) III

“Legged locomotion is cool...”

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How I Ended Up Here (Some Context) IV

"Great! Here's absolutely no funding."

"Legged locomotion is cool..."

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How I Ended Up Here (Some Context) V

“Great! Here’s absolutely no funding.”

“Umm...”

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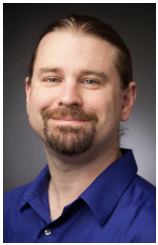
How I Ended Up Here (Some Context) VI



“Wait! Go talk to Matt Mason!”

“Umm…”

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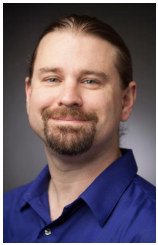
How I Ended Up Here (Some Context) VII

“Wait! Go talk to Matt Mason!”



“(skeptical) Okay...”

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How I Ended Up Here (Some Context) VIII

"Manipulation is awesome!
And I have money!
And I don't micromanage!"

"(skeptical) Okay..."

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How I Ended Up Here (Some Context) IX

"Manipulation is awesome!
And I have money!
And I don't micromanage!"

"(excited) Works for me!"

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How I Ended Up Here (Some Context) X

“Fantastic, go forth and prosper!”

“(excited) Works for me!”

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How I Ended Up Here (Some Context) XI

"I've been meaning to read Hogan's famous *Impedance Control* [4] paper, I guess I'll start there..."

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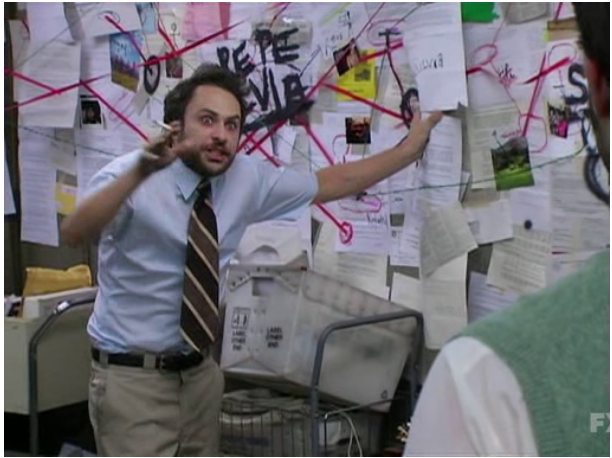
How I Ended Up Here (Some Context) XII

… Two Years Later …

Me, circa July 2018



“So it’s all about causality… and feedback!”

The Big Picture

Back to Basics

- Want a concise *theory of robotics*…
- Interested in the *physics* common to robotics problems
- Not worried about SLAM, POMDPs, etc… there are bigger fish to fry (we're skimming over the basics!)
  - i.e. Moravec's paradox [5]
- Inherently a *breadth-first* approach, since we're looking for a unifying framework

Problem 1: What is a Robot?

- I know it's a cliché to bring this up… but I must!
  - Does the ambiguity really matter?
  - Maybe not, but some unifying *theme* would be useful!

Problem 2: What is Manipulation?

- To be honest, I had a very shallow understanding of manipulation until I met Matt
  - I imagined it was just factory robot stuff
  - It took some reflection to appreciate the depth of “manipulation”

Problem 2: What is Manipulation?

"Manipulation refers to an agent's control of its environment through selective contact."

— *Matt Mason*, "Toward Robotic Manipulation" [2]

Problem 3: Locomotion and Manipulation, Segregated

- Locomotion and manipulation are studied separately in robotics
  - … and biomechanics, for that matter
  - Seems quite natural at first, we all talk about the two as separate specializations in robotics
- Eventually, the notion of *"duality"* comes up…
  - Locomotion and manipulation sometimes overlap
    - Pai et al.'s *Platonic Beasts* [6]
    - Mason et al.'s *Mobipulator* [7] [8]
    - Also, literally everywhere in biology
  - Perhaps it just comes down to a change of reference?
    - Just a matter of "what pushes off of what?"
    - Locomotion is "self-manipulation", e.g. Aaron Johnson's PhD thesis [9] and related works [10][11]

Problem 3: Locomotion and Manipulation, United

- The “self-manipulation” view of locomotion is consistent with our definition of “manipulation”:
  - An agent may control its environment through selective contact (i.e. “manipulation”) by moving about in it (i.e. “locomotion”). [2]

So locomotion is just a subset of manipulation!

[2] It helps to take on an egocentric point of view to visualize this.

Problem 3: Locomotion and Manipulation, United

- Not a terribly practical insight… but thinking back to *Problem 1*…

Manipulation *is* the central theme in robotics!

Embodiment & Hogan's Physical-Equivalence "Postulate"

- Embodiment
  - Vaguely, the idea that robots exist in the real world and are inherently tied to their environment
  - Presently resides in the cognitive science community (as in "embodied *cognition*")
- *Hogan's* Physical-Equivalent Principle
  - "It is impossible tO devise a controller which will cause a physical system to present an apparent behavior 10 its environment which is distinguishable from that of a purely physical system" [4]
  - Basic argument for this is "you can't break thermodynamic laws"
  - But more intuitively, the robot is a real thing, you can't make it do not real things

A Unifying Framework

Port-Hamiltonian Systems Theory

- The symbiosis of:
  - Bond graph theory (*Paynter, Hogan, Breedveld, van Dijk*)
  - Hamiltonian dynamics on manifolds (i.e. “geometric mechanics”)
  - Poisson / Dirac structures
- Principal contributors include *Stramigioli, van der Schaft, Maschke*

Port-Hamiltonian Systems Theory

- Port-based Analysis
  - Inherits the bond-graph notion of power ports
  - Treats systems in terms of power flow between components
  - Each bond represents the conjugate pair of an effort and flow

Port-Hamiltonian Systems Theory

- Hamiltonian Dynamics
  - Provides a fully geometric (intrinsic, coordinate free) description of system dynamics
  - Equivalent to (and convertible from/to) Lagrangian formulation, but better!
    - Riemannian geometry of Lagrangian dynamics replaced with symplectic geometry, in which fundamental invariants are preserved
    - Configuration space of Lagrangian dynamics replaced with state space
    - Hamiltonian formulation directly yields a system of first order differential equations
  - Avoiding nonholonomic constraints yields explicit ODE[3]

[3] May be a stiff explicit ODE! So, soften your intermittent contacts!

Port-Hamiltonian Systems Theory

- System fully defined by:
  - Energy function captures all energy storage elements in system
  - Resistive structure captures all dissipative elements in system
  - Poisson or Dirac interconnection structure defines power flow within system
    - *Storage port* connects to energy storage
    - *Dissipative port* connects to resistive structure
    - *Interaction port* connects to environment (**dynamic system** not known a-priori or directly controlled)
    - *Controller port* connects to controller (**dynamic system** that the designer has control over)

Working Through an Example

Closing Thoughts

Closing Thoughts

- Manipulation is the common theme in robotics
- Embodiment $\Leftrightarrow$Hogan's Physical Equivalence Principle [4]
- Port-Hamiltonian Systems Theory is the framework to unify robotics

Acknowledgments

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- Matt Mason
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Questions?

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