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Scaling Robotic Capability Using Multi-Agent Systems

Applications in Agriculture, Construction and Manufacturing

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About me

- Graduated with honours with a Masters Degree in Aerospace Engineering with a double minor in Control Theory and Robotics
- Prior industrial background in robotics and automation - worked for semiconductor and aerospace firms and led several projects
- Currently undertaking a PhD in Control, specialising in multi-agent theory for robotics
- Working as a research scientist at Airbus Robotics

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Our Lab at UoS: Bringing Digitisation to Manufacturing and Beyond

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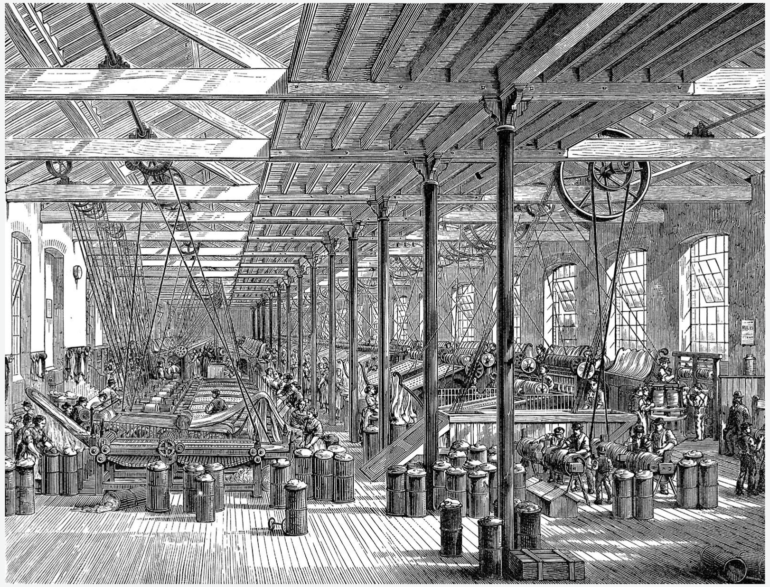
Industrie 4.0: An Automation Explosion



Source: Encyclopedia Britannica

Source: Zenoot

Source: Automation.com

Robotics and their Commercialisation

Source: Boston Dynamics

What can Robot’s Achieve?

Source: ETH Zürich

Source: John Deere

So what is stopping us?

Source: [Fluctus (YouTube)]

Current Limitations

What the current limitations with robotics in industry?

- A single robot is not capable of completing large tasks efficiently in a timely manner
- Sim2Real: what works in simulation ≠ what works in the real world
- Humans and robots don’t always work together well!

Multi-Agent Systems: A (brief) Introduction

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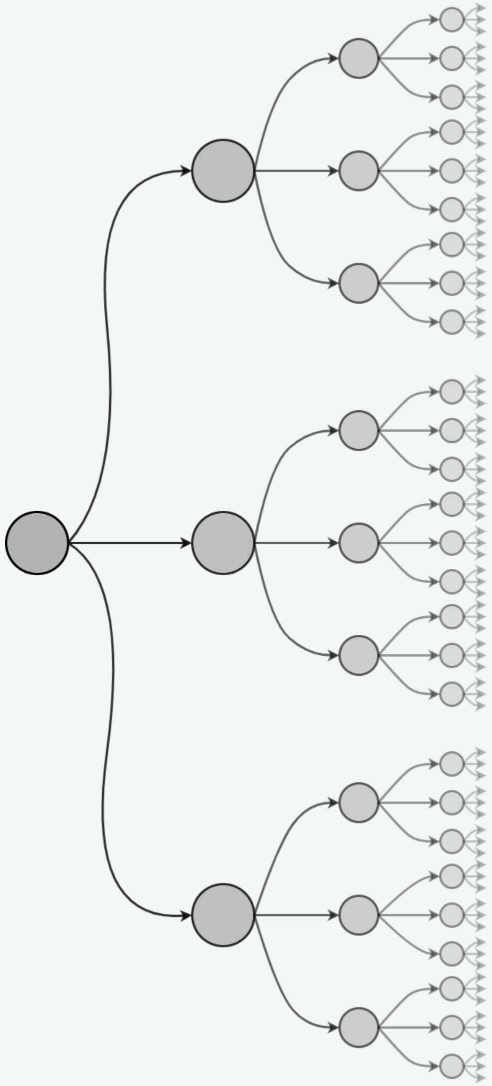
Multi-Agent Systems as *n*-player Markov Games



We define a Markov game as a tuple $\langle S, \{A\}_{1:n}, \{P\}_{1:n}, R, N \rangle$ where each agent can choose to make an action $a_n \in A_n, \ \forall n \in N$ and receives a payout R at each state $s \in S$. The objective is to maximise each individual payout of each agent across the set of states to find the optimal policy:

$$V_n^*(\pi) = \underset{s \in S, a_n \in A_n}{\operatorname{argmin}} \ \mathbb{E}\left[\sum_{s \in S} \gamma R_n\right]$$

The joint cost function for the combined set of agents is known as:

$$J(\{a, a_{-n}\}) = \underset{s \in S}{\text{maximise}} \ \mathbb{E}\left[\sum_{n \in N} \sum_{s \in S} \gamma R_n\right]$$

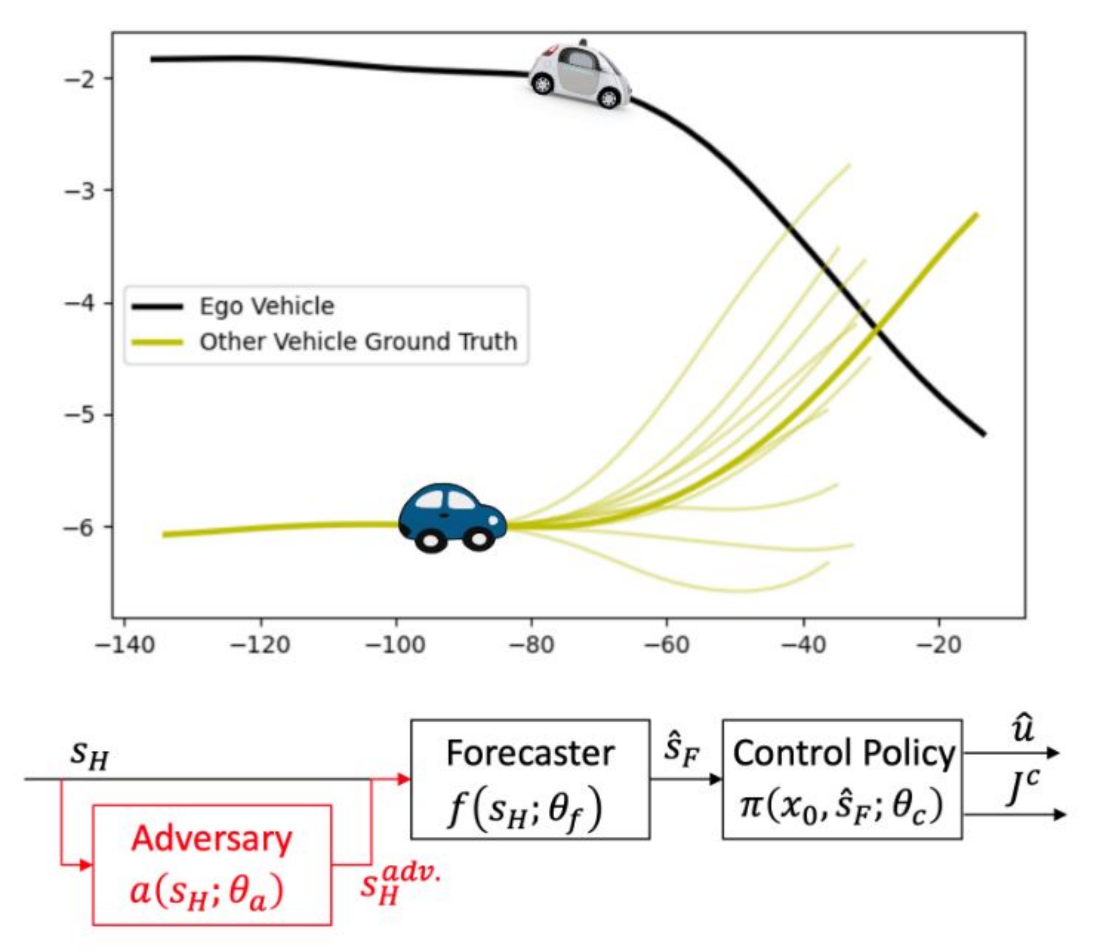
For each agent, a strategy is considered optimal and at a Nash equilibrium if, **provided they know the other agents actions**, the cost function satisfies the inequality:

$$J(\{a^*, a^*_{-n}\}) \geq J(\{a, a^*_{-n}\})$$

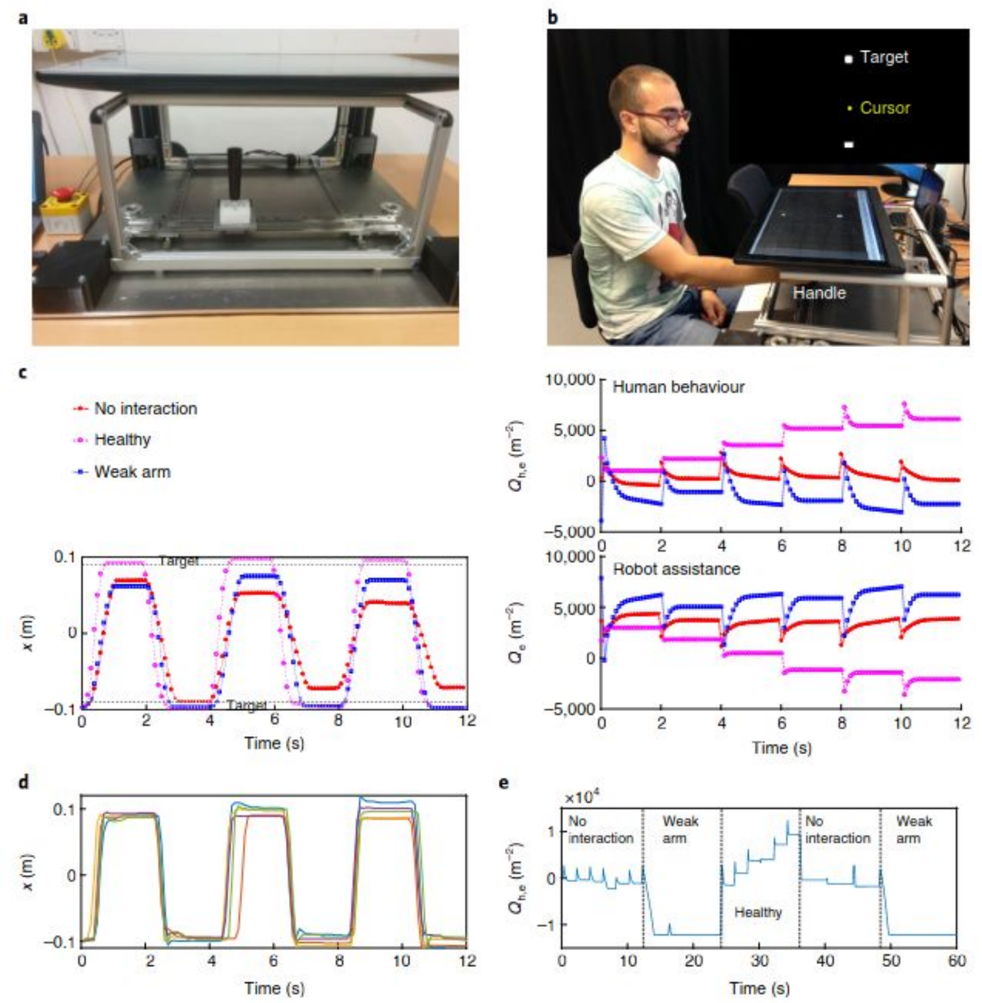
Solving Markov Games for *n*-players

- No general solution for Markov games
- Two types of agents exist: cooperative and uncooperative
- Very dependent on whether the game is discrete or continuous, finite or infinite
- Computing Nash equilibrium is not always so simple! - can have hundreds of thousands of states
- Can use methods from optimal control to compute actions for each agents

Translating Multi-Agent Theory to Robotics



Source: Agarwal et al. (2023)



Source: Li et al. (2019)

End-to-End Robotics

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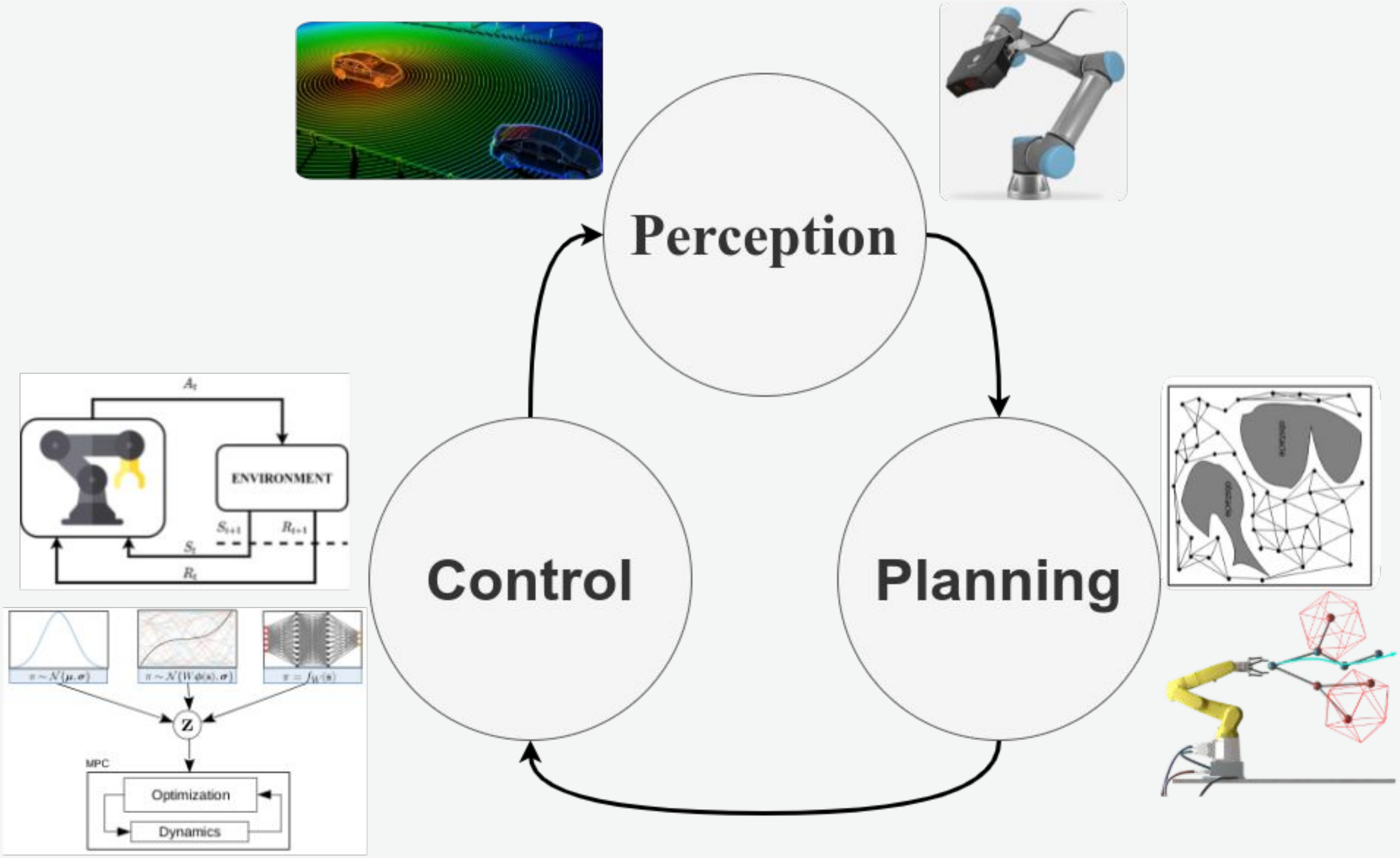
The Big Feedback Loop in Robotics



Step 1: PERCEPTION

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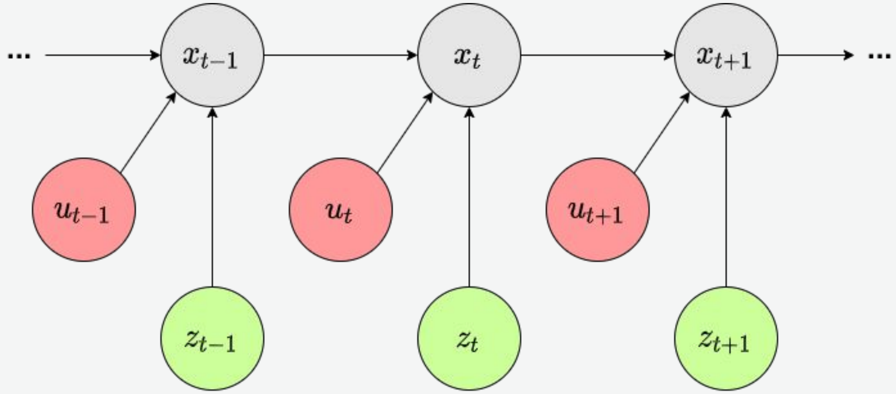
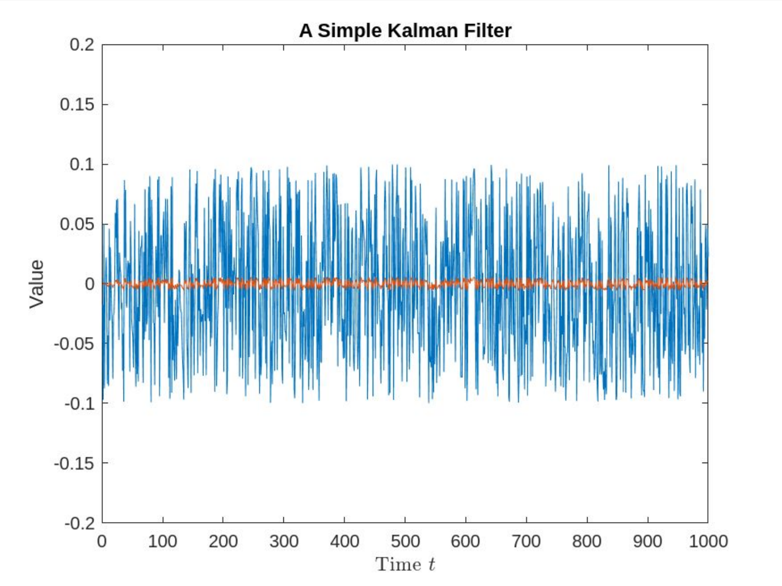
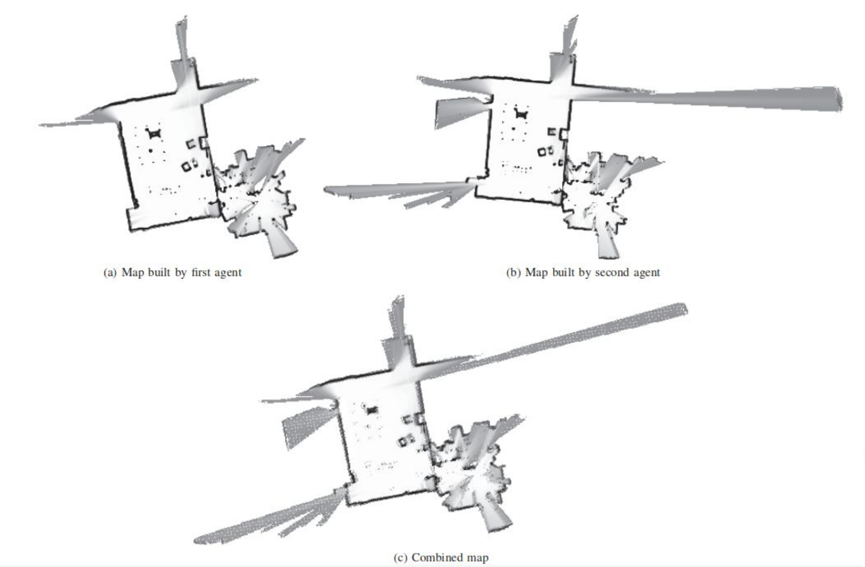


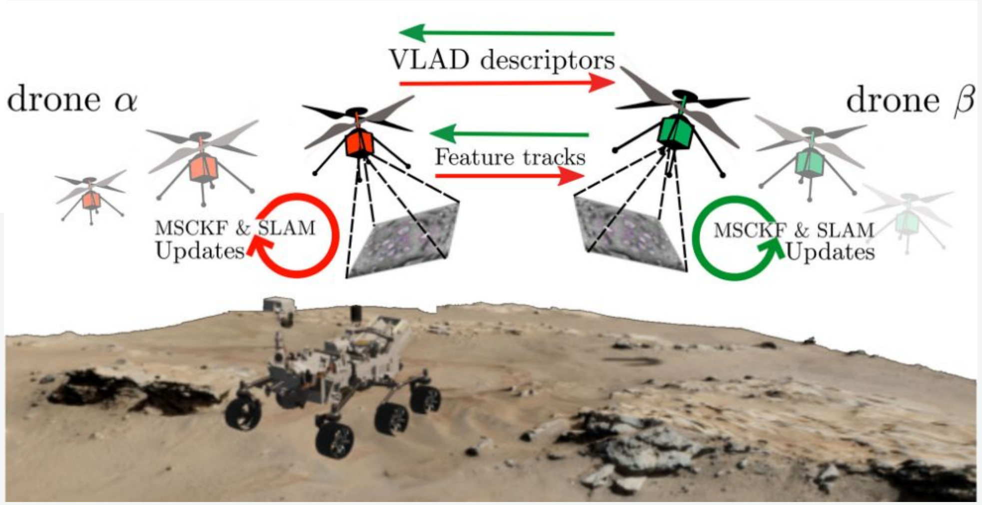
- Sometimes referred to as *State Estimation*
- How we **observe** the surroundings
- The world is noisy - need to account for uncertainty in our measurements
- A large variety of sensors that are available: cameras, LiDAR, force sensors, sonar sensors



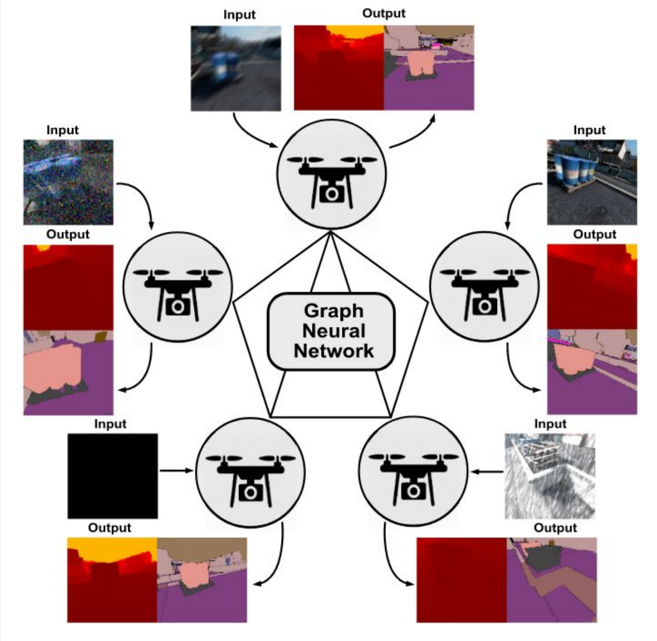
Recent Examples of Multi-Robot Perception



Source: Filatov & Krinkin (2019)



Source: Polizzi et al. (2022)



Source: Zhou et al. (2022)

Open Challenges in Multi-Robot Perception

- How agents generate or reference a global map - do they construct individual maps?
- Communication between agents - data bandwidth and mutual information
- Overlapping data samples and artifacting within readings
- What information do individual robots need?

Step 2:
PLANNING

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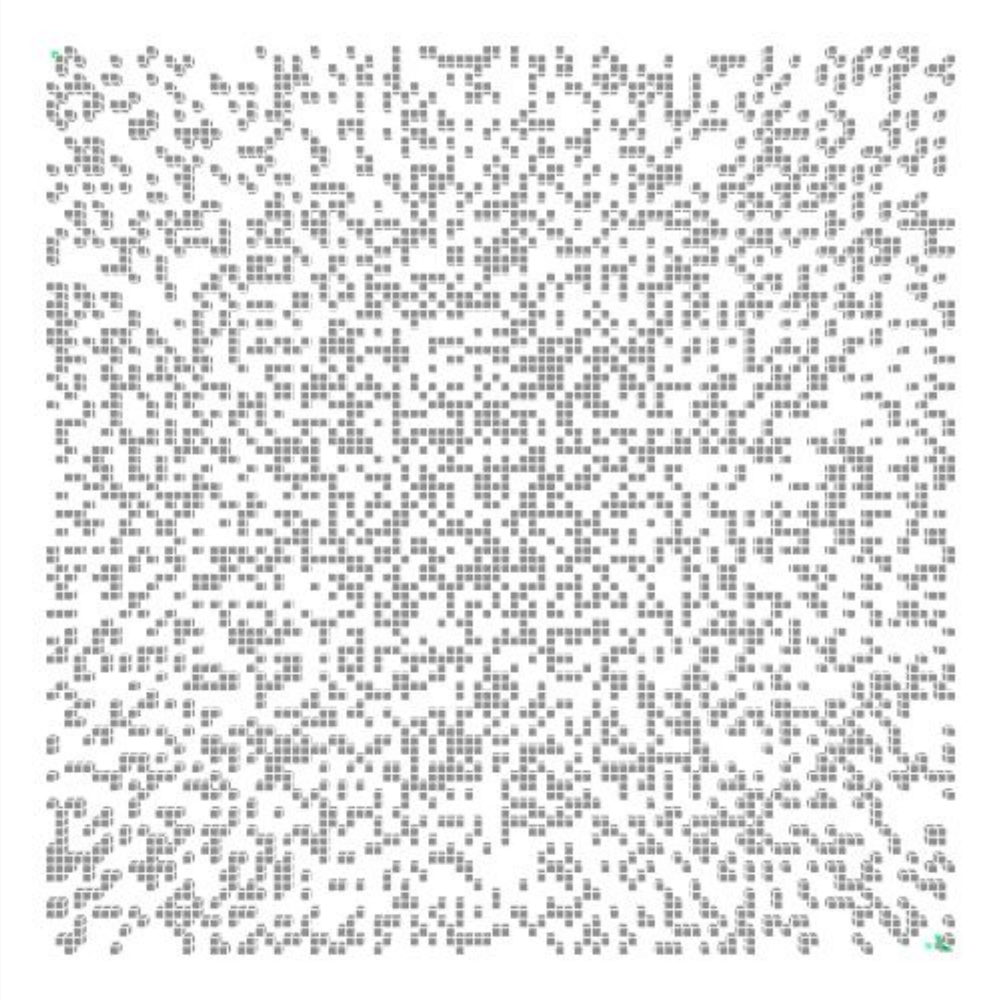
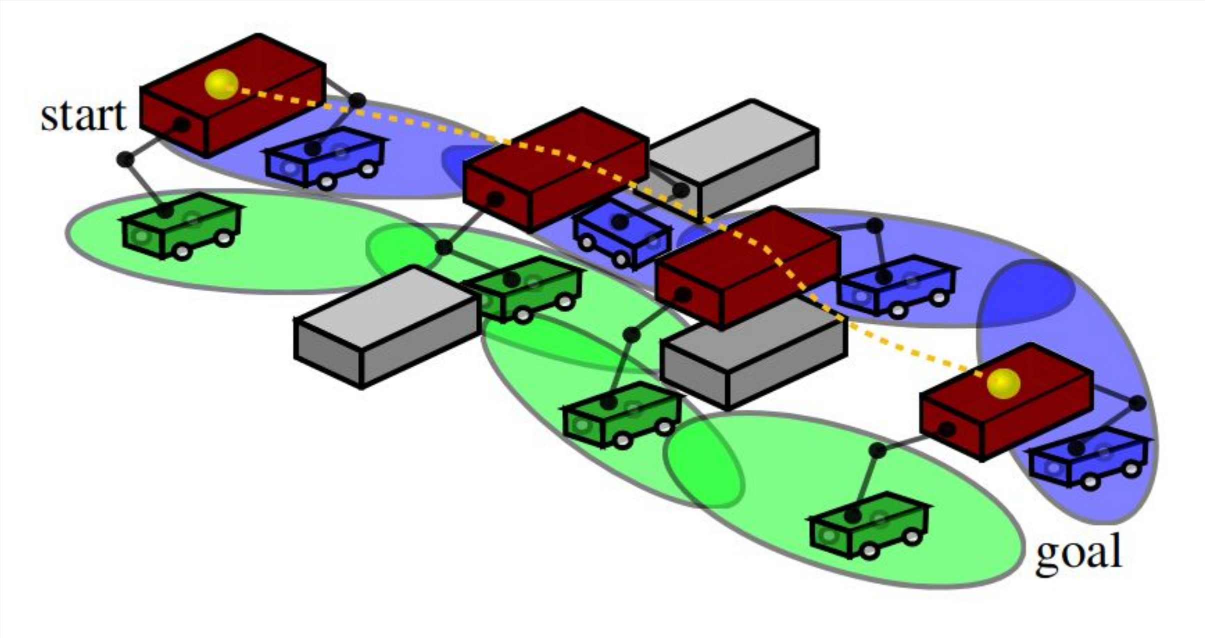
Step 2: PLANNING

- Once we know where we are, we need to know **where** we are going
- Wide variety of planning algorithms - there is a whole textbook of them!
- Combines obstacle avoidance and shortest path determination - how do you know the fastest way to school?
- Biggest problem lie in the field of exploring routes that are unfavourable - translating real-time planning to learning-based planning



Recent Examples of Multi-Robot Planning



Source: Zhang et al. (2021)

Source: Patwardhan et al. (2023)

Open Challenges in Multi-Robot Planning

- Computing local plan vs computing global plan
- For distributed robots, how do we ensure coverage across a large area?
- Guarantees of optimality exist for single robot planning - do these exist for multi-robot systems?
- How do we guarantee cooperative plans between decentralized robots?

Step 3: CONTROL

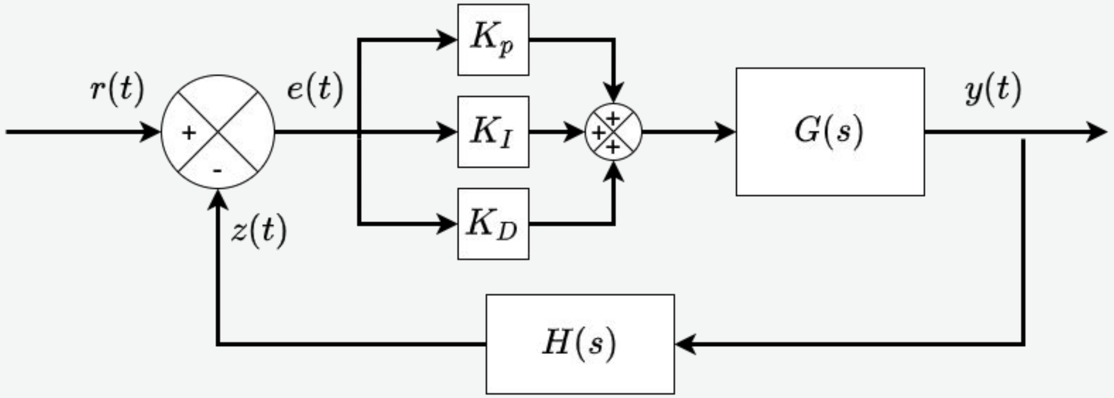
Step 3: CONTROL

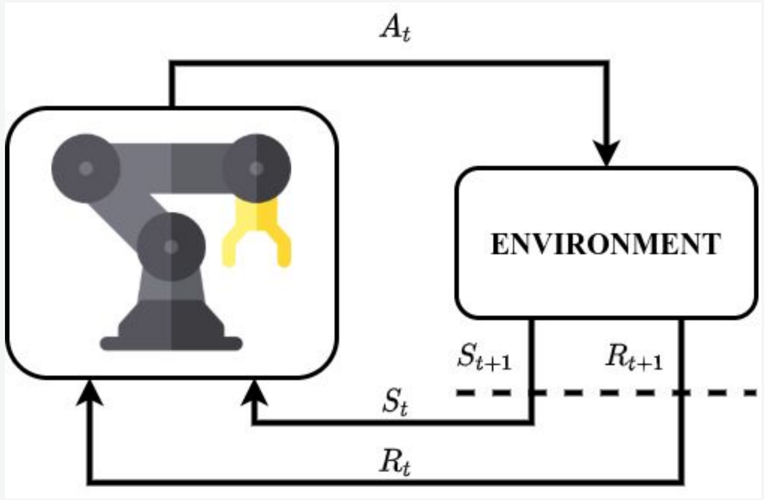
- We can see the world, we have a plan to get there - now we must actuate!
- Control has changed vastly in the last 60 years - from PID to Optimal to Robust to Adaptive to Learning-Based
- Robot platforms are diverse - need algorithms from everything such as mobile robotics and manipulators

$$x^*_{1:T}, u^*_{1:T} = \underset{x_{1:T}\in\mathcal{X}, u_{1:T}\in\mathcal{U}}{\operatorname{argmin}} \sum_{t=1}^{T} C(x_t, u_t)$$

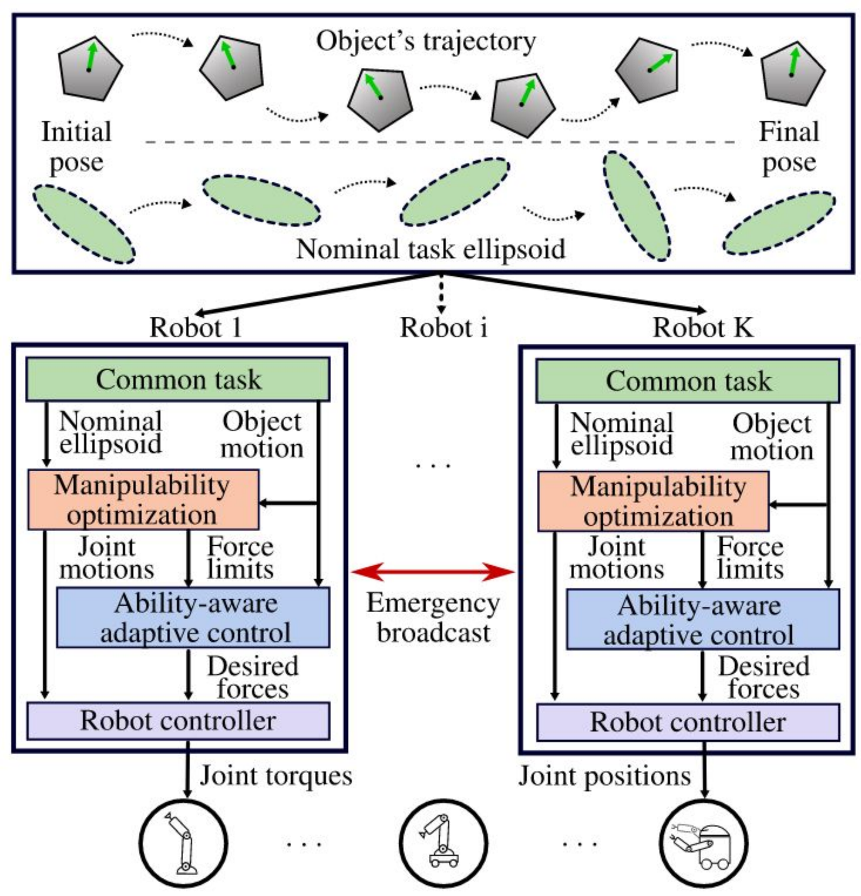
$$\text{s.t.} \quad x_{t+1} = f(x_t, u_t)$$

$$x_0 = x_{\text{init}}$$

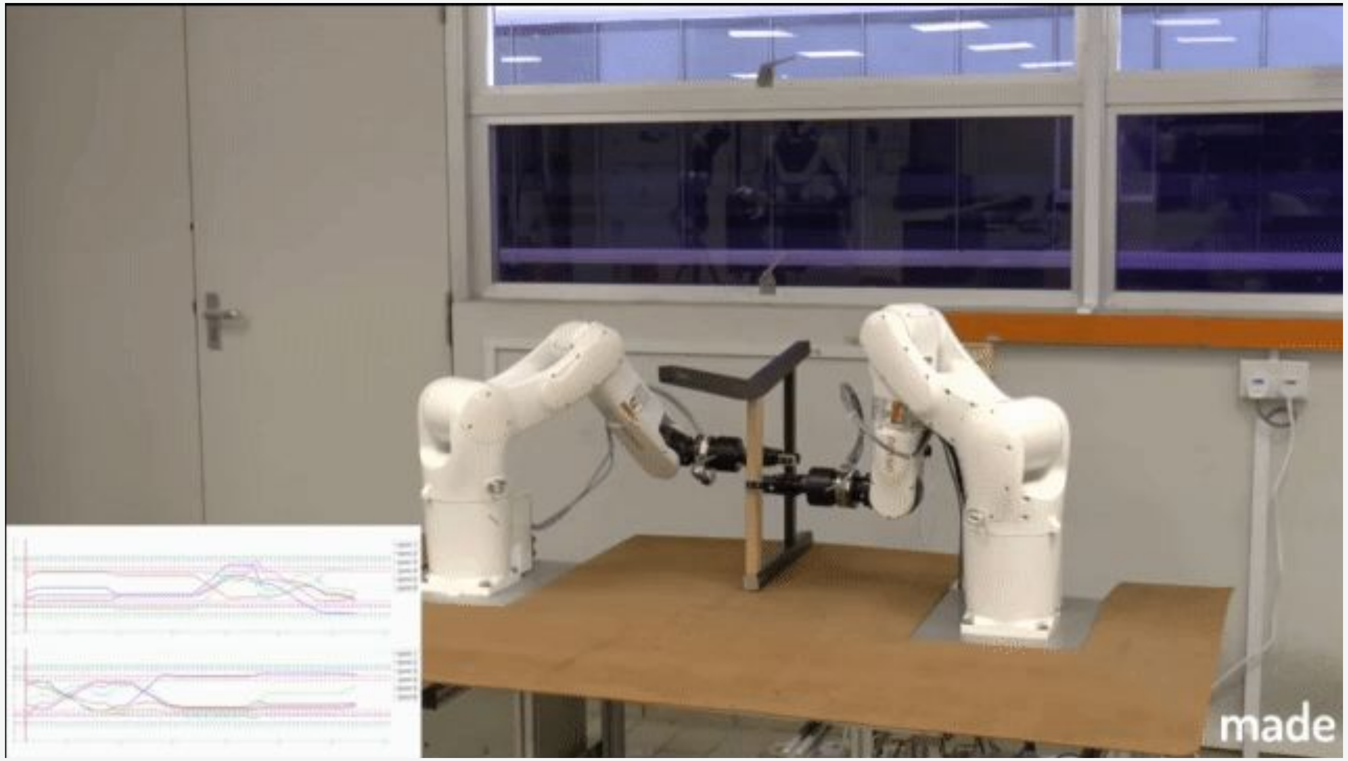




Recent Examples of Multi-Robot Control



Source: Yan et al. (2021)



Source: Xian et al. (2017)

Open Challenges in Multi-Robot Control

- For multi-robot systems, the action space is **very large** - how do we guarantee optimal actions?
- Cannot always re-grasp a component - how do we know what permissible control laws there are?
- Optimisation methods can get stuck in local optima that *appear* globally optimal
- Learning-based control has to deal with large uncertainties

Examples of Multi-Robot Systems in Agriculture, Manufacturing and Construction

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Agriculture

Source: Organifarms

Source: TopTechTopic

Manufacturing

Source: Fanuc

Source: Tech Insider

Construction

Source: CNBC

Source: Tomorrow's Build

Summary

- Multi-robot systems have the potential to improve the feasibility of robotic solutions in a variety of disciplines
- Research areas in multi-robot systems follow the trend of single robot research
- More care needs to be taken about how we evaluate the performance and robustness of the control methods
- The cost of multi-robot systems needs to be appealing enough to convince producers to invest in them

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