UPPSALA
UNIVERSITET

Reinforcement learning for multi-agent systems under semantic and perceptual uncertainties

Nils Axelsson
Division of Signals and Systems
Department of Electrical Engineering

Supervisors:
Christos Verginis
Ayça Özçelikkale
Roland Hostettler

Background

- PhD student at the division of Signals and Systems at Uppsala university
- Joined SEDDIT in 2025

SEDDIT
Sensor informatics and Decision-making for the Digital Transformation

UPPSALA UNIVERSITET

Project motivation

- Develop algorithms for collaborative autonomous multi-agent systems
- Applications
  - Search & rescue
  - Environmental monitoring
- Tasks
  - Explore, locate, track, transport, monitor
- **Challenges**
  - Distributed setting (no ’global’ information)
  - Uncertain environments
  - Unreliable and limited communication
  - Need to simultaneously perform task and learn from the environment

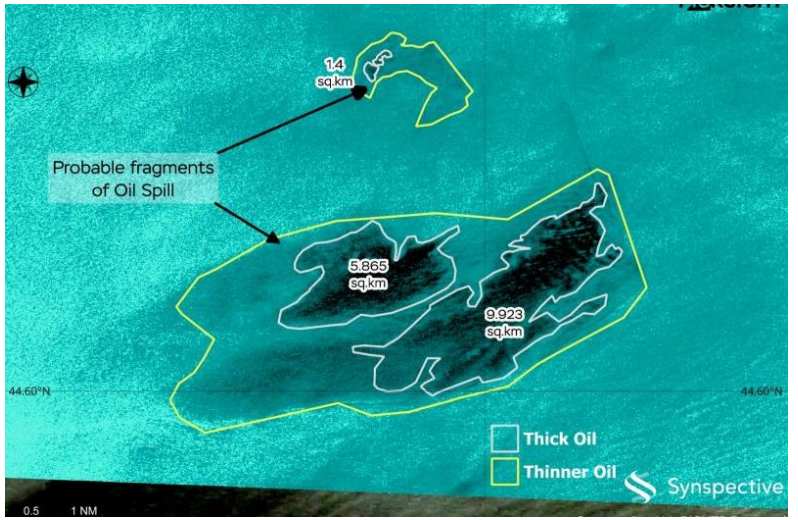
UPPSALA UNIVERSITET

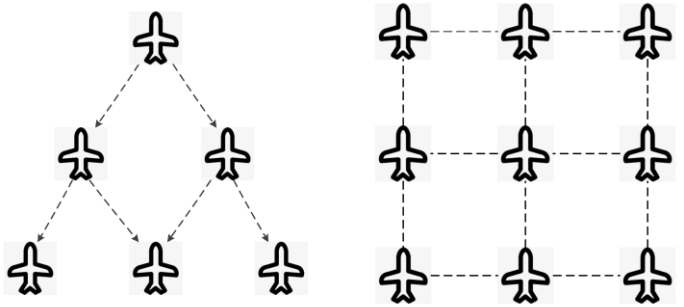
Research areas

- We aim to address these challenges by combining
  - Multi-agent control theory
  - Collaborative reinforcement learning
  - Decentralized sensor fusion

- Formation control applications
  - monitoring of environmental boundaries
  - coordinated detection and tracking

- Standard formations
  - Fixed (pre-specified) shape
  - Distance or bearing constraints
  - Rigid formations

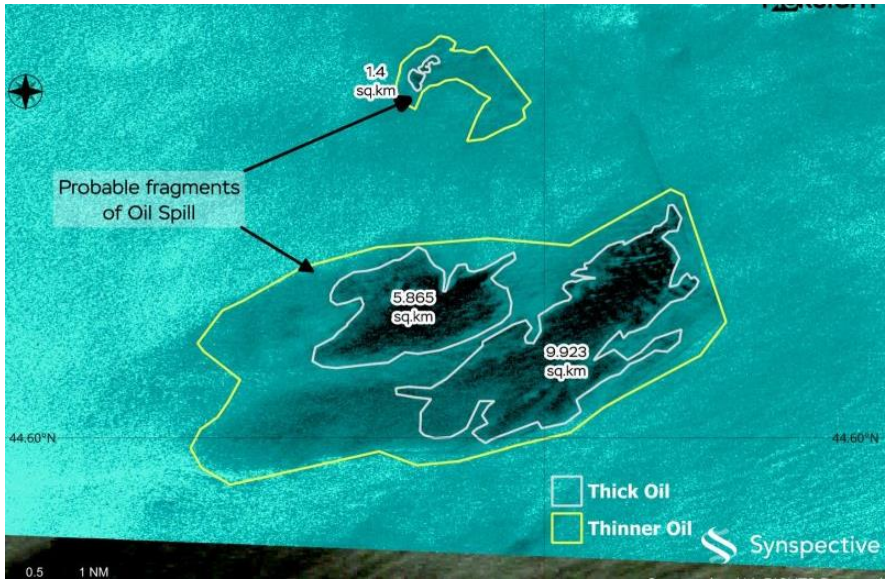




UPPSALA
UNIVERSITET

Multi-agent formation control

- Many naturally occurring phenomena are dynamic (deformable), irregular, and continuous
  - Better described by parametric curves rather than fixed geometric shapes
- In target enclosing tasks, forming a smooth, adaptive boundary around a point of interest is often sufficient
- **Current work:** flexible formation control
- Instead of specifying exact locations of each agent, control the formation shape indirectly by specifying
  - Location (center)
  - General shape (”frequency content”)



UPPSALA
UNIVERSITET

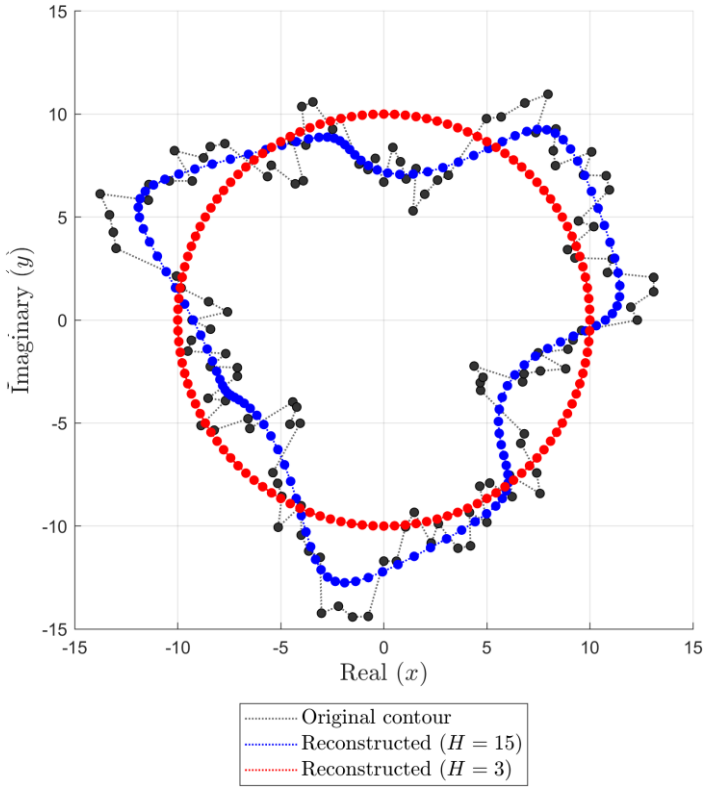
Frequency domain descriptions of shapes

- Closed curves can be seen as a superposition of a series of elliptical curves with increasing frequency

$$\begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = \begin{bmatrix} a_0 \\ c_0 \end{bmatrix} + \sum_{k=1}^{\infty} \begin{bmatrix} a_k & b_k \\ c_k & s_k \end{bmatrix} \begin{bmatrix} \cos kt \\ \sin kt \end{bmatrix}$$

- Low frequency → ”global” shape
- High frequency → details

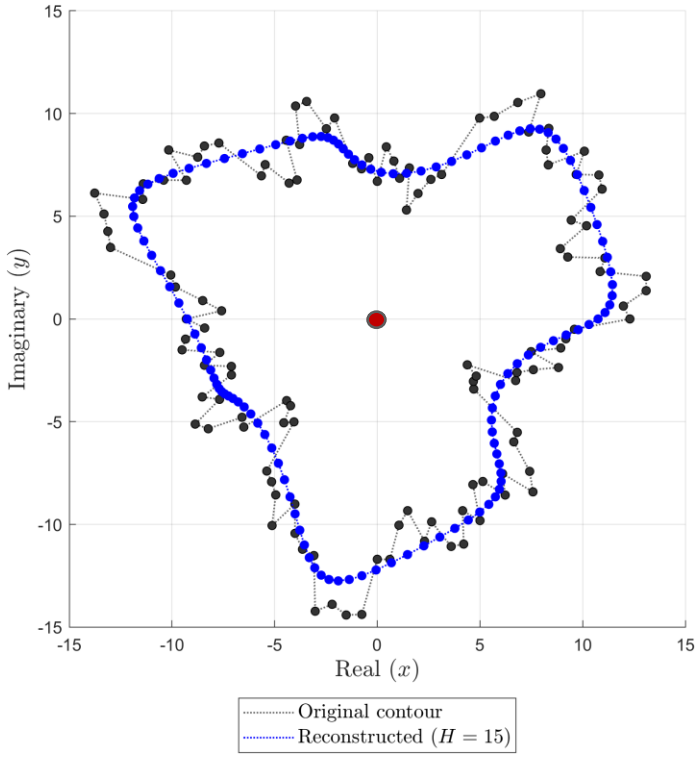
- A convenient encoding of such shapes is given by Fourier descriptors (FDs)
- FDs are the coefficients of the discrete Fourier transform (DFT)
- Convenient separation of centroid and shape



UPPSALA UNIVERSITET

Related work

- Recent works exploit Fourier descriptors to
  - track evolving irregular boundaries
  - implicitly defining formation shapes
    - agents form an ellipse from any given initial conditions
    - “emergent formations”
- There also exists algorithms for
  - Distributed estimation of FDs
  - Control laws such that agents form formations with a certain low-frequency content
    (shapes with a certain selected set of non-zero FDs)
- **Problems:**
  - Fixed formation centroid (determined by initial conditions)
  - Non-increasing scale (can lead to shrinking/flat formations)



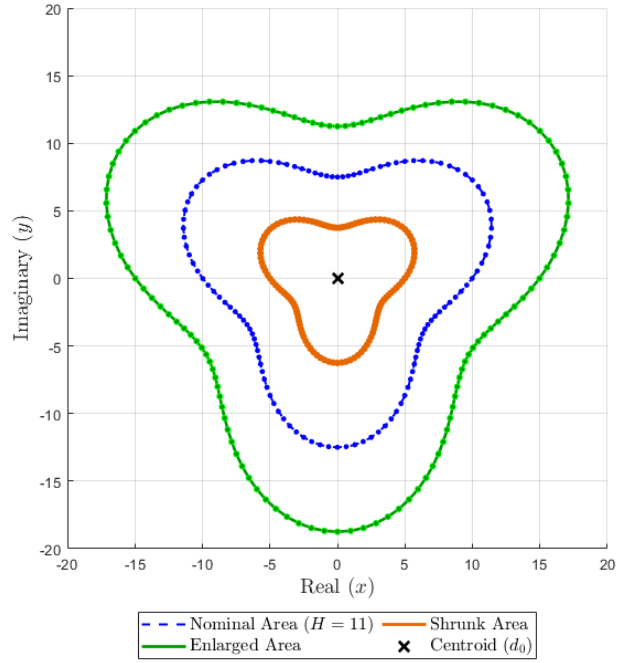
UPPSALA UNIVERSITET

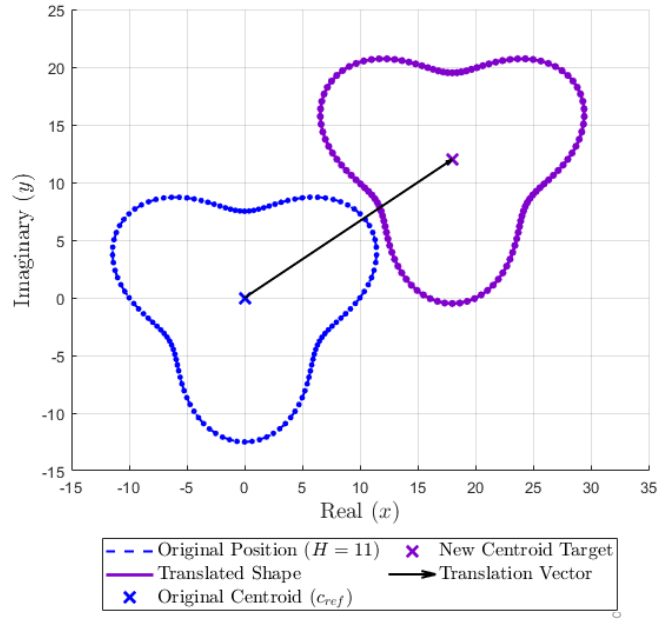
Recent work

- In a recent paper, we address the scale and centroid limitations by introducing:
  - Area regulation
  - Centroid tracking

- Interesting for high-level tasks:
  - ”Distribute around a point and track it”
  - Agent’s automatically form a shape that ’works’
  - Any formation shape with a certain
    1. low-frequency content
    2. centroid
    3. enclosed area

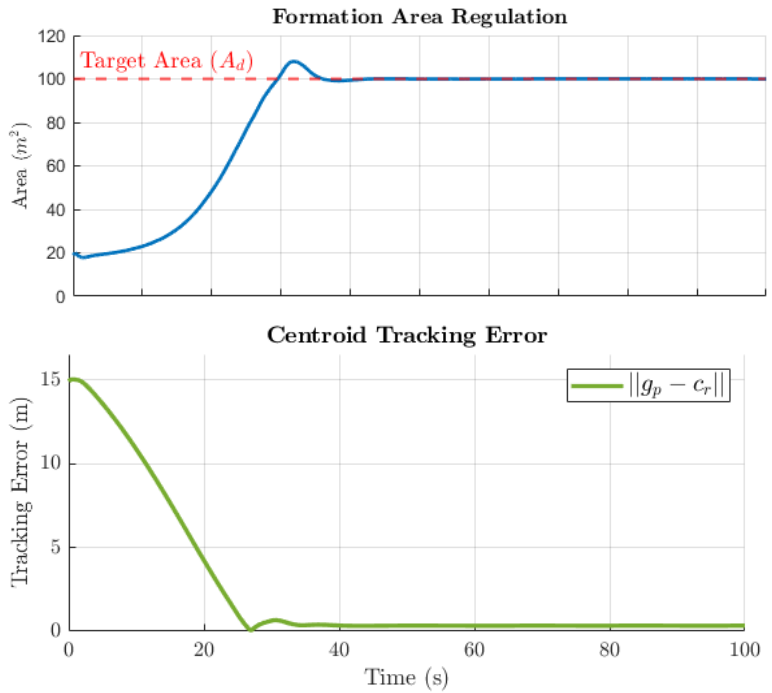
    is valid
- Distributed setting:
  - each agent only needs to know its own position and orientation + local communication (neighbour-to-neighbour)

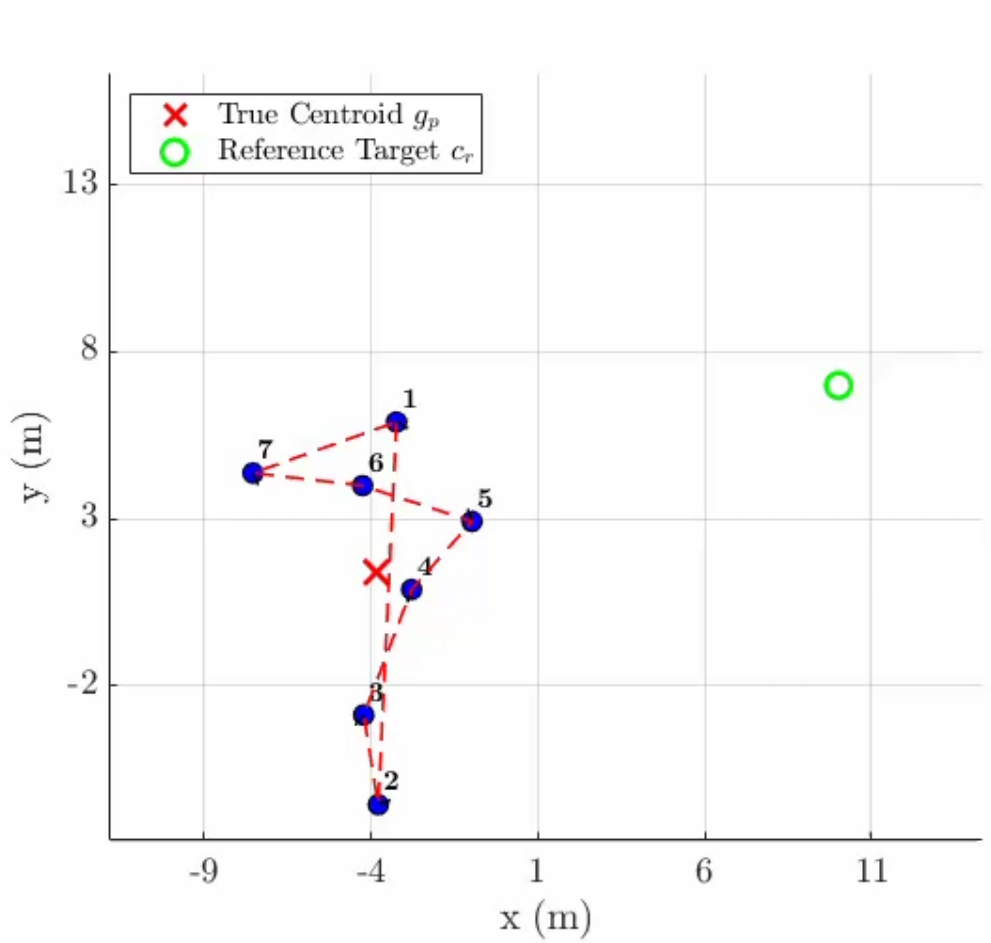




Simulations

- 7 unicycle agents in random initial locations
  - Convergence to an elliptical shape
  - Convergence to a desired enclosed area
  - Centroid tracking

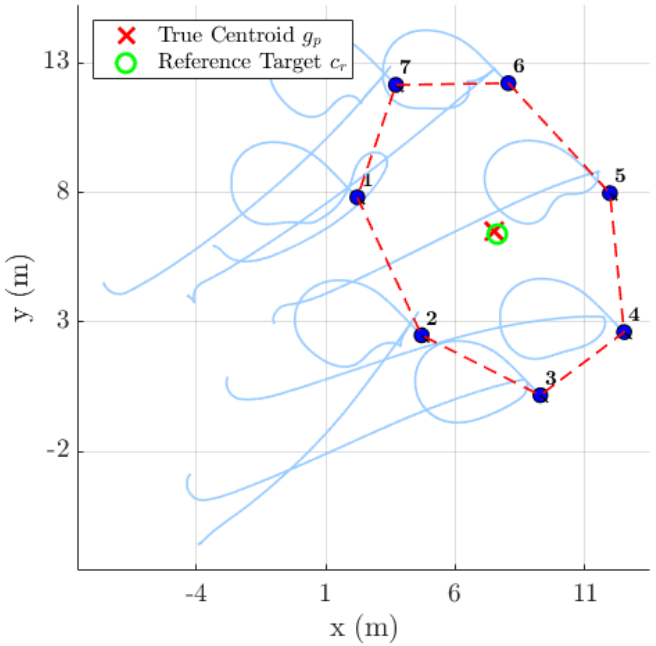




UPPSALA UNIVERSITET

Conclusion and future work

- We have developed a distributed control strategy for multi-agent formations.
- By leveraging properties of Fourier descriptors, the proposed framework allows agents to
  - form and maintain formations with a prescribed enclosed area
  - track a desired average position.
- Future work will focus on
  - Control of other geometric characteristics (shape orientation)
  - Higher-order systems (more complex agent dynamics)
  - Uncertainties in position/orientation



UPPSALA UNIVERSITET

Thank you!

- Questions?

UPPSALA
UNIVERSITET