Design and Development of a Mobile Sensor Network for the Nuclear Industry

Aydin Can [a, b], Joshua Price [b], Allahyar Montazeri [a]

[a] Engineering Department, Lancaster University, Lancaster, LA1 4YR, UK

[b] National Nuclear Laboratory, 5th Floor, Chadwick House, Warrington Road, Warrington, WA3 6AE, UK

Lancaster University

Engineering and Physical Sciences Research Council

NATIONAL NUCLEAR LABORATORY

CINDe

CENTRE FOR INNOVATIVE NUCLEAR DECOMMISSIONING

Introduction

The rapid acceleration of technological development in recent years has created a number of new challenges and opportunities for several industries. These changes that industries are facing have been coined as "Industry 4.0", which aims to utilize the Internet of Things (IoT), Artificial Intelligence (AI) and Cyber-Physical Systems (CPS) to create a new era of self-aware and autonomous industrial processes [1].

One industry that could benefit from these changes is the nuclear industry, which currently provides an option for clean energy as demand increases globally. However, several issues have been identified as "Game Changers" in the nuclear industry [2], including:

- Physical asset management.
- Condition monitoring and inspection.
- Plant characterization.

Cyber-Physical Systems are systems comprised of a software layer, as well as a physical system containing sensors and actuators. These systems also have networking capabilities [3]. A multi-agent network of autonomous quadrotor Unmanned Aerial Vehicles (UAVs) makes an ideal platform for a CPS to address the Game Changer Challenges, as they are mobile in 3D space, and can be equipped with various visual sensors for autonomy, as well as environmental sensors for collecting data [4].

Project Aims

This project aims to address three main areas in order to create a Cyber-Physical System for the nuclear industry:

- Design and develop a robust control algorithm for a single UAV to allow it to safely fly autonomously indoors in hazardous environments.
- Design an advanced Multi-Agent control algorithm for climbing of scalar fields (e.g. Temperature and Radiation) to rapidly identify hot spots
- Integrate hardware and software to provide a prototype platform and a technological demonstration of the proposed Cyber-Physical System.

Methods

In this project a combination of numerical analysis, simulation, and experimentation is being used to address the project aims, and create a Cyber-Physical System for the nuclear industry.

Numerical Analysis

- Firstly, using mathematical techniques such as stability proof using the Lyapunov Stability Criteria, we aim to prove the robustness of the proposed control systems.

Simulation

- Software is used to simulate the proposed control systems. The control systems are developed using MATLAB and Simulink where they are tuned and refined using a basic mathematical model of a quadrotor.
- More advanced simulations are then conducted using the Robotic Operating System (ROS) and Gazebo. Figure 1 demonstrates how these are connected for a co-simulation between Simulink and ROS for testing of the control systems.

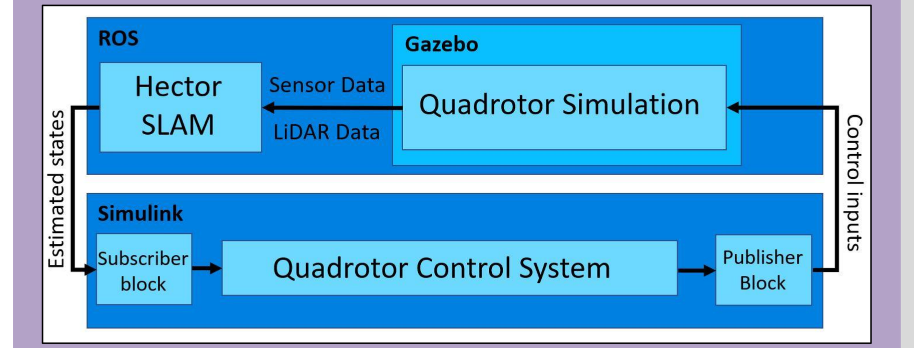

Figure 1: Flow diagram of communication between the Robotic Operating System (ROS) and Simulink.

Conceptual Design

- The hardware and software layers will then be integrated to create a network of autonomous UAVs. Figure 2 shows the flow chart design of the proposed UAV system.

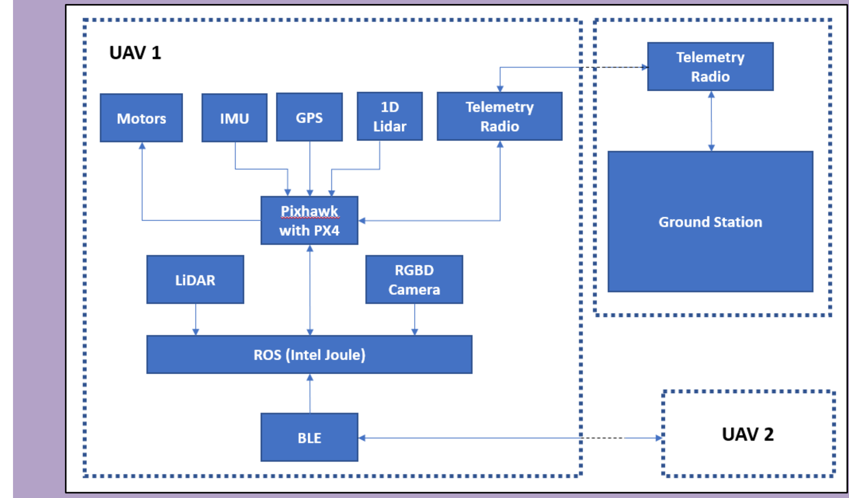

Figure 2: Flow Diagram of UAV Framework.

Results

Sliding Mode Control Systems for a Single Agent

In order to safely control a group of agents, we must first be able to control a single agent. For the controller to be considered suitable for a nuclear environment, it should have the following capabilities:

- Full position and attitude control over all 6 degrees of freedom (x, y, z, roll, pitch, yaw) for trajectory tracking.
- Ability to control a UAV with large discrete sample times to compensate for slow sensing rates of LiDAR and Camera sensors, as well as avoid chattering.
- Ability to reject external disturbances and uncertainties in parameters.

Three sliding mode control system were developed to address these challenges. Two continuous controllers were developed to avoid the chattering problem [5,6], and one discrete time controller was developed to handle larger sample times [7].

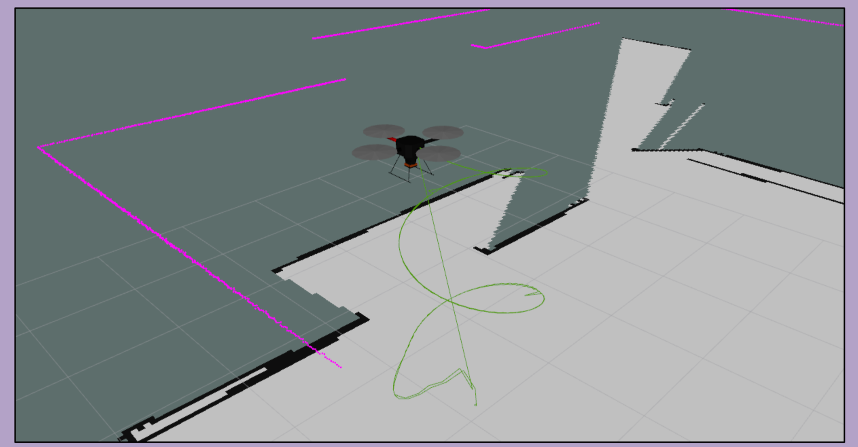

Figure 3: ROS Simulation environment RViz with quadrotor using Hector SLAM [7].

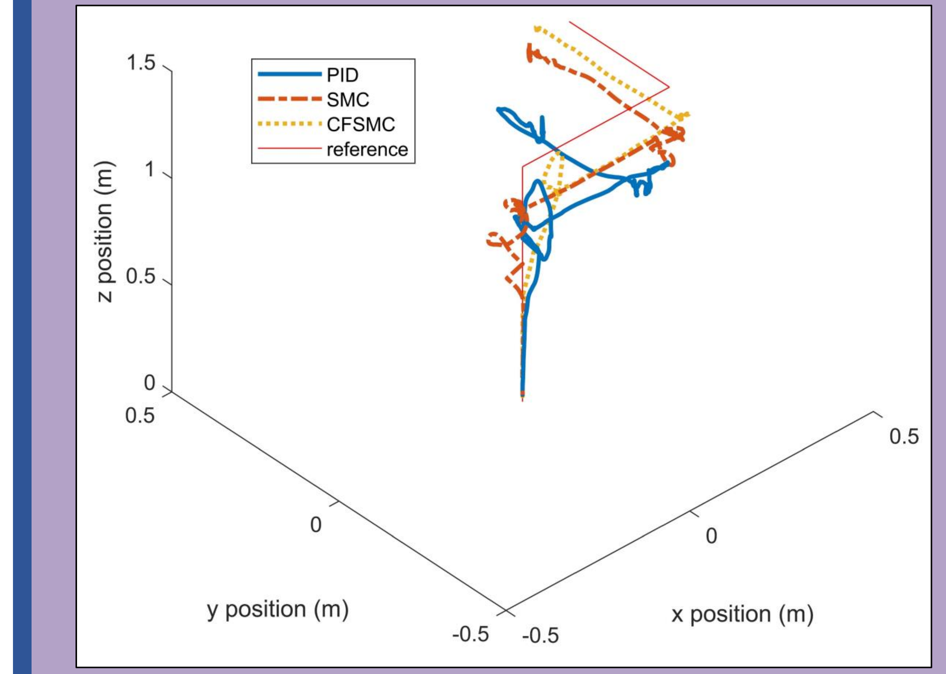

Figure 4: Experimental comparison of the proposed control systems [6].

Discrete-Time Sliding Mode Control for a Multi-Agent System

The single agent controller was extended to the case of multiple agents for the task of formation control. This is a vital step towards gradient climbing consensus control. The agents were designed to;

- Maintain a formation
- Tack a virtual leader.

The equations for the trajectory tracking formation control are shown in equations (1) and (2) [8].

$$\mathbf{u}_{x,k} = (T\mathbf{u}_{1,k}\mathbf{m})^{-1}\Bigg((\mathbf{x}_{2,k} - \Delta\mathbf{x}_{2,k+1} - \underline{\mathbf{1}}\dot{x}^0_{k+1}) - (L+B)^{-1}\Big(\boldsymbol{\mu}_x\boldsymbol{\sigma}_{x,k}T + \boldsymbol{\epsilon}_x\boldsymbol{sgn}(\boldsymbol{\sigma}_{x,k})T + \boldsymbol{\alpha}(e_{1,k+1,x}) - \boldsymbol{\sigma}_{k,x}\Big)\Bigg), \quad (1)$$

$$\mathbf{u}_{y,k} = (T\mathbf{u}_{1,k}\mathbf{m})^{-1}\Bigg((\mathbf{y}_{2,k} - \Delta\mathbf{y}_{2,k+1} - \underline{\mathbf{1}}\dot{y}^0_{k+1}) - (L+B)^{-1}\Big(\boldsymbol{\mu}_y\boldsymbol{\sigma}_{y,k}T + \boldsymbol{\epsilon}_y\boldsymbol{sgn}(\boldsymbol{\sigma}_{y,k})T + \boldsymbol{\alpha}(e_{1,k+1,y}) - \boldsymbol{\sigma}_{k,y}\Big)\Bigg), \quad (2)$$

Figure 5 shows the 3D plot of each agent in the network as well as the position of a virtual leader completing a circle trajectory.

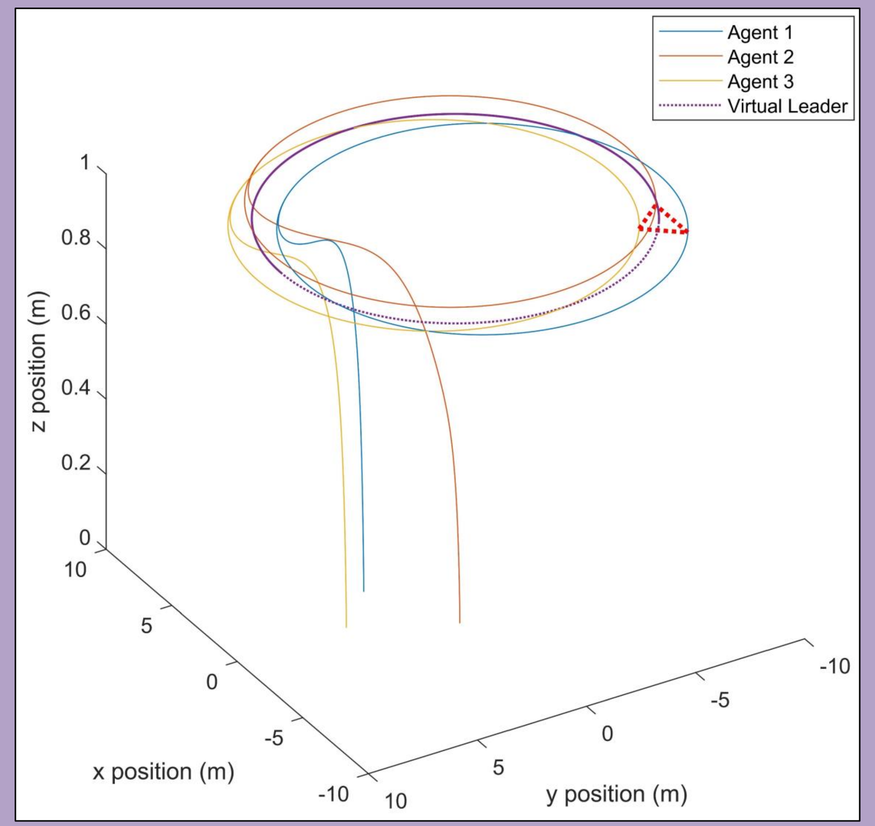

Figure 5: ROS Simulation environment RViz with quadrotor using Hector SLAM [8].

Gradient Climbing Consensus Control for a Multi-Agent System

The formation controller can then be extended to a gradient climbing case to locate peaks of scalar fields using superposition of formation control F_{form_i} and a new control for moving the formation towards the peak of the field.

$$u^i_k = F^i_{form,k} + F^i_{source,k} \quad (3)$$

$$\bar{f}_k = \frac{1}{N}\sum_{i=1}^{N} V^i_{t,k}(pos^i_k - c^i_k) \quad (4)$$

$$F^i_{source} = K^i_{source}\begin{pmatrix} cos(\angle\bar{f}_k)) \\ sin(\angle\bar{f}_k)) \end{pmatrix} \quad (5)$$

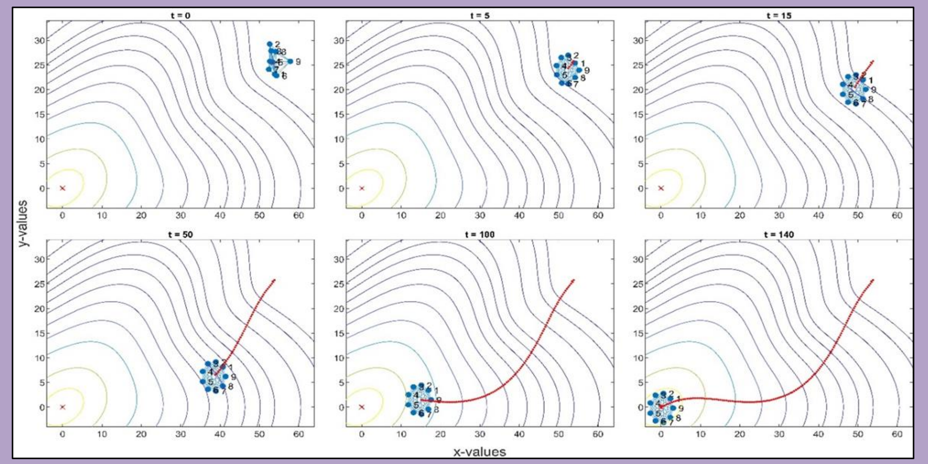

Figure 6: A group of 9 agents locating the peak of a scalar field.

Resilient Navigation and Localisation

Finally, in order to control the UAVs autonomously, a localisation system must be in place. In [7] a novel localisation system is developed based on Simultaneous Localisation and Mapping (SLAM), and is developed with a control system in the loop. This will allow the UAVs to;

- Plan and track a path.
- Estimate and compensate for biases and drifts.

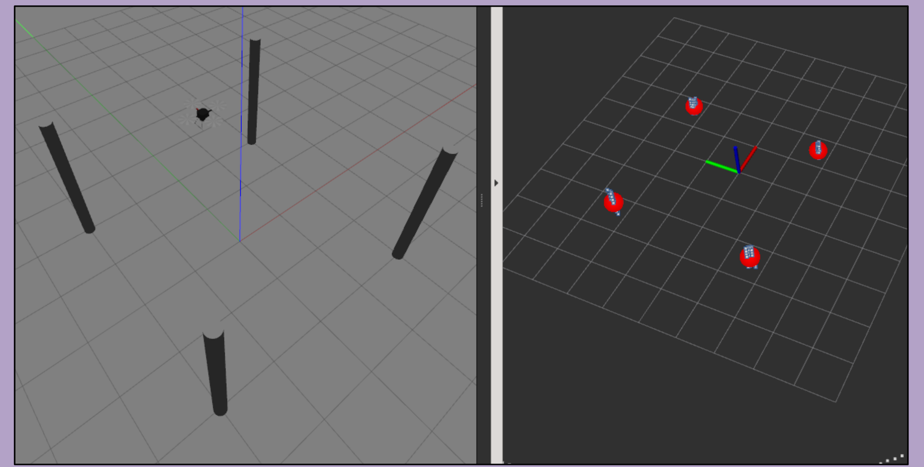

Figure 7: ROS Simulation of navigation system on a single UAV [9].

Conclusions and Future Work

In this work, the foundations for the development of a mobile sensor network for the nuclear industry have been developed and a number of aims have been addressed.

- A discrete-time sliding mode control system has been developed for a single UAV in order to provide a UAV with the capabilities of autonomous navigation in hazardous nuclear environments.
- The discrete-time sliding mode controller was extended to a multi-agent case, allowing a group of agents to maintain a desired formation while tacking a virtual leader.
- An initial solution to the gradient climbing has been proposed and simulated, with a group of 9 agents.
- A navigation system has been developed to allow each agent to compensate for estimated biases and drifts.

Future research will aim to improve the gradient climbing algorithm by extending the sliding mode control case to include environmental sensing. The work will also be combined to provide a single prototype platform of the entire system with communication between 2 or more UAVS.

References

[1] Blanchet, M. and Confais, E. (2016). 4.0 industry: a new industrial challenge and a new economic model. *Revue Generale Nucleaire*, pp.12-16.

[2] Game Changers. [Online]. Available: https://www.gamechangers.technology/challenges/.

[3] Vaidya, S., Ambad, P. and Bhosle, S., (2018). Industry 4.0 – A Glimpse. *Procedia Manufacturing*, 20, pp.233-238.

[4] Wang, H., Zhao, H., Zhang, J., Ma, D., Li, J., and Wei, J. (2020). Survey on unmanned aerial vehicle networks: A cyber physical system perspective. *IEEE Communications Surveys Tutorials*, 22(2), pp.1027–1070

[5] A. Can, H. Efstathiades and A. Montazeri. (2020). Design of a Chattering-Free Sliding Mode Control System for Robust Position Control of a Quadrotor, *International Conference Nonlinearity, Information and Robotics (NIR)*, pp. 1-6

[6] A. Can, A. Montazeri. (2021) A Finite-Time Robust Nonlinear Multi-Channel Integral Sliding Mode Control System for Trajectory Tracking in a Quadrotor System. *Submitted to Regular and Chaotic Dynamics*

[7] A. Can, J. Price, A. Montazeri. (2022). A Nonlinear Discrete-Time Sliding Mode Controller for Autonomous Navigation of an Aerial Vehicle Using Hector SLAM. *Submitted to 10th IFAC Conference on Manufacturing Modelling, Management and Control.*

[8] A. Can, I. Imran, J. Price, A. Montazeri. (2022). Robust Formation Control and Trajectory Tracking of Multiple Quadrotors Using a Discrete-Time Sliding Mode Control Technique. *Submitted to 10th IFAC Conference on Manufacturing Modelling, Management and Control.*

[9] N. Sadeghzadeh-Nokhodberiz, A. Can, R. Stolkin, A. Montazeri, Dynamics-Based Modified Fast Simultaneous Localization and Mapping for Unmanned Aerial Vehicles With Joint Inertial Sensor Bias and Drift Estimation. *IEEE Access*, 9, pp.120247-120260.