Research Statement

Robotic Systems with a Guaranteed Quality of Service under Uncertainty

Research Problem

Motivating Example. Consider a heterogeneous fleet of drones and robotic quadrupeds. The fleet is tasked with autonomously exploring mines to identify uranium deposits. Mines are hostile environments, with low lighting, dust, and possible rock fall. Robots have a limited battery life, and must change batteries via a central 'mothership'. If a robot dies within a mine, it can be very difficult to retrieve. In the worst case, the robot is permanently lost. Therefore we want the fleet to explore while *guaranteeing* that the probability of a robot's battery fully draining is very low. This is a challenging robotic problem that requires state-of-the-art solutions. To make guarantees over the performance of the fleet, we require *formal verification* techniques. Formal verification methods analyse the actions of the fleet and the effects of the environment to provide robust performance guarantees. To complete the uranium identification task, robots must be embodied with *decision-making* techniques which inform the robots how to act during execution. To achieve the battery drainage guarantee described above, decision-making and verification should occur *simultaneously*. Decision-making and verification techniques rely on a *formal model* which describes how the environment evolves, and how robot actions affect the environment. If these models are inaccurate, our expectations of how the robots behave during verification and decision-making diverge from what we observe in the real world, limiting performance and weakening our guarantees. To construct accurate models, we must capture the sources of *uncertainty* which affect the robots. Uncertainty affects the outcome and duration of robot actions, and a robot's ability to sense its surroundings. There are many sources of uncertainty during mine exploration. First, low light levels and dust affect a robot's ability to sense its environment. Rock fall may occur during exploration, blocking access to possible uranium deposit locations. Robots must also communicate with each other and to humans outside the mine. Communication within mines is fragile and easily fail due to obstructions between robots. It is challenging to obtain accurate models of these rich sources of uncertainty, as all mines are different, and robots will have limited information to build these models from. Therefore, robot models must also consider uncertainty over the model itself to prevent false confidence in the model from causing potentially harmful robot decisions.

Research Goal. The above example is a use case in an EU Horizon project proposal I recently co-authored. As discussed, solving this problem requires rich models of uncertainty, decision-making solutions, and formal verification techniques. My research lies at the intersection of these three topics. My research goal is to develop *robotic systems with a guaranteed quality of service under uncertainty*. This requires robots that i) learn accurate models of uncertainty which are improved over their lifetime; and ii) exploit these models to synthesise efficient behaviour that satisfies a formal specification. This research is inherently cross-disciplinary, combining techniques from AI, robotics, and formal verification.

Existing Work. Existing research has addressed components of the quality of service problem. There are numerous robotic modelling techniques for capturing action outcome uncertainty, temporal uncertainty, partial observability, and the effects of robot interactions. These techniques trade between model accuracy and the scalability of corresponding solution methods. This balance often requires informed assumptions, such as localising where certain sources of uncertainty occur. Advancements in modelling are not reflected in simultaneous verification and decision-making techniques, which are often limited to deterministic models or action outcome uncertainty. This is often for scalability reasons, as richer forms of uncertainty are complex to model, and solution methods scale poorly as the model size increases. I will address these issues through an *holistic* approach to modelling uncertainty, decision-making, and verification.

Research Plan

In my first five years as assistant professor, I will investigate the following:

1) Guaranteed Robotic Systems under Rich Models of Spatiotemporal Uncertainty.

2) Guarantees which Improve with the Model.

3) Anytime Algorithms for Simultaneous Decision-Making and Verification.

Research Philosophy. I believe in a *practical approach* to robotics research. The benefits of any robotic technique are not fully understood until they have been deployed on hardware to solve a real-world problem. This brings many practical challenges, but is essential for effective dissemination across the robotics community. Moreover, hardware deployments often highlight interesting, undiscovered problems which feed back into the research process.

Dissemination & Collaborations

Dissemination. I have a strong publication record in top venues such as the *IEEE Transactions on Robotics (T-RO)*, the *Journal for Artificial Intelligence Research (JAIR)*, and the *International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS)*. To highlight the current challenges in my field, I ran a half day tutorial on multi-robot planning under uncertainty at AAMAS 2023. Here, I covered the sources of uncertainty which affect multi-robot systems, and discussed how researchers can design decision-making techniques to make robots robust to these effects.

This was supported with a survey article published in *Springer's Current Robotics Reports*[1].

Collaborations. The strength of my PhD research spawned two external collaborations. I worked with the University of Lincoln on the First Fleet project to deploy multi-robot decision-making techniques I developed onto agricultural robots in fruit fields. Fruit fields constrain robot movement, introducing interesting challenges for the guaranteed quality of service problem, as one poor decision may cause a robot to traverse large parts of the field. I also led a collaboration with Accenture Labs to apply my novel multi-agent modelling formalisms[2] to evaluate human-robot teams in warehouses. Warehouses often contain tens to hundreds of agents. This necessitates the use of sampling-based verification techniques which will be fundamental to my work on **Anytime Algorithms for Simultaneous Decision-Making and Verification**.

I am a technical work package lead in EU Horizon project CONVINCE, where I lead research on task and motion planning in dynamic environments. CONVINCE is developing a fully verifiable toolchain for robotic systems, and is made up of partners from academia, industry, and the public sector. My expertise in modelling uncertainty, decision-making, and verification allows for close collaboration within the consortium, especially with the verification team. This will be reflected in the project's first software release and upcoming collaborative works.

The school of computer science will provide me with opportunities to foster new research collaborations. There are academics within the school whose research interests overlap with mine. For example, Dr Mirco Giacobbe's research lies between formal verification and artificial intelligence, and Dr Leonardo Stella investigates multi-agent decision-making through reinforcement learning. I have already spoken to Mirco and Leonardo about my work, and recently co-authored an application to the Google Research Scholar Program with Leonardo on applying his multi-agent reinforcment learning methods to robotics.

Summary

My research has produced rich models of uncertainty and decision-making techniques which exploit them. Formal verification and model checking have been at the core of my work but never at the forefront. As outlined in this statement, I will address this by developing novel frameworks for guaranteed quality of service which can be deployed on physical robotic systems for safety and reliability. This research brings numerous challenges, and the inter-disciplinary expertise in the school of computer science will provide an exicting environment to address them in.

[1] Street, C., Mansouri, M. and Lacerda, B., 2023. Formal Modelling for Multi-Robot Systems Under Uncertainty. Current Robotics Reports, 4(3), pp.55-64.

[2] Street, C., Lacerda, B., Staniaszek, M., Mühlig, M. and Hawes, N., 2022. Context-Aware Modelling for Multi-Robot Systems Under Uncertainty. In Proceedings of the International Conference on Autonomous Agents and Multiagent Systems (AAMAS).