Research Statement

Robotic Systems with a Guaranteed Quality of Service under Uncertainty

Research Problem

Motivating Example. Consider an autonomous fleet of drones and robotic quadrupeds tasked with finding uranium deposits in mines. Mines are hostile environments with little light, dusty air, and falling debris. Robots have a limited battery, and must travel to a central 'mothership' to recharge. If a robot dies within a mine, it is difficult to retrieve, and in the worst case lost. For safety and reliability, we want to *guarantee* that the probability of a robot's battery dying during exploration is very low.

Mine exploration is a challenging robotic problem that requires state-of-the-art solutions. To efficiently explore the mine and identify uranium deposits we require automatic *decision-making* techniques which inform the robots how to act during execution. The results of decision-making will dictate where robots should map, and where to take rock samples. To obtain robot battery level guarantees as described above, decision-making should occur simultaneously with *formal verification*. Formal verification methods rigorously analyse the evolution of the robots and environment to make quantitative or qualitative statements about robot performance.

Decision-making and verification methods often rely on a *formal model* which describes how robot actions impact the environment, and how the environment evolves. The success of these methods correlates strongly with model accuracy. To construct accurate models, we must capture the sources of *uncertainty* which affect the robots. Uncertainty is highly prevalent during mine exploration. For example, low light levels and dust may affect a robot's sensors, falling rocks may block parts of the mine, and robot communications may fail due to unexpected obstructions between robots. Model construction is difficult, as robots have limited prior information about the mine. Therefore, robots must reason over the uncertainty in their model to avoid potentially harmful decisions, such as mistakingly entering a high radiation area.

Research Goal. The above problem is a use case for an EU Horizon project proposal I recently co-authored. To address this problem we require rich models of uncertainty, efficient decision-making, and formal verification. My research goal is to tackle each of these sub-problems 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 for efficient decision-making while satisfying formal guarantees. This research is inherently crossdisciplinary, combining techniques from artificial intelligence, 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) Simultaneous Robot Decision-Making and Verification under Rich Models of Uncertainty. Existing decision-making and verification techniques are often limited to models of action outcome uncertainty. This does not reflect real-world environments, where sources of uncertainty affect the duration of robot actions, and a robot's observations in the environment. To address this, I will research new decision-making and verification techniques which are more applicable to realistic problems. My expertise in this area is demonstrated by my PhD research. In my thesis, I presented multiple techniques for multi-robot modelling and decision-making under temporal uncertainty. I proposed novel temporal models which capture how robots affect each other's navigation performance. I used these models for multi-robot decision-making under congestion, i.e. robots may take longer but less congested routes to reach their destination quicker [1], [2]. I also developed formal models which capture when and where robot tasks will appear. This admits proactive decision-making, i.e. robots can predict when and where they're needed, and arrive early [3]. Both of these approaches rely on formal verification techniques for probabilistic analysis to support decision-making.

2) Improving Quality of Service Guarantees through Model Learning. Formal guarantees are only as good as the model used for verification. In many real-world problems, robots will not have an accurate model of the environment at the start of their deployment. Therefore, robots should learn and improve their model during execution, and use this to strengthen guarantees. I have recently investigated techniques for robot decision-making under uncertainty where the robot has no prior knowledge of the environment. Here, the robot repeats its task periodically, and uses its observations during each run to improve its model. Model improvements were reflected in increased decision-making performance. This insight suggests the same philosophy can be applied to formal verification techniques.

3) Anytime Algorithms for Simultaneous Decision-Making and Verification. As discussed above, simultaneous decision-making and verification techniques scale poorly as model size increases. This becomes especially challenging when robots receive new tasks during execution, limiting the time for decision-making and verification. To mitigate these scalability issues, I will develop anytime algorithms for simultaneous decision-making and verification. As these algorithms run for longer, decsion-making performance will improve, and guarantees will strengthen. I have a strong expertise in anytime decision-making methods, which have appeared frequently during my research career. During my PhD, I used anytime algorithms for multi-robot decision making under rich temporal models of congestion [1], [2]. Recently, I applied a state-of-the-art anytime algorithm for decision-making under spatiotemporal uncertainty where the robot can only partially sense its environment. Anytime decision-making algorithms share a similar philosophy with statistical, sampling-based verification methods. My initial approach to this work will investigate how these approaches can be combined in a principled way.

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* [4].

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 to evaluate human-robot teams in warehouses [5], [6]. 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.

References

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