Research Statement

Robotic Systems with a Guaranteed Quality of Service under Uncertainty

As robotic systems become prevalent in healthcare, manufacturing, and on our roads, there is a growing need for safe and reliable autonomy. For this, we desire *formal guarantees* over the behaviour of our system. For example, we may want to ensure that an autonomous vehicle only breaks road rules when there is danger to life. Formal guarantees are often specified by the system designer in a temporal logic. Robot behaviour should then be synthesised automatically to satisfy this specification. This requires tight coupling between formal verification, and robot coordination and decision-making. To obtain accurate guarantees and efficient behaviour, robots require models which capture the sources of *uncertainty* that affect their behaviour in real-world environments. Uncertainty affects the outcome and duration of robot actions, and a robot's ability to sense its surroundings. If robot models are inaccurate, our expectations of behaviour during verification and coordination diverge from what we observe during execution, limiting task performance and weakening guarantees. However, model inaccuracies are unavoidable due to limited data etc. Therefore, robots must reason over the *epistemic uncertainty* in their models to bound guarantees, and acquire knowledge through physical interactions with the environment.

As an example, consider a heterogeneous fleet of wheeled robots and drones in a search and rescue scenario. Drones must identify human survivors who are retrieved by wheeled robots. The fleet designer wants to guarantee that over 99% of survivors are rescued unharmed. This domain has many complex sources of uncertainty which are challenging to model. For example, smoke may surround a drone, limiting its sensing. Moreover, the spread of fire may affect a wheeled robot's navigation, and broken power lines may limit robot communication. Robot interactions also contribute towards uncertainty, as wheeled robots operating in the same area may affect each other's navigation performance. To address this problem, we require robot models which capture the spatiotemporal dynamics of the environment under limited sensing. The complexity of these models necessitates novel coordination and verification solutions which exploit the structure of the problem. Further, obtaining such models is challenging, as search and rescue domains are unique, and robots have little opportunity to learn complex environmental dynamics prior to deployment. Solution methods must acknowledge where model confidence is low to prevent potentially harmful robot decisions.

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 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 making informed modelling assumptions, such as localising where certain sources of uncertainty occur. Advancements in modelling are not reflected in combined verification and coordination 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 aim to mitigate these issues through a *holistic* approach for rich stochastic modelling, coordination, verification, and epistemic reasoning.

My interest in robotic quality of service guarantees began during my PhD. In my thesis, I presented multiple techniques for multi-robot modelling and coordination under temporal uncertainty. For example, I proposed novel temporal models which capture how robots affect each other's navigation performance. I used these models to plan for multiple robots under congestion, i.e. robots may take longer but less congested routes to reach their destination quicker[1]. In another line of work, I 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[2]. Though these techniques do not provide guarantees, they rely on model checking techniques for probabilistic analysis to support decision-making. In the 2023 International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS), I gave a half day tutorial on multi-robot planning under uncertainty. This covered the sources of uncertainty which affect multi-robot systems, and how researchers can design coordination techniques to synthesise robust robot behaviour. This was supported with a survey article published in Springer's Current Robotics Reports[3].

The utility of my formal approach to robotics has been demonstrated through external collaborations. I've worked alongside the University of Lincoln to deploy planning techniques developed during my PhD onto agricultural robots operating in fruit fields. Fruit fields constrain robot movement, which would make it challenging to obtain effective quality of service guarantees, as one poor decision may cause a robot to traverse large parts of the field. I've also worked with Accenture Labs to apply formal multi-agent modelling techniques to evaluate order picking systems in warehouses. Order picking systems can contain tens to hundreds of agents. This work highlighted the role of sampling-based statistical model checking techniques for verifying robotic systems at scale, and will impact my future research. External collaborations reveal interesting and novel research questions, and I will initiate new collaborations during my time in the school of computer science.

My research interests have broadened through my work on EU Horizon project CONVINCE. CONVINCE is developing a fully verificable toolchain for robotic systems. Though my focus is

[1]Street, C., Pütz, S., Mühlig, M., Hawes, N. and Lacerda, B., 2022. Congestion-Aware Policy Synthesis for Multirobot Systems. IEEE Transactions on Robotics, 38(1), pp.262-280.

[2]Street, C., Lacerda, B., Mühlig, M. and Hawes, N., 2024. Right Place, Right Time: Proactive Multi-Robot Task Allocation Under Spatiotemporal Uncertainty. Journal of Artificial Intelligence Research, 79, pp.137-171.

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

on robot planning in dynamic and uncertain environments, I work closely with those focused on formal verification. It was in CONVINCE I discovered the importance of epistemic reasoning. For example, I've investigated techniques for robot area coverage given no prior information of the environment. Here, the robot must learn the environment dynamics over its lifetime, and reason over its knowledge of these dynamics. In another line of work I've explored behaviour trees, a popular formalism for describing robot behaviour. These are often designed by humans without considering uncertainty, and provide no formal guarantees. I have developed techniques for refining behaviour trees to attain robustness under uncertainty which are transferrable to formal verification. This provides a different perspective on the guaranteed quality of service problem, and I look forward to extending this research at the University of Birmingham.

I believe in a practical approach to robotics research. The benefits of any technique for cyber-physical systems 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.

My existing work has opened multiple future strands of research. How can we retain richer forms of uncertainty in our models while controlling their size? How can we develop more scalable decision-making techniques which exploit rich models to synthesise efficient and robust robot behaviour? Further to this, how can we simultaneously verify robot behaviour during decision-making on large, complex models in a tractable way? How can we incorporate epistemic uncertainty into simultaneous decision-making and verification methods? These questions require varied solutions, and the inter-disciplinary expertise in the school of computer science will provide a great environment to foster new collaborations to address these challenges.