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 quality of service guarantees for robotic systems began during my PhD. My thesis presented multiple techniques for multi-robot coordination under temporal uncertainty, with a focus on modelling and decision-making. In one piece of work, presented in the IEEE transactions on robotics[1] I constructed temporal models which capture how robots affect each others' navigation performance when they operate in the same area simultaneously. This allowed us to plan for multiple robots under congestion, i.e. one robot may take a longer but less congested route as it is lkely to reach its goal quicker. In work presented in the journal of artificial intelligence research[2], I developed temporal models which capture when and where robots will be required for tasks. This was used to admit proactive decision-making, where robots predict when and where they are needed, and arrive there early. These kinds of modelling and decision-making techniques are crucial for developing performant robots with a guaranteed quality of service. Though the above techniques do not provide guarantees, model checking techniques are core to their success. By model checking our temporal models, we can provide accurate predictions to support decision-making. Following my PhD, I summarised the state-of-the-art in multi-robot modelling under uncertainty for the community into a survey article in Springer's current robotics reports[3], and gave a half day tutorial in the international conference on autonomous agents and multi-agent systems.

The practical benefits of my PhD work have been demonstrated through external collaborations. I've worked with the university of Lincoln[4] on deploying my congestion-aware multi-robot planner onto agricultural robots aiding human fruit pickers. This proposes interesting challenges for robot decision-making, as robots are constrained to narrow aisles in the fields. I've also worked with Accenture Lab[5] on applying multi-agent modelling techniques developed during my PhD[6] on order picking systems in warehouses. The aim was to utilise my models to evaluate the effects of congestion between robots and humans on KPIs such as throughput in warehouses. My models capture congestion more precisely than existing approaches, and revealed key insights into when robotic systems are useful for businesses, and how many should be purchased[7].

My research goals have broadened during my recent work on EU horizon project CONVINCE[8]. The aim of CONVINCE is to develop a fully verifiable toolchain for robotic systems. My role within CONVINCE involves robot planning in dynamic and uncertain environments In one line of research, I explored techniques for robots to efficiently cover environments given no prior knowledge of its dynamics. Here, the robot should learn the dynamics over its lifetime, and reason over how much it knows about its environment. An alternate line of research investigates behaviour trees, a popular software formalism for defining robot

[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.

[4]https://lcas.lincoln.ac.uk/wp/

[5]https://www.accenture.com/gb-en/about/accenture-labs-index

[6]Street, C., Lacerda, B., Staniaszek, M., Mühlig, M. and Hawes, N., 2022. Context-aware modelling for multi-robot systems under uncertainty.

[7]Street, C., Jujjavarapu, S.S., Chen, M.N.A., Paul, S. and Hawes, N., 2023, July. Analysing the Effects of Congestion on Hybrid Order Picking Systems Using a Discrete-Event Simulator. In International Conference on Intelligent Autonomous Systems (pp. 393-404). Cham: Springer Nature Switzerland.

[8]https://convince-project.eu/

behaviour. These are often designed in an ad-hoc manner, without formal guarantees or any consideration of uncertainty. I have developed planning techniques which refine existing behaviour trees to attain robustness under uncertainty. Such techniques also provide the groundwork for introducing model checking methods to achieve formal guarantees.

I believe strongly in the important of testing and evaluating robotic technologies on physical systems to solve real-world problems. This has been demonstrated through my work with external collaborators, and time spent leading Oxford's RoboCup team. I argue that the benefit of any methodology for cyber-physical systems isn't truly understood until it has been deployed on hardware. Real-world deployments provide a unique set of problems which often feedback into the research process. This focus on hardware will form a core philosophy of my future research, and the resources within the school of computer science will enable this.

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.