2018/19 ECR Project

Co-Evolving Built Environments and Mobile Autonomy for Future Transport and Mobility

Final Reporting

July 10, 2019

Name of ECR	Affiliation: **University of Cambridge**
Dr Amanda Prorok University Lecturer in the Department of Computer Science and Technology	Email address: **asp45@cam.ac.uk**

Publishable Report

Abstract

What would an autonomous vehicle's dream city look like? Autonomous navigation and automated mobility are hard problem that are compounded by the unpredictability and dynamics of urban environment. As we re-think and re-design our built environments, we have the unique opportunity to transform them so that automated mobility systems a can perform efficiently and robustly. The main idea behind this project is to tackle the challenges of autonomous navigation and automated mobility by explicitly considering the *coupling* of the autonomous vehicles with the environments that they operate in.

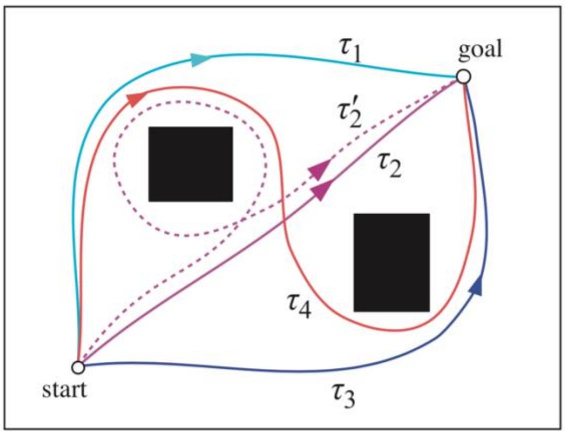
Main Text

Our approach is to pose the built environment as a design variable, and to jointly optimize mobile autonomy. Our goal is to support mobile autonomy through re-designs of the built environment; in particular, we are interested in how its morphology, topography, and technological enhancement aid us in this endeavor.

In this project, we have focused on **three research thrusts**: *(1)* modeling and optimising built environment topographies and understanding their affects on vehicle navigation efficiency, *(2)* optimising transport network layouts for robustness in mobility systems, and *(3)* building a simulation framework for infrastructure enhancement through sensor placement.

<u>(1) Modeling environment topographies and their impact on navigation</u>

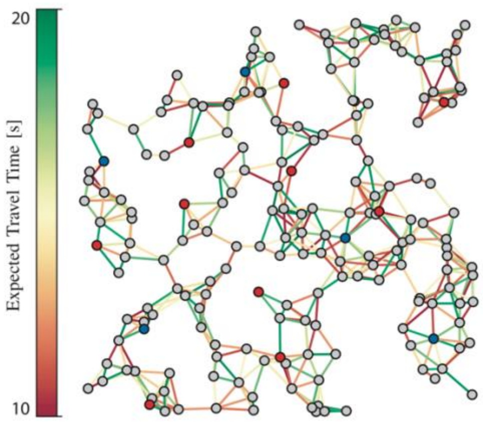
This research [1] presents a novel model of path planning environments that allows vehicles to navigate efficiently in them through better prioritization of path plans. Our innovation is to formalize a vehicle's *path prospects* to reach its goal from its current location. To this end, we consider the number of homology classes of trajectories (a notion derived from algebraic topology), and use this as a prioritization rule in a decentralized path planning algorithm, whenever any vehicles enter negotiation to deconflict path plans. This prioritization rule guarantees a partial ordering over the vehicle set. We perform simulations that compare our method to five benchmark algorithms, to show that it strikes the best balance between makespan and flowtime.



We build our work on theory from algebraic topology. The prioritization heuristic is based on *Z2*-coefficient homology classes, which quantifies a vehicle's number of available path options. This heuristic makes use of two key components. First, it estimates the number of path options available to a robot for it to reach its goal. Second, it defines an area within which these path options are computed. We compare our method to five alternate heuristics. Although it is a well-known fact that the objectives (minimum makespan and minimum flowtime) cannot be simultaneously optimised, we show that our method strikes the best balance, and lies on the empirical Pareto front of these considered benchmarks.

Our solution is decentralised and distributed. In this work, we not only expose the tight coupling between a vehicle's mobility constrains and the built environment, but also, we show that by explicitly considering this relationship, we are able to improve navigation performance. This is a milestone result that will underpin subsequent works in this domain.

(2) Optimising transport networks for robustness in mobility systems



This research [2] is motivated by the problem of assigning mobile assets (automated vehicles) to goals (passenger or product pickup locations) when travel times from vehicle origin locations to goal locations are *uncertain*. This uncertainty is a common issue, due to traffic anomalies such as accidents and jams; future automated transport systems must be able to deal with this robustly and swiftly. However, existing robust mobility assignment methods deal with uncertainty by minimizing risk, or by predefining acceptable risk thresholds. In this research, we propose a complementary method that offers resilience to uncertainty by making use of *vehicle and path redundancy*. In other words, we assign more vehicles than necessary to a given destination, in the expectation that one of the redundant vehicles will reach the goal faster (than the originally assigned vehicle) by choosing a complementary path (route). However, solving this redundant assignment problem is computationally intractable for large systems (it is strongly NP-hard). By characterizing the mathematical problem as a supermodular optimisation problem, we show how the redundant assignment problem can be solved very efficiently.

We apply our assignment algorithm to transport network problems to reduce average waiting times (of clients) at goal locations, when travel times from vehicle origins to destinations are uncertain. Our results show that *exploiting redundancy is an effective approach to reducing waiting times.* Importantly, our results indicate an interesting connection between *robustness and diversity*: the paths selected by our algorithm tend to be more diverse, and correlate with better performance. This insight can be directly applied to the design of transport networks, where measures must be taken to provide redundant and diverse travel paths that connect same start and goal locations, in order to increase transport efficiency.

(3) Simulation framework for enhancement of built urban infrastructure

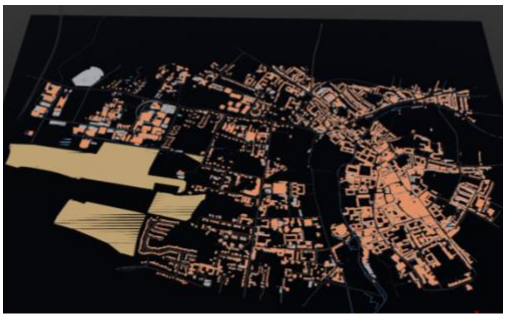
This research considers deploying built environments with embedded networks of heterogeneous sensors that cooperate with the autonomous vehicles. Specifically, are inerested in methods that optimise the placement and configuration of sensor nodes for *perceptive infrastructure* in aid of mobile autonomy. For example, we envision perceptive sidewalks that detect anomalous pedestrian activity and alert oncoming vehicles; we envision perceptive road networks that infer the state of traffic, to optimally coordinate and route vehicle trajectories; we envision perceptive landmarks that can localize lost vehicles. This begs the question: *What is the optimal placement of sensor nodes for* *an optimally enhanced infrastructure?* Unfortunately, the sensor placement problem is hard to solve: the number of possible sensor configurations scales exponentially, and classical combinatorial optimization methods are intractable for large-scale problems. Tools from data science, machine learning and predictive analytics are now being routinely used to solve such complex decision-making problems, yet, they come with the burden of requiring vast amounts of data.

This research thrust provides new tools in support of a novel framework that facilitates the development of enhanced infrastructure for mobile autonomy in built environments. We have been building such a framework within the Webots robotic simulator, and are currently in the process of:

1. studying how enhanced, perceptive infrastructure can increase the robustness of autonomous systems in complex, dynamic scenarios by providing contextual information that facilitates resilient path planning over longer time-horizons, beyond a vehicle's local line-of-sight and field-of-view,
2. providing solutions to massively large-scale problems that include hundreds or thousands of heterogeneous integrated sensor nodes, and
3. accommodating specific topographical variables and constraints that are encountered in the built environment.

The framework wil leverage our theoretical results obtained in research thrusts (1) and (2) to accomplish the above mentioned subgoals.

Screenshots from the simulation tool (showing parts of Cambridge):



Conclusions

In this project, we have provided results along **three research axes**: *(1)* modeling and optimising built environment topographies and understanding their affects on vehicle navigation efficiency, *(2)* optimising transport network layouts for robustness in mobility systems, and *(3)* building a simulation framework for infrastructure enhancement through sensor placement.

Our research highlights include the following insights:

- We were able to expose the *tight coupling between a vehicle's mobility constrains and the topography of the built environment*. Also, we showed that by explicitly considering this relationship, we are able to improve navigation performance. This is a milestone result that provides a fundamental new understanding of naviation in cluttered environments.
- We were able to show that *exploiting redundancy in transport networks is an effective approach to reducing waiting times in mobility systems.* Importantly, our results also indicate an interesting connection between *robustness and diversity*: the paths selected by our mobility assignmment algorithm tend to be more diverse, and correlate with better performance. This insight can be applied

to the *design of transport networks*, where measures must be taken to provide redundant and diverse travel paths that connect same start and goal locations, in order to increase transport efficiency. This is a milestone result that provides guidance towards the planning, design and routing of road networks.

Acknowledgements

I acknowledge research collaborations with W. Wu (Cambridge, UK) and S. Bhattacharya (Lehigh, USA), as well as collaborations with my team members and interns: Jiayi Zhao, Hehui Zheng, Rupert Mitchell, Jenny Fletcher. I would also like to acknowledge the support provided through the local Cambridge CDBB team. Finally, I am very grateful for the funding provided to me through this InnovateUK grant, which has allowed me to spearhead research in this important and extremely relevant domain.

References

[1] W. Wu, S. Bhattacharya, A. Prorok, *"Multi-Robot Path Deconfliction through Prioritization by Path Prospects"*, IEEE Robotics and Automation Letters (R-AL), under review

[2] A. Prorok, *"Resilient Assignment Using Redundant Robots on Transport Networks with Uncertain Travel Time",* IEEE Transaction on Automation Science and Engineering, under review.