Final Year Project: Interim Report

Daniel Atticus Williams
CID 01044837

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Executive Summary

This interim report details planning and preliminary work for the final year project under the supervision of Dr Eric Kerrigan and Ian McInerney in the Department of Electrical and Electronic Engineering, Imperial College, London. I propose a novel distributed control architecture relying on model predictive control for real-time trajectory optimization to address the problem of cooperative payload transportation by multiple unmanned aerial vehicles. I incorporate dynamic zone contracts into agent path constraints to avoid obstacles and agent collisions. I draw on the ICLOCS2 software package for trajectory optimization to create simulations of the proposed cooperative payload transportation scheme in Simulink. I devise a new software interface to integrate ICLOCS2 functionality with the Robot Operating System (ROS) environment. Towards the end of the paper I present a schedule of planned deliverables, examine methods of evaluation and discuss potential safety, legal and ethical issues.

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1 Project Specification

1.1 Previous Work

This final year project (FYP) addresses the problem of optimal control for cooperative payload transportation (CPT) using unmanned aerial vehicles (UAVs). The FYP was inspired by previous research conducted as part of a summer placement [1]. In the earlier project my goal was to devise a decentralized control algorithm for autonomous CPT by two UAVs as depicted in Figure 1. The proposed control scheme relied on one UAV as a 'leader' agent tracking a preset trajectory in one dimension, and the second UAV as a 'follower' agent implementing a simple PID controller.

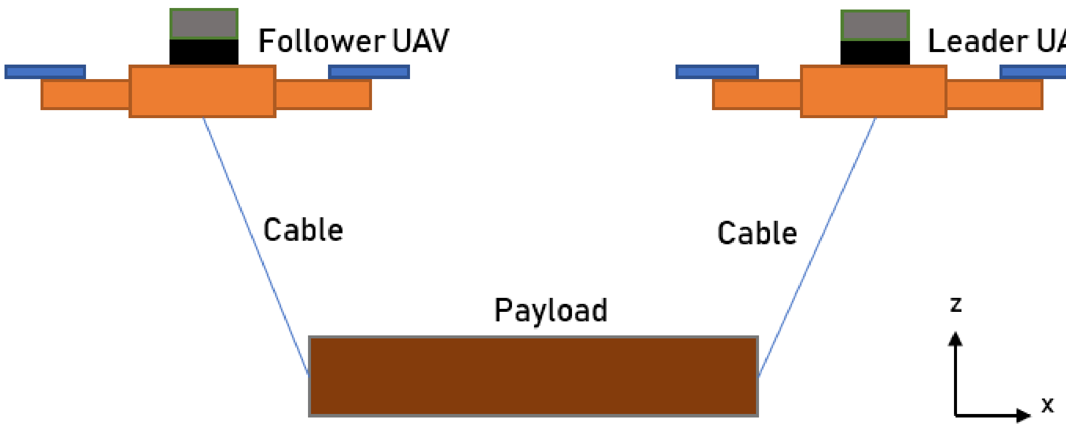


Figure 1: Cooperative Payload Transportation using Unmanned Aerial Vehicles

1.2 Project Goals and Objectives

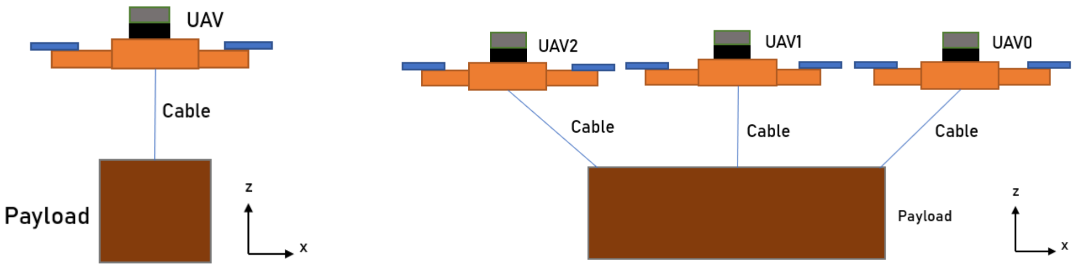
In the FYP I re-examine the CPT problem from an optimal control perspective. My primary goal of the FYP will be to design and simulate a novel distributed optimal controller for a multi-agent CPT scheme, relying on model predictive control (MPC) for real-time optimization of the agents' trajectories, obstacle avoidance and prevention of inter-agent collisions. I have three intermediate objectives for the FYP:

- To implement the optimal controller using the ICLOCS2 software package developed by Dr Kerrigan, Yuanbo Nie, and Omar Faqir, and numerically simulate its performance using Simulink
- To develop and document a software interface for ICLOCS2 in a closed control loop with agent nodes that are running inside the Robot Operating System (ROS) environment
- To create visualizations of missions under the proposed CPT scheme using the Gazebo simulation package for ROS

1.3 Project Deliverables

Alongside the stated project goals and objectives, I will:

1. Survey the academic literature focusing on multi-agent CPT schemes using UAVs
2. Create a set of design requirements for a distributed optimal multi-agent CPT scheme
3. Satisfy the identified design requirements
4. Devise a mathematical formulation of the problem
5. Create numerical simulations of the system with ICLOCS2 in Simulink
6. Document the software interface between ICLOCS2 and ROS
7. Demonstrate a successful mission using Gazebo
8. Submit a final report documenting the FYP
9. Present the work to academic staff



(a) Single-Agent System (b) Multi-Agent System

Figure 2: Aerial Payload Transportation

2 Background

2.1 Cooperative Payload Transportation

Context in Robotics: Transporting objects is a fundamental task in the field of robotics [3]. As a subset of the manipulation problem, payload transportation is conducted by mobile agents, typically UAVs. Single-agent aerial payload transportation has been studied by numerous sources but such systems are inherently limited by the thrust capabilities of the agent's hardware [4] (Figure 2a). In recent years, increasing interest in aerial payload transportation from the commercial [5], industrial [6], agricultural [7], public health [8] and military [9] sectors has motivated the development of CPT schemes [10] (Figure 2b). CPT schemes exploit multiple agents' carrying capabilities to transport bulky and heavy objects. This allows for a wider set of possible transportation maneuvers at the cost of an increased model complexity. CPT schemes may be classified according to their design [11], as presented in Figure 3.

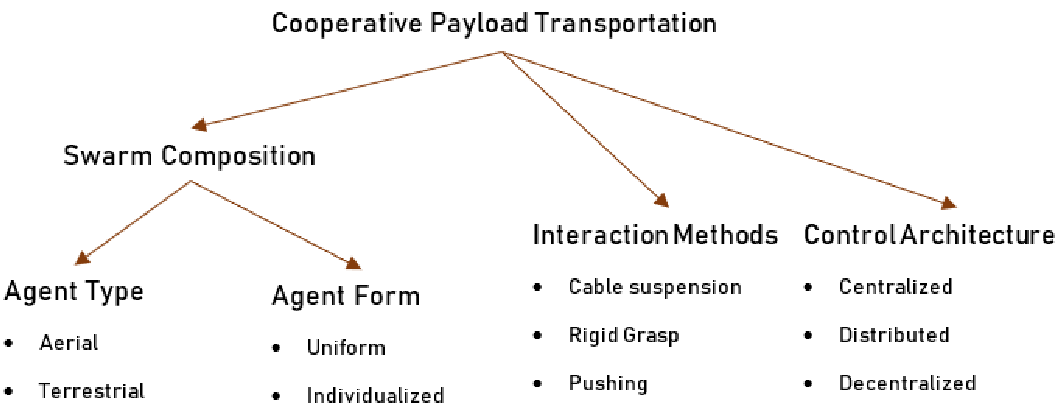
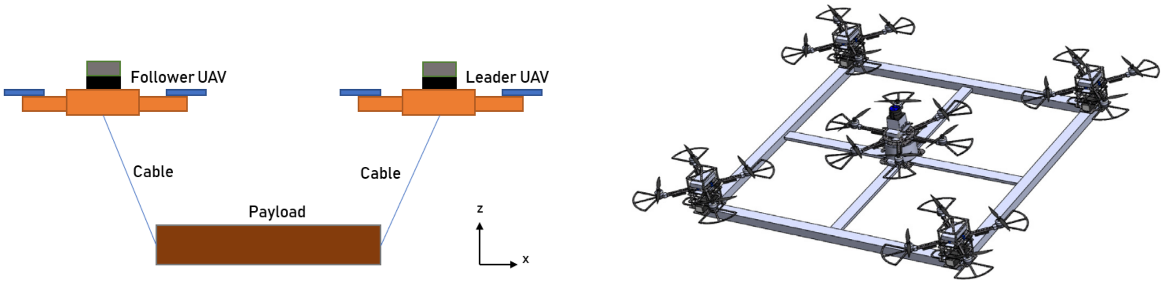


Figure 3: Taxonomy of CPT Schemes

Swarm Composition: Choosing the agent type has an important impact on design: UAVs allow agile motion in three dimensions but may have shorter mission durations than terrestrial vehicles due to their limited onboard battery life. The composition of the formation must also be considered: i.e. whether each agent should have a uniform design or an individualized design (perhaps for task specializations, as seen in [12]).

Interaction Methods: Once a decision has been made about the formation structure, the next issue involves interacting with the payload (Figure 4a).In slung-load systems the payload is suspended by a cable that permits versatile tensile manipulation in three dimensions [10]. Systems that use rigid attachment to the agents' bodies allows direct inference of the payload's location but may not suit certain payload sizes and shapes (Figure 4b).

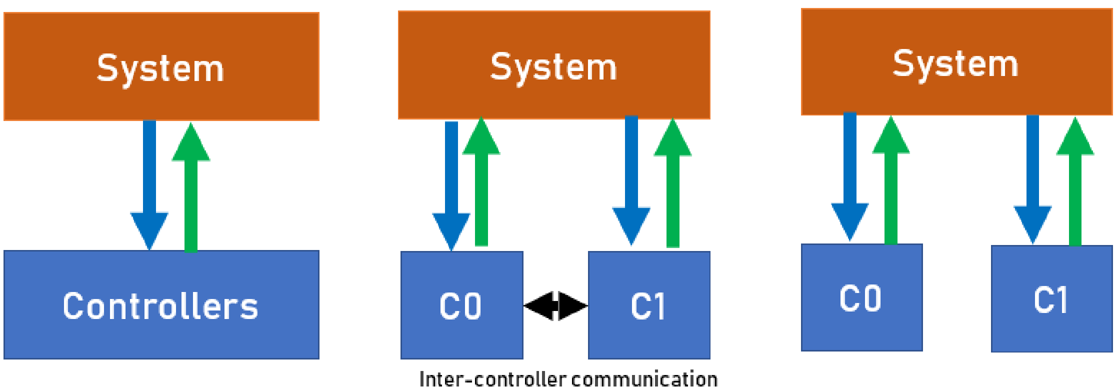


(a) Cable-Suspended CPT [1]

(b) Rigid-Grasp CPT [2]

Figure 4: Interaction Methods for CPT Schemes

Control Architecture: How one chooses an appropriate control architecture is important [13]. Centralized control (Figure 5a) involves decisions made in one location that are communicated to all agents. Distributed control (Figure 5b) allows for each agent to make decisions with some communication with peers. Decentralized control (Figure 5c) requires each agent to make their own decisions without communicating with peers.



(a) Centralized Control

(b) Distributed Control

(c) Decentralized Control

Figure 5: Control Architectures

2.2 Survey of CPT Literature

2.2.1 Design Requirements for CPT Schemes

The literature has identified several important requirements for UAV-based CPT systems:

- Robustness in a range of environments
- Minimal reliance on external infrastructure [14]
- To the extent possible, minimization or elimination of dependence on explicit communication between agents (thus adopting a decentralized control architecture) [15]

The following design requirements are also identified in [16]:

- Operability in unstructured indoor and outdoor environments
- Robust flight capabilities
- Autonomous, onboard decision making (this requires control algorithms with lower computational complexity [17])
- Modular and flexible sensing and control
- No dependence on external navigation aids

Mission Objectives: Mission objectives occupy a hierarchy that is specific to UAV-based CPT schemes [18]:

1. Avoid obstacles (also featured in [4] and [17])
2. Secondary objectives:
   (a) Avoid collisions and excessive separation between agents
   (b) Evenly distribute payload weight between vehicles
3. Reduce oscillations caused by external disturbances such as wind (this is incompatible with fast and aggressive agent maneuvers [17])

Control Architecture: Once the objectives are known, an appropriate control solution may be chosen. Optimal control algorithms will minimize mission duration and actuator effort to conserve battery life.

2.2.2 Existing CPT Schemes and Limitations

The literature proposes a selection of aerial- and terrestrial-based schemes representing various combinations of interaction methods, degrees of control centralization, and formation control algorithms. They are summarized in Figure 6.

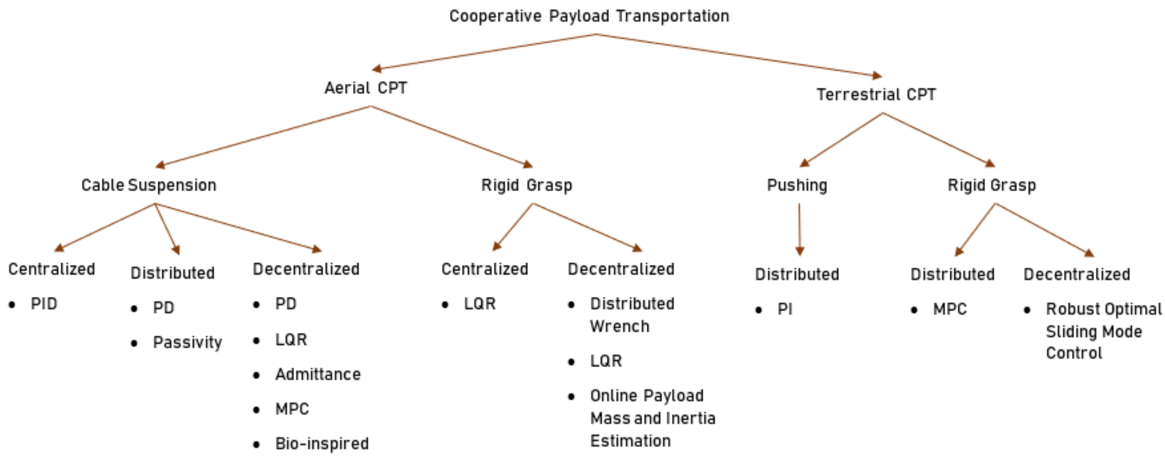


Figure 6: State of the Art for CPT Schemes

Control Centralization: Current trends in UAV-based CPT research have seen a shift from centralized control to decentralized control. When centralized and distributed architectures rely on communication they channel latencies, are susceptible to infrastructure failure and increase consumption of power and spectrum. Each problem may be avoided by eliminating explicit communication. However, fully-decentralized architectures rely on alternative methods of mutual localization that are more computationally-complex [1].

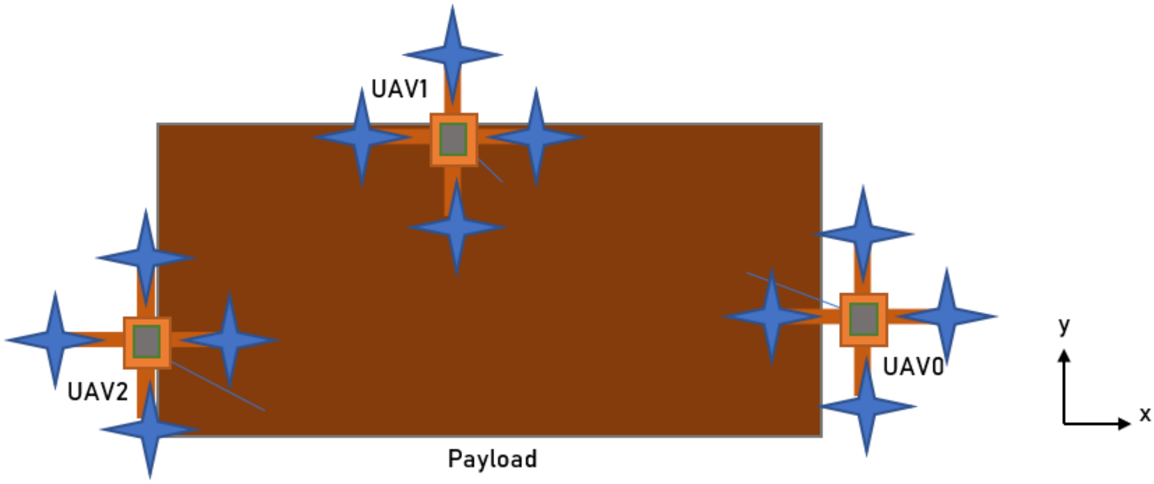
System Assumptions: All methods of implementation of CPT schemes make certain operational assumptions. Common environmental assumptions include the absence of obstacles and external disturbances such as wind. Most CPT schemes assume external infrastructure for agent localization ([19] is a notable exception). Few CPT schemes perform trajectory optimization in real-time (among them [20] and [21]).

Aerial CPT: CPT schemes using cable-suspension employ all three types of control architectures. Centralized architectures relying on PID controllers are proposed in [18], [22] and [23], while a nonlinear PD controller is proposed in [24]. Decentralized control underpins several recent proposals involving LQR [15], [25], admittance control [19], a bio-inspired algorithm [12] and MPC [21]. Fewer proposals have implemented a distributed control architecture, using a PD controller [26] or a passivity-based approach [27]. In the CPT schemes which use rigid payload grasping, a centralized control architecture relying on LQR is presented in [2], while a distributed wrench controller is proposed in [28]. The distributed control architecture in [29] features online estimation of the payload's mass and inertial properties.

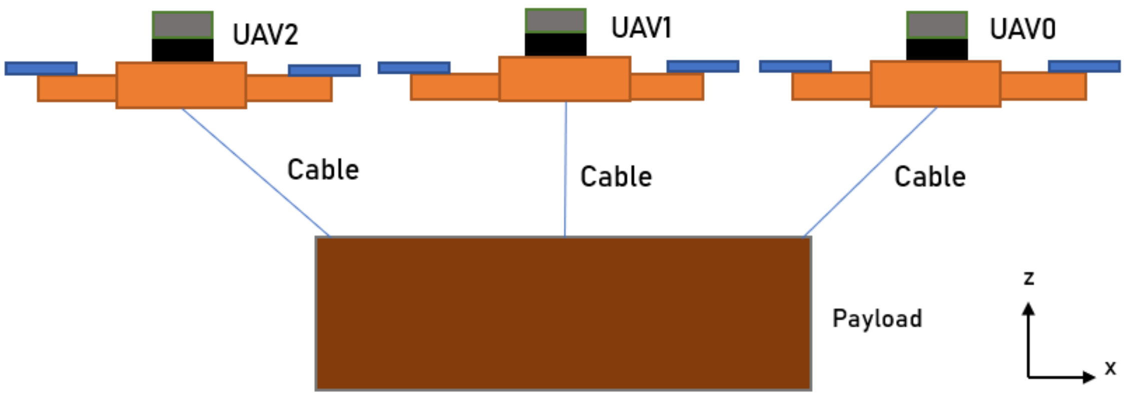
Terrestrial CPT: A small number of proposed CPT schemes rely on terrestrial vehicles. A distributed controller for collaborative pushing using PI controllers is explored in [30]; in contrast, [20] and [31] use rigid schemes. It is noteworthy that the distributed MPC algorithm in [20] has not yet been applied to aerial CPT.

2.3 Problem Statement

Agent Configuration: This FYP focuses on aerial CPT using a homogeneous swarm of UAV agents. For simplicity of modeling, I assume that the payload has a rigid, homogeneous composition and the shape of a rectangular prism. The agents will be attached to the payload using cables of identical composition and length, positioned symmetrically around the payload's center of mass on the payload's top face. Figure 7 depicts such a configuration using three agents.



(a) Top View



(b) Side View

Figure 7: System Configuration for Three Agents

Control Architecture: The proposed CPT scheme will require three distinct flight modes: takeoff, payload carriage, and landing. Inspired by [20], these flight modes will be implemented using a distributed optimal control architecture. Each agent will run an onboard MPC algorithm for planning and tracking an optimized trajectory in real-time (Figure 8).

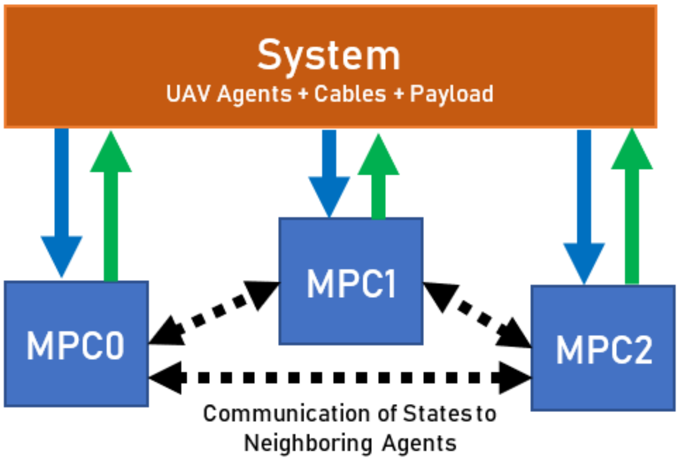


Figure 8: Proposed Control Architecture

The onboard controller will use a double-integrator model of the agent's dynamics, motivated by the widespread contemporary usage of flight controllers such as the Pixhawk [1]. The sum of the squared actuator effort in three dimensions will be the optimization's stage cost, and the terminal cost will be the duration of the mission.

I will impose path constraints on each agent in the form of zone contracts between peers. Each agent will communicate its state with its peers and calculate a zone of safety by subtracting its radius from its permitted tip span (defined as half of the shortest distance to the nearest peer, see Figure 9). This approach will prevent collisions between agents and requires minimal explicit communication. Real-time estimation of the evolution of peer agents' safety zones may give a better picture of an agent's path constraints over time, hence such estimates may also be fed into the onboard trajectory optimization algorithm.

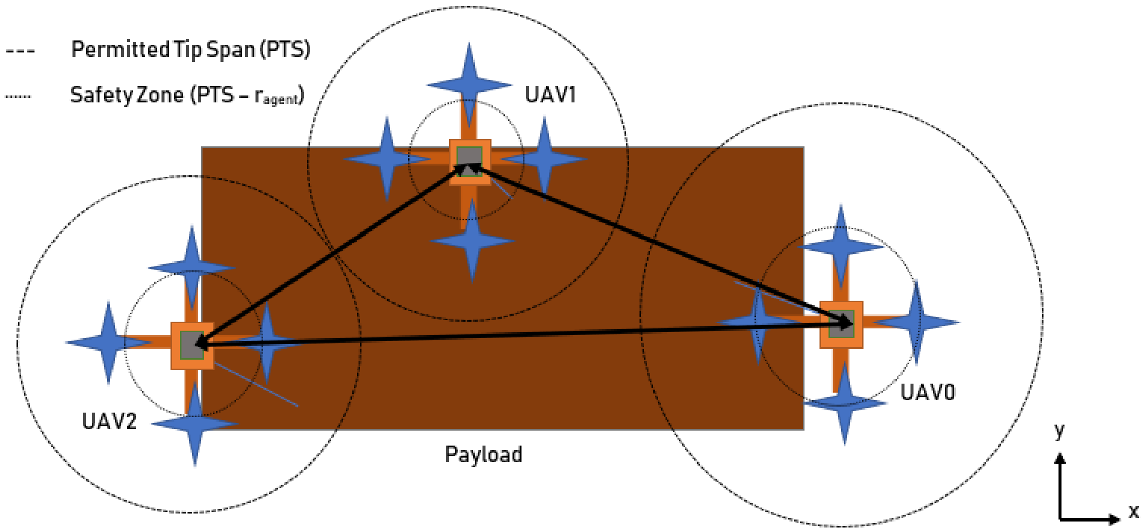


Figure 9: Zone Configuration, Top View

3 Implementation

3.1 Completed Work

Work completed for the FYP has covered three topics: reviewing the state of the art, familiarization with the use of ICLOCS2 for trajectory optimization and mission simulation, and preparation for the present report.

Reviewing the State of the Art: In the initial phase of the FYP I focused on gathering information about the state of the art. I completed the literature survey on the 16th of November, 2018 and devised a preliminary definition of the problem on the 23rd of November, 2018.

Trajectory Optimization: The focus then shifted to using ICLOCS2 to run simulations of optimal control applications, first by studying examples provided on the ICLOCS2 website [32], then by using ICLOCS2 to solve the minimum-work single-agent aerial locomotion problem. There have been some obstacles to testing:

- The instructions on how to provide analytical derivatives to ICLOCS2 in order to reduce runtime delays have been incomplete, thereby preventing execution of the example problem
- Delayed access to sufficient computing power for running ICLOCS2 occurred; this issue has been mitigated by access to a more powerful workstation in the Robot Intelligence Lab at Imperial College London
- Even with use of analytical derivatives there are significant sources of runtime delays hindering timely execution of the example problem

I completed basic implementation of the open-loop control problem (i.e. planning the entire trajectory before the mission) on the 7th of December, 2018 and did further work to refine the code and to introduce spatial obstacles up to the first week of Spring Term (Figures 10 and 11).

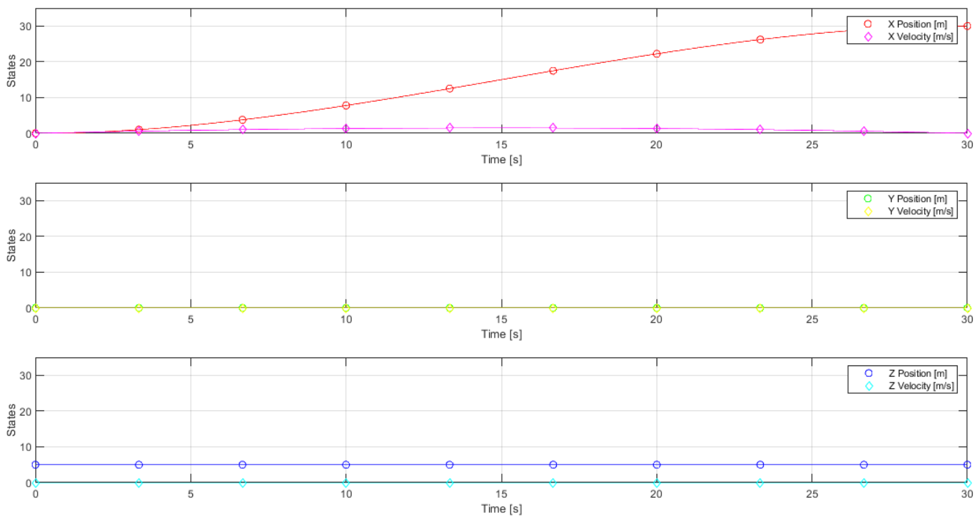


Figure 10: Minimum-Work Single-Agent Locomotion – State Evolution under Open-loop Planning

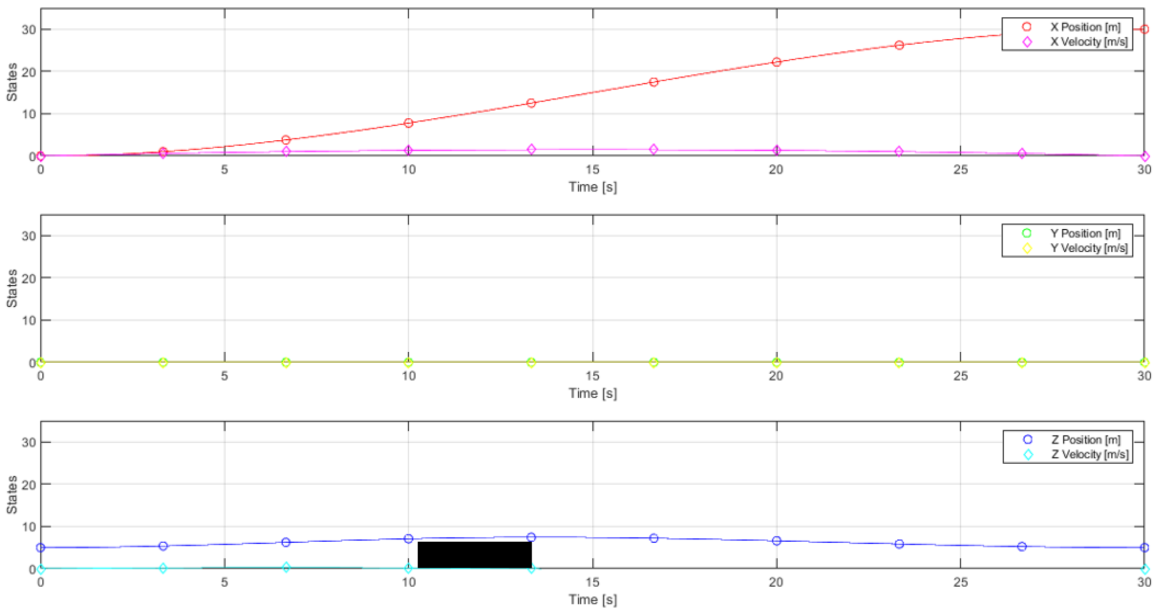


Figure 11: Minimum-Work Single-Agent Locomotion – State Evolution under Open-Loop Planning with Spatial Obstacle

I implemented the closed-loop control problem in Simulink on the 14th of January, 2019, running ICLOCS2 as a trajectory optimization block in a feedback loop with a double-integrator model for the single-agent dynamics (Figure 12). Evolution of the agent's position under closed-loop control without obstacles was concluded successfully on the 24th of January, 2019 (Figure 13).

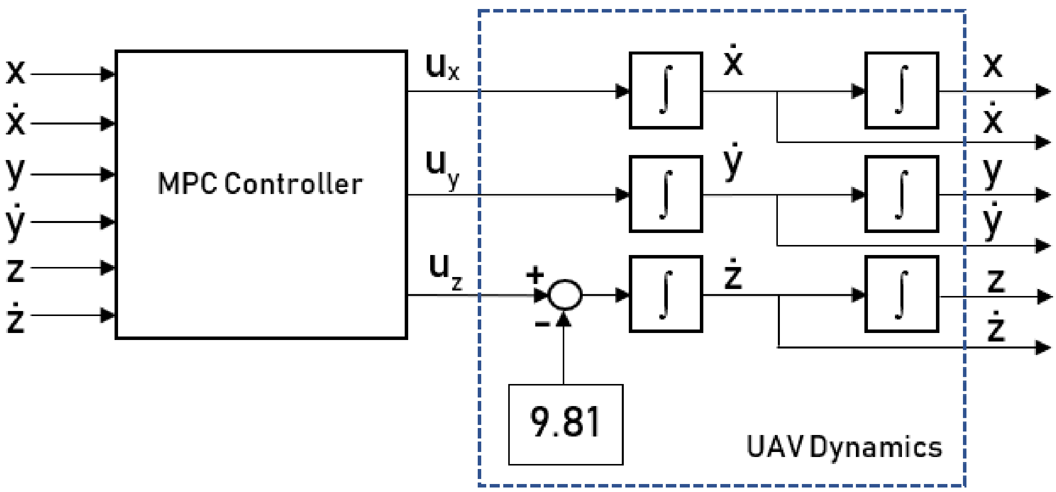


Figure 12: Minimum-Work Single-Agent Locomotion – Block Diagram for Closed-Loop System

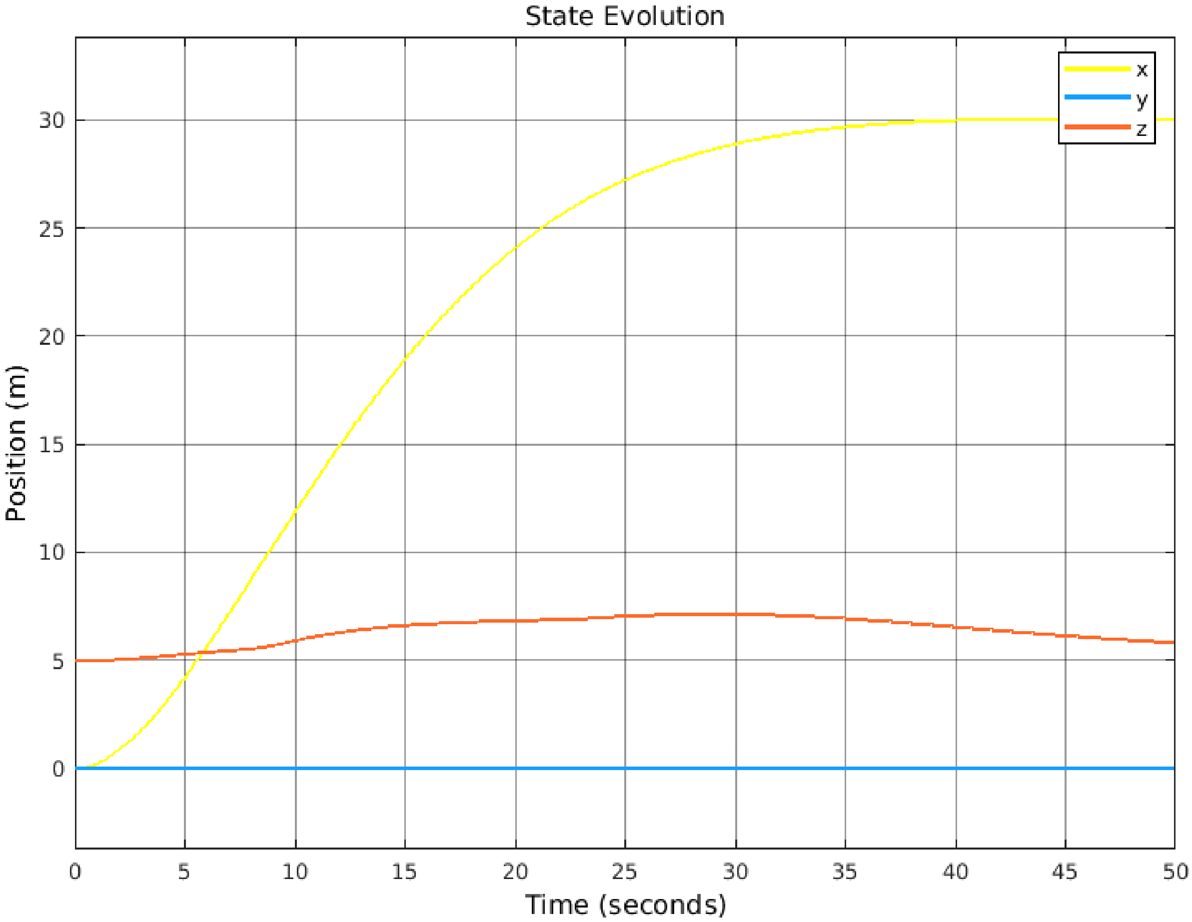


Figure 13: Minimum-Work Single-Agent Locomotion – State Evolution under Closed-Loop Planning

3.2 Proposed Work

Table 1 contains a summary of the proposed work schedule for the remainder of the FYP.

Table 1: Proposed Work Schedule

Stage	Task	Deadline
Problem Formulation	Mathematical formulation of the proposed solution	1 February 2019
Developing the ICLOCS2-ROS Interface	Simulations using ICLOCS2 and Simulink with ROS in closed-loop	19 February 2019
	Visualization of simulations using Gazebo	20 February 2019
	Documentation of software interface between ICLOCS2 and ROS	21 February 2019
Implementing the Proposed CPT Scheme	Closed-loop trajectory planning for proposed CPT scheme using ICLOCS2 and Simulink	14 March 2019
	Simulations using ICLOCS2 and Simulink with ROS in closed-loop	20 March 2019
	Visualization of simulations using Gazebo	21 March 2019
Final Report and Presentation	Abstract and draft report	3 June 2019
	Revised report	19 June 2019
	Presentation of Results	24-26 June 2019

Project Management: Increasingly crowded conditions in the Robot Intelligence Lab may adversely impact my access to the workstation during business hours. I can address this by shifting planned work to early morning time slots and conducting all but the most essential work on my laptop computer.

Delays in troubleshooting issues with ICLOCS2 and ROS are likely to continue and will have a multiplicative impact because of the linear nature of the project's objectives and work schedule.

To minimize delays I have divided the work into smaller units, built tolerance into the schedule and am regularly meeting with my FYP supervisors.

4 Evaluation Plan

The success of the FYP will depend on verified completion of each major task identified in the proposed work schedule. Table 2 outlines the methods that I will use to verify the technical soundness and correct operation of the FYP objectives.

Table 2: Evaluation Methods for FYP Objectives

Task	Method of Evaluation
Mathematical formulation of the proposed solution	• Simulate the proposed CPT scheme using ICLOCS2 in Simulink. • The standard CPT task will involve moving the payload by 30 m in the $+x$ direction
Closed-loop trajectory planning using ICLOCS2 and Simulink	• Perform the standard CPT task. • Check for undesired runtime phenomena: – delays (greater than one second) – excessive memory usage – quantitative agent constraint violations – unsafe operation (such as excessive payload swings).
Simulations using ICLOCS2 and Simulink with ROS in closed-loop	• Ensure that ICLOCS2 output data can be read by agent nodes in ROS and vice versa. • Perform the standard CPT task and check for undesired runtime phenomena. • Compare results with the closed-loop Simulink-only simulation.
Visualization of simulations using Gazebo	• Verify the structural and inertial properties of each model component in Gazebo manually. • Perform the standard CPT task and check for undesired runtime phenomena (cf. real-time factor). • Compare results with the closed-loop Simulink-only simulation.
Documentation of software interface between ICLOCS2 and ROS	• Users competent in ROS but unfamiliar with ICLOCS2 must be able to read the instructions and install the ICLOCS2 interface with ROS without difficulty or delays. • Ask these users for qualitative feedback on the documentation.

5 Safety, Legal and Ethical Considerations

5.1 Safety Considerations

Given the software orientation of the FYP, there are no significant physical hazards. Future hardware implementation will need to be handled safely (see the UK Drone Code [33]). Longer term, widespread adoption of CPT technology could adversely impact noise pollution and existing aerial traffic in urban environments.

5.2 Legal Considerations

Intellectual Property: MATLAB and Simulink are used extensively as platforms for prototyping and testing [34]. Imperial College's academic software licence covers such research. Trajectory optimization is performed by ICLOCS2 [35], which is dependent on the Ipopt software package [36]. Both require inclusion of the provided copyright notices, conditions and disclaimers in all source code and documentation for binaries because they are released under modified BSD licences [37]. Such licences do not prevent future commercialization of derivative works.

UK Drone Code: Future implementations of the proposed CPT scheme must adhere to legal regulations concerning safe operation of UAVs. Recent events at Gatwick and Heathrow Airports present a timely reminder of the potential disruption that drones can inflict on scheduled air traffic [38]. The UK government has released guidelines for civilians that prohibit UAV operation in certain locations (Figure 14) [39]. In the more distant future, legal regulations for commercial fleets of CPT hardware concerning noise, aerial traffic, and accident responsibility will need to be developed by policy makers, analogous to the UK Drone Code for individuals.

Figure 14: Operational Restrictions for UAVs in the UK [39]

5.3 Ethical Considerations

Several industries are seeking to integrate CPT into their operations, raising complex ethical issues. Many potential applications could be beneficial, for example monitoring infrastructure and environmental conditions, search and rescue, crowd control, police pursuits, building inspections, town planning and delivering vaccines and medicines to remote communities [40]. There is a risk of abuse of CPT technology for criminal activities: UAVs have been used to deliver weapons and illicit drugs to a prison [41], disrupt police operations [42], and allow terrorists to launch attacks from the air [43]. The military sector has a strong interest in drone technology that may lead to CPT being incorporated into advanced weaponry [9].

CPT technology could have a wide social impact, particularly on the employment of unskilled and low-skilled workers in the logistics industry. Porters, food and parcel delivery drivers, couriers and postal workers could see a change in the volume and type of work they handle. Nevertheless, the technology may make other workers more productive and efficient.

6 Conclusions

This report has detailed the rationale for implementing CPT with UAVs using distributed optimal controllers. The literature survey has provided information on the relative merits of various design choices in CPT schemes and the selection of appropriate requirements to guide the development of a new system. To date, the application of optimal control to cable-suspended CPT schemes has relied on a decentralized architecture, requiring significant computational resources for the onboard estimation of peer agents' states. By exploiting a distributed architecture, the computational burden for each agent is reduced in exchange for minimal reliance on explicit communication with peers. Work planned for the remainder of the term will culminate in a visualization of a CPT mission using the proposed scheme. demonstrating the viability of the proposed scheme and extending the potential applications of real-time trajectory optimization using ICLOCS2 to the ROS software ecosystem.

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