Final Year Project: Interim Report

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Executive Summary

This interim report details planning and preliminary work completed 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. Addressing the problem of cooperative payload transportation by multiple unmanned aerial vehicles, a novel distributed control architecture relying on model predictive control for real-time trajectory optimization is proposed. Avoidance of obstacles and agent collisions is enabled by the incorporation of dynamic zone contracts into agent path constraints. Simulations of the proposed cooperative payload transportation scheme in Simulink draw on the ICLOCS2 software package for trajectory optimization, while a new software interface is planned to integrate ICLOCS2 functionality with the Robot Operating System (ROS) environment. A schedule of planned deliverables and methods for their evaluation are presented, followed by a discussion of potential safety, legal and ethical issues regarding the proposed cooperative payload transportation scheme.

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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]. The goal of the earlier project 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.

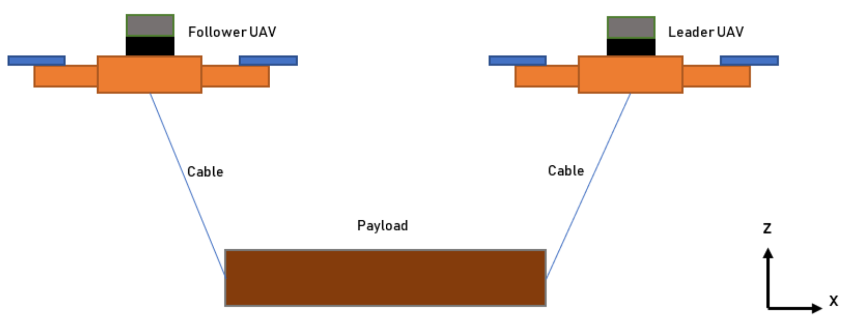


Figure 1: Cooperative Payload Transportation using Unmanned Aerial Vehicles

1.2 Project Goals and Objectives

The CPT problem is re-examined from an optimal control perspective. The 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. There are three intermediate objectives for the FYP:

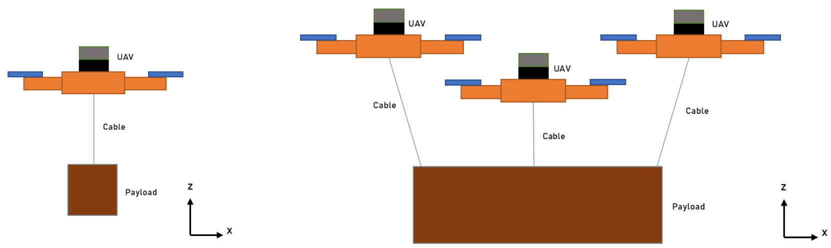
- The optimal controller will be implemented using the ICLOCS2 software package developed by Dr Kerrigan, Yuanbo Nie, and Omar Faqir, and its performance will be simulated numerically using Simulink.

- A software interface for ICLOCS2 in a closed control loop with agent nodes that are running inside the Robot Operating System (ROS) environment will be developed and documented.
- Visualizations of missions under the proposed CPT scheme using the Gazebo simulation package for ROS will be created.

1.3 Project Deliverables

Alongside the stated project goals and objectives, the FYP will produce the following deliverables:

1. A survey of academic literature focusing on multi-agent CPT schemes using UAVs.
2. A set of design requirements for a distributed optimal multi-agent CPT scheme.
3. A scheme that satisfies the identified design requirements.
4. A mathematical formulation of the problem.
5. Numerical simulations of the system with ICLOCS2 in Simulink.
6. Documentation for the software interface between ICLOCS2 and ROS.
7. Demonstration of a successful mission using Gazebo.
8. Submission of a final report documenting the FYP.
9. Presentation of 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 The transportation of 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, however 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, industrial, agricultural, public health and military sectors has motivated the development of CPT schemes [5] (see 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 [6], as presented in Figure 3.

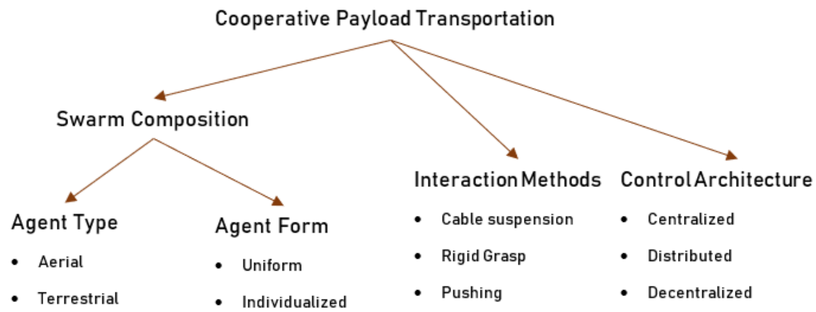
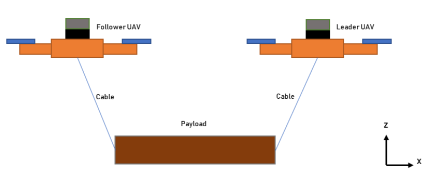


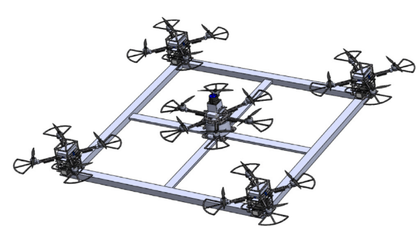
Figure 3: Taxonomy of CPT Schemes

Swarm Composition An important design choice is the agent type: 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 [7]).

Interaction Methods Once a decision has been made about on the formation structure, a method for interacting with the payload has to be chosen (Figure 4a). Slung-load systems indicate that suspension by cable permits versatile tensile manipulation in three dimensions [5], whereas rigid attachment to the agents' bodies allows direct inference of the payload's location but may not suit certain payload sizes and shapes (see Figure 4b).

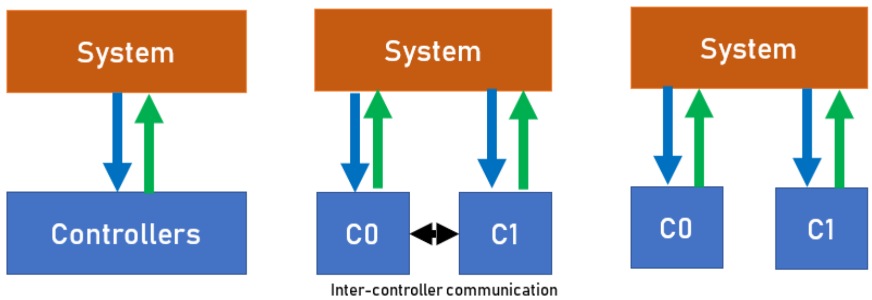


(a) Cable-Suspended CPT [1]



(b) Rigid-Grasp CPT [2]

Figure 4: Interaction Methods for CPT Schemes



(a) Centralized Control (b) Distributed Control (c) Decentralized Control

Figure 5: Control Architectures

Control Architecture Selection of an appropriate control architecture is important [8]. 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.

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:

- A need for robustness in a range of environments
- Minimal reliance on external infrastructure [9].
- To the extent possible, minimization or elimination of dependence on explicit communication between agents (thus adopting a decentralized control architecture) [10]

The following design requirements are also identified in [11]:

- Operability in unstructured indoor and outdoor environments
- Robust flight capabilities
- Autonomous, onboard decision making (this requires control algorithms with lower computational complexity [12])
- Modular and flexible sensing and control
- No dependence on external navigation aids

Mission Objectives Specific to UAV-based CPT schemes, the mission objectives occupy a hierarchy [13]:

1. Obstacle avoidance (also featured in [4] and [12])
2. Secondary objectives:
   (a) Avoidance of collisions and excessive separation between agents
   (b) Even distribution of payload weight between vehicles
3. Reduction of oscillations caused by external disturbances such as wind (this is incompatible with fast and aggressive agent maneuvers [12])

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

2.2.2 Existing CPT Schemes and Limitations

A selection of aerial- and terrestrial-based schemes have been proposed in the literature, representing various combinations of interaction methods, degrees of control centralization, and formation control algorithms. These are summarized in Figure 6.

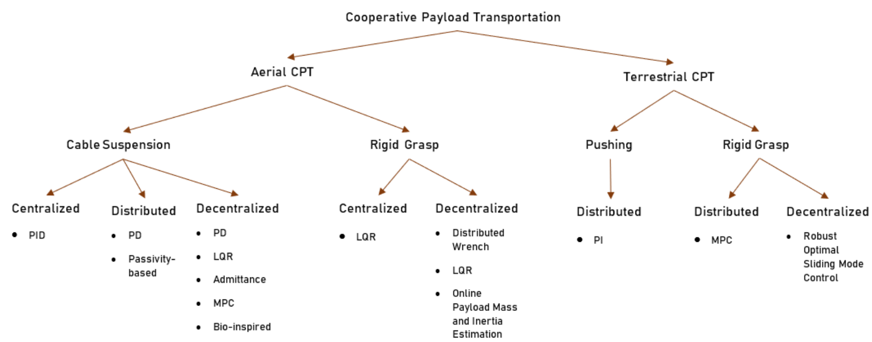


Figure 6: State of the Art for CPT Schemes

Control Centralization The current trend in UAV-based CPT research has seen a shift from centralized control to decentralized control. The reliance of centralized and distributed architectures on communication entails channel latencies, susceptibility to infrastructure failure, and increased consumption of power and spectrum. Each may be avoided if explicit communication is eliminated. However fully-decentralized architectures rely on alternative methods of mutual localization that are more computationally-complex [1].

System Assumptions All implementations 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 ([14] is a notable exception). Few CPT schemes perform trajectory optimization in real-time (among them [15] and [16]).

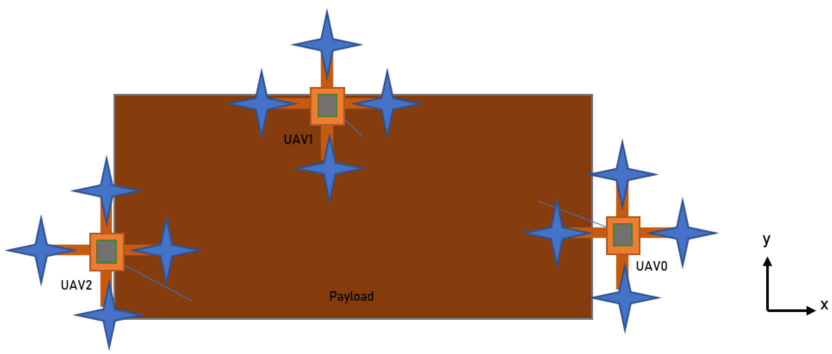
Aerial CPT Among CPT schemes using cable-suspension, all three types of control architectures have been implemented. Centralized architectures relying on PID controllers are proposed in [13], [17] and [18], while a nonlinear PD controller is proposed in [19]. Decentralized control underpins several recent proposals involving LQR ([10], [20]), admittance control ([14]), a bio-inspired algorithm ([7]) and MPC ([16]). Fewer proposals have implemented a distributed control architecture, using a PD controller ([21]) or a passivity-based approach

([22]). Among CPT schemes using rigid payload grasping, a centralized control architecture relying on LQR is presented in [2], while a distributed wrench controller is proposed in [23]. The distributed control architecture in [24] features online estimation of the payload's mass and inertial properties.

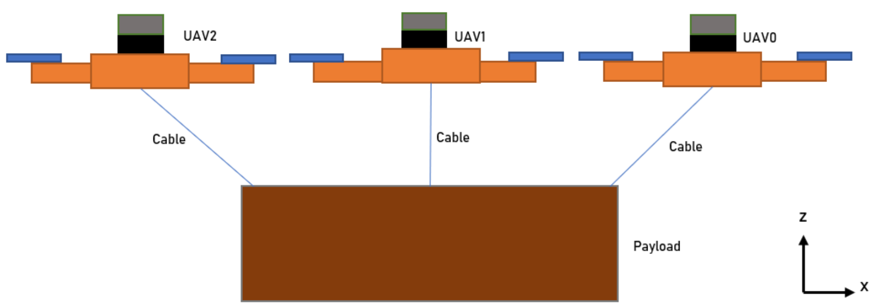
Terrestrial CPT A small number of proposed CPT schemes rely on terrestrial vehicles. A distributed controller for collaborative pushing using PI controllers is explored in [25], while rigid-grasp schemes are used in [15] and [26]. It is noteworthy that the distributed MPC algorithm in [15] has not yet 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, the payload is assumed to have 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 for takeoff, carrying the payload, and landing safely. Inspired by [15], 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).

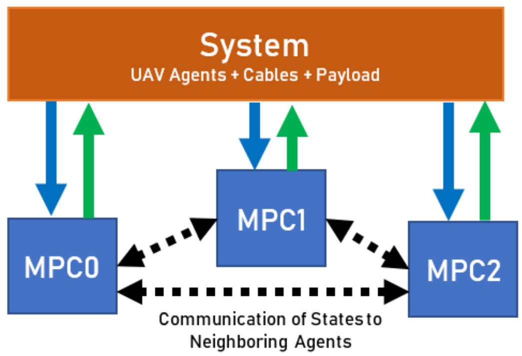


Figure 8: Proposed Control Architecture

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 optimization's stage cost will be the sum of the squared actuator effort in three dimensions, and the terminal cost will be the duration of the mission.

Path constraints will be imposed on each agent in the form of zone contracts between peers. As depicted in Figure 9, 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). Requiring minimal explicit communication, this will prevent collisions between agents. 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.

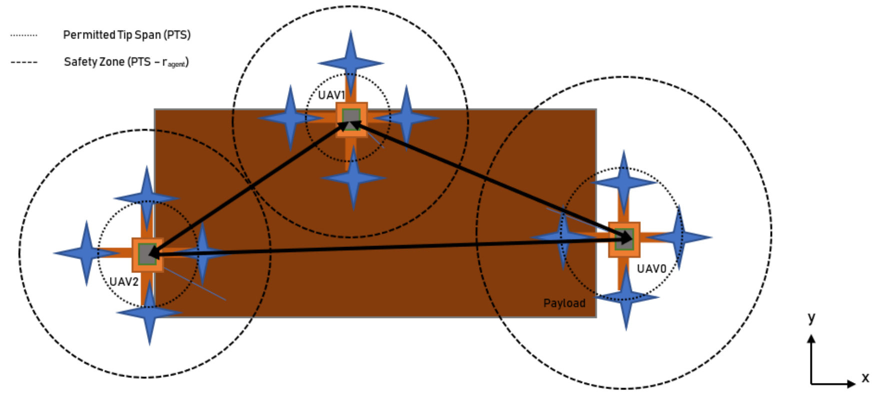


Figure 9: Zone Configuration, Top View

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 The initial phase of the FYP focused on gathering information about the state of the art, with the literature survey completed on the 16th of November, 2018, followed by a preliminary definition of the problem for the FYP on the 23rd of November, 2018.

Trajectory Optimization Thereafter the focus of the FYP shifted towards using ICLOCS2 to run simulations of optimal control applications, first by studying examples provided on the ICLOCS2 website [27], 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; 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

The basic implementation of the open-loop control problem (i.e. planning the entire trajectory before the mission) was completed on the 7th of December, 2018, with further code refinement and introduction of spatial obstacles extending into the first week of Spring Term (Figures 10 and 11).

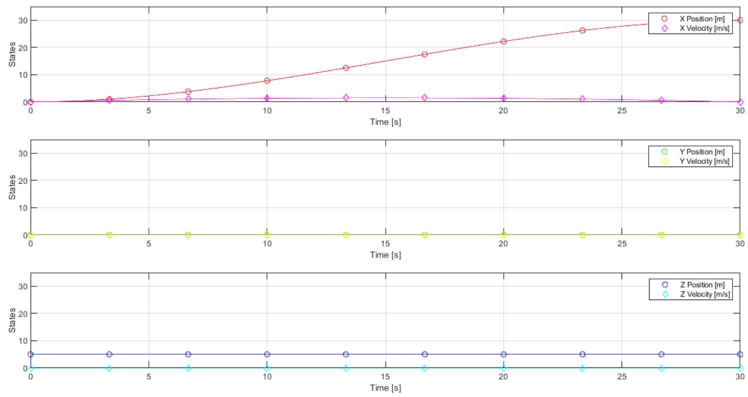


Figure 10: Minimum-Work Single-Agent Locomotion – State Evolution under Open-loop Planning

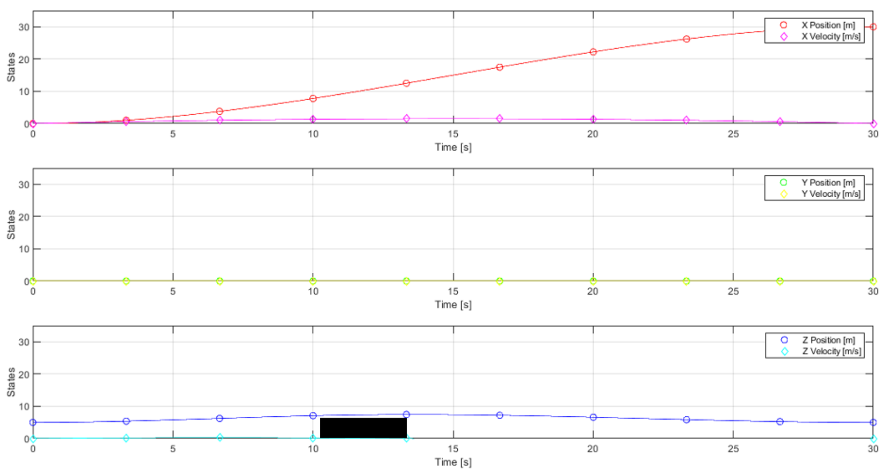
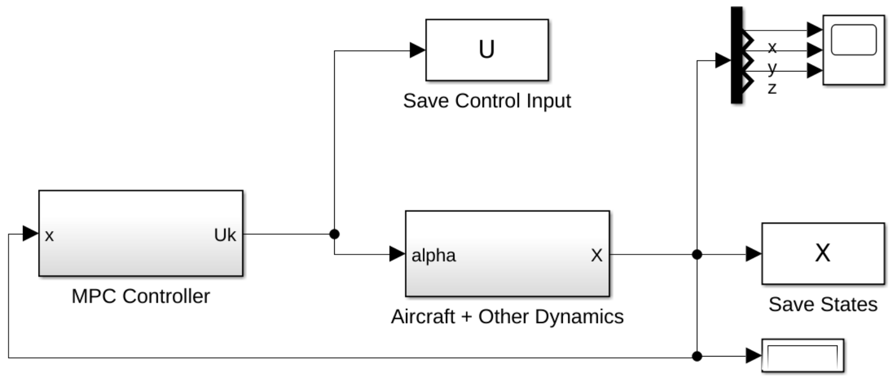
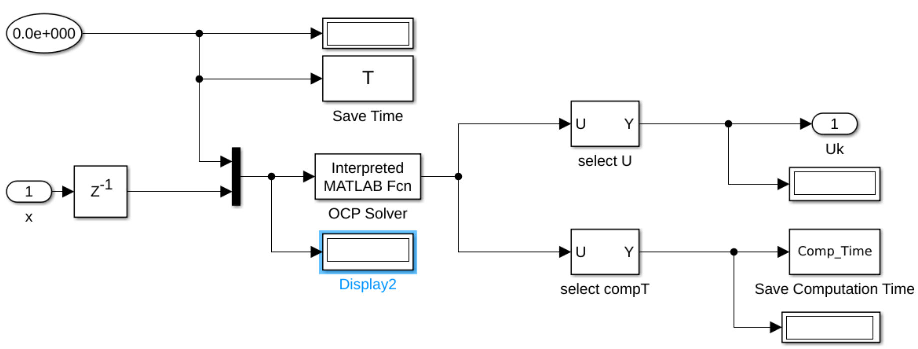


Figure 11: Minimum-Work Single-Agent Locomotion – State Evolution under Open-Loop Planning with Spatial Obstacle

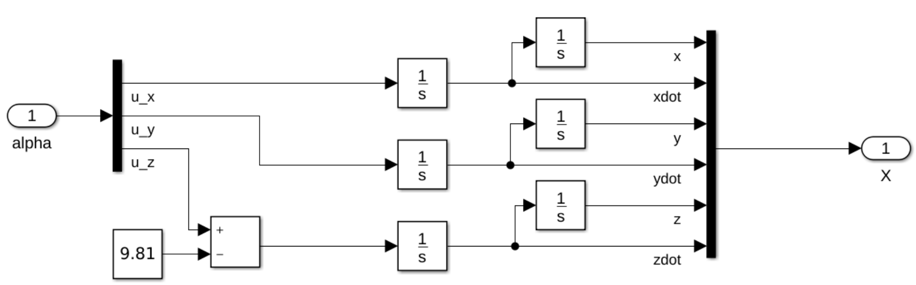
The closed-loop control problem was subsequently implemented in Simulink on the 14th of January, running ICLOCS2 as a trajectory optimization block in a feedback loop with a double-integrator model for the single-agent dynamics (see Figure 12). Troubleshooting the simulation's runtime delays is currently ongoing.



(a) Top-Level Schematic



(b) MPC Block Schematic



(c) System Dynamics Block

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

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	Closed-loop trajectory planning for single-agent aerial transportation using ICLOCS2 and Simulink	14 February 2019
	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. This can be mitigated 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. Due to the linear nature of the FYP's objectives and planned work schedule, delays will have a multiplicative impact on subsequent planned work.

To minimize the possibility of obstruction, the work has been divided into smaller units, tolerance has been built into the schedule and regular meetings with FYP supervisors have occurred.

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 relevant methods that will be used 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 while avoiding a ground obstacle during the mission
Closed-loop trajectory planning using ICLOCS2 and Simulink	• Perform the standard CPT task • Check for undesired runtime phenomena such as delays (greater than one second), excessive memory usage, quantitative agent constraint violations, and 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 (particularly the 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 implementation of the results of the FYP using hardware will need to be able to safely handle humans in the environment (see the UK Drone Code [28]).

5.2 Legal Considerations

Intellectual Property MATLAB and Simulink are used extensively as platforms for prototyping and testing [29]. Such research is covered by Imperial College's academic software licence. Trajectory optimization is performed by ICLOCS2 [30], which is dependent on the Ipopt software package [31]. Both are released under modified BSD licences, which require inclusion of the provided copyright notices, conditions and disclaimers in all source code and documentation for binaries [32]. 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 [33]. The UK government has released guidelines for civilians that prohibit UAV operation in certain locations (see Figure 13) [34]. 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 13: Operational Restrictions for UAVs in the UK [34]

5.3 Ethical Considerations

Strong interest from the military sector in drone technology could lead to the incorporation of CPT into advanced weaponry. However, CPT could also enable more rapid and effective search and rescue missions in the event of natural disasters, and could facilitate the delivery of vaccines and medicines to remote communities [35]. Increasing prevalence of CPT schemes in commercial activities could also have implications for airport flight paths and delivery and logistics companies, with potential unemployment for porters, couriers and delivery drivers. For the foreseeable future, it is likely that only small deliveries within strictly defined areas will be commercially viable. Widespread adoption of CPT technology could adversely impact noise pollution and existing aerial traffic in urban environments.

6 Conclusion

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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