**Final Year Project: Interim Report**

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# Executive Summary

# Project Specification

This final year project (FYP) addresses the problem of optimal control for cooperative transportation of a payload (CPT) using unmanned aerial vehicles (UAVs). The FYP was inspired by previous research conducted as part of a summer placement under the supervision of Professor Jeff Shamma of RISC Lab at the King Abdullah University of Science and Technology.[[1]](#footnote-1) The goal of the earlier project was to devise a decentralized control algorithm for autonomous cooperative transportation of a payload (CPT) by two unmanned aerial vehicles (UAVs). The proposed control scheme relied on one UAV as a ‘leader’ agent tracking a preset trajectory, and the second UAV as a ‘follower’ agent implementing a simple PID controller.

Under the supervision of Dr Eric Kerrigan and Ian McInerney, I am re-examining the CPT problem 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 this FYP. First, the optimal controller will be implemented using a software package developed by Dr Kerrigan, Yuanbo Nie, and Omar Faqir (ICLOCS2), and its performance will be simulated numerically using Simulink. Second, I will 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. Finally, I will create visualizations of missions under the proposed CPT scheme using the Gazebo simulation package for ROS.

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

1. A survey of academic literature focusing on multi-agent CPT schemes using UAVs
2. 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

# Background

## Cooperative Payload Transportation

The transportation of objects is a fundamental task in the field of robotics.[[2]](#footnote-2) As a subset of the manipulation problem, payload transportation is conducted by mobile agents, typically unmanned aerial vehicles (UAVs). Aerial payload transportation using single-agent systems has been studied in numerous sources[[3]](#footnote-3), however such systems are inherently limited by the carrying capabilities of the agent’s hardware. In recent years, increasing interest in aerial payload transportation from the commercial, industrial and military sectors has motivated the development of cooperative payload transportation (CPT) schemes.[[4]](#footnote-4) 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 aspects of their design. [[5]](#footnote-5) 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. One must also consider the composition of the formation, i.e. whether the agents will have a uniform or heterogeneous design (perhaps reflecting task specializations, as seen in [[6]](#footnote-6)).

After deciding on the formation structure, a method for interacting with the payload can be chosen. Inspired by research on slung-load systems, suspension by cables permits versatile tensile manipulation in three dimensions. Used less frequently in CPT, rigid attachment to the agents’ bodies allows direct inference of the payload’s location but may not be suitable for all payload sizes and shapes.

Finally, an appropriate control architecture must be selected.[[7]](#footnote-7) Centralized control algorithms require decisions to be made in one location and communicated to all agents. Distributed control algorithms involve each agent making decisions with some communication with peers. Decentralized control algorithms involve each agent making their own decisions without communicating with peers.

## Survey of CPT Literature

### Design Requirements for CPT Schemes

The literature survey identified several important requirements for UAV-based CPT systems. In analyzing the feasibility of UAV delivery systems, d’Andrea emphasized a need for robustness in a range of environments and minimal reliance on external infrastructure [d’Andrea]. Motivated by the latter factor, eliminating dependence on explicit communication between agents (and therefore moving towards a decentralized control architecture) is explored in [Gassner17]. Tomic et al. explicitly identified the following design requirements [Tomic12]:

* Operability in unstructured indoor and outdoor environments
* Robust flight capabilities
* Autonomous, onboard decision making (this requires control algorithms with lower computational complexity [TangKumar15])
* Modular and flexible sensing and control capabilities
* No dependence on external navigation aids

Specific to UAV-based CPT schemes, Gimenez et al. ordered several common objectives in a hierarchy [Gimenez18]:

1. Obstacle avoidance (also featured in [TangKumar15] and [Ruggiero18-Intro])
2. Secondary objectives:
   1. Avoid collisions and excessive separation between agents
   2. Evenly distribute the payload weight between vehicles
3. Reduce oscillations caused by external disturbances such as wind (this is incompatible with fast and aggressive agent maneuvers [TangKumar15])

Once the objectives are known, Gimenez et al. recommend that an appropriate control solution may be chosen. If an optimal control algorithm is used, one may seek to minimize mission duration and actuator effort in order to conserve battery life.

### Existing CPT Schemes and Limitations

A selection of UAV- and terrestrial-based schemes have been proposed in the literature, representing various combinations of interaction methods, degrees of control centralization, and formation control algorithms.

A prominent 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 of these consequences can be avoided if dependence on explicit communication is eliminated [FR DAW15]. Nevertheless, fully-decentralized architectures must therefore rely on alternative methods of mutual localization that are more computationally-complex.

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 ([Tognon18] is a notable exception). Finally, few CPT schemes perform trajectory optimization in real-time (among them [Verginis18] and [Tagliabue17]).

Among CPT schemes using cable-suspension, all three types of control architectures have been implemented. Centralized architectures relying on PID controllers are proposed in Michael10, Gimenez18 and Pereira18, while a nonlinear PD controller is proposed in Lee14. Decentralized control underpins several recent proposals involving LQR (Gassner17, Shirani18), admittance control (Tognon18), a bio-inspired algorithm (Gabellieri18) and MPC (Tagliabue17). Fewer proposals have implemented a distributed control architecture; Cotsakis18 use a PD controller, while Klausen18 adopt a passivity-based approach. Among CPT schemes using rigid payload grasping, a centralized control architecture relying on LQR is presented in [Tan18], while a distributed wrench controller is proposed in Wang18. A notable feature of the distributed control architecture in Lee18 is the online estimation of the payload’s mass and inertial properties.

A small number of proposed CPT schemes involve terrestrial vehicles. Ebel and Eberhard18 propose a distributed architecture for collaborative pushing of an object by mobile robots, relying on PI controllers for agent propulsion and penalty forces for inter-agent collision avoidance. Babaie and Ehyaie17 study a decentralized sliding mode controller for a rigidly-grasped payload, while Verginis18 implement a distributed controller using receding horizon MPC. Notably the latter technique has not yet been applied to an aerial CPT scheme.

## Problem Statement

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 X depicts such a configuration using three agents.

Figure X – Three-agent config, top view and side view

The proposed CPT scheme will require three distinct flight modes for takeoff, carrying the payload, and landing safely. Inspired by the work of Verginis18, these flight modes will be implemented using a distributed optimal control architecture. Each agent will run an onboard receding horizon MPC algorithm for planning and tracking an optimized trajectory. 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 [FR DAW15]. 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.

Figure XX – Diagram of Zones

Path constraints will be imposed on each agent in the form of zone contracts between neighbors. As depicted in Figure XX, each agent will communicate its state with its neighbors and calculate a zone in which it can move safely. Requiring minimal explicit communication, this will prevent collisions between agents and eliminate the need for neighbor state estimation, further reducing the computational complexity of the onboard control algorithm.

# Implementation

## Completed Work

Work completed for the FYP to date 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. With the completion of the present report, the first, second and third objectives of the FYP have been achieved.

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.

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 [ICLOCS2], then by using ICLOCS2 to solve the minimum-work single-agent aerial locomotion problem. Due to an initial lack of familiarity with the software package and computational limitations, 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 (see figures XXX and XXXX). [[FOOTNOTE: Since the start of the Spring Term, these issues have been mitigated by access to a more powerful workstation in the Robot Intelligence Lab at Imperial College London.]]

Figure XXX – Minimum-work Single-agent Locomotion – Open-loop planning

Figure XXXX – Minimum-work Single-agent Locomotion – Open-loop planning with obstacles

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 XXXXX). Troubleshooting delays with the simulation’s runtime is currently ongoing.

Figure XXXXX – Minimum-work Single-agent Locomotion – Block diagram for closed-loop planning

Parallel to the technical work for the FYP, twice-weekly meetings with Dr Eric Kerrigan and Ian McInerney have assisted in defining the focus of the FYP and reflecting on the performance issues of the simulations to date.

## Proposed Work

Building on the problem statement outlined in the present report, renewed focus will be placed on generating a mathematical formulation of the problem and proposed solution. This will involve defining a coordinate scheme for agents and the payload, creating an approximation of the dynamics of the agents and payload, modeling the mechanical interactions between agents and the payload, and defining a communication protocol between agents. The mathematical formulation of the entire system (the fourth FYP objective) is due for completion by the 1st of February, 2019.

Further work in troubleshooting the Simulink simulations of the closed-loop single-agent aerial locomotion system is due for completion by the 14th of February, 2019. The preliminary interface between ICLOCS and Simulink with the ROS environment will model the same single-agent system, allowing for simulations using Simulink (due 19th of February, 2019) and visualization of the system evolution using Gazebo (20th of February, 2019). Documentation for the software interface with ROS will be completed by the 21st of February, 2019, and shared with the ICLOCS2 maintenance team (the sixth FYP objective).

After the ICLOCS2-ROS software interface is developed, tested and documented, the final phase of technical work will commence. Numerical simulations of the proposed CPT scheme will be conducted in Simulink (the fifth FYP objective) and are due for completion by the 14th of March, 2019. Once system performance is verified, the proposed CPT scheme will be simulated in Simulink with the ICLOCS2-ROS interface (20th of March, 2019). The seventh objective, visualization of a successful mission under the proposed CPT scheme, will immediately follow on the 21st of March, 2019.

Preparation for the final report and presentation will begin over the Easter holidays, with the abstract and draft of the report to be submitted by the 3rd of June, 2019. Following discussions with Dr Eric Kerrigan and Ian McInerney, a revised copy of the final report will be submitted by the 19th of June (the eighth FYP objective). The final FYP objective, the presentation of work to academic staff, is expected to happen between the 24th and 26th of June, 2019, with the exact date and time to be confirmed at a later date.

Two important issues are anticipated. 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. More importantly, given the novelty of the software implementation component of this FYP, delays in troubleshooting issues with ICLOCS2 and ROS are likely. 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 and tolerance has been built into the schedule. To prevent serious blockages, I have met regularly with Dr Eric Kerrigan and Ian McInerney for advice on resolving any arising issues and consulted Yuanbo Nie for further assistance with ICLOCS2.

## Proposed Work Schedule

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| --- | --- | --- |
| Stage | Task | Deadline |
| Problem Formulation | Mathematical formulation of the problem and 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 of report | 3 June 2019 |
| Revised report | 19 June 2019 |
| Presentation of Results | 24-26 June 2019 |

# Evaluation Plan

The success of the FYP will depend on verified completion of each major task identified in the proposed work schedule. Table X outlines the relevant methods that will be used to verify the technical soundness and correct operation of each component of the proposed solution.

|  |  |  |
| --- | --- | --- |
| Stage | Task | Method of Evaluation |
| Problem Formulation | Mathematical formulation of the problem and proposed solution | Successful simulation of the proposed CPT scheme using ICLOCS2 in Simulink: the standard CPT task will involve moving the payload by 30 m in the positive x direction while avoiding a ground obstacle during the mission. |
| Developing the ICLOCS2-ROS Interface | Closed-loop trajectory planning for single-agent aerial transportation using ICLOCS2 and Simulink | The standard locomotion task will involve moving the agent by 30 m in the positive x direction while avoiding a ground obstacle during the mission.  Perform the standard locomotion task and 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 | First ensure that ICLOCS2 output data can be read by agent nodes in ROS and vice versa with empty messages.  Perform the standard locomotion task and check for undesired runtime phenomena. Compare results with the closed-loop Simulink-only simulation. |
| Visualization of simulations using Gazebo | First verify the structural and inertial properties of each model component in Gazebo manually.  Perform the standard locomotion 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 | Colleagues competent in the use of ROS but unfamiliar with ICLOCS2 must be able to read the instructions and install both ICLOCS2 and the interface with ROS without difficulty or delays. These individuals will be asked for qualitative feedback on the comprehensibility of the documentation. |
| Implementing the Proposed CPT Scheme | Closed-loop trajectory planning for proposed CPT scheme using ICLOCS2 and Simulink | Perform the standard CPT task and check for undesired runtime phenomena. |
| Simulations using ICLOCS2 and Simulink with ROS in closed-loop | 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 | Perform the standard locomotion task and check for undesired runtime phenomena, particularly the real-time factor. Compare results with the closed-loop Simulink-only simulation. |

# Safety, Legal and Ethical Considerations

Given the software orientation of the FYP, there are no significant physical hazards. Nevertheless, principles of occupational health and safety when working on a computer (such as maintaining adequate lighting and posture) should be followed. Future implementation of the results of the FYP using hardware will need to be able to safely handle humans in the environment, hence attention should be given to the UK Drone Code[[8]](#footnote-8).

An important legal issue is the use of others’ intellectual property for the development and execution of the proposed CPT scheme. For the FYP, MATLAB and Simulink are used extensively as platforms for prototyping and testing.[[9]](#footnote-9) Due to the exclusively academic nature of the FYP, such research is covered by Imperial College’s academic software licence. Trajectory optimization is provided by ICLOCS2, which in turn relies on the Ipopt software package.[[10]](#footnote-10) Both are released under modified BSD licences, which can be respected by reproducing the provided copyright notices, conditions and disclaimers in all source code and documentation for binaries.[[11]](#footnote-11) Such licences do not prevent future commercialization of derivative works.

Future implementations of the proposed CPT scheme will need to adhere to legal regulations concerning safe operation of UAVs. The UK government has released guidelines for civilians that prohibit UAV operation in certain locations (airports, built-up areas, crowds, areas within 50m of a person, vehicle or building not under control of the operator).[[12]](#footnote-12) 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.

The development and application of CPT schemes raises several ethical issues. Strong interest from the military sector in this technology could lead to the incorporation of CPT into advanced weaponry but could also enable more rapid and effective search and rescue missions in the event of natural disasters. Increasing prevalence of CPT schemes in commercial activities could also have implications for delivery and logistics companies, with potential unemployment for porters, couriers and delivery drivers. For the foreseeable future, it is likely that only small deliveries over short distances will be feasible due to the limitations of current battery technology.

# Conclusions

1. Cite FR DAW15 [↑](#footnote-ref-1)
2. Gupte12 [↑](#footnote-ref-2)
3. Ruggiero18 – Intro to Special Issue [↑](#footnote-ref-3)
4. Ruggiero18 – Aerial Manipulation, Literature Review [↑](#footnote-ref-4)
5. Khamseh et al. 2018 – see November notes surveys.docx [↑](#footnote-ref-5)
6. Gabellieri18 [↑](#footnote-ref-6)
7. Farina&Trecate12 : http://www.eeci-institute.eu/GSC2012/Photos-EECI/EECI-GSC-2012-M4/1-Intro\_DeDiCo.pdf [↑](#footnote-ref-7)
8. https://dronesafe.uk/. [↑](#footnote-ref-8)
9. Mathworks citation [↑](#footnote-ref-9)
10. Ipopt citation [↑](#footnote-ref-10)
11. http://www.linfo.org/bsdlicense.html [↑](#footnote-ref-11)
12. https://www.gov.uk/government/news/drones-are-you-flying-yours-safely-and-legally [↑](#footnote-ref-12)