Research Placement Final Report

19 AUGUST 2018

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EXECUTIVE SUMMARY

This final report reflects upon my experiences of conducting a research project as part of the third-year Research Placement, under the supervision of Professor Jeff Shamma in the RISC Lab at the King Abdullah University of Science and Technology, Saudi Arabia. It follows a preliminary report dated 3 June, 2018 which described expectations of the placement jointly agreed with Professor Shamma and Professor Yiannis Demiris.

On a technical level, I explain my motivation for selecting Cooperative Payload Transportation (CPT) as the subject matter of my research project; briefly recount preliminary work leading to defining the scope of the subject matter; discuss the findings of a preliminary literature survey I had to conduct to understand the technical context and background; provide a detailed description of the engineering design process leading up to a proposal for a system implementing a CPT scheme using unmanned aerial vehicles; formulate mathematical models for the proposed system's dynamics; evaluate the results of subsequent numerical simulations in MATLAB; describe current efforts and issues related to preparing control algorithms for use with the ROS environment onboard a hardware prototype; identify work which I intend to pursue in the time available before the conclusion of the placement; and, identify future lines of inquiry which I, or another researcher, could pursue to progress work in this area .

On a personal level, I reflect on the many and varied opportunities I have been provided to build transferable technical competencies and skills; examine the practical experience that has deepened and broadened my theoretical understanding of the degree course; consider the value of meeting and interacting with a variety of senior colleagues; think about the different collection of personal qualities required (motivation, persistence, independence, courage, maturity, responsibility, creativity, collegiality, co-operation) to steer and manage a research project; and anticipate the positive influence this research placement experience is likely to have on how I approach future study and employment.

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1 INTRODUCTION

For the purpose of completing a Third Year Industrial Placement, I have undertaken a research placement under the supervision of Professor Jeff Shamma in the Robotics, Intelligent Systems, and Control Laboratory ('RISC Lab') at the King Abdullah University of Science and Technology ('KAUST') in the Kingdom of Saudi Arabia.

The present report follows a preliminary report dated 3 June, 2018 which described the expectations of the placement jointly agreed between myself, Professor Shamma and Professor Yiannis Demiris. The preliminary report anticipated that I would independently devise, develop and conduct an individual research project in an area of personal interest during the placement. In broad terms the present report provides a summary of motivations for the individual research project I elected to do, presents an update of progress made, discusses the project's management and design processes and identifies future lines of inquiry which I, or another researcher, could pursue to progress work in this area. It concludes with reflections about the personal and professional lessons I learned during the placement experience.

I joined KAUST's Visiting Students Research Program (VSRP) in April 2018. KAUST is a private research university located on the Red Sea coast of Saudi Arabia, 90 kilometers north of Jeddah [1]. Established in 2009, the university focuses on interdisciplinary research within three academic divisions: Biological and Environmental Science and Engineering; Physical Science and Engineering; and Computer, Electrical and Mathematical Science and Engineering (CEMSE). An integral constituent of the CEMSE academic division, the RISC Lab conducts research into intelligent autonomous systems and their applications [2]. The RISC Lab is directed by Professor Jeff S. Shamma, Chair of Electrical Engineering at KAUST. His research interests include feedback control and systems theory, distributed multi-agent systems, human-machine networks, and robotics. Current topics of interest at the RISC Lab include aerial swarms, pedestrian crowd modelling and smart grid management

My decision to embark on a research project involving autonomous multi-agent robotics was made based on working within and extending an existing RISC Lab topic of interest. On the recommendation of Professor Shamma, I decided to build a hardware prototype which had been proposed and simulated, but not constructed, by a RISC Lab alumnus (Toumi) in his dissertation. [3] The prototype would implement a scheme for cooperative payload transportation (CPT) using unmanned aerial vehicles (UAV).

2 PROJECT DEVELOPMENT

2.1 THEORETICAL BACKGROUND

2.1.1 Project Goals

Increasing industrial and military interest in UAV payload delivery has motivated interest in CPT schemes for bulky and heavy objects. Several papers have examined proposals for CPT schemes, addressing issues such as payload attitude and controlling multiple agents [4] [5] [6] [7] [8]. Two common limitations of most proposed CPT systems are a reliance on centralized control and the need for explicit communications between agents. These limitations increase the control system's complexity and power requirements. Decentralized CPT schemes can eliminate the need for explicit communication between agents, thus reducing the system's power usage. In his dissertation, Toumi proposed and simulated a decentralized dual-agent CPT scheme [3]. The primary goal of this project is to extend Toumi's work by building a hardware prototype for a decentralized CPT scheme using unmanned aerial vehicles (UAV).

Construction and testing of the hardware prototype would require completion of the following deliverables:

- A literature survey of academic papers, concentrating on aerial robotic systems and CPT schemes using UAVs.
- A set of design requirements for a decentralized dual-agent CPT scheme
- A system that meets the nominated design requirements
- Mathematical formulation of the problem
- Numerical simulations of the system using MATLAB
- Observation of flight behavior in the Gazebo visualization tool for ROS
- Adaptation of the 'RISC Boot Camp' UAV hardware platform to implement the scheme
- Presentation of findings and hardware demonstration to members of the RISC Lab

2.1.2 Outcome of Literature Survey

The literature identified several important requirements for UAV 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 [9]. Tomic et al. explicitly identified the following design requirements [10]:

- Operability in unstructured indoor and outdoor environments
- Robust flight capabilities
- Autonomous operation, onboard decision making (this requires control algorithms with lower computational complexity [7])
- Modular and flexible sensor and planning capabilities
- Independence from external navigation aids

Specific to CPT schemes, Gimenez et al. ordered several common objectives in a hierarchy [11]:

1. Avoid obstacles (also featured in [12] and [7])
2. Secondary objectives:
    a. Maintain safe distances between vehicles to avoid collisions or undesirable separation
    b. Properly distribute the load weight between vehicles
3. Follow a predetermined trajectory to reduce oscillations caused by external factors such as wind. (This is incompatible with fast and aggressive agent maneuvers [7])

Once the objectives are known, Gimenez et al recommend that an appropriate control strategy be chosen. Many classes of control algorithms have been successfully applied to CPT, including PID techniques [4].[1]

Regarding control architectures, earlier CPT schemes focused on centralized control, while recent proposals have shown a trend towards decentralized control. For example, Michael et al. implemented a 'leader-follower' system in which one agent's trajectory is tracked by the other [4]. Gassner et al. have combined this formation with a novel mutual localization method to eliminate explicit communication between agents [8]. Other scenarios may require some communication between agents, justifying a distributed control architecture [13].

The control strategy may be dictated by the choice of payload configuration. Two common attachment methods exist for CPT schemes with UAVs: grasping the payload rigidly and suspending the payload by cables. Rigid grasping is explored in [5], [13] and [14]. This configuration enables agents to infer the payload's location with respect to themselves but may not be suitable for all payload sizes and shapes. Cable suspension is more common, as it builds on existing research about single-UAV slung-load systems [3] [4] [6] [8] [15]. Despite having a more complex control problem, cable suspension allows for more versatile control of the payload's attitude.

[1] Please refer to Appendix 1 for a list of papers discussing CPT schemes and their respective algorithms.

2.1.3 Design Requirements

I condensed observations from the literature survey into a set of design principles, which were used to develop the system design requirements.

Table 1. System Design Requirements

System Aspect	Requirement
UAV Platform	• Fast pose changes in three dimensions • Operable in an indoor GPS-denied environment • Agents capable of mutual localization • Flight endurance of at least two minutes • Onboard decision making • A failsafe mode in the event of hardware failure • A secure method of attachment to the payload • Can be assembled using existing hardware platforms in the RISC lab.
Control Scheme	• Avoid collisions between agents • Distribute weight evenly between agents • Minimize oscillations in the payload's motion • Decentralized control • Onboard control algorithms with low latency • Low computational complexity of control algorithms • Minimize explicit communication between agents • Must perform a specific task: cooperatively transport a PVC tube along a preset trajectory of length 6 m.

2.1.4 Proposed Solution

I devised a solution to fulfill the requirements of the system design specification and consulted Professor Shamma for advice on how to proceed. He advised making explicit assumptions to simplify the control problem. Following his advice, I made two assumptions about the system and its environment: each UAV agent would navigate through an obstacle-free environment, and there would be no external disturbances for the UAV agents.

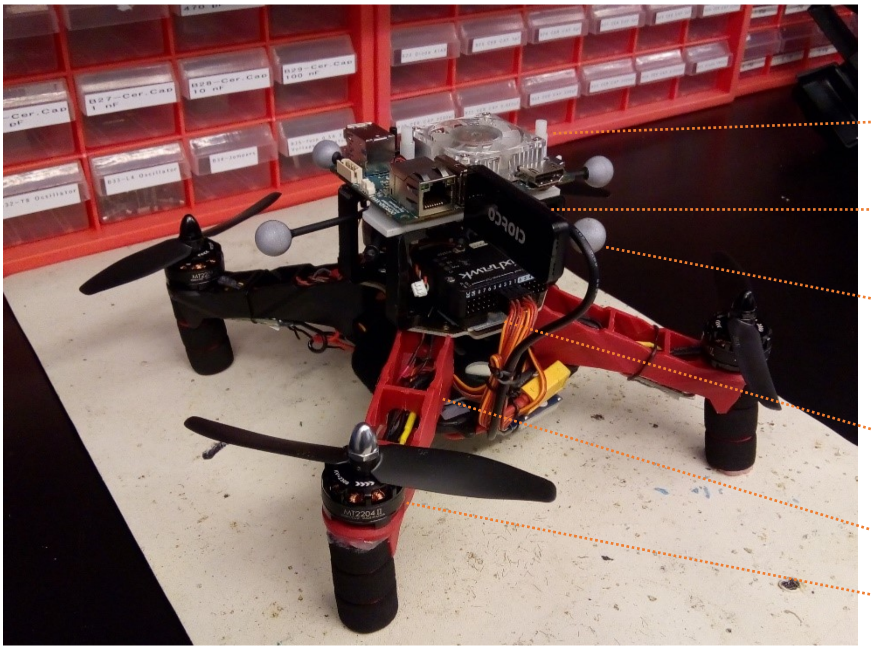

Figure 1. RISC Boot Camp UAV Platform

The hardware platform would comprise two UAV agents, cabling and attachments for the payload. The quadrotor UAV described in [16] was appropriate for this project; a diagram depicting its key components is shown in Figure 1. Each UAV would have a Pixhawk flight controller featuring an inertial measurement unit, interfaces for external inputs, and flight capabilities that would permit dynamic pose manipulation. For self-localization in the RISC Lab, reflector beads would allow the RISC Lab's motion capture infrastructure to identify each UAV's pose and communicate this to the Pixhawk flight controller. For safety, a Spektrum DX8 remote control would provide a 'kill switch' for each UAV in the event of an emergency. Most importantly, each agent would have an ODroid XU4 computer with a minimal installation of Ubuntu Linux and ROS. The computer would execute all high-level control algorithms onboard and would send these instructions to the Pixhawk flight controller.

Figure 2 depicts the intended configuration of the agents for CPT.

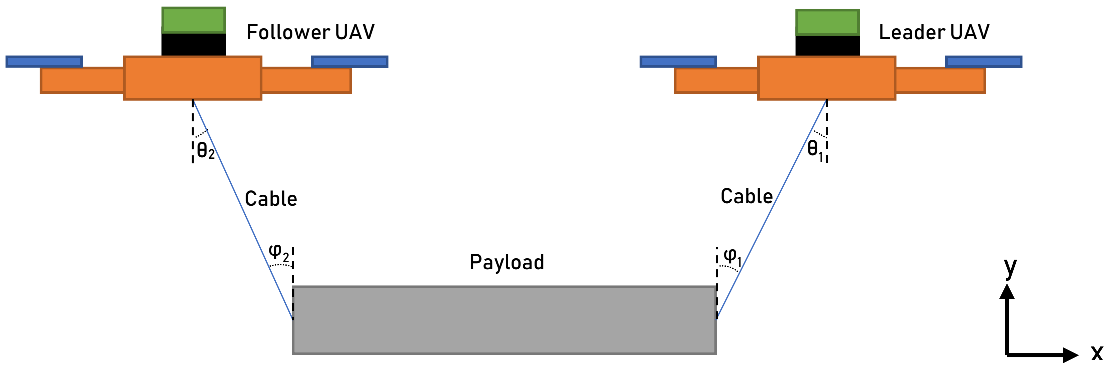

Figure 2: Proposed CPT Scheme (Side View)

The 'leader-follower' transportation strategy described in [3] would guide the design of the control algorithms. The leader agent would have to follow a preset trajectory as closely as possible, while the follower would have to move itself to minimize θ_2 and φ_2. Assuming both agents were constricted to motion in a single dimension (here, the x axis), this configuration would balance the weight of the payload as evenly as possible and would maintain a safe distance between each agent. Due to their relatively low computational complexity, PID controllers would be used for the agents' pose control. A finite state machine would be used to switch between different flight modes, such as takeoff, trajectory tracking and landing. All controller firmware would be written in Python as a ROS package for onboard execution.

In the feedback for the interim report, Professor Demiris advised me to proceed to numerical simulations of the solution as soon as practicable, to build up practice with simulation software and to identify useful observations about system performance early. In a subsequent video conversation Professor Demiris also recommended that I begin tests with the hardware platform while carrying out the simulations, to get a realistic idea of system behavior. I have kept this advice in mind as I have proceeded through the different stages of implementation.

2.2 Implementation of Solution

2.2.1 Problem Formulation

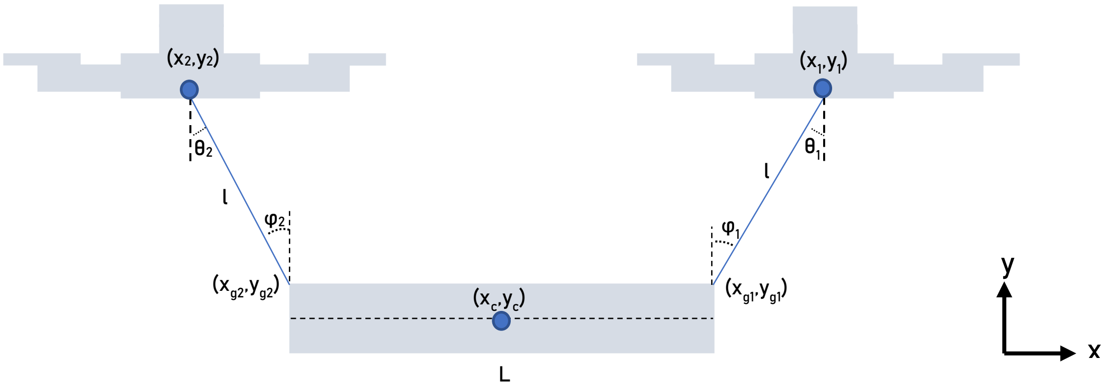

Figure 3. Simplified System Diagram of the Proposed Solution

Before proceeding with further analysis, I have defined several important variables and state the main assumptions. For simplicity I have assumed that all motion will occur in the x-y plane, as depicted in Figure 3. The coordinates of the center of mass for the leader agent, follower agent and payload are respectively (x_1, y_1), (x_2, y_2) and (x_c, y_c). A massless cable of length l connects the leader's center of mass to the payload at $\left(x_{g1}, y_{g1}\right)$, while an identical cable connects the follower's center of mass to the payload at $\left(x_{g2}, y_{g2}\right)$. The payload is a hollow cylindrical tube of length L; its longitudinal axis makes an angle ϕ with the x-axis. Each quadrotor will execute position control by varying the net thrust produced by its four rotors. It is therefore appropriate to model the motion of both agents using a double integrator model, in which an object's acceleration in one dimension equals a time-varying input $u(t)$ [17]:

$$\ddot{s} = u(t) \tag{1}$$

The choice of input $u(t)$ will depend on the specific control requirements for each variable; in practice I have found that a PID algorithm is suitable for simple tracking of position setpoints.

2.2.1.1 Start-up Flight Mode Dynamics

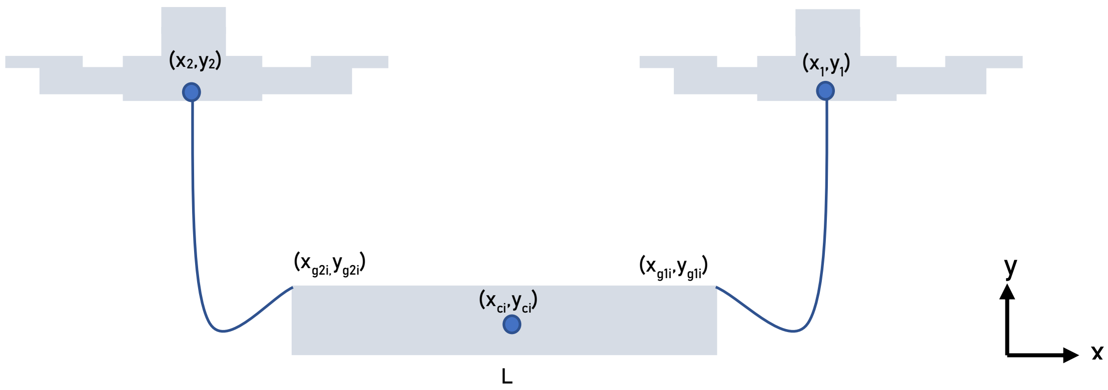

Figure 4. Simplified System Diagram: Start-up Flight Mode

When starting up, the agents must begin climbing to a predefined altitude. For the duration of this flight mode there is no tension in the cables and the payload rests flat on the ground at (x_{ci},y_{ci}-R_2), as shown in Figure 4. Let the desired altitude be $y_{des.1}$, the initial coordinates of the leader and follower $(x_1(0), y_1(0))$ and $\left(x_2(0), y_2(0)\right)$ respectively. The acceleration inputs can be implemented using PID algorithms with suitably-tuned PID gain terms:

$$\ddot{x}_1(\mathrm{t}) = k_{i.x1.1}\int_0^t \left(x_1(0) - x_1(\tau)\right).d\tau + k_{p.x1.1}\left(x_1(0) - x_1(t)\right) + k_{d.x1.1}(0 - \dot{x}_1) \tag{2}$$

$$\ddot{y}_1(\mathrm{t}) = k_{i.y1.1}\int_0^t \left(y_{des.1} - y_1(\tau)\right).d\tau + k_{p.y1.1}\left(y_{des.1} - y_1(t)\right) + k_{d.y1.1}(0 - \dot{y}_1) \tag{3}$$

$$\ddot{x}_2(\mathrm{t}) = k_{i.x2.1}\int_0^t \left(x_2(0) - x_2(\tau)\right).d\tau + k_{p.x2.1}\left(x_2(0) - x_2(t)\right) + k_{d.x2.1}(0 - \dot{x}_2) \tag{4}$$

$$\ddot{y}_2(\mathrm{t}) = k_{i.y2.1}\int_0^t \left(y_{des.1} - y_2(\tau)\right).d\tau + k_{p.y2.1}\left(y_{des.1} - y_2(t)\right) + k_{d.y2.1}(0 - \dot{y}_2) \tag{5}$$

The cables will become taut when the agents exceed a certain altitude y_s. Using the Pythagorean theorem this height can be estimated:

$$l^2 = \left(x_{g2i} - x_2(0)\right)^2 + \left(y_s - y_{g2i}\right)^2 = \left(x_1(0) - x_{g1i}\right)^2 + \left(y_s - y_{g1i}\right)^2 \tag{6}$$

$$y_s = y_{g2i} + \sqrt{l^2 - \left(x_{g2i} - x_2(0)\right)^2} \tag{7}$$

This value can be calculated before the flight and used to determine a sufficiently large value of $y_{des.1}$ for the acceleration equations above.

2.2.1.2 Carrying Flight Mode Dynamics

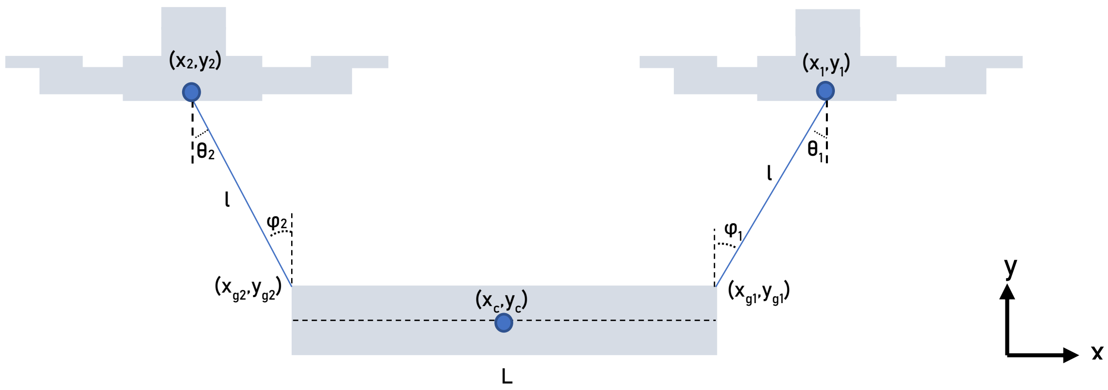

Figure 5. Simplified System Diagram: Carrying Flight Mode

As soon as the cables become taut, the system must enter a second flight mode, depicted in Figure 5. In the carrying flight mode the leader must track a predefined trajectory $(x_{des.2}, y_{des.2})$ in the x-y plane, so $\ddot{x}_1$ and $\ddot{y}_1$ can be set using PID controllers. Due to the change in loadings on each agent, the PID gain values may differ from the previous flight mode.

$$\ddot{x}_1(\mathrm{t}) = k_{i.x1.2}\int_0^t \big(x_{des.2}(\tau) - x_1(\tau)\big).\,d\tau + k_{p.x1.2}\big(x_{des.2}(t) - x_1(t)\big) + k_{d.x1.2}(\dot{x}_{des.2} - \dot{x}_1) \quad (8)$$

$$\ddot{y}_1(\mathrm{t}) = k_{i.y1.2}\int_0^t \big(y_{des.2}(\tau) - y_1(\tau)\big).\,d\tau + k_{p.y1.2}\big(y_{des.2}(t) - y_1(t)\big) + k_{d.y1.2}(\dot{y}_{des.2} - \dot{y}_1) \quad (9)$$

The follower's accelerations may also be modeled using PID controllers. Let θ_2 represent the angle between the cable and the vertical normal, and φ_2 the angle between the cable and the edge of the payload. The placement of sensors that measure cable tension magnitudes and angles would influence the follower's disturbance rejection capabilities. If a force sensor were installed at both (x_2, y_2) and (x_{g2}, y_{g2}), the follower could control $\ddot{x}_2$ and $\ddot{y}_2$ to minimize θ_2 and φ_2 respectively and thus track the leader's trajectory:

$$\ddot{x}_2(\mathrm{t}) = k_{i.x2.2}\int_0^t \big(0 - \theta_2(\tau)\big).\,d\tau + k_{p.x1.2}\big(0 - \theta_2(t)\big) + k_{d.x1}\big(0 - \dot{\theta}_2\big) \quad (10)$$

$$\ddot{y}_2(\mathrm{t}) = k_{i.y2.2}\int_0^t \big(0 - \varphi_2(\tau)\big).\,d\tau + k_{p.y2}\big(0 - \varphi_2(t)\big) + k_{d.y2.2}(0 - \dot{\varphi}_2) \quad (11)$$

To eliminate the need for communications between the follower agent and a remote sensor at (x_{g2}, y_{g2}), I also considered the consequences of using only one sensor at (x_2, y_2). In this case the follower would only be able to measure θ_2, so the follower could use feedback control with

$\ddot{x}_2$ to minimize θ_2 but it would not detect height discrepancies with the leader (which requires knowledge of φ_2). Consequently the follower could still be made to follow the leader's trajectory if both agents were constrained to one-dimensional motion at a given height y_{des}. Any efforts by the follower to minimize θ_2 would also drive φ_2 towards zero. The corresponding acceleration inputs would be the following:

$$\ddot{x}_2(\mathrm{t}) = k_{i.x2.2}\int_0^t \left(0-\theta_2(\tau)\right).d\tau + k_{p.x1.2}\left(0-\theta_2(t)\right) + k_{d.x1}\left(0-\dot{\theta}_2\right) \tag{12}$$

$$\ddot{y}_2(\mathrm{t}) = k_{i.y2.2}\int_0^t \left(y_{des.2}-y_2(\tau)\right).d\tau + k_{p.y2}\left(y_{des.2}-y_2(t)\right) + k_{d.y2.2}\left(0-\dot{y}_1\right) \tag{13}$$

There are two disadvantages with using one force sensor. First, it would limit the ability of agents to execute agile maneuvers by limiting motion to one dimension. Secondly, since agents cannot move up or down, an additional flight mode would be needed to allow drop-off of the payload. This would need extra infrastructure in the form of either an inactivity timer or an external trigger signal to move the system into the next flight mode. Despite these disadvantages, a single-sensor system would be simpler to prototype and require less computation than a two-sensor system, hence I adopted a single-sensor approach.

It is important to note that the equations for the follower's dynamics are incomplete without cable angle data. Consider a single-sensor configuration. In practice θ_2 will be measured experimentally, however for simulations the dynamics of the cable angles and the payload's pose must be calculated in real time. The modeled payload behavior can then provide feedback when searching for control parameters that reduce the payload's oscillation magnitude (an important design requirement).

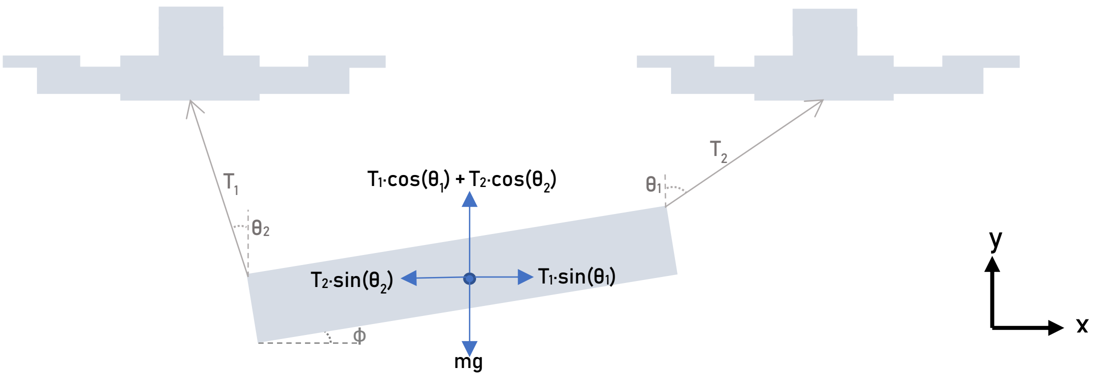

Figure 6. Free Body Diagram of Payload

To derive the equations of motion for $\theta_1, \theta_2, x_c, y_c$ and ϕ, first consider the free body diagram of forces acting on the payload's center of mass as shown in Figure 6. The equations for tension in the cables leading to the leader and follower are modeled as springs with the same spring constant [2]:

$$T_1 = k\left(\sqrt{\left(x_1 - x_{g1}\right)^2 + \left(y_1 - y_{g1}\right)^2} - l\right) \qquad (14)$$

$$T_2 = k\left(\sqrt{\left(x_2 - x_{g2}\right)^2 + \left(y_2 - y_{g2}\right)^2} - l\right) \qquad (15)$$

Assuming a very high spring constant for the cables and even distribution of the weight between the cables, the tension equations can be approximated with the constant T. The components of the net force acting on the center of mass can be resolved as follows:

$$F_x = m\ddot{x}_c = T_1 \sin\theta_1 - T_2 \sin\theta_2 \qquad (16)$$

$$F_y = m\ddot{y}_c = T_1 \cos\theta_1 + T_2 \cos\theta_2 - mg \qquad (17)$$

$$\ddot{x}_c = \frac{1}{m}(T_1 \sin\theta_1 - T_2 \sin\theta_2) \qquad (18)$$

$$\ddot{y}_c = \frac{1}{m}(T_1 \cos\theta_1 + T_2 \cos\theta_2) - g \qquad (19)$$

Assuming the payload is a cylindrical tube of length L, let R_1 represent the tube's inner radius and R_2 represent the tube's outer radius. The net torque acting on the payload's center of mass in the x-y plane can be expressed as the sum of the torques exerted by each cable at the points of connection:

$$\tau = I\ddot{\phi} = T_1\sqrt{\frac{L^2}{4} + {R_2}^2}\cos(\theta_1 - \phi) - T_2\sqrt{\frac{L^2}{4} + {R_2}^2}\cos(\theta_2 - \phi) \qquad (20)$$

The moment of inertia is calculated about the center of mass at (x_c, y_c) parallel to the z-axis [18]:

$$I = m\left(\frac{{R_1}^2 + {R_2}^2}{4} + \frac{L^2}{12}\right) \qquad (21)$$

Rearranging the torque equation gives an expression for $\ddot{\phi}$:

$$\ddot{\phi} = \frac{T_1}{I}\sqrt{\frac{L^2}{4} + {R_2}^2}\cos(\theta_1 - \phi) - \frac{T_2}{I}\sqrt{\frac{L^2}{4} + {R_2}^2}\cos(\theta_2 - \phi) \qquad (22)$$

Applying the constant tension approximation and expanding the compound angle expressions:

$$\ddot{\phi} \approx \frac{T}{I}\sqrt{\frac{L^2}{4} + {R_2}^2}[\cos(\theta_1 - \phi) - \cos(\theta_2 - \phi)] \qquad (23)$$

$$\ddot{\phi} \approx \frac{T}{I}\sqrt{\frac{L^2}{4} + {R_2}^2}\left[\cos(\phi)[\cos(\theta_1) - \cos(\theta_2)] + \sin(\phi)\,[\sin(\theta_1) - \sin(\theta_2)]\right] \qquad (24)$$

[2] The following formula is used to calculate the spring constant [20]:

$$k = \frac{AE}{L}$$

Where E is Young's Modulus. For stainless steel, $E \approx 190\ GPa$ [21].

By substituting the value $\phi \approx 0$ the expression for $\ddot{\phi}$ is simplified further:

$$\ddot{\phi} \approx \frac{T}{I}\sqrt{\frac{L^2}{4} + {R_2}^2}[\cos(\theta_1) - \cos(\theta_2)] \quad (25)$$

Under desired operation $\theta_1 = \theta_2 = 0$, therefore $\ddot{\phi} = 0$ and the payload will not experience a net torque.

The dynamical equations for θ_1 and θ_2 can be derived from the geometry found in Figure 5.

$$\sin\theta_1 = \frac{x_1 - x_{g1}}{l} \quad (26) \qquad \sin\theta_2 = \frac{x_{g2} - x_2}{l} \quad (27)$$

$$x_{g1} = x_c + \frac{L\cos\phi}{2} - R_2\sin\phi \quad (28) \qquad x_{g2} = x_c - \frac{L\cos\phi}{2} - R_2\sin\phi \quad (29)$$

$$\sin\theta_1 = \frac{x_1 - x_c - \frac{L\cos\phi}{2} - R_2\sin\phi}{l} \quad (30) \qquad \sin\theta_2 = \frac{x_c - \frac{L\cos\phi}{2} - R_2\sin\phi - x_2}{l} \quad (31)$$

Using the small angle approximation $(\sin\alpha \approx \alpha)$ and assuming $\phi \approx 0$:

$$\theta_1 = \frac{x_1 - x_c - \frac{L}{2}}{l} \quad (32) \qquad \theta_2 = \frac{x_c - x_2 - \frac{L}{2}}{l} \quad (33)$$

$$\dot{\theta}_1 = \frac{\dot{x}_1 - \dot{x}_c}{l} \quad (33) \qquad \dot{\theta}_2 = \frac{\dot{x}_c - \dot{x}_2}{l} \quad (34)$$

$$\ddot{\theta}_1 = \frac{\ddot{x}_1 - \ddot{x}_c}{l} \quad (35) \qquad \ddot{\theta}_2 = \frac{\ddot{x}_c - \ddot{x}_2}{l} \quad (36)$$

By combining all the derived differential equations into a state transition matrix, it will be possible to simulate the evolution of the state trajectory over time.

2.2.1.3 Drop-off Flight Mode Dynamics

For systems constrained to one-dimensional horizontal motion, this flight mode can be considered as a counterpart to the start-up flight mode. Let (x_{1f}, y_{1f}) and (x_{2f}, y_{2f}) represent the mode's initial positions of the leader and follower respectively. To achieve a safe drop-off, the payload must not land directly beneath either of the agents. The position setpoints for the leader and follower can incorporate a safety margin to constrain the possible final resting positions for the payload, e.g. a margin of $0.95 * l$ corresponds to the setpoint coordinates $(x_{1f} + 0.95 * l, y_1(0))$ and $(x_{2f} - 0.95 * l, y_2(0))$ respectively. These can be incorporated into PID controllers (again, possibly with different gain values):

$$\ddot{x}_1(\mathrm{t}) = k_{i.x1.3}\int_0^t \left(x_{1f} + 0.95 * l - x_1(\tau)\right).d\tau + k_{p.x1.3}\left(x_{1f} + 0.95 * l - x_1(t)\right) - k_{d.x1.3} * \dot{x}_1 \tag{37}$$

$$\ddot{y}_1(\mathrm{t}) = k_{i.y1.3}\int_0^t \left(y_1(0) - y_1(\tau)\right).d\tau + k_{p.y1.3}\left(y_1(0) - y_1(t)\right) - k_{d.y1.3} * \dot{y}_1 \tag{38}$$

$$\ddot{x}_2(\mathrm{t}) = k_{i.x2.3}\int_0^t \left(x_{2f} - 0.95 * l - x_2(\tau)\right).d\tau + k_{p.x2.3}\left(x_{2f} - 0.95 * l - x_2(t)\right) - k_{d.x2.3} * \dot{x}_2 \tag{39}$$

$$\ddot{y}_2(\mathrm{t}) = k_{i.y2.3}\int_0^t \left(y_2(0) - y_2(\tau)\right).d\tau + k_{p.y2.3}\left(y_2(0) - y_2(t)\right) - k_{d.y2.3} * \dot{y}_2 \tag{40}$$

2.2.1.4 Velocity Limiting

In certain situations it may be desirable to place limits on the velocities of an agent, for example during the descent of the payload. This may be implemented using the following function, which for a control variable $\ddot{s}(t)$ takes a PID control term $u(t)$ and a velocity limit v_{max} as inputs and either permits or blocks the output:

$$\ddot{s}(t) = \begin{cases} 0, & condition\ 1\ OR\ condition\ 2 \\ u(t), & otherwise \end{cases} \tag{41}$$

$$Condition\ 1: \dot{s}(t) \geq v_{max}\ AND\ \ddot{s}(t) \geq 0$$

$$Condition\ 2: \dot{s}(t) \leq v_{max}\ AND\ \ddot{s}(t) \leq 0$$

2.2.2 Numerical Simulation with MATLAB

The rationale for a numerical simulation of the proposed system was twofold. First, key parameters were extracted from the physical system and combined with the system dynamics into an abstract model. This allowed the study of the system's stability properties in preparation for implementation on hardware. In addition, numerical simulations as a proof-of-concept are a step towards more complex 'software-in-the-loop' tests with the Gazebo visualization tool for ROS. I opted to use MATLAB for running the simulations because of prior experience with its development environment.

The conversion of the mathematical model into code was straightforward, with interrupts used to trigger transitions between the different flight modes. Table 2 in Appendix 2 contains the assumed values for the simulation's parameters. The gain terms for each flight mode and each of the UAVs' coordinate variables $\{x_1, y_1, x_2, y_2\}$ were determined using trial and error. The proportional gain term was tuned first to reach the setpoint as fast as possible, then the differential gain term was tuned to eliminate overshoot. Steady-state errors were negligible, so the integral gain terms were set to zero. The system's response was constrained by a velocity-limiting function, both to reflect the reality of the hardware and as an extra means to control the transient behavior of the system. The velocity limits were visible during rapid position changes, as shown in Figure 7.

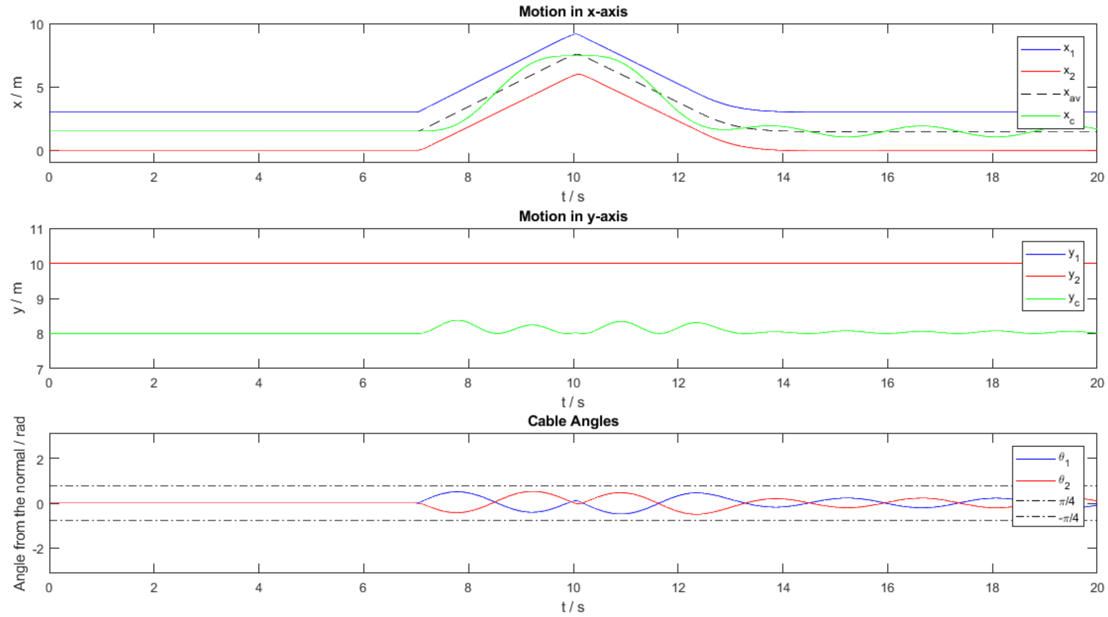

Figure 7. System Velocity Limits during Rapid Ascent and Descent in Carrying Flight Mode

Another factor that influenced the selection of parameter values was the payload's oscillation. Numerous sets of parameter values resulted in dangerously large swings (e.g. in Figure 8 the cable angle amplitudes momentarily approach ±90°), so these values were rejected.

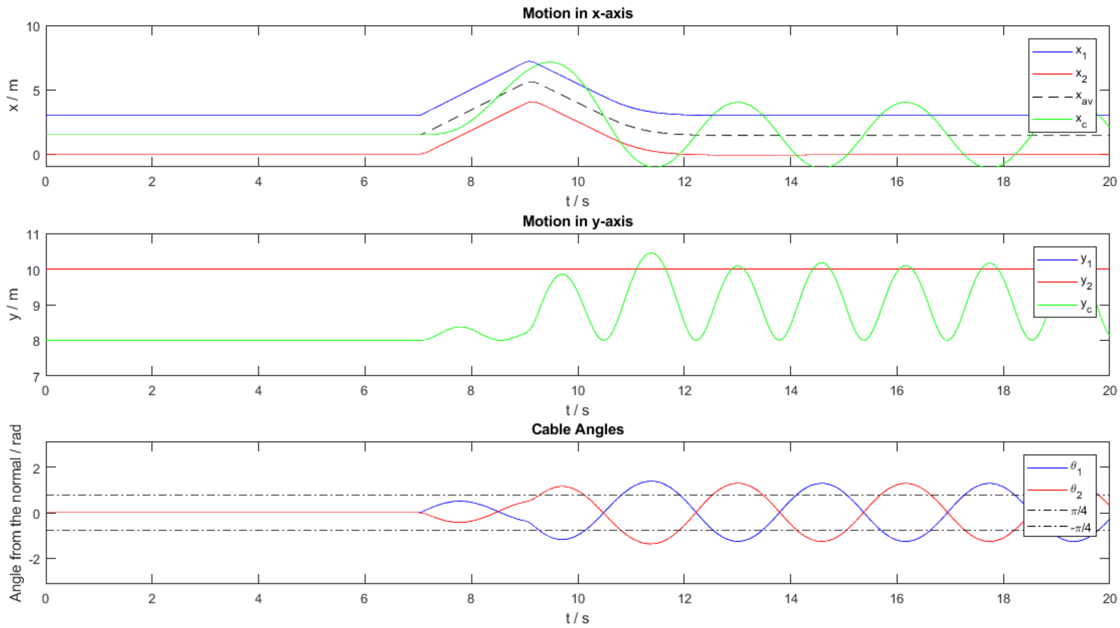

Figure 8. Unsafe Payload Swings during Carrying Flight Mode

Whilst the parameter values selected using the method described above were appropriate for the simulation model, these values would not necessarily be optimal for the physical system. The simulation model did not account for losses due to friction forces, damping by the payload's weight or aerodynamic drag. The external losses could significantly reduce the magnitude and frequency of the payload's oscillations, widening the range of possible parameter values that would be safe to use with the physical system.

Despite the inherent limitations, the numerical simulations have demonstrated the viability of the proposed system. Figure 9 depicts the system's trajectory while performing the task specified in section 2.1.3 of this report. Notably, the three successive flight modes (picking up the object, carrying it forward by 6 m, and descending) are distinguishable and the oscillations in the payload are small. There appears to be scope for optimizing the different flight modes' control parameters to perform more agile and aggressive maneuvers.

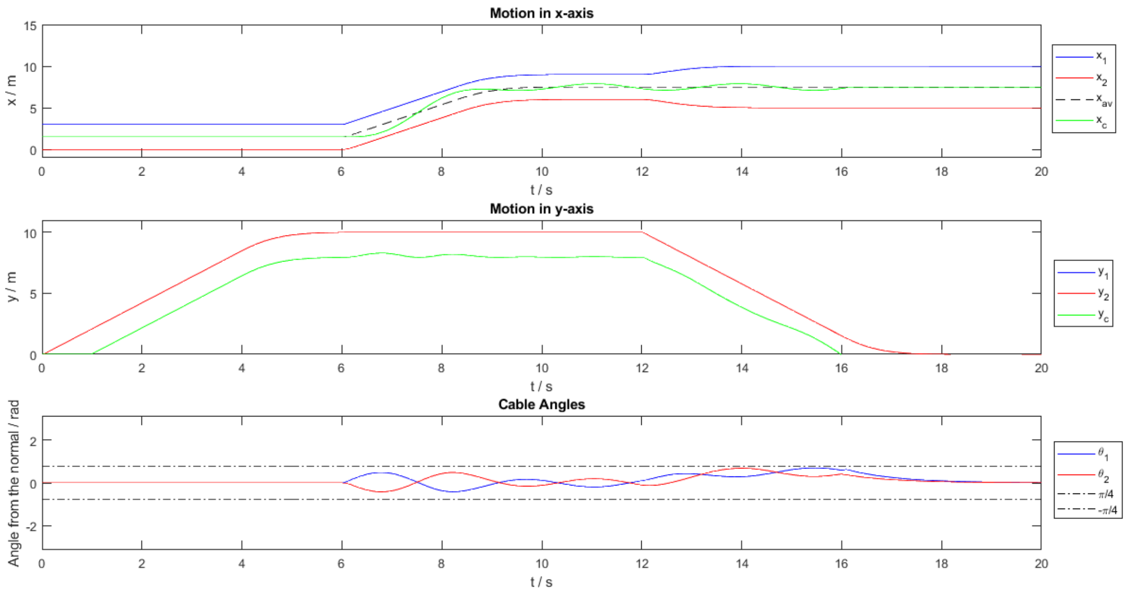

Figure 9. Evolution of System Trajectory while Performing Specified Task

2.2.3 Planned Work: Visualization and Hardware Testing

Since completing the initial set of numerical simulations with MATLAB, I have turned to focus on developing a hardware prototype for demonstrations. To avoid delays, I am currently assembling the hardware components for the proposed system as described in section 2.1.4. I will then begin an iterative process of writing functionality into the agents' custom firmware, simulating the physical system's behavior using the Gazebo visualization tool for ROS, and implementing the new functionality on the hardware prototype.

The first stage of this prototyping cycle will draw on my previous experience with ROS development during the RISC Boot Camp in May. This will involve writing custom firmware packages in Python for ROS to execute onboard each agent. The end goal is to implement the control algorithms described in section 2.2.1 and use the MAVROS software library in ROS to control each agent's pose. MAVROS converts high-level position and velocity instructions into low-level commands for the Pixhawk flight controller and feeds back flight data to the firmware for computation. In each prototyping cycle I will progressively add functionality to the firmware:

- Basic pose control for each agent,
- Sending position commands,
- Ascending and descending,
- Integrating angle data from the follower's force sensor,
- Running the complete algorithm for each agent.

The firmware may not initially work as intended on the hardware system, so the second stage of the prototyping cycle will involve testing with Gazebo. Gazebo performs a near-realistic simulation of the physical system while running the firmware in ROS, allowing observation of the behavior of the closed-loop system. This will allow early detection of bugs in the firmware before implementation on hardware. I anticipate a mild learning curve during the initial CAD modeling of the physical system; any subsequent revisions of the hardware setup will require a new CAD model in Gazebo.

Following each successful Gazebo simulation, the firmware will be uploaded to each agent's onboard ROS computer and conduct test flights. Issues with the hardware's performance not foreseen by the Gazebo simulation may arise, hence I will need to troubleshoot the problem before adding further functionality. Such problems could include faulty flight controllers, excessive control loop latencies due to the firmware's computational complexity, and an inability to generate enough thrust to carry the payload. As soon as a solution is determined, I will repeat the prototyping cycle by making necessary adjustments to the hardware, the firmware and the Gazebo model.

Assuming no major delays, each cycle should take approximately five days to complete, so I expect that the hardware prototype should be ready for demonstration by mid-September. As soon as the hardware prototype is ready, I will arrange a meeting with Professor Shamma and other members of the RISC Lab to present my work and demonstrate the system's behavior.

2.3 TECHNICAL PROGRESS AND CHALLENGES

The project has proceeded in the direction outlined in the preliminary report and has complied with the plan's tentative deadlines.[3] At the time of writing the preliminary report, I did not have a detailed appreciation for the project's specific requirements. For this reason I had to elaborate on the list of the project's tasks as new details became available during the project. Referring to section 2.1.1 of this report, I have completed five out of eight deliverables: a literature survey, a design specification, a proposed solution, a mathematical formulation of the system, and a numerical simulation. Recently I have begun work on a further two deliverables: a visualization of the system in Gazebo and the hardware prototype. At my current rate of progress, I expect that the final deliverable (a hardware demonstration to members of the RISC Lab) will be achieved by the end of September 2018, when the placement concludes.

Several technical challenges have arisen during the project, predominantly concerning the mathematical formulation of the design problem. Given the coupled nature of the agents with the payload, I initially had significant difficulty modeling the dynamic equations for the system. To overcome this conceptual barrier, I made a small-scale model of the system using a spool of thread with strings attached to the sides, simplifying the problem to a double-stringed pendulum with each agent acting as a cable position node. After consulting the literature for analysis of rotational dynamics [19], I created a tentative formulation of the payload's dynamics. During subsequent numerical simulations I needed to balance model complexity with solution tractability: state equations with large numbers of variables and many interdependencies would crash the numerical solver, while making too many simplifications to the dynamics equations would lead to unrealistic simulation results (e.g. no payload twisting or swinging). The assumptions that I have made in section 2.2.1 have led to minor loss of complexity in the simulated rotational motions of the payload, however this has not prevented the simulation demonstrating the viability of the proposed control algorithms for either agent.

Looking ahead, I expect to encounter issues with hardware, however I am now familiar with troubleshooting common issues with the components of the UAV platform and infrastructure (sensor calibration for the Pixhawk flight controller, wireless connectivity for the ODroid XU4, reading UAV pose coordinates via the motion capture system etc.). Concerning package development for ROS, I will need to convert the analytical formulation of the system dynamics into code for embedded application on the ODroid XU4. I will draw on both my prior experience from the Boot Camp and coding practices acquired in the third-year module *EE 3-24 Embedded*

[3] Please refer to Table 1 in the Interim Report for an early version of the proposed tasks and deadlines.

Systems. Finally, a senior colleague in the RISC Lab has advised me that preparing models for simulation in Gazebo will take significant time. I will keep this in mind and consult tutorials on Gazebo modeling.

2.4 Future Lines of Enquiry

In the medium term, two outstanding issues should be addressed to enhance the proposed system's capabilities. First, the current proposal assumes motion in one dimension, however the inclusion of additional force sensors on the follower (for the z-axis angle) and on the payload (for the discrepancy in heights between the leader and follower) would enable more-complete cable attitude determination and therefore motion control in three dimensions. Secondly, the existing decentralized architecture could accommodate more followers to reduce the loading per agent. This could save energy and extend flight missions, desirable due to the relatively short flight times allowed by LiPo batteries. These tasks would naturally follow from the work completed during the placement.

Longer term, I would reconsider certain operational practices. These involve complex issues and are the subject of ongoing research in the field. The behavior of the system while carrying different payloads should be studied, considering features such as asymmetry, fragility, non-rigidity, and non-homogeneous composition (e.g. a bucket filled with a liquid). Hardware failures (whether due to a quadcopter or a supporting cable) are not considered by the existing controller architecture, leaving room for unsafe and undefined system behavior. Detecting hardware failures, creating a failsafe flight mode and possibly jettisoning 'dead weights' by detachable cables are measures that could alleviate this concern. The mathematical model also largely neglects environmental conditions. For operation in the presence of obstacles, visual sensors could feed data to a depth detection module. This in turn feeds into a higher-level path-planning module for the leader. Considering the special cases of people and machinery, these could be incorporated into the system as ad-hoc leaders or remain as bystanders with unknown dynamics. In either case, concerns about coordination, personal safety and noise pollution would need to be addressed. Other environmental conditions (such as wind or rain) could adversely affect the system's operations, so measures to make the system more robust should be investigated. Similarly, the platform must eliminate dependence on motion capture data for localization, in favor of GPS or visual odometry techniques. Finally, reducing energy usage should be pursued even as battery technology matures in the coming years.

This concludes the technical part of the report. I will now turn to look at the research project experience and the placement in a wider context.

3 REFLECTIONS ON THE PLACEMENT

3.1 TECHNICAL OUTCOMES

My technical skills have grown significantly and I will feel more confident about applying them in future. This is directly attributable to my experience in the placement. In the first phase of the placement I completed the RISC Boot Camp, comprised of tutorials on mobile robotics, ROS and quadrotor UAVs. At every step I was introduced to contemporary practices in working with quadrotors and given a chance to solve example problems using the hardware and infrastructure of the RISC Lab. Tutorials gave me the opportunity to consolidate and reinforce skills (for example, hardware assembly and programming) that I had been able to develop over three years of lab work in my undergraduate course. During the course I found that the rationale for some technical steps was not explained in enough depth. It was only by performing practical tasks iteratively during the placement that these gaps were filled. The breadth of the RISC Boot Camp laid a solid foundation for the specialization I undertook in the second phase of the placement.

My research and analytical skills have been honed and improved. The opportunity to analyze and synthesize technical material in a sustained way has improved my capacity for absorbing and understanding complex technical ideas. I have developed a deeper understanding of cooperative transportation and the requirements of autonomous systems. In discussions with Professor Shamma I decided to use a simple PID control scheme, extending the work completed by Toumi [3] with insights from similar successful schemes. By identifying key design requirements, I was able to formulate a system specification that guided the design of the proposed solution. To probe the feasibility of the solution I analyzed the dynamics of the proposed solution. Drawing on mechanics and control theory I refined my initial mathematical models of the agents and ran numerical simulations of the system transporting a payload. This has led me to the present objective (and one of the first tasks of the RISC Boot Camp): writing control algorithms in ROS for UAV platforms.

3.2 PROFESSIONAL OUTCOMES

The placement has provided me with the opportunity to observe and work within a post-graduate research environment outside my own educational institution. Until now I have been used to seeing things from an undergraduate perspective. Staff and colleagues in the RISC Lab have modelled a mature, professional post-graduate research environment that has encouraged independence and self-reliance. A sense of professional collegiality with colleagues in the RISC Lab helped me to maintain my focus.

I have learned that individual responsibility for a project cannot be achieved without a continuing high level of personal motivation. The most impressive feature of the academic environment is the responsibility of the researcher to personally manage their outcomes. Motivation, time management, the meaning and purpose of work are all left to the individual. Collaborations and interdependencies are common in labs, but I have learned that it is ultimately the motivated individual who advances the work. The Boot Camp was a case in point: as an introduction to the lab's facilities, it had to ensure that every newcomer achieved a minimum competency with the hardware and equipment in the lab. Tutorials were self-paced, so perfunctory instruction-following would lead to a superficial understanding, while inquisitive questioning and reflection on the material would lead to more enduring engagement with the activities. At times I found some instructions ambiguous, so I quickly learned strategies for formulating questions about what I wanted to know. In order of precedence, I sought to resolve each question using my own knowledge, online resources, asking other colleagues working on the tutorials, and consulting the lab manager. The process rewarded persistence in troubleshooting and communicating one's understanding effectively to others. Courage and perseverance are needed all the time in the face of the many technical issues which have to be overcome, The Boot Camp also brought to my attention the practicalities of working in a lab. Certain times were busier than others, so some resources and infrastructure could be occupied by others. I learned the importance of planning ahead of time and coordinating with others to minimize such barriers to productivity. My colleagues' occasional feedback and suggestions helped me to improve my technical skills. I kept these observations in mind while working on the research project.

The research project provided me with different perspectives on operating in an independent environment. In this situation the instructions are not known beforehand, although a supervisor can help by providing direction. Self-discipline and a continual process of self-organization are critical for developing a plan to follow.[4] Each aspect of the project must be crafted deliberately: the initial research question, the literature survey, the research proposal etc. Once I had created an initial roadmap of tasks, I knew the self-imposed deadlines that I needed to work towards. For the initial phase of the literature survey I had to quickly develop a necessary working knowledge of the field and decide which papers merited further attention. By undertaking an open-ended but time-constrained reading trail, I built up a broader

[4] Please refer to Appendix 3 for an up-to-date task roadmap for the project.

understanding of research into CPT schemes using UAVs. This understanding was indispensable later in the project. Combined with the control theory that I learned in the second and third years of my undergraduate course, this accumulated knowledge helped me to formulate models of the proposed system. The progress that I have made has been fed back into the task roadmap regularly, helping me to maintain focus on the tasks at hand.

3.3 Personal Outcomes

One of the most positive aspects of the placement experience has been meeting post-graduate students and staff at KAUST. The international mix of personnel, disciplinary backgrounds and research interests in the RISC Lab has created a rich environment for my intellectual curiosity. I have been able to develop mutually-supportive and professional friendships with other young researchers focused on robots and autonomous systems. The resulting work atmosphere is collegial, productive and encourages the interdisciplinary sharing of knowledge.

The ensemble of experiences the KAUST placement has offered will provide lasting benefits. The practical training that I received with UAVs and ROS exposed me to the complexity of mobile robotic systems and the array of control methods available. At this stage I feel that I have only just scratched the surface of the field and I would like to learn more. I am far from exhausting the possibilities for further work with CPT schemes (and autonomous robotics in general), so I will most likely return to this topic in my final-year project. In the coming academic year I intend to deepen my exposure to autonomous robotics by registering for several control theory modules and a module on human-centered robotics.

I have had a very formative and positive experience with research and development in the RISC Lab and, if the opportunity arose, I would seriously consider pursuing a career in research and development.

4 CONCLUSION

In this report I have detailed the experiences and outcomes of a research project at KAUST's RISC Lab. Having contemplated the motivations for cooperative payload transportation, I conducted a survey of existing literature on the topic and extracted the design requirements for an ideal implementation. I then developed a solution to meet the design requirements, progressing from mathematical equations describing the system's dynamics to numerical simulations of the system's trajectory. Currently I am working on packaging the control algorithms for use with MAVROS and Gazebo, and I am on the point of beginning development and testing of the hardware prototype.

By reflecting on the outcomes of the placement, I have gained a more nuanced appreciation of the method behind academic research. I have learned to adapt to a self-managed work environment and feel that I have built up competencies in several technical skills. The training that I have received is transferable to many academic and professional situations. In the medium term I have identified several lines of inquiry to extend the scope of the research project, and I have outlined steps that I will take to further my education. The placement experience has provided me with a considerable degree of clarity about the direction I would like to take in the future with respect to study and employment.

REFERENCES

[1] King Abdullah University of Science and Technology, “Media Relations: About,” King Abdullah University of Science and Technology, 4 May 2016. [Online]. Available: https://www.kaust.edu.sa/en/about/media-relations#part2. [Accessed 22 May 2018].

[2] RISC Lab, “Robotics, Intelligent Systems, and Control (RISC),” King Abdullah University of Science and Technology, 1 November 2017. [Online]. Available: https://risc.kaust.edu.sa/Pages/Home.aspx. [Accessed 22 May 2018].

[3] N. Toumi, *Decentralized Control of Multi-Agent Aerial Transportation System,* Thuwal, KSA: KAUST, 2017.

[4] N. Michael et al., “Cooperative Manipulation and Transportation with Aerial Robots,” *Autonomous Robots,* vol. 20, no. 1, pp. 73-86, January 2011.

[5] D. Mellinger et al., “Cooperative Grasping and Transport Using Multiple Quadrotors,” in *Distributed Autonomous Robotic Systems*, A. Martinoli, Ed., Berlin, Springer, 2013, pp. 545-558.

[6] T. Lee, “Geometric control of multiple quadrotor UAVs transporting a cable-suspended rigid body,” in *53rd IEEE Conference on Decision and Control*, Los Angeles, 2014.

[7] S. Tang and V. Kumar, “Mixed Integer Quadratic Program trajectory generation for a quadrotor with a cable-suspended payload,” in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, Seattle, 2015.

[8] M. Gassner et al., “Dynamic collaboration without communication: Vision-based cable-suspended load transport with two quadrotors,” in *2017 IEEE International Conference on Robotics and Automation*, Singapore, 2017.

[9] R. d'Andrea, “Guest Editorial: Can Drones Deliver?,” *IEEE Transactions on Automation Science and Engineering,* vol. 11, no. 3, pp. 647-648, July 2014.

[10] T. Tomic et al., “Toward a Fully Autonomous UAV: Research Platform for Indoor and Outdoor Urban Search and Rescue,” *IEEE Robotics & Automation Magazine,* vol. 19, no. 3, pp. 46-56, September 2012.

[11] J. Gimenez et al., “Multi-objective control for cooperative payload transport with rotorcraft UAVs,” *ISA Transactions,* 2018.

[12] F. Ruggiero et al., “Introduction to the Special Issue on Aerial Manipulation,” *IEEE Robotics and Automation Letters,* vol. 3, no. 3, pp. 2734-2737, July 2018.

[13] H. Lee et al., “An Integrated Framework for Cooperative Aerial Manipulators in Unknown Environments,,” *IEEE Robotics and Automation Letters,* vol. 3, no. 3, pp. 2307-2314, July 2018.

[14] G. Loianno and V. Kumar, “Cooperative Transportation Using Small Quadrotors Using Monocular Vision and Inertial Sensing,” *IEEE Robotics and Automation Letters,* vol. 3, no. 2, pp. 680-687, April 2018.

[15] M. Tognon et al., “Aerial Co-Manipulation With Cables: The Role of Internal Force for Equilibria, Stability, and Passivity,” *EEE Robotics and Automation Letters,* vol. 3, no. 3, pp. 2577-2583, July 2018.

[16] M. Abdelkader et al., “Distributed Real Time Control of Multiple UAVs in Adversarial Environments: Algorithm and Flight Testing Results,” in *2018 IEEE International Conference on Robotics and Automation (ICRA)*, Brisbane, 2018.

[17] V.G. Rao and D.S. Bernstein, “Naive control of the double integrator,” *IEEE Control Systems,* vol. 21, no. 5, pp. 86-97, October 2001.

[18] J.A. Myers, “Handbook of Equations for Mass and Area Properties of Various Geometrical Shapes,” U.S. Naval Ordnance Test Station, China Lake, California, 1962.

[19] J. Walker, D. Halliday, R. Resnick, Fundamentals of Physics, 10th ed., Hoboken: Wiley, 2014.

[20] C. de Crousaz et al., “Unified motion control for dynamic quadrotor maneuvers demonstrated on slung load and rotor failure tasks,” in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, Seattle, 2015.

[21] B. Lautrup, “Hooke's Law,” in *Physics of Continuous Matter: Exotic and Everyday Phenomena in the Macroscopic World*, Copenhagen, The Niels Bohr Institute, 2010, pp. 125-138.

[22] Cambridge University Engineering Department, “Physical and Mechanical Properties of Materials,” in *Materials Data Book*, Cambridge, Cambridge University Engineering Department, 203, p. 11.

APPENDIX 1 LIST OF CONTROL ALGORITHMS FOR CPT SCHEMES

Here is a selection of papers on CPT schemes with their respective control algorithms:

- Michael et al. relied on PID techniques [4].
- Lee discussed geometric control [6].
- Given that UAVs are non-linear, highly underactuated and unstable systems, Crousaz et al. suggested the use of non-linear control strategies for cooperative transportation [19]. They subsequently developed a sequential linear quadratic controller which required only a system model and cost function to create a system's control policy.
- Tang and Kumar extended the work of Crousaz et al. by considering the use of more trajectory optimization techniques for controller design [7].
- Gassner et al. relied on LQR control [8].
- Toumi developed a control algorithm based on PD control and invariant set theory [3].
- Gimenez et al. mentioned several previously-used control strategies: non-linear H_∞ control, iterative LQR optimal control, particle swarm optimization with PID tuning, and adaptive fuzzy theory and Lyapunov techniques for dealing with wind perturbations [11].
- To accommodate competing control objectives, Gimenez et al. chose to implement a controller based on null-space theory.
- Lee et al. attempted to use an adaptive controller for estimating online the weight and inertial properties of an unknown payload [13].

APPENDIX 2 PARAMETER VALUES FOR MATLAB SIMULATIONS

The table below contains the assumed initial parameter values used for the MATLAB simulations discussed in section 2.2.2.

Table 2. Assumed Values for Simulation Parameters

Parameter	Value	Unit
t_i	0.00	s
t_f	20.0	s
l	2.00	m
L	3.00	m
R_1	0.099	m
R_2	0.100	m
m	1.00	kg
g	9.81	$m.s^{-2}$
T	4.91	N
k_{cable}	2.83×10^5	$N.m^{-1}$
$k_{i.x1.1}$	0.00	$N.m^{-1}.s^{-1}$
$k_{i.x1.2}$	0.00	$N.m^{-1}.s^{-1}$
$k_{i.x1.3}$	0.00	$N.m^{-1}.s^{-1}$
$k_{i.x2.1}$	0.00	$N.m^{-1}.s^{-1}$
$k_{i.x2.2}$	0.00	$N.rad^{-1}.s^{-1}$
$k_{i.x2.3}$	0.00	$N.m^{-1}.s^{-1}$
$k_{i.y1.1}$	0.00	$N.m^{-1}.s^{-1}$
$k_{i.y1.2}$	0.00	$N.m^{-1}.s^{-1}$
$k_{i.y1.3}$	0.00	$N.m^{-1}.s^{-1}$
$k_{i.y2.1}$	0.00	$N.m^{-1}.s^{-1}$
$k_{i.y2.2}$	0.00	$N.m^{-1}.s^{-1}$
$k_{i.y2.3}$	0.00	$N.m^{-1}.s^{-1}$
$k_{p.x1.1}$	5.00	$N.m^{-1}$
$k_{p.x1.2}$	5.00	$N.m^{-1}$
$k_{p.x1.3}$	5.00	$N.m^{-1}$
$k_{p.x2.1}$	5.00	$N.m^{-1}$
$k_{p.x2.2}$	5.00	$N.rad^{-1}$
$k_{p.x2.3}$	5.00	$N.m^{-1}$
$k_{p.y1.1}$	5.00	$N.m^{-1}$
$k_{p.y1.2}$	5.00	$N.m^{-1}$
$k_{p.y1.3}$	5.00	$N.m^{-1}$
$k_{p.y2.1}$	5.00	$N.m^{-1}$
$k_{p.y2.2}$	5.00	$N.m^{-1}$
$k_{p.y2.3}$	5.00	$N.m^{-1}$
$k_{d.x1.1}$	4.00	$N.m^{-1}.s$
$k_{d.x1.2}$	4.00	$N.m^{-1}.s$
$k_{d.x1.3}$	4.00	$N.m^{-1}.s$
$k_{d.x2.1}$	4.00	$N.m^{-1}.s$
$k_{d.x2.2}$	60.0	$N.rad^{-1}.s$
$k_{d.x2.3}$	4.00	$N.m^{-1}.s$

Parameter	Value	Unit
$k_{d.y1.1}$	4.00	$N.m^{-1}.s$
$k_{d.y1.2}$	4.00	$N.m^{-1}.s$
$k_{d.y1.3}$	4.00	$N.m^{-1}.s$
$k_{d.y2.1}$	4.00	$N.m^{-1}.s$
$k_{d.y2.2}$	4.00	$N.m^{-1}.s$
$k_{d.y2.3}$	4.00	$N.m^{-1}.s$
$v_{max.x1}$	2.00	$m.s^{-1}$
$v_{max.x2}$	2.00	$m.s^{-1}$
$v_{max.y1}$	2.00	$m.s^{-1}$
$v_{max.y2}$	2.00	$m.s^{-1}$
$x_{1.i}$	3.00	m
$x_{2.i}$	0.00	m
$x_{c.i}$	1.50	m
$y_{1.i}$	0.00	m
$y_{2.i}$	0.00	m
$y_{c.i}$	0.00	m
$\theta_{1.i}$	0.00	rad
$\theta_{2.i}$	0.00	rad
ϕ_i	0.00	rad
$\dot{x}_{1.i}$	0.00	$m.s^{-1}$
$\dot{x}_{2.i}$	0.00	$m.s^{-1}$
$\dot{x}_{c.i}$	0.00	$m.s^{-1}$
$\dot{x}_{1.i}$	0.00	$m.s^{-1}$
$\dot{y}_{2.i}$	0.00	$m.s^{-1}$
$\dot{y}_{c.i}$	0.00	$m.s^{-1}$
$\dot{\theta}_{1.i}$	0.00	$rad.s^{-1}$
$\dot{\theta}_{2.i}$	0.00	$rad.s^{-1}$
$\dot{\phi}_i$	0.00	$rad.s^{-1}$

Appendix 3 Task Roadmap

Table 3. Task Roadmap

Topic	Task	Deadline	Completion Date
Mathematical Modeling	Define coordinate frames and derive equations of motion.	4/8/2018	4/8/2018
	Derive PID-based control schemes for leader agent and follower agent.	15/8/2018	8/8/2018
	Determine performance metrics for the transportation system and a specified task for benchmarking.	15/8/2018	8/8/2018
MATLAB Modeling	Write the proposed algorithms as a script in MATLAB.	22/8/2018	12/8/2018
	Create a script-based simulation for the evolution of the system state.	29/8/2018	15/8/2018
	Simulate the evolution of the system state and performance metrics while completing the specified task.	29/8/2018	15/8/2018
Flight Simulation	Create a ROS package to implement the proposed control algorithms and model the proposed system.	8/9/2018	*Ongoing*
	Simulate the specified task in ROS/Gazebo.	15/9/2018	*Ongoing*
Hardware Testing	Perform the specified task using the proposed hardware platform; log performance metrics.	22/9/2018	*Ongoing*