Chapter 2

Literature study

This chapter will present a study of the literature regarding the transportation of payloads with multirotors. Firstly, an overview of different payload configurations and control techniques for payload transportation will be discussed. Thereafter, the study will focus on control techniques that consider suspended payloads. A summary will be provided of different swing damping controllers proposed for the multirotor-payload system and a few literature trends will be highligted ~~discussed~~. The chapter will conclude with a summary of the literature study and focus areas of this thesis.

2.1. Payload transportation with multirotors

The usage of Unmanned Aerial Vehicles (UAVs) for payload transportation has significantly grown in popularity over recent years [12]. Multirotor UAVs are specifically useful for many transportation applications due to their agility and Vertical Takeoff and Landing (VTOL) capability. The types of payloads attached to multirotors can usually be categorised as either a sensor (e.g. cameras and meteorological sensors), or freight (e.g. mail parcels or fire extinguishing material) [13]. Furthermore, the payload attachment is mainly categorised as either a rigid connection or a suspended connection [13]. In rare cases, a robotic actuator is attached to the multirotor to manipulate a payload [14, 15]. Figure 2.1 shows practical implementations of these three payload configurations.

(a) Rigid connection [16] **(b)** Suspended cable [17] **(c)** Robotic actuator [18]

Figure 2.1: Different multirotor payload configurations

2.1.1. Rigid connection payloads

Payloads are often rigidly attached to a multirotor for transportation. This configuration is especially popular for commercial package deliveries [19]. There is minimal relative movement between the multirotor and the rigidly connected payload. ~~hence,~~ The payload only affects the Centre of Mass (CoM), the moment of inertia, and the aerodynamics of the vehicle. Often, the ~~weight~~ mass and size of the payload are unknown before a flight. PROBABLY NEGLECTABLE

Different control approaches have been proposed to deal with the altered flight dynamics in this applications, including Adaptive Robust Control (ARC) [20] and Model Reference Adaptive Control (MRAC) [21]. These control architectures mostly involve a parameter estimation algorithm to estimate the inertial parameters, and an adaptive control law based on the estimated parameters and the predetermined dynamical model of the system.

An advantage of rigidly connected payloads is that the flight dynamics is not altered significantly. The payload does not add a degree of freedom to the system and only the inertial parameters need to be accounted for. However, this configuration limits the shape and size of a potential payload, because the payload needs to be compatible with the vehicle gripper. The multirotor also needs to land or approach the payload closely to attach to the payload, which may be impractical in many applications.

2.1.2. Suspended payloads

Figure 2.2 shows an example of a practical application of a suspended payload used during search and rescue missions. The shape and mass of the payload affect the flight dynamics, but the payload parameters are often unknown before a flight. The control system should be able to account for these uncertainties and fly well despite the altered flight dynamics.

Various suspended payload configurations have been considered in ~~the~~ literature. The classical suspended payload application involves a small payload suspended below the vehicle with a rigid link [5, 6, 22, 23, 24, 25]. Kotaru et al. [26] considered a suspended payload system with an elastic cable modelled as a spring-damper system. Tang and Kumar [27] modelled the multirotor-payload system with a hybrid dynamical model to consider aggressive manoeuvres where the cable transitions from taut to slack. The transportation of payloads with flexible cables have also been studied, where the cable is modelled as a set of serially connected rigid links [28, 29, 30]. Furthermore, the control of a group of multirotors cooperatively transporting a suspended payload was also considered in various studies [28, 31, 32, 33].

Figure 2.2: A practical suspended payload used for search and rescue missions [1]

From numerous examples in the literature, it is clear that the control of multirotors with suspended payloads is a popular research topic. The suspended payload configuration is very useful in situations where a multirotor cannot land since the payload can be attached during hover. This configuration also has the advantage that a payload can have an arbitrary shape or size as long as it has an attachment point for a cable. However, the suspended payload increases the degrees of under-actuation of the system, which makes the control problem challenging [30].

2.2. Control of multirotors with suspended payloads

A major drawback of transporting a suspended payload is that the payload is free to swing during flight, which affects the dynamics of the multirotor. Two main control strategies are applied in the literature to stabilise a multirotor with a suspended payload, namely, trajectory generation and swing damping control. Some methods combine the two methods into a single control architecture. Trajectory generation methods involve determining multirotor trajectories that result in minimal oscillations or specific payload trajectories. Swing damping control involves feedback controllers that apply a control law to actively counteract the swing of a payload.

2.2.1. Trajectory generation

Trajectory generation methods for suspended payload systems are based on open-loop control techniques. The objective of these techniques is to determine a trajectory in which the multirotor motion would induce a specific payload trajectory to reduce oscillations or avoid obstacles. Numerous trajectory generation methods have been explored in the literature for suspended payload transportation [34, 35, 36, 37, 38, 39, 40, 41, 42].

Zeng et al. [36] and Tang and Kumar [34] applied differential flatness based trajectory planning methods for multirotors in obstacle-filled environments. Instead of only considering swing reduction of the suspended payloads, these studies consider specific payload trajectories to avoid obstacles during aggressive motion. Xian et al. [37] proposed an efficient online trajectory planning method without iterative optimizations. The swing-reduction performance of this method was verified with experimental results.

Dynamic programming methods have also been implemented to generate swing-free trajectories with suspended payloads [38, 39, 40]. These methods require accurate models of the plant dynamics and are sensitive to the accuracy of these models. Reinforcement Learning (RL) methods do not require prior models of the dynamics and have also been applied for swing-free trajectory generation [41, 42]. Faust et al. [42] implemented a RL method for minimal swing trajectories which provides sufficient criteria to allow the learned policy to be transferred to a variety of different models, starting positions, and trajectories. Furthermore, this RL trajectory generation method was verified with experimental results.

Input shaping is another open-loop control method applied for minimal swing control that is related to trajectory planning. This technique involves modifying a reference signal, usually with a set of timed impulses, to cancel the oscillatory modes of a system [43]. These techniques were originally designed for transporting suspended payloads using gantry systems [44, 45]. Later, these input shaping techniques were also applied for reduced swing control of helicopters [46, 47] and multirotors [48, 49, 50] that carry suspended payloads.

Ichikawa et al. [51] compared different input shaping techniques for velocity control of a quadrotor with a suspended payload in simulations. The specific input shaping techniques considered were: Zero Vibration (ZV), Negative Zero Vibration (NZV), Extra Insensitive (EI), and 2-hump EI. These methods convolve a baseline input command with precisely timed impulses based on the length of the suspended cable. Simulation results showed that the input shapers significantly decreased the residual payload oscillations compared to a baseline velocity controller. The study highlighted that EI and 2-hump EI were more robust to cable length uncertainty than ZV and NZV.

Slabber and Jordaan [6] considered a system with unknown payload parameters and applied a notch filter to reduce payload oscillations for velocity control of a multirotor in simulation. The unknown payload mass and cable length were estimated with Recursive Least Squares (RLS) and Fast Fourier Transform (FFT) parameter estimators respectively and the natural frequency was calculated based on these estimates. The notch filter could then be designed to suppress the frequency band containing this natural frequency and was applied to the velocity setpoint signal. It was shown in simulation that the notch filter attenuated the payload oscillations to a near swing-free motion despite large parameter estimation errors [6].

2.2.2. Swing damping controllers

Swing damping control is a closed-loop method where a feedback controller is applied to reduce the payload swing angles during a flight. This control method is also referred to as active vibration damping. Instead of finding a trajectory that reduces oscillations, these controllers follow a given trajectory as close as possible while trying to reduce the payload oscillations.

Linear Quadratic Regulator (LQR) is a popular optimal control technique and has often been used as a baseline controller to evaluate the performance of other swing damping controllers [6, 52, 53, 54, 55, 56]. Erasmus and Jordaan [57] proposed a Linear Quadratic Gaussian (LQG) controller for swing damping control of a multirotor with suspended cable. The payload state remained unmeasured and a Extended Kalman Filter (EKF) was implemented for full-state estimation of the multirotor-payload system. The EKF was combined with an LQR full-state feedback controller to produce LQG control. Simulation results showed good swing damping control with position step inputs despite the unmeasured payload state, external disturbances, sensor noise, and parameter uncertainty.

Slabber and Jordaan [6] implemented a LQR controller augmented with a notch filter input shaper for improved swing damping performance. The notch filter was applied to the velocity step reference and the LQR was then applied with the filtered reference signal for swing-damping control. The LQR was designed with integral action added to the velocity state to ensure zero steady-state velocity tracking. Furthermore, this work involved estimating the unknown payload state with a vision-based estimator for use in the full-state feedback controller. Simulation results showed that this controller provided good swing damping performance in the presence of external disturbances, sensor noise, and parameter uncertainty.

Model Predictive Control (MPC) is an optimal control technique related to LQR and can also be applied to suspended payload systems. Notter et al. [56] implemented an MPC for active swing damping control of a quadrotor with a suspended payload. A non-linear model of the quadrotor-payload system was linearised and discretised to apply a discrete, linear MPC formulation. The physical parameters of the quadrotor, cable, and payload were assumed to be exactly known and the controller was tested with only one payload. The controller received a position trajectory reference and determined force setpoints to control the vehicle. Furthermore, constraints were applied to the heigh, attitude, and control inputs to ensure safe flight manoeuvres. Simulation results showed a superior trajectory tracking performance with the MPC compared to a baseline LQR controller. The MPC simulation results were also verified with experimental results in an indoor environment.

Santos et al. [58] implemented a robust tube-based MPC for trajectory tracking and payload stabilisation of a tilt-rotor UAV and suspended payload. This approach consists of a pre-stabilising control policy for the nominal system and an additive control policy for the mismatch error. The MPC was applied as an outer-loop position controller and a mixed $\mathcal{H}_2/\mathcal{H}_\infty$ controller was applied for inner-loop attitude control. Integral action is applied in the MPC to the position states to ensure zero steady-state error despite external disturbances and modelling errors.

The tube-based MPC was designed to be robust against the additive uncertainties from the decoupling, linearization and discretisation modelling errors. However, the physical parameters of the model were assumed to be exactly known and non-additive parameter uncertainty was not considered. Simulation results showed successful stabilised control of the system along a square-like trajectory with sharp corners.

In other studies, more types of controllers were applied for active swing damping and these studies will be discussed in Section 2.3. Swing damping controllers generally perform better than open-loop, trajectory generation methods for systems with model uncertainties and external disturbances [59]. This is expected since trajectory generation requires accurate plant models, and small modelling uncertainties can significantly alter a trajectory. The remainder of this study will focus on swing damping controllers.

Table 2.1: Summary of literature considered regarding the swing damping control of multirotors with suspended payloads

Author	Year	Proposed controller	Baseline controller	Plant model	Parameter uncertainty	Unknown dynamics	Different payloads	Practical data	Outdoor experiments
Muthusamy et al. [4]	2021	BFBEL	PID	-	✓	✓		✓	
Allahverdy et al. [60]	2021	BISMC with ILC	-	non-linear	✓	✓			
Faust et al. [61]	2014	RL (CAFVI)	-	-	✓	✓		✓	
Wang et al. [3]	2020	ADRC	PID	linear	✓	✓		✓	✓
Hua et al. [62]	2021	RL (non-linear)	BS, EB	non-linear	✓			✓	
Taylor et al. [63]	2020	$\mathcal{H}_\infty$ loop-shaping	LQR	linear	✓		✓		
Erasmus and Jordaan [5]	2020	MRAC	LQR	linear	✓		✓	✓	✓
Slabber and Jordaan [6]	2020	NF with LQR	PID	linear	✓		✓		
Dai et al. [64]	2014	RCAC	-	non-linear	✓				
Santos and Raffo [65]	2016	MPC	-	linear	✓				
Andrade et al. [66]	2016	MPC	LQR	linear	✓				
Zurn et al. [67]	2016	MPC	-	linear				✓	
Son et al. [68]	2019	MPC	-	linear				✓	
Son et al. [69]	2018	MPC	-	linear				✓	
Son et al. [70]	2017	MPC	-	linear					
Trachte et al. [52]	2014	MPC	LQR	non-linear					
Trachte et al. [71]	2015	MPC	LQR	non-linear					
Liang et al. [59]	2021	Non-linear	LQR, PD	non-linear			✓	✓	
Zeng and Sreenath [72]	2019	Geometric	-	non-linear					
Yang and Xian [73]	2018	RISE	-	non-linear					
Martinez-Vasquez et al. [74]	2020	SMC	-	linear					
Mosco-Luciano et al. [75]	2020	BS	-	linear				✓	
Rigatos et al. [76]	2018	$\mathcal{H}_\infty$	-	linear					
Alothman et al. [77]	2015	LQR	PD	linear					
Alothman and Gu [55]	2016	iLQR	LQR	linear					

Refer to Page (xvii) for the abbreviations expanded into words.

2.3. Review of swing damping control studies

This section will discuss trends in ~~the~~ literature regarding the swing damping control of multirotors with suspended payloads. Table 2.1 lists other studies in the literature that consider this topic. The entries of this table are ordered to keep similar studies together, with a priority on unknown dynamics, parameter uncertainty, and proposed controllers. Studies that exclusively consider trajectory generation or cooperative transportation of a payload with multiple multirotors are excluded from this table. From Table 2.1, it is clear that suspended payload transportation with multirotors is a popular and current research topic.

For each study in Table 2.1, the type of proposed controller is listed along with a baseline controller if applicable. Baseline controllers are techniques considered to be well-known that are applied to a task for a reference performance used to evaluate a proposed technique. Other studies compare variations of the proposed controller to each other to highlight the effect of design decisions, but these comparisons are not considered as baseline comparisons.

Many studies in Table 2.1 do not consider a baseline controller, which makes it difficult to evaluate the performance of the proposed technique objectively. These studies can conclude that the proposed technique solves the considered problem, but can not determine whether the technique improves on the performance of known controllers. However, from Table 2.1 it is clear that LQR is a popular baseline controller for swing damping techniques and especially for optimal control techniques.

From the studies considered in Table 2.1, it also appears that MPC is a popular technique for the considered control problem. Historically, MPC was designed for slow-moving processes in the chemical industry because the computational intensity of this method limited the controller frequency on the available hardware [78]. However, due to improvements in the speed of computational hardware, MPC has become a viable controller for faster systems. Various MPC implementations were successfully applied in experimental flight tests which shows that MPC is suitable for practical multirotor implementations [67, 68, 69].

It is also noted that most proposed controllers, including MPC implementation, are based on a linearised plant model of the non-linear multirotor-payload dynamics. This shows that a linearised plant model can provide a sufficient representation of the suspended payload dynamics for effective swing damping control. Non-linear MPC implementations that depend on a non-linear plant model have also been studied for multirotors with suspended payloads [52, 71]. However, the non-linear MPC results were not compared to linear MPC results, therefore the studies do not conclusively justify the need for a non-linear plant model. Non-linear MPC is more computationally intensive than linear MPC, which makes it more challenging to implement in practical flights. None of the studies considered in Table 2.1 that were implemented on practical systems used non-linear plant models. However, some practical implementations apply controllers which do not depend on a plant model [4, 61, 62].

Note from Table 2.1, that many studies only consider the proposed controllers in simulations and do not include practical data. Practical data may include sensor noise, modelling uncertainties, external disturbances, and other computational hardware effects such as latency that are often not considered in simulations. Unlike simulation results, experimental results clearly show that a proposed method is suitable for real-life applications. It also shows that the proposed algorithms can run in real-time on the available hardware, which is a challenge for complex techniques.

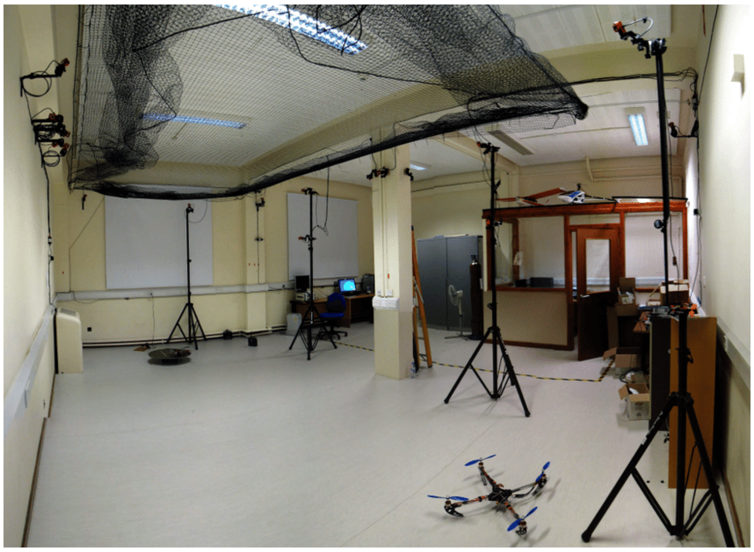

Figure 2.3: Optitrack motion capture system for multirotor experiments [2]

It is also noted that few studies in the literature consider outdoor flights. Most studies only consider practical flights performed in controlled indoor environments. Figure 2.3 shows an indoor motion capture setup used for multirotor experiments. In these experiments, motion capture systems like Vicon [4, 61, 62, 67, 68, 69], Qualisys [59] or Optitrack [75] provide high accuracy state feedback data. However, this setup is often impractical for real-life multirotor applications.

Outdoor payload transportation is dependant on inaccurate sensors like Global Positioning System (GPS) and potentiometers, which greatly increase the difficulty of the control problem. The multirotor-payload system may also be exposed to uncontrolled wind disturbances which further complicates the control problem. Figure 2.4 shows a multirotor in an outdoor practical experiment with a suspended payload [3].

Figure 2.4: Multirotor and suspended payload for outdoor experiments [3]

As observed by Hua et al. [62], most reported controllers in the literature are designed based on accurate plant models without considering dynamical uncertainties in the studies. This is also evident from the literature listed in Table 2.1. The *Parameter uncertainty* column identifies studies that account for parameter uncertainty in the considered plant model. These controllers either apply robust techniques [63] to ensure stability despite the parameter uncertainty, or adaptive techniques [64] to change the control law to result in improved control with the resultant dynamics. Other controllers combine robust and adaptive techniques into a single control architecture [5, 6].

The *Different payloads* column identifies studies that consider more than one payload. It is interesting to note that few studies test the proposed controllers on more than one payload. Some studies proposed controllers to account for parameter uncertainty, but only tested the controller on a single payload case. This does not conclusively demonstrate the adaptability or robustness of a controller, because the payload could be cherry-picked or the controller could be specifically tuned for that payload only. Therefore, it is noted that it is valuable to demonstrate a controller on multiple payload cases. NICE :)

In Table 2.1, the *Unknown dynamics* column identifies studies that account for unknown dynamics of a multirotor with a suspended payload. This does not include the uncertainty due to modelling errors as a result of linearisation and discretisation methods. Studies identified by this column propose stabilising controllers that are not design without a priori knowledge of the payload dynamics. This approach is considered useful for complicated working conditions and model uncertainties [62]. This appears to be a promising research area that has been considered in only a few different studies. It is also interesting to note that ~~the publication dates of most of~~ these studies are quite recently plublished.

2.4. Multirotor and suspended payload systems with unknown dynamics

Only a few studies have been identified that consider the stabilised control of a multirotor and suspended payload without prior knowledge of the payload dynamics [3, 4, 60, 61]. Some methods are not based on a plant model and learn a stabilising control law without prior knowledge of the dynamics [4, 61]. Other strategies control the multirotor with a model-based method and consider the effect of the suspended payload as an external disturbance [3, 60]

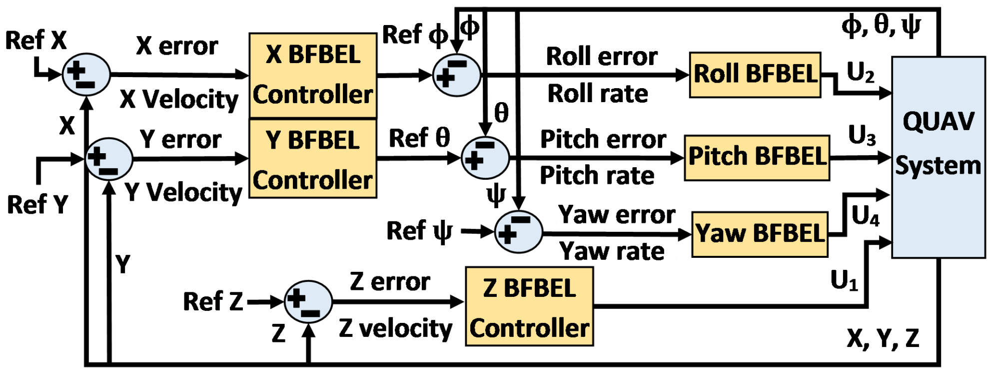

Figure 2.5: Controller structure proposed by Muthusamy et al. [4]

Muthusamy et al. [4] proposed a BFBEL controller which incorporated fuzzy inference, neural networks and the Bidirectional Brain Emotional Learning (BBEL) algorithm. A separate BFBEL feedback controller was applied to each degree of freedom of the Six Degrees of Freedom (6DOF) multirotor system, as shown in Figure 2.5. The payload state remained unmeasured and the objective of the controller was to stabilise the multirotor system and provide accurate position tracking without knowledge of the multirotor-payload dynamics. Experimental results demonstrated the rapid adaptation capability and the trajectory tracking performance of the proposed BFBEL controller. Without prior knowledge of the system, the controller weights were autonomously tuned within 30 s of flight time to provide stable trajectory tracking with the multirotor. However, the payload state was not explicitly measured or damped, causing residual oscillations in the position data of the multirotor.

WHAT DOES THIS ACRONYMN STAND FOR?

A ADRC was proposed by Wang et al. [3] for the control of a multirotor with an unknown suspended payload. A transfer function model of a practical multirotor without a payload was determined with a frequency sweep excitation method of each control channel. The effect of the suspended payload was considered as an external disturbance and Extended State Observers (ESOs) were applied to estimate the disturbance. An ADRC could then actively reject the disturbance caused by the payload and stabilise the system without prior knowledge of the payload dynamics. Experimental results showed that trajectory tracking was significantly improved compared to a standard PID controller. It should be noted that this technique did not show significant swing damping performance but rather showed robustness against the disturbance effect of the swinging payload.

These methods provide stabilised control of the multirotor, but do not provide optimised control of the entire multirotor-payload system. These controllers focus on counteracting the current swinging payload disturbance but does not learn how to directly control the unknown payload.

System identification methods can determine a model of the unknown dynamics and a controller could be designed based on the identified plant model. This could provide improved control of the entire dynamical system. Control architectures involving data-driven model identification and resultant model-based controller have been proposed for multirotors [3, 79]. However, we were not able to find similar studies in the literature that involves an unknown suspended payload.

2.5. Summary

This chapter reviewed a range of different control solutions for multirotors with suspended payloads. A few observations were made regarding the literature on this subject. ~~including the following:~~ The main observations are:

1. Most of the studied controllers are based on accurate models of the system dynamics.
2. Swing damping methods perform better than trajectory generation methods when considering model uncertainty.
3. Many studies consider some parameter uncertainty, but only a few studies consider unknown system dynamics.
4. Only a few studies that account for parameter uncertainty are also demonstrated with different payload parameters.
5. Methods that consider unknown system dynamics usually consider the suspended payload as an external disturbance and do not attempt to actively control the payload.

6. No studies were found in the literature that consider data-driven system identification and control of multirotors with suspended payloads.

The focus of this thesis will involve the stabilised control of a multirotor with an unknown suspended payload. The dynamics of the suspended payload system will be considered unknown before a flight. Furthermore, the proposed controller will be based on an estimated model of the multirotor-payload dynamics and it will be tested on different payloads.

Baie goed!

Chapter 6

Experimental design

As discussed in the literature study in Chapter 2, experimental data is a valuable part of any work involving multirotors control. This chapter will provide an overview of the hardware, software, HITL simulations, and practical methodology used in this work.

6.1. Hardware components

IS THIS THE RIGHT TERM? SHOULD NOT BE "COMPANION COMPUTER"?

The main hardware components in this work include a multirotor vehicle, a payload angle sensor, and an OBC. These components are coupled together into the final multirotor system which will be used for practical flights.

6.1.1. Multirotor

Figure 6.1: Honeybee quadrotor equipped with a OBC and payload angle sensor

The multirotor used in this work is a custom-built, lightweight quadrotor named *Honeybee*. This vehicle was developed in the Electronic System Laboratory (ESL) at Stellenbosch University [11]. Figure 6.1 shows a photo of Honeybee equipped with an OBC and payload angle sensor.

The physical parameters of this multirotor are summarised in Table 6.1. Note that the mass and inertial parameters include the OBC and payload angle sensor. The thrust profile of each motor is given by the third-order polynomial mapping the input Pulse-Width Modulation (PWM) signal, x, to the thrust output, T_m [11]:

$$T_m(x) = -3.508 \cdot 10^{-9}x^3 + 1.627 \cdot 10^{-5}x^2 - 0.0172x + 4.528 \tag{6.1}$$

Table 6.1: Physical parameters of Honeybee.

Description	**Parameter**	**Value**
Mass	m_Q	0.952 kg
Motor distance	d	0.11 m
Virtual yaw moment arm	R_N	$7.997 \cdot 10^{-3}$ m
Motor time constant	τ	15 ms
Mass moment of inertia about $\bar{\boldsymbol{x}}_\mathcal{B}$	I_{xx}	$2.00 \cdot 10^{-3}$ kg·m^2
Mass moment of inertia about $\bar{\boldsymbol{y}}_\mathcal{B}$	I_{yy}	$1.32 \cdot 10^{-3}$ kg·m^2
Mass moment of inertia about $\bar{\boldsymbol{z}}_\mathcal{B}$	I_{zz}	$3.35 \cdot 10^{-3}$ kg·m^2
Aerodynamic drag coefficient in $\bar{\boldsymbol{x}}_\mathcal{B}$	C_{Q_X}	0.096 m^2
Aerodynamic drag coefficient in $\bar{\boldsymbol{y}}_\mathcal{B}$	C_{Q_Y}	0.096 m^2
Aerodynamic drag coefficient in $\bar{\boldsymbol{z}}_\mathcal{B}$	C_{Q_Z}	0.256 m^2

The Flight Controller (FC) implemented on Honeybee is a *Pixhawk 4 mini* shown in Figure 6.2. This board includes internal IMU, magnetometer, and barometer sensors and is connected to an external GPS sensor and an additional magnetometer. Furthermore, a Radio Control (RC) receiver is used to communicate with a radio transmitter for manual pilot control. A telemetry radio module is used for communication with a ground control station. The OBC and external payload angle sensors are also connected to the FC.

Figure 6.2: Photo of a Pixhawk 4 mini FC [9]

6.1.2. Payload angle sensor

A sensor is required to measure the payload state as Euler angles about the $\bar{\boldsymbol{x}}_{\mathcal{B}}$ and $\bar{\boldsymbol{y}}_{\mathcal{B}}$ axes. Figure 6.3 shows a customised sensor attached to the Honeybee airframe for this purpose.

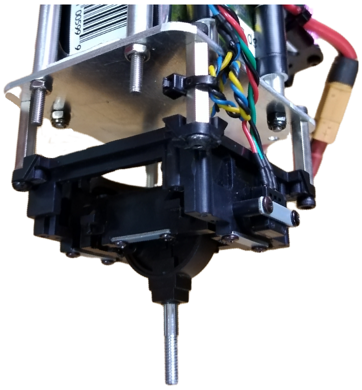

Figure 6.3: Payload angle sensor with linear potentiometers

This sensor was constructed from a two-axis joy-stick and two linear potentiometers. Each potentiometer is implemented as a voltage divider and attached to an ADC channel on the FC. Experimental data was used to map the ADC reading to an angle measurement with a best-fit straight line function. A cable can therefore be attached to this device to transport a suspended payload and measure the payload swing angles during flight.

Companion computer

6.1.3. On-Board Computer

ok, ok, dan seker nie nodig nie..

An OBC, also called a companion computer, is used to run intensive computational processes that cannot be handled by the FC. A NVIDIA® Jetson Nano™, which is shown in Figure 6.4, is used as the OBC for Honeybee. This has 4GB memory and a quad-core processor which runs at 1.43 GHz. The OBC is connected to a serial port on the FC for communication.

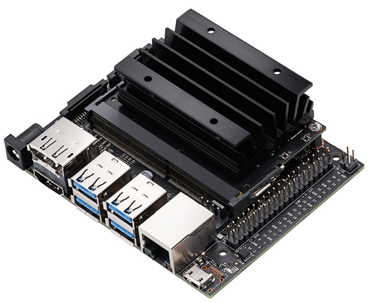

Figure 6.4: NVIDIA® Jetson Nano™ [10] used as a OBC

6.2. Software Toolchain

The software toolchain used with Honeybee includes PX4-Autopilot, QGroundControl, ROS, and Gazebo simulator. This toolchain ~~and~~ was also implemented and described well by Erasmus and Jordaan [5], Slabber and Jordaan [6], and Grobler and Jordaan [11]. A brief overview of the software toolchain is provided here.

6.2.1. PX4-Autopilot

define ... as in HITL

PX4-Autopilot is an open-source flight stack that focuses on autonomous UAVs [96] and is used in research and industrial applications. SITL and Hardware-in-the-Loop (HITL) simulations are supported by PX4, which is helpful for research and development.

6.2.2. QGroundControl

QGroundControl (QGC) is the recommended ground station software for PX4 systems [9]. A ground station computer running QGC can be used to monitor and control a PX4 vehicle. QGC communicates with PX4 via the MAVLink protocol over a telemetry connection during practical flights. During SITL simulations, QGC connects to PX4 over a local User Datagram Protocol (UDP) connection. QGC is also an open-source ~~product~~. project.

6.2.3. Gazebo simulator

Gazebo is an open-source graphical-based physics simulator used for robotics. This is the recommended simulator in the PX4 development toolchain and is capable of both SITL and HITL simulations [9]. The PX4 flight stack includes quadrotor models developed for Gazebo which include realistic sensor plugins. These plugins apply sensor noise, drift and bias which replicates the actual sensors used on Pixhawk boards. The physical parameters of these models were changed to match Honeybee and a suspended payload was added to the model as shown in Figure 6.5.

6.2.4. Robot Operating System (ROS)

ROS is a communication framework with a set of tools used for robotics and control applications [122]. ROS is also open-source and is supported by PX4. In this framework, executables are called ROS nodes and these nodes interact with each with a publish-subscribe architecture. A ROS node can publish messages to a topic, and a different node can subscribe to that topic to read those messages.

MAVROS is an open-source ROS package that provides a bridge between ROS and PX4 through the MAVLink protocol. A MAVROS node receives MAVLink messages from PX4

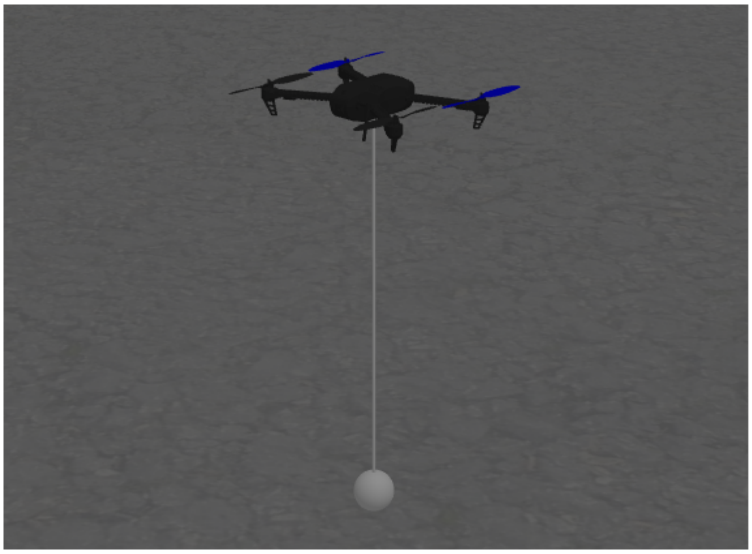

Figure 6.5: Model of Honeybee in the Gazebo simulator

and converts this to published ROS topics for other ROS nodes to access. The MAVROS node also subscribes to other topics to receive ROS messages and send this data to PX4.

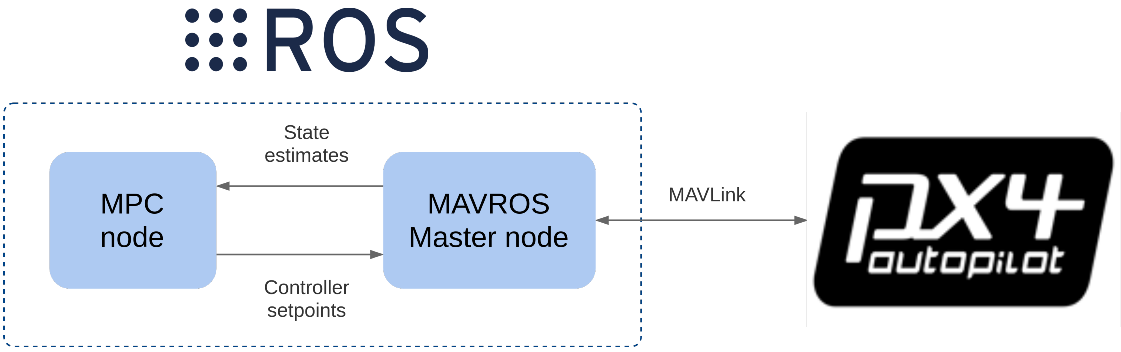

Figure 6.6: Communication between ROS, flight stack, simulator, and ground station [11]

MATLAB/Simulink was used to convert the MPC controller developed in Section 5.4 to C++ code and generate a standalone ROS node. Figure 6.6 illustrates how the MPC node is used as an offboard controller with PX4 and MAVROS. A MAVROS Master node receives data, including state estimates, from PX4 through MAVLink communication. This data is published by MAVROS to various ROS topics. State estimate data is received by the MPC node by subscribing to the appropriate MAVROS topic. After the MPC node calculates the next controller decision, it publishes the controller setpoint data to a MAVROS topic. The MAVROS node then sends it to PX4 via MAVLink.

6.3. Hardware-in-the-Loop simulations

In HITL simulations, the simulator mimics the sensor outputs, but the PX4 firmware and the accompanying software runs on the designated hardware. Figure 6.7 illustrates how the different software and hardware components interlink for HITL simulations.

QGC runs on the desktop computer and communicates with the Gazebo simulator with MAVlink messages over a local UDP connection. The Gazebo simulator also runs on the desktop computer and simulates the Honeybee quadrotor. The simulator mimics the quadrotor sensor values and sends them to PX4 with MAVlink messages over a USB connection.

The PX4 firmware runs on the FC board. Based on the received sensors values, the PX4 controllers determine PWM actuator commands which are communicated back to Gazebo. The OBC runs the MPC and MAVROS nodes which send and receive MAVLink messages over a serial port connection to the FC.

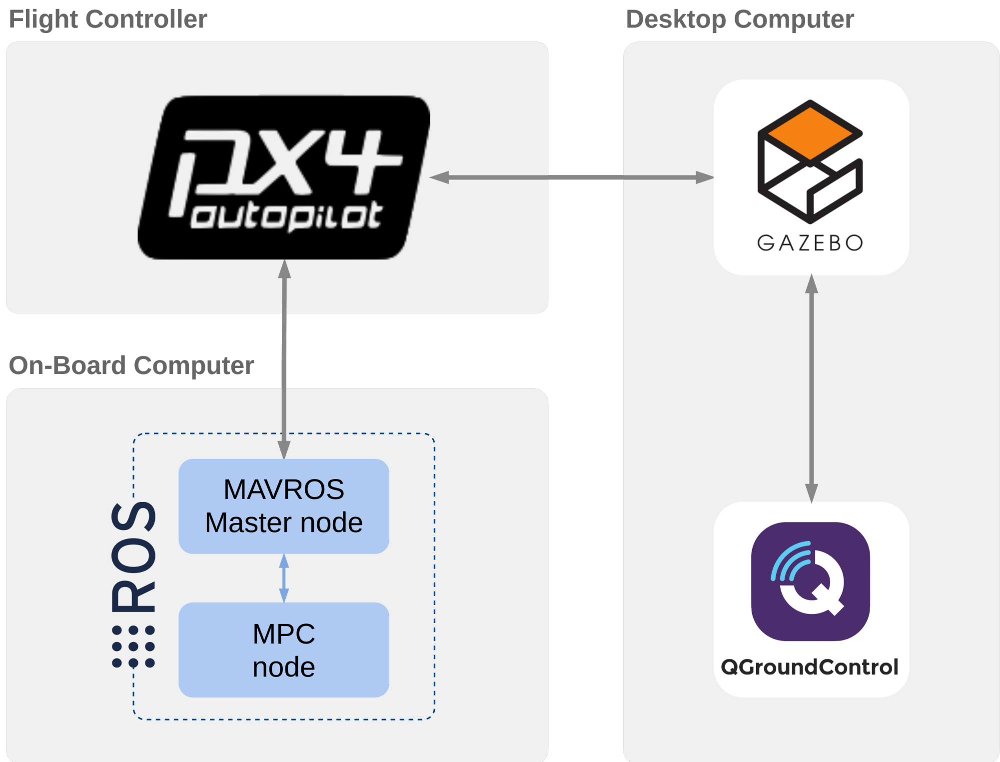

Figure 6.7: Different software and hardware components of a HITL simulation

6.4. Practical flights

The major differences between simulated and practical flights involve wind disturbances and the attachment of the payload. In simulations, the payload cable is attached to the exact CoM of the multirotor. However, for practical flights the cable is attached slightly below the CoM of Honeybee due to mechanical constraints. Practical flights are also influenced by wind gusts which are difficult to model accurately in simulations. The measurement noise experienced by a practical multirotor may also differ from the noise models used in simulations.

Figure 6.8: Practical flight with Honeybee and a suspended payload

Figure 6.8 shows Honeybee with a suspended payload during a practical flight. Numerous flights were performed with different payload masses, cable lengths and wind conditions. Different flights were also performed with a dynamic payload. The system identification methods were then applied to the flight data logged by PX4. The results of these flight experiments will be discussed in Chapter 7.

The same general methodology used for simulations ~~will be~~ was used for practical flights:

1. Arm the multirotor for data logging to start.
2. Takeoff and hover with the multirotor.
3. Command velocity step setpoints.
4. Land the multirotor.
5. Disarm the multirotor for data logging to stop.
6. Download the data log from the multirotor.
7. Split the data into separate training and testing periods.

8. Build a model from the training data.
9. Evaluate model predictions with the testing data.

6.5. Summary

This chapter provided an overview of the hardware and software used in this work. The HITL simulation and practical flight setups were also discussed. This provides a background for the experimental tests, results, and discussion in the next chapter.