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**Revision Record**

|  |  |  |  |
| --- | --- | --- | --- |
| Document Issue/Revision Status | **Description of Change** | **Date** | **Approved** |
|  | Initial Issue |  |  |

**Distribution List**

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Affiliation** | **Distribution Date** | **Approved** |
| Avionics Lab File Archive | QUT Avionics |  |  |

**Abstract**

The purpose of the Predictive Flight Management System (PFMS) project is to develop an improved trajectory prediction engine with aircraft dynamics and constraint considerations to replace current rudimentary Queensland University of Technology (QUT) systems. The PFMS must be validated and then subsequently integrated onboard the QUT Uninhabited Aerial System (QUAS). To achieve the projects aims literature was surveyed and revealed that a 6-Degree-of- Freedom (DOF) model would be required to reflect the dynamics of the aircraft, and an appropriate Proportional Integral Derivative (PID) controller for control across the flight trajectories. A 3D prediction engine using surveyed recommendations is then presented, and appropriate methods of system testing and validation.

Recommendations detailed by the literature survey allowed for derivation of required methodologies to achieve project objectives which were detailed in a comprehensive Project Management Plan (PMP). The project plan details the required successive stages to complete the project on schedule.

Further, this report provides contemplation on methodologies undertaken thus far in the project, and provides proposed and the in the future of the project. The documentation also details encountered risks and mitigation procedures.

The document concludes that the project is currently on schedule, and provides evidence that the system will be delivered on time.

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**Definitions**

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| --- | --- |
| PFMS | Predictive Flight Management System |
| PID | Proportional Integral Derivative |
| PMP | Project Management Plan |
| UAS | Unmanned Aerial System |
| ATCo | Air Traffic Controller |
| ARCAA | Australian Research Centre for Aerospace Automation |
| QUT | Queensland University of Technology |
| QUAS | QUT Uninhabited Aerial System |
| HLO | High Level Objective |
| NASA | National Aeronautics and Space Administration |
| TE | Trajectory Engine |
| MPC | Model Predictive Control |
| DOF | Degree-of-Freedom |

# Introduction

This document reports on the current progress of the PFMS project. It provides contemplation on methodologies undertaken thus far and the in the future of the project. The documentation also details encountered risks and mitigation procedures.

## Scope

This document serves as evidence of the progress of the PFMS against its objectives.

## Background

QUT has been developing Unmanned Aerial System (UAS) technology in various forms since 1991. In the past, subsequent to receiving commands from an autonomous traffic controller, flight trajectory prediction has been performed by linear methods which ignore the dynamics of the aircraft, weather effects and successive waypoints. A PFMS allows for an UAS to have some level of intelligence to determine whether it will be capable of intercepting a demanded waypoint at a given time, whether to ignore waypoints that may/may not be invalid if there is a higher then expected latency in the system, and how to handle the difference between mandatory (mission) waypoints and the demanded waypoints from the Air Traffic Controller (ATCo). In advanced stages of the project the PFMS may include concepts such as autonomous collision avoidance that is independent of the autonomous traffic controller.

This year the Australian Research Centre for Aerospace Automation (ARCAA) requires a PFMS for the Smart Skies QUAS resulting in the PFMS project. This document is a progress report detailing the work undertaken during the first semester of the PFMS project.

# Reference Documents

## QUT Avionics Documents

|  |  |  |
| --- | --- | --- |
| RD/1 | QUAS-PFMS-HO-0001 | QUAS Project, PFMS, High Level Objectives for |
| RD/2 | QUAS-PFMS-PM-0001 | QUAS Project, PFMS, Project Management Plan for |
| RD/3 | QUAS-PFMS-TS-0001 | QUAS Project, PFMS, Trade Stud for |

## Non-QUT Documents

|  |  |  |
| --- | --- | --- |
| RD/4 | SP-601S | NASA Systems Engineering Handbook |
| RD/5 | P. Narayan,.P. Wu and D. Campbell, “Unmanning UAVs – Addressing Challenges in On-Board Planning and Decision Making” in *Proceedings of the First International Conference on Humans Operating Unmanned Systems*, pp. 159-171, France, 2008 | |
| RD/6 | M. Porretta, M. Dupuy, W. Schuster, A. Majumdar and W Ochieng. “Performance Evaluation of Novel 4D Trajectory Prediction Model for Civil Aircraft”, in *The Journal of Navigation*, vol. 61, pp. 393–420, 2008 | |
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| RD/8 | L. Singh and J. Fuller, “Trajectory generation for a UAV in urban terrain, using nonlinear MPC”, in *Proceedings of the 2001 American Control Conference*, Arlington, VA, 2001 | |
| RD/9 | H. J. Kin, D. H. Shim and S. Sastry, “NonlinearModel Predictive Tracking Control for Rotorcraft-based Unmanned Aerial Vehicles*”*in *Proceedings of the American Control Conference,* Anchorage, AK, 2002 | |
| RD/10 | T. Schouwenaars, B. Mettler, E. Feron and J. How, “Robust Motion Planning Using a Maneuver Automaton with Built-In Uncertainties”, in *AIAA Aerospace Sciences and Exhibit*, Reno Nevada, 2003 | |
| RD/11 | MATLAB, The MathWorks, 2009 | |
| RD/12 | Aerosim Blockset. Unmanned Dynamics, 2003 | |
| RD/13 | JSBsim [internet]. 2009 [cited 2009 April 15]. Available from:http://jsbsim.sourceforge.net/ | |
| RD/14 | MATLAB Simulink [internet]. 2009 [cited 2009 April 15], Available from: http://www.mathworks.com/products/simulink/ | |
| RD/15 | FlightGear [internet]. 2009 [cited 2009 April 15], Available from: http://www.flightgear.org/ | |
| RD/16 | B.Gill and B. Maddock, “Prediction of Optimal 4D Trajectories in thePresence of Time and Altitude Constraints”, EUROCONTROL, 1997 | |

In the event of any conflict between this document and any RD referenced herein, such conflict shall be notified to Dr Luis Mejias.

In the following text, RD/x identifies referenced documents, where "x" denotes the actual document.

# 05757517 Project Summary

The Predictive Flight Management System is a trajectory prediction system currently in development for the QUAS. The system provides insight into the performance of a UAS across a finite prediction horizon allowing for scrutiny of if commanded waypoints developed by the ATCo, for collision free paths, are achievable by the platform. The system also will provide a level of intelligence to ensure ATCo data is valid due to inherent system latency or corruption during communication. The PFMS is required by the QUAS to install another level of safety to autonomous system to ensure safe cooperation with other unmanned and manned aircraft in busy airspace.

Current QUT trajectory prediction algorithms calculate waypoint arrival times using displacement between the current waypoint and the platform velocity. Evidently, present systems ignore platform performance boundaries such as minimum (stall) and maximum velocities, minimum turn radius, climb and descent rates, and attitude rate constraints. The inclusion of vehicle dynamics during trajectory generation allows for trajectories which allow for platform constraints and increases prediction accuracy.

Hence, the PFMS project is to develop, validate and integrate onboard a UAS an improved trajectory prediction engine with aircraft dynamics and constraint considerations. The High level Objectives (HLOs) for the PFMS project can then be developed as defined in Figure 1, where successive objectives define the stages of the project.



Figure – PFMS Project’s High Level Objectives

This document outlines the development, methodology, conclusions and associated risks to reflect the progress of the PFMS project as per the HLOs [RD/1] undertaken thus far.

## Methodology for Delivering Against Milestones

This section of the document details a synopsis of how the projects HLOs, as defined by , will be met. The project methodology is designed so delivery against milestones is realistic and feasible for the planned project lifecycle. For the purpose of ensuring the project can be delivered as defined on time Systems Engineering practices have been used according to the NASA Systems Engineering Handbook [RD/4]. In addition the project methodologies have been developed using evidence from literature to ensure best practice [RD/3].

Details on project management, surveyed trajectory prediction methods, project execution and the future of the project respectively are detailed in the following sections providing evidence of the status of the project objectives.

### Project Management

The PFMS project requires effective management to ensure achievement of its HLOs [RD/1]. In early stages of the project concurrent to initial research a comprehensive guideline for the lifecycle of the project was developed to ensure cohesive completion of objectives and the quality of the final product according to Systems Engineering practices.

The Project Management Plan [RD/2] detailed the project reporting structure, document requirements and standards, risk, progressive project stages and a work breakdown. The work breakdown is a critical element of ensuring delivery against milestones as it outlines how the work for the project will be completed. For the project work breakdown see RD/2.

The work breakdown was developed from evidence in literature the required stages of the project to deliver the trajectory prediction system. It provides detailed information of the work required to complete the project and defines deliverables and requirements to be completed during each package. Further, a schedule was derived from these work packages in the form of a Gantt chart and allowing for the progress of the project can be tracked. Such project management methods will facilitate the successful delivery of the project.

### Surveyed Trajectory Prediction Methods – Achieving HLO-1

Trade studies on past methodologies have been conducted to identify best practices for development of a prediction engine for the UAS. The trade studies also consider the process difficulties pertaining to feasibility of implementation using available project resources. The following paragraphs provide an abstract of the recommendations made in RD/3, as per HLO-1. The recommendations made are implemented in section 3.1.3.

#### System Architecture

The process of prediction over time of the location of the UAS is a multi-disciplinary problem that combines the fields of trajectory planning, guidance and control, and vehicle dynamics [RD/5]. For the purpose of prediction of location at a required time the PFMS must develop a trajectory based on the aircraft intent and simulate aircraft guidance along the intended route in time.

A common published [RD/6, RD/7] simulation model, known as Trajectory Engine (TE), for trajectory prediction is detailed in . The TE contains an aircraft control model, an aircraft dynamics model, system inputs, aircraft performance constraints and outputs a trajectory prediction. Through interaction of these two models over time the evolution of the state of the aircraft can be predicted as it transverses along its desired route in time.



Figure - Trajectory Engine

This review provides primarily insight on implementation of the aircraft control and vehicle dynamics models. An abstract of the selection of the implementation method of the system blocks is discussed below.

#### Aircraft Control Model

The control model is concerned with the guidance of the UAS along its trajectory. Many current approaches for trajectory prediction available in literature, with control considerations, are performed in three-dimensions where expected times of arrival are ignored in the control methods [RD/6]. Such methods are not suitable as time considerations must be made along the intended route in order to make predictions in time and, consequently, only four-dimensional (4D) trajectory control methods are suitable.

Model Predictive Control (MPC) and manoeuvre automation theory are published approaches to trajectory generation with attitude considerations [RD/8, RD/9, RD/10] to trajectory generation. However, the control processes for the duration of the project implementation is not feasible due to time constraints. A PID system controller is to be implemented with waypoint considerations over time. This system will simulate the control methods of the MicroPilot [RD/11] autopilot across the prediction horizon.

#### Vehicle Dynamics Model

The inclusion of vehicle dynamics during trajectory generation allows for trajectories which account for platform constraints and increase prediction accuracy [RD/5]. The type of performance bounds which can be considered during the trajectory planning process depends on the number of states simulated. Further, the inclusion of a greater number of performance states provides a better model of the true vehicle dynamics and thereby increased prediction accuracy.

A 3-Degree-of-Freedom (DOF) model allows for platform constraints of minimum stall velocity, maximum velocity, minimum turn radius and maximum climb and descent rates [RD/5]. For incorporation of attitude rate constraints a more complex 6-DOF is required. From an ATCo perspective a trajectory can be sufficiently generated through the use of a 6-DOF model [RD/6]. Consequently a 6-DOF model has been deemed adequate to model the vehicle dynamics of a UAS for the PFMS.

Supporting this selection is the availability of the Aerosonde UAV data set, containing a 6-DOF model, provided by the Aerosim Blockset [RD/12]. This will allow for validation of simulations of the PFMS during implementation. The Aerosim Blockset in addition utilises the JSBsim [RD/13] model, an open source C++ 6 DOF aircraft dynamics model. This allows for using the JSBsim dynamics models C++ source for later stages of the project.

### Project Execution – Achieving HLO-2

This section discusses the implementation of the 2D 3-DOF Trajectory Prediction model and the 3D 6-DOF Trajectory Prediction Model respectively and details the methodologies undertaken to complete HLO-2. It provides insight into the considerations and validations for the methodologies taken at each successive stage derived from the previous literature survey.

#### 3-DOF Trajectory Prediction Model

For learning purposes it was defined within the project schedule to develop a two dimensional 3-DOF model. Implementation was against the recommendations of the literature survey, however, the system was considered to be a future verification tool for the 6-DOF system.

The model was implemented within a Matlab script and it considered rate of turn constraints. This model was using the velocity state of the aircraft across the prediction horizon. A simple proportional controller with saturation for constraints was used for control the rate of turn. Considerations such as capture policy and the requirements of altitude and decent rate requirements were developed at this stage.

This model was later developed into a 3D model by implementing rate of climb and decent rates over the prediction horizon. The system is capable of a prediction to a defined horizon for control of the QUAS to a single waypoint.

#### 6-DOF Trajectory Prediction Model

For implementation of the vehicle dynamics model, with 6-DOF, and aircraft control model Matlab Simulink [RD/14] was utilised. Simulink was used as it provides an interactive graphical environment and a customizable set of block libraries that allow for design, simulation, implementation, and testing a variety of time-varying systems including control systems. It offers tight integration with the rest of the Matlab thereby can utilise its suite of analysis, plotting and scripting tools. Simulink also offers the functionality to build simulation models in C++, decreasing model development time.

Aerosim [RD/12] was used within the Simulink model where a 6 DOF model was employed with modification to reflect the performance of the QUAS. An aircraft can be modelled with editing of provided Matlab script with the aircraft dynamics. The vehicle dynamics model modifications can be later reflected in the C++ implementation

To implement waypoint, navigation functions were developed to stage the waypoints successively. The required heading and altitude is calculated and fed into the controller at each time step. A capture policy for waypoints was also defined within the navigation system which attempts to model the policy adopted by the MicroPilot autopilot.

FlightGear [RD/15], an open-source, multi-platform, cooperative flight simulator is utilised as a 3D simulation environment for the trajectory implementation. FlightGear can be configured with Matlab to allow for output of aircraft states in real time and then reflect the dynamics of the aircraft within the 3D environment. This allows for control system performance to be visualised and providing a means of system optimisation.

Validation of system will be undertaken using telemetry data from the QUAS recorded by MicroPilot. Initially, validation was considered to be performed using flight telemetry over previous QUAS flight days. It was found that recorded telemetry data did not detail location of waypoints as during flight testing way points had been moved over the flight duration. It was not possible to obtain data that could be simulated using the PFMS system. Consequently future testing has been organised and is discussed in the next section. Test will be undertaken with appropriate testing documentation according to Systems Engineering Standards.

### Future Work

To complete HLO-3 and HLO-4 there are numerous project stages will be undertaken in the future of the PFMS project. This section discusses the steps required to achieve the projects remaining milestones. Further, it provides evidence that planned methodologies exist for future stages of the project.

#### Completion of HLO-2

The model requires validation using standard telemetry captured during a QUAS test day. Telemetry data will be compared following an arranged test where the UAS will follow a series of recorded waypoints at a recorded velocity and altitude. Waypoints will be developed to consider multiple approach angles to develop data for complex trajectories for comparison to the PFMS. Weather conditions will be in addition recorded for analysis.

Further work is required on the simulation model require optimisation of the PFMS to reflect the control and waypoint capture of the MicroPilot autopilot and this will be analysed during validation using telemetry data.

Determination of invalid waypoints will be a consideration after the prediction model is developed.

#### Completion of HLO-3

Implementation of the PFMS onboard the UAS requires conversion of the Simulink simulation environment into C++ for compilation and execution. The Real Time Workshop, a feature of Simulink, provides compilation functionality of simulation libraries for rapid model development in C++. This method is not possible, however, for user defined scripts and hence these will have to be developed in C++. The C++ implementation will then be composed of the JSBsim system dynamics model configured with the dynamics of the QUAS, a Real Time Workshop build of the Simulink system control model, and custom implementation of the navigation model, which utilises user defined scripts. The PFMS will be compiled under Linux for operation using the PC104.

The system is to be compared to the simple 3-DOF model and the difference in prediction accuracy analysed.

#### Completion HLO-4

In advanced stages of the project the PFMS may include concepts such as autonomous collision avoidance. The trajectory engine developed within this document is alike that published in literature [RD/5, RD/6, RD/16] which are capable collision avoidance. Collision avoidance considerations will require additional constraints to be applied to the control algorithm. With the use of PID control the system will need a level of intelligence to stage new waypoints to produce a safe flight trajectory for the PID loop to fly about. This consideration will be further developed in later stages of the project.

With the increasing complexity of UAS it is possible to investigate meteorological forecasts in real time to predict the effects of a flight trajectory due to wind and temperature, such as the advanced FMS described in literature [RD/6]. In later stages of the project meteorology may be accounted for during trajectory prediction. Wind effects are considered within the JSBsim flight dynamics model.

### Review of Methodology Used and Approach Taken

The methodology of the project encompasses published approaches including NASA Systems Engineering Structure and those detailed within referenced literature.

The initial literature survey detailed the necessary steps for successful completion of the projects objectives and this was reflected with the generation of a comprehensive project plan. Following the guidelines of the project plan, and its associated work packages, have enabled the project to successively progress and complete milestones as detailed in the previous sections. The project methodologies have been effective to date and continuation using the same guidelines guarantees the system will be delivered as defined on schedule.

## Statement of Progress against Milestones

The project schedule for the PFMS project is well defined and allows for analysis of the projects current progress against milestones. The following Gantt chart, , indicates the work packages that were structured to complete HLO-1 and HLO-2 during the first semester. It can be noted that all work packages were completed on schedule; however a small delay has been experienced with validation of the 3D prototype (WP-9) as discussed in section . No modifications have been made to the initial proposal.

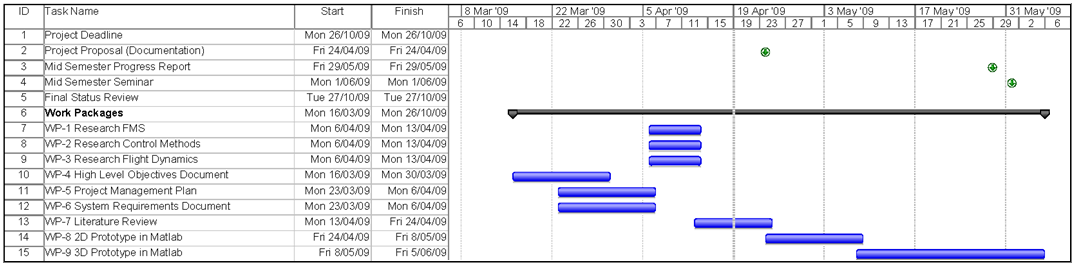


Figure - Project Schedule for Semester 1

Evidence is then provided that the project is currently on plan, and the current delay will be accounted for over the university semester break. A schedule has been developed for the future of the project and is detailed within the Project Management Plan [RD/2].

## Risks

Risks are an important consideration during the PFMS project. The project schedule, and thereby project outcomes, could be compromised if delays are incurred. This section of the document contains abstracts of the detail Risk Management Plan [RD/2] to ensure that any incident with potential to delay or cause harm can be successfully avoided or properly handled with a detailed mitigation procedure. In addition it details unforseen problems with the project so far and suggest future risks that may be encountered as the project evolves.

Delays pertaining to a single working engineer were a significant consideration as progress will not continue until the delay is overcome. As the project involves complex control methodologies and advance coding requirements it is important that close relation with the projects supervisor for consultation if problems occur to attain a suitable course of action in order to minimise delay.

Such a delay was experienced following the recommendations of the literature survey where MPC was suggested. The time available for implementation of the controller was not feasible and much time was wasted attempting to implement the system using such methods. This was mitigated following a meeting with the project customer where it was discussed alternative simpler control strategies would be used and hence ensure the completion of the projects objectives. The risk of underestimating work package completion times was later developed from the above described risk and future work was reviewed to ensure it conformed to the directives developed.

Sickness or increased university workload poses a potential risk to the project. Varying workload throughout the semester was experienced and work hours were redistributed as required. In addition it was ensured that margin for delay was structured into the project schedule.

For delivery of future project work, the project requires planned flight days which require the PFMS project team to be present. It is then important that the flight tests are well planned and established before using team resources. Telemetry capture requires a ground operator, launch controller, supervising controller and payload specialist. It is then critical to ensure team resources are not wasted on non critical tests.

Lastly, poor testing of the flight model may induce risk of code failure in future UAS tests. If this is to occur during a flight it may induce loss of the control of the UAS. It is critical that all implemented code is verified and tested prior to execution onboard the aircraft. Risks associated with system failure are further detailed in the QUAS risk documentation.

# Conclusions

The PFMS is required by the QUAS to install another level of safety to autonomous system to ensure safe cooperation with other unmanned and manned aircraft in busy airspace. Current QUT trajectory prediction algorithms calculate waypoint arrival times using displacement between the current waypoint and the platform velocity which ignore aircraft dynamics.

Consequently, the PFMS project is to develop, validate and integrate onboard a UAS an improved trajectory prediction engine with aircraft dynamics and constraint considerations. The methodology of the project encompasses published approaches including NASA Systems Engineering Structure and those detailed within referenced literature.

The initial literature survey detailed the necessary steps for successful completion of the projects objectives and this was reflected with the generation of a comprehensive project plan. Following the guidelines of the project plan, and its associated work packages, have enabled the project to successively progress and complete objectives. The project methodologies have been effective to date and continuation using the same guidelines it can be guaranteed the system will be delivered as defined on schedule. This is reflected in the status of the projects schedule.

Project risks have been identified and mitigation procedures have been developed. Such procedures have been applied and used in early stages of the project when problems were encountered verifying the validity of the risk management plan. Recommendations were subsequently made and directives developed from encountered problems during the project.

It is hence feasible to conclude, due to the contents of this document, that the project is currently on schedule, and provides evidence that the system will be delivered on time.

# Lessons Learnt and Recommendations

Through the progressive project stages experience has been gained on the feasibility of work for a project with restricted resources. Such experience has developed recommendations for future project stages and goals.

During work package development estimates were made for the implementation time for each system required to develop the system. Difficulty was experienced estimating completion time frames and of consequence in later stages of the project, as identified by the risk plan, some stages were underestimated. Consequently this caused schedule, and measures had to be taken to ensure the project was not delayed.

It was also experienced that work was considered to be undertaken which the project resources were not significant allow for, in particular working hours. Measures had to be taken following delays after undertaking methodologies that were too complex. It is important in the future of the project that resource constraints are considered prior to recommendations. The literature recommendations were revised and project risk plan reflected the subsequent required project changes.

Assumptions were made that the telemetry data would be adequate when it was later discovered that the data did not provide enough information to validate the model. In future stages of the project it’s important to develop and ensure validation data is usable as quickly as possible through strong test planning.

# Appendices

None.