Title: ,

*“A Project”*

Prepared by Date \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

,

Authorised for use by Date \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

, Project Coordinator

**QUT Avionics**

Queensland University of Technology

S1110

Gardens Point Campus

Brisbane, Australia, 4001.

Telephone (+61 7) 313**8 1411**

e-mail luis.mejias@qut.edu.au

This document is Copyright 2009 by the QUT. The content of this document, except that information which is in the public domain, is the proprietary property of the QUT and shall not be disclosed or reproduced in part or in whole other than for the purpose for which it has been prepared without the express permission of the QUT

**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**

This paper is generated subsequent to review of literature pertaining to the development of a Predictive Flight Management System (PFMS) for an Uninhabited Aerial System (UAS).

Through extensive review of literature it is concluded that the PFMS will utilise MPC for the aircraft control model and a 6 Degree of Freedom (DOF) model for simulation of vehicle dynamics. Further, the document details considerations of incorporation of advanced concepts and recommends additional investigation prior to implementation.

**Table of Contents**

Paragraph Page No.

[1 Introduction 7](#_Toc228367772)

[1.1 Scope 7](#_Toc228367773)

[1.2 Background 7](#_Toc228367774)

[2 Reference Documents 8](#_Toc228367775)

[2.1 QUT Avionics Documents 8](#_Toc228367776)

[2.2 Non-QUT Documents 8](#_Toc228367777)

[3 Trajectory Engine 10](#_Toc228367778)

[4 Aircraft Control Model 11](#_Toc228367779)

[4.1 Model Predictive Control 11](#_Toc228367780)

[4.2 Manoeuvre Automation Theory 12](#_Toc228367781)

[4.3 Recommendation 12](#_Toc228367782)

[5 Vehicle Dynamics Model 13](#_Toc228367783)

[5.1 Recommendation 13](#_Toc228367784)

[6 Further Considerations 14](#_Toc228367785)

[6.1 Aircraft Intent 14](#_Toc228367786)

[6.2 Meteorology 14](#_Toc228367787)

[6.3 Collision Avoidance 14](#_Toc228367788)

[6.4 Computational Load 14](#_Toc228367789)

[6.5 Flight Management Systems 15](#_Toc228367790)

[7 Conclusions 16](#_Toc228367791)

[8 Appendices 17](#_Toc228367792)

**List of Figures**

Figure Page No.

[Figure 1 - Trajectory Engine 10](#_Toc228367793)

**List of Tables**

Table Page No.

No Tables.

**Definitions**

|  |  |
| --- | --- |
| PFMS | Predictive Flight Management System |
| UAS | Uninhabited Aerial System |
| DOF | Degree of Freedom |
| UAV | Unmanned Aerial Vehicle |
| ARCAA | Australian Research Centre for Aerospace Automation |
| QUAS | QUT Unmanned Aerial System |
| TE | Trajectory Engine |
| MPC | Model Predictive Control |
| RHPC | Receding Horizon Predictive Control |
| ATCo | Air Traffic Controller |
| 4D | Four Dimensional |

# Introduction

This paper is generated subsequent to review of literature pertaining to the development of a PFMS for a UAS. From the literature details recommendations for the implementation of the PFMS.

## Scope

This document outlines recommendations according to surveyed literature on the implementation of the PFMS.

## Background

QUT has been developing UAV 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 states of the aircraft, weather effects and successive waypoints. A PFMS allows for an Unmanned Aerial Vehicle (UAV) 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 traffic controller. 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 QUT Unmanned Aerial System (QUAS) resulting in the PFMS project. This paper is generated subsequent to review of literature pertaining to the development of a PFMS for a UAS.

# Reference Documents

## QUT Avionics Documents

|  |  |  |
| --- | --- | --- |
| RD/1 | QUAV-PFMS-SYS-HO-0001 | QUAV Project, PFMS, High Level Objectives for |

## Non-QUT Documents

|  |  |  |  |
| --- | --- | --- | --- |
| RD/2 | | 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/3 | | 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 | |
| RD/4 | | C. L. Castillo, W. Moreno and K. P. Valavanis, “Unmanned Helicopter Waypoint Trajectory Tracking Using Model Predictive Conrol”, in 2007 Mediterranean Conference on Control and Automation, Athens, 2007 | |
| RD/5 | | 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/6 | | 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/7 | | E. F. Camacho and C. Bordon, *Model Predictive Control,* London: Springer-Verlang, 2004. | |
| RD/8 | | A. Bemporad, M. Morari and H. L. Ricker, *Model Predictive Control Toolbox User’s Guide,* The MathWorks, Inc, 2006 | |
| RD/9 | E. Frazzoli, M. A. Dahleh, and E. Feron, “*Maneuver-based motion planning for nonlinear systems with symmetries*”, in IEEE Transactions on Robotics, pp.1077-1091, 2005 | |
| 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 | | T. Schouwenaars, J. How, E. Feron, “Receding horizon path planning with implicit safety guarantees” in *Proceedings of the 2004 American Control Conference*, Massachusetts, 2004 | |
| RD/12 | | L. Singh, J. Plump, M. W. McConley and B. D. Appleby, “Software Enabled Control:Autonomous Agile Guidance and Control for a UAV in Partially Unknown Urban Terrain”, in. *AIAA Guidance, Navigation, and Control Conference and Exhibit*, Austin, Texas (2003) | |
| RD/13 | | Aerosim Blockset. Unmanned Dynamics, 2003 | |
| RD/14 | | B.Gill and B. Maddock, “Prediction of Optimal 4D Trajectories in thePresence of Time and Altitude Constraints”, EUROCONTROL, 1997 | |
| RD/15 | | Flight Management System [internet]. 2007 [cited 2009 April 15]. Available from: http://en.wikipedia.org/wiki/Flight\_management\_system | |

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

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

# Trajectory Engine

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/2]. For the purpose of prediction of location at a required time the PFMS must develop a trajectory based on the aircraft intent, see section 6.1, and simulate aircraft guidance along the intended route in time.

A common published [RD/3, RD/4] 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

It is then reasonable that this review provides primarily insight on implementation of the aircraft control and vehicle dynamics models. In addition, the document investigates the implementation of aircraft intent, advanced considerations such as meteorology and required aircraft initial state information.

# Aircraft Control Model

A flight trajectory represents the motion of an aircraft as it moves to a desired position, or successive desired positions. 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 considerations of expected times of arrival are not considered in the control methods [RD/3]. 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.

Two suitable published 4D trajectory control methods investigated below in the sections.

## Model Predictive Control

Model Predictive Control (MPC), also called Receding Horizon Predictive Control (RHPC), has been used in industry since of the end of the 1970’s and is a published approach [RD/5, RD/6] with attitude considerations to trajectory generation. It can be considered the most general approach to a control problem in the time domain [RD/7]. MPC refers to a set of control strategies that are based on the ideas and concepts [RD/7] as follows.

* Explicit use of a model to predict the process output at future time instants;
* Computation of a control sequence minimising a cost or object function;
* Receding horizon strategy, in which at each instant the predicted behaviour is displaced towards the future and only the first control signal calculated at each step is applied.

The advantages of utilising MPC for the purpose of trajectory prediction over other methods are as follows.

* Attractive to users with only a limited knowledge of control as the concepts are intuitive;
* Supports constrains of variables associated with a control problem such as inputs, outputs or state variables;
* It can be used to control a systems with complex dynamics with intrinsic compensation for dead time, non-minimum phase dynamics and unstable systems;
* Basic formulation can be extended to multivariable plants easily;
* Ability to use future values of references when they are available, allowing MPC to improve performance in navigation such as trajectory generation;
* MPC can be implemented using the Matlab Model Predictive Control Toolbox (MPCTB) [RD/8], which has a graphical user interface (GUI) that allows for an interactive design of controllers.

## Manoeuvre Automation Theory

An alternative approach to trajectory prediction, with attitude considerations, is the application of manoeuvre automation theory. Manoeuvre automation theory is a published approach [RD/9] where a hybrid model of the dynamics of a vehicle, known as a manoeuvre automaton (MA), is developed. The MA consists of a finite collection of two types of motion primitives, specifically trim conditions and manoeuvres [RD/10]. A trim condition is a dynamic equilibrium of the vehicle and a manoeuvre is defined as a finite time transition between two trim conditions. Hence, smooth feasible flight trajectories can be formed via concatenation of predefined trim and manoeuvre primitives [RD/2]. The implementation of manoeuvre automation theory requires advanced concepts such as dynamic programming, as employed in related research [RD/11, RD/12].

## Recommendation

Due to the detailed advantages the implementation of a model predictive controller is more feasible then use manoeuvre automation theory for trajectory planning. This is due to project time constraints, limited knowledge of control theory and availability of support tools and related research regarding MPC.

# Vehicle Dynamics Model

The inclusion of vehicle dynamics during trajectory generation allows for trajectories which account for platform constraints and increase prediction accuracy [RD/2]. 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-DOF model allows for platform constraints of minimum stall velocity, maximum velocity, minimum turn radius and maximum climb and descent rates [RD/2]. For incorporation of attitude rate constraints a more complex 6-DOF is required.

## Recommendation

From literature, from an Air Traffic Controllers (ATCo) perspective a trajectory can be sufficiently generated through the use of a 6-DOF model [RD/3]. 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/13]. This will allow for validation of simulations of the PFMS during implementation.

# Further Considerations

In the subsequent sections further considerations pertaining to the implementation of the PFMS are detailed with relevant literature.

## Aircraft Intent

Aircraft intent is the navigation data, aircraft waypoints as defined by the ATCo, and the control power available to intercept a waypoint. The measure of control power is valuable as platforms may reduce control power to decrease the chance of loss of platform control [RD/2]. Thereby, the PFMS control model requires constraints on the control power available.

## Meteorology

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/14]. In later stages of the project meteorology may be accounted for during trajectory prediction.

## Collision Avoidance

In advanced stages of the project the PFMS may include concepts such as autonomous collision avoidance. The trajectory engine proposed within this document is alike that published in literature [RD/2, RD/3, RD/14] which are capable, with more computational load, of collision avoidance.

In advanced stages of the project literature will be reviewed to provide insight into implementing collision avoidance considerations.

## Computational Load

The prediction accuracy is coupled with the complexity of the trajectory planning and guidance models and consequently the computational effort required [RD/3]. Thereby, the relationship between computational effort and trajectory prediction accuracy defines the limits of the trajectory engine as it must be suitable for airborne implementation where computational resources available are limited.

For the initial stages of the project it is assumed that the hardware will capable to operate the prediction model. Similar models in literature [RD/4] as proposed in this document suggest that implementation is possible considering available computational power onboard a UAS.

## Flight Management Systems

An FMS is a fundamental part of a modern aircraft in that it controls the navigation, for further information see [RD/15]. For an unmanned autonomous aircraft navigation is performed by the aircraft control system. For the purpose of the PFMS it is not required to control the navigation of the aircraft, rather aid in validation of navigation data. This is reflected in the projects HLOs as per RD/1.

# Conclusions

Through extensive review of literature it is concluded that the PFMS will utilise MPC for the aircraft control model and a 6-DOF model for simulation of vehicle dynamics. Further, the document details considerations of incorporation of advanced concepts and recommends additional investigation prior to implementation.

# Appendices

None.