Title: , Autonomous Helicopter Navigation System, System Level, Traceability Matrix and Lessons Learnt

*“A Project”*

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**Foreword**

This document outlines the verification of success for the system requirements establish for the 2010 AHNS system. The system requirements and its corresponding test report which verifies the level of success is outlined in tractability matrices. At the commencement of the project, twenty system requirements were outlined in RD/2, to which eighteen requirements were completed at the end of the AHNS project. The two system requirements that were not completed were localisation with computer visions (SR-B-07) and position hold of the platform (SR-D-04).

At the completion of the project, several recommendations from project members experiences were recorded, which are to be used for future years to ensure difficulties and poor decisions faced this year are not repeated.

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**Definitions**

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| --- | --- |
| AHNS | Autonomous Helicopter Navigation System |
| QUT | Queensland University of Technology |
| CoM | Centre of Mass |
| IMU | Inertial Measurement Unit |
| HLO | High Level Objective |
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# Introduction

The traceability matrix is a systems engineering tool which allows verification of success for the project with respect to the system requirements outlined at the commencement of the year. By documenting the completion of system requirements, and thus the HLOs, can be verified. The linking of test outcomes for system requirements provides traceability of the HLOs. This document details the traceability of the 2010 Autonomous Helicopter Navigation System project system requirements.

## Scope

This document outlines verification of success for individual system requirements for the 2010 AHNS project.

## Background

Throughout the semester, testing on the autonomous helicopter navigation system has been undertaken to provide feedback on the level of success for each of the pre-determined system requirements.

# Reference Documents

## QUT Avionics Documents

|  |  |  |
| --- | --- | --- |
| RD/1 | AHNS-2010-SY-HL-001 | AHNS, High Level Objectives of |
| RD/2 | AHNS-2010-SY-SR-001 | AHNS, System Requirements of |

## Non-QUT Documents

None.

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.

# Requirements Traceability and Conformance

A traceability matrix is necessary to document whether or not the system requirements were verified; and in turn, indicate the standing of the HLOs. The system requirements, as found in RD/2, have been classified as baseline and derived. The following sections outline the conformance for all system requirements.

## Baseline Requirements

Table - Traceability Matrix for Baseline Requirements

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Number** | **Definition** | **Status** | **Reference Document** | **Additional Information** |
| SR-B-01 | The platform shall have the ability to be manually manoeuvred with a radio controller. | Completed | AHNS-2010-PL-TR-002 |  |
| SR-B-02 | The GCS shall enable autopilot flight mode switching between manual, stability augmented flight, and autonomous station keeping. | Completed | AHNS-2010-GC-TR-001 |  |
| SR-B-03 | The airborne system shall provide control updates at an average rate of 50Hz. | Completed | AHNS-2010-AP-TR-001 |  |
| SR-B-04 | The estimator shall provide Euler angle and rate estimation for the system an average rate of 50 Hz. | Completed | AHNS-2010-SE-TR-001 |  |
| SR-B-05 | The estimator shall provide altitude estimation for the system an average rate of 50 Hz. | Completed | AHNS-2010-SE-TR-001 |  |
| SR-B-06 | The estimator shall provide x and y estimation in an Earth fixed co-ordinate system an average rate of 50 Hz. | Completed | AHNS-2010-SE-TR-002 |  |
| SR-B-07 | The system shall use image processing to aid in state estimation of x and y in an Earth fixed co-ordinate system. | Not Complete |  | The introduction of VICON resulted in the image processing to become redundant. |
| SR-B-08 | The autopilot system gain and reference parameters shall be updatable in flight using an 802.11g WLAN uplink from the GCS. | Completed | AHNS-2010-GC-TR-001 |  |
| SR-B-09 | The airborne system shall transmit telemetry data including state data to the GCS using 802.11g WLAN. | Completed | AHNS-2010-AP-TR-002 |  |
| SR-B-10 | The autopilot control methodology shall be based on cascaded PID control loops. | Completed | AHNS-2010-AP-DD-001 |  |

## Derived Requirements

Table - Traceability Matrix for Derived Requirements

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Number** | **Definition** | **Status** | **Reference Document** | **Additional Information** |
| SR-D-01 | The platform shall be capable of maintaining controlled flight with a total payload of 400 grams. | Completed | AHNS-2010-PL-TR-002 |  |
| SR-D-02 | A maintenance document shall be used to log airframe flight time, battery cycles and aircraft repairs. | Completed | AHNS-2010-PL-TR-001 |  |
| SR-D-03 | The autopilot shall provide stability augmented flight. | Completed | AHNS-2010-SY-TR-001  AHNS-2010-SY-TR-002 |  |
| SR-D-04 | The autopilot shall provide autonomous station keeping capability within a 1 meter cubed volume of a desired position. | Not Completed | AHNS-2010-SY-TR-003  AHNS-2010-SY-TR-004 | Hardware and software fully implemented, but safety concerns stopped testing for position hold. |
| SR-D-05 | The airborne system shall receive and process measurement data from the state estimation and localisation sensors; supporting IMU, Camera, and Ultrasonic sensor. | Completed | AHNS-2010-AP-TR-002 |  |
| SR-D-06 | The airborne system shall collect avionics system health monitoring information in the form of radio control link status, flight mode status and battery level. | Completed | AHNS-2010-AP-TR-002 |  |
| SR-D-07 | The airborne system shall transmit all actuator inputs, including radio control inputs, to the GCS. | Completed | AHNS-2010-AP-TR-002 |  |
| SR-D-08 | The GCS shall log all telemetry and uplink data communications. | Completed | AHNS-2010-GC-TR-001 |  |
| SR-D-09 | Aircraft state data and control inputs received shall be displayable on the GCS along with appropriate time references. | Completed | AHNS-2010-GC-TR-001 |  |
| SR-D-10 | The GCS shall provide display of avionics system health monitoring including telemetry, uplink, radio control link and battery level status read-outs. | Completed | AHNS-2010-GC-TR-001 |  |

# High Level Objective Conformance

Using the information outlined in the traceability matrices for the system requirements, the high level objectives are analysed for level of success. The project goals have been split into six HLO’s, with encompasses all requirements that must be achieved to complete the project.

Table - High Level Objective Conformance Matrix

|  |  |  |  |
| --- | --- | --- | --- |
| **High Level Objective** | **Definition** | **Status** | **Additional Information** |
| HLO-1: Platform | A platform should be developed and maintained to facilitate flight and on board hardware integration. | Completed |  |
| HLO-2: Localisation | The system should be capable of determining its position with the aid of image processing within an indoor environment to an appropriate time resolution. | Not Completed | Due to the introduction of VICON, image processing no longer required. |
| HLO-3: State Estimation | A method of estimating the states of the helicopter system should be designed and implemented. The resolution of the estimations should facilitate their employment in the control system design. | Completed |  |
| HLO-4: Autonomous Hovering Flight | An autopilot system should be developed to enable sustained indoor autonomous hovering flight. The control system should be designed to enable future ingress and egress manoeuvre to longitudinal and hovering flight. | Part Completed | Attitude stability without position hold accomplished. |
| HLO-5: Ground Control Station | A ground control station that supports appropriate command and system setting inputs and data display and logging should be developed. The design should be derived from previous AHNS developments and enable future ground station developments. | Completed |  |
| HLO-6: Communications | The communications system should enable transfer of control, state and localisation data to the ground control station. It should provide with a flexible wireless data link available on consumer-electronic devices. | Completed |  |

# Lessons Learnt

At the completion of the project, several recommendations from project members experiences are recorded below, which are to be used for future years to ensure difficulties and poor decisions faced this year are not repeated. The lessons learnt are divided into four categories below, system level, hardware, on-board software and the ground control station.

## System Level

The following recommendations for the system level and administration of the AHNS project should be taken into consideration for future projects.

* Ensure all system requirements and preliminary designs are defined early, as changes to the goals or system introduces large scheduling risks.
* The work breakdown structure should be organised into large overall tasks, as the project aims, designs and methods will change during the semester, therefore resulting in project plans that do not lead to the desired outcome.
* The testing phase of the project should commence at the beginning of semester two, as the AHNS project requires a lot of time for calibrating the system for flight conditions.
* Organise the project time schedule to incorporate other subject assignment due dates, as project productivity was found to drop significantly during this time.
* The risk management plan must be completed and approved well before testing commences, and ensure that all possible testing locations has been authorised.
* Safety with the platform while being powered is paramount, as engines can often start without warning with unverified code.
* Ensure all flight tests are recorded for future review against logged data.
* Due to batteries requiring four times longer recharging that the flight time they produce, ensure a large number are available for flight-testing.
* Purchase additional electrical hardware components to mitigate schedule delay from broken parts after flight crashes.

## Hardware

* Using the Overo Fire for the flight computer created system update lag. This was because the Overo Fire is running an operating system (Linux based) and is thus utilising a soft real time system. The flight computer therefore could never guarantee that it would execute system updates within a specified time period. Precise system updates could be achieved by porting the flight computer to a dedicated processor. The dedicated processor should only be running the flight computer process, meaning that the entire system will be updated as fast as possible.
* Porting the flight computer code onto a non based operating system solution has ramifications for the communications subsystem. The communications protocol is built off a UDP client server architecture which can only be available when using an operating system. Thus the communications server located on the flight computer should stay on the Overo Fire but all other flight computer processes should be relocated to a dedicated processor. The Overo Fire will thus be transformed into a telemetry link so that clients can receive flight computer data. The connection between the Overo Fire and the dedicated processor should be implemented via the USB link on the Overo Fire pinto board. Using a USB connection will remove the need for logic level shifting since the Overo Fire sends and receives serial data at 1.8V levels.
* The scope of the project needs to be considered carefully to ensure too much work is not being expected. There is limited time to develop a system within an undergraduate course. If the objective of a project is to simply develop hardware than this is all that should be achieved. If the objective of the project is to achieve any form of waypoint navigation or station keeping, hardware should be acquired by other means. That is, all hardware components should be adopted from tested, open source projects or commercial systems. Given the limited time and resources available during an undergraduate degree there is simply insufficient time to develop and test a low level hardware system and develop high levels functionality.
* The development of an autopilot hardware system is a complex undertaking. Given, this, a minimum of two people should be assigned to this system. Two hardware oriented people would ensure all designs are double check more efficiently. It would also mean that designs can be broken up between two people and developed in parallel. Additionally two people could be used to speed up the manufacturing and testing process associated with hardware development.
* Another consideration to be made is to project more time for the hardware development stage. In this project, the time taken for development of hardware by a single person was underestimated. The development stage should be started sooner and time should be allocated to allow the process to end later. In addition to this considerations should be made to facilitate parallel development of software and hardware. This created a bottleneck as software development was held up, waiting for the hardware to be completed.
* As a final note on lessons learnt for hardware development, considerations should be made to establish a standalone project for the hardware development of an autopilot. This would allow the entire year to develop the system and ensure the best possible design decisions are made.

## On-board Software

* Accelerometer data sent by the IMU is completely raw ADC data transmitted via a serial UART. Under normal circumstances this accelerometer data is generally useful and can provide good coarse measurements for and . However during dynamic platform movement, vibrations began to develop which affected the accelerometer data readings. To reduce the effect of the vibrations, low pass filtering needed to be introduced. Care had to be taken when deciding on the level of low pass filtering by adjusting certain smoothing parameters. Too much smoothing caused the and estimates to become unresponsive even under static platform attitude manoeuvres. The use of low pass filters wasn’t just limited to accelerometers, all sensors which used ADC data output had to be filtered using this method as well.
* Developing high level control using vision based sensors proved to be difficult to design. This was primarily because the quadrotor platform was built in house and no commercial off the shelf solutions were sought (as per the project specifications). Due to this and the strict project timeline, a stable quadrotor platform was only achieved towards the end of the project. The ability to design visual high level control (within the project timeline) would require a stable quadrotor platform to be available at the beginning of the project inception. Only then could visual based control be designed and implemented effectively.

## Ground Control Station

* Development of the GCS from scratch required a considerable time investment. The effects of such a time outlay where felt until the end of the project as flight testing time was effectively reduced by three months. Although this time was also used in other subsystems it limited the time available for systems testing and control development; arguably the most important aspects of the project. In 2009 AHNS also developed two GUIs from scratch representing more time lost from the development of an autonomous system. Much of the 2009 code was not used due to a major changing in system architecture; specifically the change in communications and control location. It is recommended that future groups avoid making GCS development a project objective and either modify legacy code (of which there are now two proven, available and modular solutions) or rely on MATLAB or pre-built solutions such as the open source QGroundStation.
* If major pieces of software such as a GCS or network library do need to be developed, documentation and unit testing should be considered part of the development time rather than extra task to be completed. It was realised only after the majority of code was implemented that documentation tools such as Doxygen were capable of generating high quality code documentation. With respect to unit testing, no time was explicitly allocated to test the implementation or develop methods to test individual aspects of the implementation. Although the GCS is stable, without unit testing there is only user experience to support this claim.
* As the software project became large, it became increasingly difficult to add features to the coupled and often confusing Qt signal/slot architecture. This could have been avoided,, particularly in the handling new UDP messages, by using generic programming and centralising more code behaviour.

## Control

* Controller development relied on states provided by the state estimation subsystem during initial testing. Development of both subsystems was rapid therefore it was not always possible to have a coordinated understanding of the system’s behaviour. Future efforts should focus on developing tested control and state estimation systems prior to their combined flight testing.
* Initial control design was verified using a rigid body quadrotor simulator. In simulations with ideal engine and propeller dynamics and with perfect knowledge of the states, control was a simple exercise in angle control. Ultimately the results from the simulations proved unusable as the pilot needed to correct aircraft drift and the state estimation was not capable of ideal state determination. It was learnt that controller design based on proven controller designs from a practical projects are generally superior to those developed with idealised simulations.
* To avoid platform damage, several testing apparatus were created. The use of these was generally only useful in checking the direction of controller corrections as the platform dynamics are affected or restricted. Gains could only be tuned in practical flight tests.
* Tunning position and altitude control proved to be inherently hazardous to equipment, personnel and the platform itself. With the discrediting of the test rigs and bungee apparatus there was insufficient time to reconsider mitigation methods to tune these controllers, their flight testing was therefore discontinued. Measures such as safety nets, foam padding or isolated testing rooms should be considered to enable safer flight testing.
* The effects pulse capture and pulse generation have on controllability of the system should be examined. The current PWM generation resolution of 16 micro-seconds has been seen to offer imprecise control loop updates. That is, in altitude control essentially the controller is either on or off resulting in considerable oscillations. An improved method of ESC control should therefore be developed. This involves essentially choosing an MCU crystal that enables a hardware generation, high frequency PWM signals with a precise resolution. If this is not possible I2C ESCs should be considered or a software based PWM generation scheme used.
* The update rate of the control is limited by choice of MCU baud rate, which is limited by the choice of pulse width capture resolution which is limited by the choice of hardware crystal. To solve the update rate limitations it is suggest the control is move to the same microprocessor that handles pulse capture so that RC information is not delayed.

# Conclusions

The Autonomous Helicopter Navigation System aim is to develop a helicopter system capable of autonomous control, navigation and localising within a GPS denied environment. The 2010 AHNS project was focused around developing a platform that was capable to stabilise attitude using an on-board PID controller, and design the platform to enable future development. The system requirements developed at the beginning of the year were all completed, with the exception of one baseline and one derived requirement. The baseline requirement was focused on developing localisation using computer vision, which due to the introduction of VICON, image processing no longer required. The derived requirement that was not completed was to achieve position hold to a desired location. The hardware and software for this requirement were designed and implemented into the platform, but due to safety concerns with testing the position hold, the requirement was never tested.

The lessons learnt from all members of the 2010 AHNS project are outlined to ensure that for future years do not repeat difficulties and poor decisions faced this year are not repeated.