UAV Challenge: Outback Rescue 2014
Search and Rescue Challenge

# Deliverable 2: Technical Report & Video

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## 1 Statement of originality and accuracy

We declare this report is entirely the work of the team members listed below, and has not previously been submitted by us, or others for this challenge or any other similar event.

We have acknowledged external material with appropriate references, quotes or notes to indicate its source.

We declare that this report is an accurate record of activities carried out by us in preparing for this specific challenge. The events, data and other material contained within this report actually occurred and have been fully detailed.

**Team members:** Ben Dyer, Daniel Dyer

## 2 Compliance statement

**Team name:** [SFWA]

We declare that this report and the entry that it describes complies with the rules of the 2014 UAV Challenge Outback Rescue, and that we enter with the intention of competing in the spirit of the challenge. Specifically we declare that our entry is compliant with the following topics and provide reference to within our Deliverable 2 document where our method of compliance is described.

| Rules reference | Topic | Compliance | D2 reference |
|---|---|---|---|
| **Mandatory / essential** | | | |
| § 2.3 | The aircraft and other infrastructure | Compliant | § 5.3 (p. 9),<br>§ 5.4 (p. 10),<br>§ 5.8 (p. 11) |
| § 3.2 | Aeronautics | Compliant: airspeed | § 5.5 (p. 10) |
| § 3.3 | Altimetry | Compliant | § 5.5 (p. 10),<br>§ 5.8 (p. 11) |
| § 5.1 | Aircraft requirements and limitations: all | Compliant | § 5.2 (p. 9),<br>§ 7.1 (p. 18) |
| §§ 5.3.1, 5.3.2, 5.19, 8 | Radio equipment frequencies: ACMA compliance and licensing | Compliant | § 6.9 (p. 15) |
| § 5.4 | UAV controller overide: compliance to override requirement or safety case provided | Compliant: override | § 5.7 (p. 11) |
| § 5.5 | In-flight failures and emergencies: all (once activated cannot be overridden) | Compliant | § 5.9 (p. 11) |
| § 5.5.1 | Criteria for flight termination: all (state machine diagrams and transitions provided) | Compliant | § 5.9 (p. 11),<br>§ 6.10 (p. 16) |
| § 5.5.2 | Loss of data link: all | Compliant | § 6.11 (p. 16) |
| § 5.5.3 | Engine failure: procedure provided | Compliant | § 6.15 (p. 17) |
| § 5.5.4 | Loss of GPS: all and nomination of the implemented option for recovery | Compliant: flight termination | § 6.12 (p. 16) |

| Rules reference | Topic | Compliance | D2 reference |
|---|---|---|---|
| §§ 5.5.2, 5.5.4 | Loss of data link and loss of GPS: all | Compliant | § 6.12 (p. 16) |
| § 5.5.5 | Mission boundary crossing — geofence: all | Compliant | § 5.9 (p. 11),<br>§ 6.10 (p. 16) |
| §§ 5.5.2, 5.5.5 | Loss of data link and mission boundary crossing — geofence: all | Compliant | § 5.9 (p. 11),<br>§ 6.10 (p. 16) |
| § 5.5.6 | Lock-up or failure of autopilot: all | Compliant | § 6.13 (p. 16) |
| § 5.5.7 | Lock-up or failure of GCS: all | Compliant | § 6.14 (p. 16) |
| § 5.5.8 | Lock-up or failure of stability augmentation system: all | Not applicable | |
| § 5.5.9 | Lock-up or failure of mission boundary crossing detection: all | Compliant | § 5.9 (p. 11),<br>§ 6.13 (p. 16) |
| § 5.6 | Flight termination: all | Compliant: § 5.6 implemented | § 6.10 (p. 16) |
| § 5.6.1 | Commercial/off-the-shelf flight termination system used: manfacturer evidence provided | Not applicable | |
| § 5.10 | Team sponsors: all | Compliant | § 2 (p. 6) |
| § 5.16 | Situational awareness: graphical display of waypoints and aircraft location | Compliant | § 5.8 (p. 11) |
| § 5.16 | Situational awareness: NMEA 0183 output | Compliant | § 5.8 (p. 11) |
| § 5.23 | Search strategy | Compliant | § 8 (p. 20) |
| § 5.24 | Cooperation between teams | Compliant | § 3 (p. 7) |
| § 6.2.1 | Statement of originality and accuracy: all | Compliant | § 1 (p. 3) |
| § 6.2.2 | Compliance statement: all | Compliant | § 2 (p. 4) |
| § 6.3.1 | Overview of Deliverable 3 | Not applicable: Deliverable 2 submission | |
| § 6.3.1 | Deliverable 3 Requirements | Not applicable: Deliverable 2 submission | |

| Rules reference | Topic | Compliance | D2 reference |
|---|---|---|---|
| **Highly desirable** | | | |
| § 5.15 | Access to video stream from UAV | Compliant, subject to 3G connectivity | § 5.8 (p. 11) |
| § 5.17 | Lithium polymer battery management | Compliant | § 6.16 (p. 17) |
| § 5.22 | Off-site data processing | Not applicable | |
| § 5.25 | Soft geo-fence | Not applicable | |
| § 6.2 | Deliverable 2: max 21 pages | Compliant | p. 2 |

**Additional information:** No sponsorship was sought. All costs involved in the *Challenge* have been borne by members of the team.

Although we have benefited from publicly available reports written by previous *Challenge* competitors, no direct co-operation with any other teams has occurred to date.

The video component of our Deliverable 2 submission is available at vimeo.com/bdyer/sfwa-d2.

**Date:** 20th April, 2014
**Signed by a team representative, on behalf of all team members:**

**Printed name:** Ben Dyer

## 3 Executive summary

Using a combination of simple, low-risk aerodynamic and mechanical design with innovative, high-performance measurement and control systems, the UAS we are developing for the *Search and Rescue Challenge* event in the *UAV Challenge: Outback Rescue 2014* (hereafter *Challenge*) will provide greater reliability and navigational accuracy than has previously been feasible in small uncrewed aircraft. From the outset, our system has been developed with the requirements of the *Challenge* in mind, and key features like failsafe hardware, geofencing, and fault handling procedures are fully integrated into our design.

Our approach to risk assessment and management has focused on reduction of hazards to safety and mission capability, preferring to invest in up-front engineering effort in order to reduce the probability of failure during the *Challenge* scrutineering and mission. We have developed comprehensive checklists covering all stages of flight operation, and use sound change management practices to facilitate continual improvement in our systems.

In addition to the extensive software and hardware testing we have performed, we have flown for several hours in a variety of conditions including wind up to $15\,\mathrm{m\,s^{-1}}$ (29 kn). All flight testing has been conducted using aircraft identical to the one we will use in the *Challenge*.

Excepting of the main search camera, all mechanical and electronic systems have been fully integrated and flown several times with positive results. With a 12–month record of safe flight operations, we have obtained sufficient data and experience to support a high degree of confidence in our design's ability to meet the requirements of the *Challenge* and successfully complete the mission.

In acknowledgement of the significant benefit we derived from the reported experiences of teams in previous *Challenges*, most notably CanberraUAV, we are publishing a number of reports covering our progress towards meeting the requirements of the *Challenge*, and have released the source code for our software under a permissive open-source licence. This report and the associated video are also available on our website.

# 4 Introduction

Following on from the high-level design approach outlined in our Deliverable 1 submission, this report details our compliance with the *Search and Rescue Challenge: Mission, rules and judging criteria [version 1.2]* (hereafter *Rules*) and our ongoing efforts to develop a reliable, safe UAS with a high degree of autonomy. Section 5 (p. 9) provides further information about our system design, including aerodynamic requirements, control capability and fault response procedures; section 6 (p. 13) describes the steps we have taken to ensure regulatory and *Rules* compliance. Finally, section 7 (p. 18) contains a brief overview of the current status of our entry, including performance test results and an empirical evalution of our earlier risk assessments.

The documentation of our design approach has been divided into sub-sections covering each of the major components and sub-systems used. These components and sub-systems were selected on the basis of a set of system requirements obtained from the *Rules* as well as a review of past *Challenge* results. This report focuses on compliance and safety aspects of our design; more detailed technological documentation on the hardware and software involved are outside the scope of this report, but are available on our website.

The basis for our approach to risk management was the risk assessment matrix we submitted in Deliverable 1. Since that time we have revised the matrix based on our flight testing experiences. This document includes a revised version of the matrix as a high-level overview of the remainder of our risk management documentation, which focuses on detailing our compliance with applicable sections of the *Rules* as well as ACMA and CASA regulations.

Our discussion of flight test results covers the major sub-systems and of our UAS in a topical manner, with the performance of each major sub-system justified using the data we have collected. We also outline our review of earlier risk assessments and discuss steps we will take to manage risk later in the development process.

# 5 Design approach and rationale

## 5.1 Objective

Prior to commencing design, we conducted a review of previous *Challenge* results and the reports of various participating teams; this review informed our understanding of the performance requirements of the *Challenge*, as well as our assessment of the risks involved. Our UAS design objective was to minimize operational risk, subject to the constraints imposed by specific *Challenge* requirements and the *Rules*.

## 5.2 Requirements and constraints

We identified the following primary requirements (subject to *Rules* § 5.1):

- Ability to map 2 $\text{km}^2$ within 30 min at 10 cm $\text{pixel}^{-1}$ resolution with georeferencing accuracy around 10 m;
- On-board processor for image recognition;
- Radio communications range of at least 10 km;
- Communications bandwidth sufficient to transmit a 1 ha tile (1000 × 1000 pixels) every minute;
- 60 min endurance at cruise speed;
- Ability to fly under manual or automatic control in winds up to 13 $\text{m s}^{-1}$ (25 kn);
- Ability to carry a 600 g detachable payload and 900 g of equipment (camera, autopilot, on-board processor and radios).

Based on these requirements we determined a set of constraints on performance:

- Maximum take-off weight (MTOW) from 4–25 kg;
- Cruise speed 20–30 $\text{m s}^{-1}$;
- Endurance of 60 min with a 15 min reserve;
- Range 70–100 km;
- Camera resolution at least 1 Mpixel with a 60° diagonal field of view;
- On-board imaging processor at least 1.5 GHz ARM with 512 MiB RAM;
- AHRS error lower than 5° at 95th percentile.

## 5.3 Airframe

A number of suitable airframes were available, ranging from larger battery-powered foam models through to mid-size petrol-powered models up to 20 kg. From an operational risk standpoint we judged that the primary disadvantage of smaller airframes was that range and stability would be impacted more significantly by wind; the primary disadvantage of larger airframes was that the increased complexity (time, space, experience) involved in operating them safely would greatly reduce the time that could be spent in flight testing.

We decided that the increased testing opportunities afforded by a smaller airframe would outweigh the range and stability advantages of a larger airframe. Of the smaller airframes, we judged the battery-powered Skywalker X-8 flying wing, with a MTOW of approx 5 kg most suitable for this application.

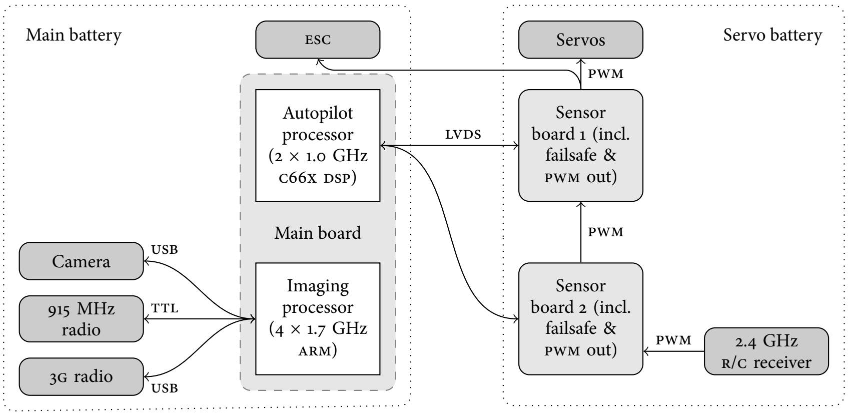
### 5.4 Autopilot

Aside from the airframe the most important development choice was the autopilot platform. Based on our review of off-the-shelf systems it was not clear that any of them performed sufficiently well in moderate winds (15–25 kn, cf. *Rules* §§ 3.2, 9) on smaller airframes; in addition, our review of previous *Challenge* participants suggested the complexity of many systems was an impediment to reliable operation.

Thus, with reference to *Rules* § 3.2 we decided to develop an autopilot platform optimised for platforms with challenging aerodynamics, placing emphasis on implementation simplicity and robustness. The operational requirements of the *Challenge* (failsafe, geofencing, control transitions, loss of data link and loss of GPS procedures) would be designed into the system, and therefore subject to extensive testing. While this approach would expose our entry to greater development risk, operational risk would be correspondingly reduced.

Our autopilot software incorporates algorithms that have been the subject of extensive research, and that offer near-optimal performance within our problem domain. The AHRS and position estimator uses an unscented Kalman filter (UKF) running at 1000 Hz, with feeds from dual-redundant sensor modules. The navigation system generates reference trajectories from path-based flight plans which are then refined and executed by a non-linear model predictive control (NMPC) system running at 50 Hz with a 2 s horizon. The control system uses a flight dynamics model developed for our aircraft, ensuring that the controller maintains appropriate airspeed and alpha.

The electronic configuration of our aircraft is outlined below:



### 5.5 Sensors

Each of the two sensor boards contains an MPU-6000 triaxial MEMS accelerometer/gyroscope, read at 1000 Hz; an HMC5883L triaxial magnetometer, read at 110 Hz; an MS5611 barometric pressure sensor, read at 330 Hz; an MS4525DO differential pressure sensor connected to a pitot tube, read at 1000 Hz; and a u-blox NEO-7N GPS module, read at 10 Hz. Under normal circumstances, the AHRS fuses data from both sets of sensors to improve noise rejection; however, only one of each sensor is required for the system to remain mission-capable (*Rules* § 5.5.9 ¶¶ 2–3).

### 5.6 Imaging

Our imaging processor is a quad-core 1.7 GHz ARM CPU with 1 GiB of DDR3 RAM, linked directly to the autopilot processor. Image processing and target recognition will be performed entirely on-board using the OpenCV imaging library.

### 5.7 Communications

In addition to the 2.4 GHz manual radio control receiver (Spektrum DX6i), our aircraft has two on-board radios: an RFD900 915 MHz radiomodem, and a Sierra Wireless 3G modem. All radios have diversity antennas.

The RFD900 radiomodem is the primary telemetry link, and is connected to the autopilot processor via one of the two sensor boards. The primary telemetry link includes a small amount of bandwidth for imaging data to provide redundancy.

The 3G modem is a mini-PCIe form factor card integrated into the main board, and connected to the imaging processor via on-board USB. This link transmits imaging data to the GCS, and also contains a redundant telemetry feed from the autopilot processor.

Manual control override (*Rules* § 5.4) is implemented via the 2.4 GHz radio control link. A two-position switch located on the transmitter is able to activate manual control regardless of the state of the autopilot, except during flight termination (*Rules* § 5.5).

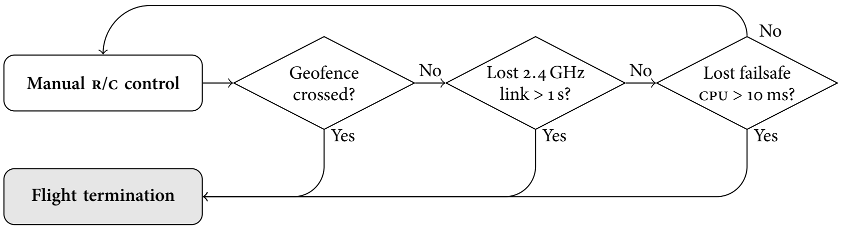
### 5.8 Ground control station

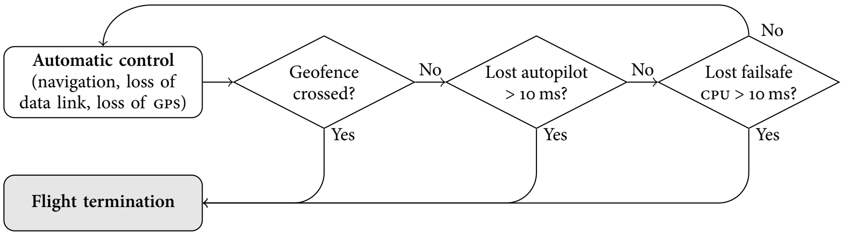
The ground control station (GCS) is a client/server system based on a BeagleBone Black single-board computer (the server) and one or more laptop computers (the clients). The server is connected to an RFD900 with diversity directional antennas, a 3G modem, and a barometric pressure sensor board for real-time update of pressure at ground level.

The server manages all communications with the aircraft, and presents a custom browser-based interface to the client systems. This interface displays the configured waypoints, the current state of the aircraft (including airspeed and pressure altitude), and if sufficient bandwidth is available, a low-rate video feed from a forward-facing camera on the aircraft (*Rules* § 5.15). The server also provides a NMEA 0183 serial feed (*Rules* §5.16).

### 5.9 Flight termination and geofencing

Flight termination (*Rules* § 5.6) is performed by the AVR32 processors on the redundant sensor boards. These boards have an electrically separate power supply dedicated to them and the servos, ensuring that flight termination can occur even after complete failure of the main batteries. All electrical connections between the sensor boards and the autopilot board are isolated.



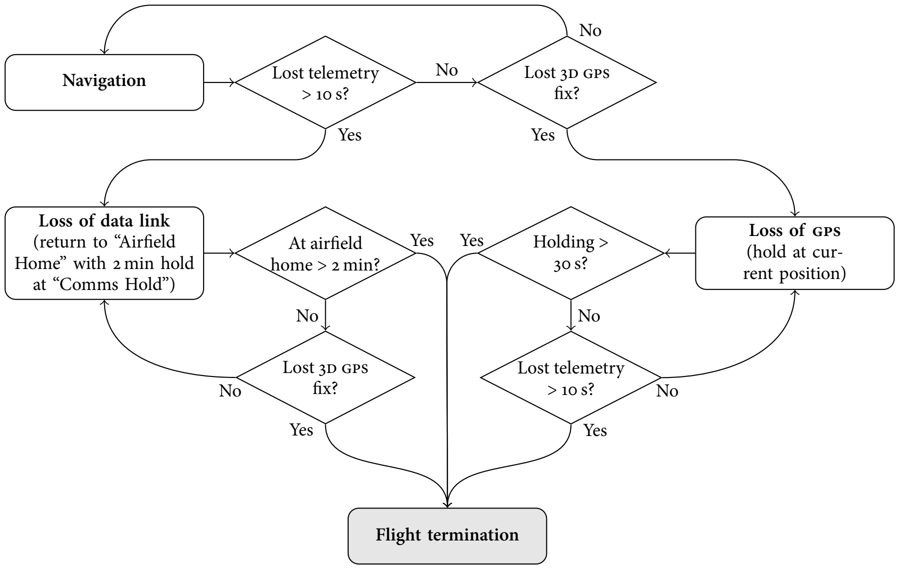


Since the boards have integrated GPS modules, both boards perform geofencing based on the GPS position estimates before they have been fused by the autopilot processor. The autopilot processor performs its own geofencing as well, and if a single device detects a mission boundary crossing in any operating mode—including loss of data link or loss of GPS (by dead reckoning)—the flight will be terminated.

Once flight termination has commenced (for any reason), it is not able to be overridden or reset except by removing power from all on-board electronics (*Rules* § 5.5). The diagrams above describe the control logic governing flight termination in manual and automatic modes respectively; the indicated logic for automatic control is active during normal automatic flight as well as the loss of data link and loss of GPS procedures.

### 5.10 Autonomous handling of fault states (loss of data link, loss of GPS)

The *Challenge* procedures for loss of data link and/or loss of GPS are implemented in the core of our autopilot, and are active in all automatic flight modes. The effect of these procedures on the flight control and termination state is outlined in the diagram below; full descriptions of the procedures as implemented are available in §§ 6.11 and 6.12 (p. 16).



### 5.11 Autonomous handling of additional fault states (AHRS divergence, loss of control)

In addition to the procedures defined in the *Challenge* rules, we also implement procedures for AHRS divergence and loss of control. The AHRS divergence procedure is triggered when the estimated 95th percentile error for the aircraft's attitude, velocity or position exceeds defined thresholds; the effect is the same as loss of GPS (see above). Loss of control is triggered when the the predicted trajectory of the aircraft diverges from the reference trajectory. This triggers a switch to a stabilisation trajectory, relaxing navigational accuracy requirements in order to ensure a quick return to level flight. Once the aircraft has been stabilised, it resumes normal navigation. In the event of control surface or motor failure, the loss of control procedure will enter a shallow dive leading to ground impact.

# 6 Risk management approach

## 6.1 Overview

Our Deliverable 1 submission included a detailed risk assessment which has guided our implementation of development and operating procedures. Since preparing that assessment the only major change has been a switch to lithium polymer batteries, replacing the more stable lithium iron phosphate batteries we used earlier in development. Our battery management procedures are described in § 6.16 on page 17.

A revised risk assessment matrix is provided below. Frequency and severity estimates are available in our Deliverable 1 submission and are not repeated here.

## 6.2 UAV structure and control

| **Risk** | **Impact** | **Mitigation measures** |
|---|---|---|
| Servo failure | Loss of control | Test servos through full range prior to launch. FCS to detect condition and terminate flight. (CASR 101.395; *Rules* §§ 5.3, 5.6) |
| Motor failure | Loss of control | Test motor through full thrust range prior to launch. FCS to detect condition and terminate flight. (*Rules* §§ 5.3, 5.5.3) |
| Structural failure | Loss of control | Inspect control surfaces, wing attachment and motor mount prior to launch. FCS to detect condition and terminate flight. (CASR 101.395; *Rules* §§ 5.3, 5.6) |
| Propeller failure | Loss of control; injury from blade fragments | Inspect propeller prior to launch. Discard propeller if any cracks found, and after any hard landings or impact to propeller. (*Rules* § 5.3) |
| Unintended payload detachment | Injury / damage due to payload impact | Flight test with payload locked in place and release mechanism disabled. Only enable mechanism on specific payload drop tests under controlled conditions. Inspect and test release mechanism prior to launch. (CASR 101.090; *Rules* §§ 2.1.1, 2.1.3, 5.3) |

## 6.3 UAS electronics

| **Risk** | **Impact** | **Mitigation measures** |
|---|---|---|
| Pitot failure | Reduction in accuracy of airspeed, $\alpha$, $\beta$ estimates; UAV controllability | Use dual pitot tubes. Check for blockage prior to launch. Calibrate periodically. Reduce manoeuvre load limit if airspeed error increases beyond acceptable bounds. (*Rules* § 5.6) |
| Sensor failure (incl. GPS) | Loss of control | Use dual IMUs with results fused in AHRS. Ensure IMU power is overload protected, and isolate IMU inputs / outputs. Restart IMU if error detected. Terminate flight if both IMUs fail. (*Rules* § 5.6) |
| Radio link failure | Loss of manual controllability and monitoring, mission abort capability | Range test to ensure sufficient link margin available prior to launch. Monitor link margin during flight and adapt course if required. FCS firmware to enforce mission boundary, comms hold and home waypoints configuration for all flights. (*Rules* §§ 5.5.2, 5.5.5, 5.6) |
| Battery failure | Loss of thrust and FCS | Flight termination device to activate within 20 ms. (*Rules* § 5.6) |
| FCS failure | Loss of control | Flight termination device to activate within 20 ms. (*Rules* §§ 5.5.6, 5.6) |
| GCS failure | Loss of data link | Activate LOSS OF DATA LINK mode within 10 s. Replace GCS with spare and terminate flight if link unrecoverable. (*Rules* §§ 5.5.2, 5.5.7) |

| Risk | Impact | Mitigation measures |
|---|---|---|
| Battery fire | May spread to property or vegetation | Ensure no exposed metal near battery, and sufficient impact protection. Ensure Class ABE fire extinguisher available. Do not fly when fire risk severe or above. (*Rules* § 5.17) |

### 6.4 Human factors

| Risk | Impact | Mitigation measures |
|---|---|---|
| Contact with propeller | Severe cuts, loss of digits | Do not connect motor until immediately prior to launch. Ensure ISEA Level 5 cut / impact resistant glove worn. Ensure communication between team members. |
| Set-up errors | Electrical damage, loss of control | Ensure servo and throttle operation is tested prior to launch. |
| Configuration errors | Waypoints or mission boundary not enabled, unintended operation | FCS firmware to ensure UAV cannot be armed without mission boundary, comms hold and home waypoints configured. (*Rules* § 5.5.5) |

### 6.5 External factors

| Risk | Impact | Mitigation measures |
|---|---|---|
| Wind | Loss of controllability in winds > 20 $\mathrm{m\,s^{-1}}$ | Check wind before flight and do not launch if > 10 $\mathrm{m\,s^{-1}}$. Abort mission if wind > 15 $\mathrm{m\,s^{-1}}$. (*Rules* § 2.4) |
| Rain | Damage to UAV electronics in moderate / heavy rain | Check weather before flight and do not launch in rain. Abort mission if light rain appears to be worsening. (*Rules* § 2.4) |
| Fog | Loss of visibility and control | Do not launch in fog. Abort mission if fog reduces visibility. (CASR 101.095, 101.385) |
| Other aircraft | Impact with aircraft | Do not fly in controlled airspace, near airfields, or near helipads. Abort mission if aircraft seen nearby. (CASR 101.055, 101.065–101.085, 101.400) |

### 6.6 Software development methodology

Due to the significant software development effort involved in our entry, and the potential impact of bugs in our autopilot systems, we have adopted a set of guidelines and standards for code based on published best practices from organisations involved in high-assurance systems development. Particular references include NASA's *JPL Institutional Coding Standard for the C Programming Language*, as well as the commonly-used MISRA-C standard.

Key guidelines for our on-board software include:

- No dynamic memory allocation (JPL rule 5);
- Statically verifiable upper bounds on all loops except the main task loop (JPL rule 2.3);
- Statically verifiable stack usage: avoid interrupts and no recursion permitted (JPL rule 4);
- All compiler warnings are to be enabled and treated as errors (JPL rules 1.1 and 1.2);

- Use static verification software (Coverity Scan) where possible, and resolve all warnings;
- Use version control and ensure all code is reviewed prior to merging into the stable branch.

### 6.7 Hardware development methodology

Our hardware has been designed for maximum robustness, with significantly over-specified power regulation, filtering and decoupling as well as conservative thermal budgets. Prior to production, schematics and layouts undergo an extensive manual verification process and automated design rules checks; the manufacturer also reviews the layouts to confirm they can be manufactured and assembled correctly.

After PCB assembly, boards are verified using X-ray inspection and a visual check. Once we receive the boards, we run full functional tests, including multi-hour runs to catch early failures.

Where possible, all components are high-reliability or automotive-qualified. Sensors are powered by individual current-limited switches, so "stuck" sensors can be power-cycled and shorts will not affect power to the rest of the board; power-good outputs from regulators are monitored and independent logic is used to power-cycle CPUs in the event of a brown-out. All PCBs are multi-layer with stackups designed to minimise EMI.

### 6.8 Operating procedures

We have developed a comprehensive checklist covering pre-flight and post-flight operating procedures based on our equipment setup requirements as well as the risk mitigation measures listed in § 6.1 (p. 13). This checklist is available for download on our website, and key tasks are highlighted in our video submission for this deliverable.

### 6.9 Spectrum management

The following transmitting devices are mounted to our airframe:

- RFDesign RFD900 radiomodem, 915–928 MHz band with a calculated EIRP of 30 dBm as configured with 6 dBi diversity half-wave dipole antennas. Licensed under *Radiocommunications (Low Interference Potential Devices) Class Licence 2000* Sch. 1 items 45 and 45A (cf. *Rules* § 8.4).
- Sierra Wireless 3G mini-PCIe modem, configured with diversity antennas. Licensed under *Radiocommunications (Cellular Mobile Telecommunications Devices) Class Licence 2002*.

Our GCS contains the following transmitting devices:

- RFDesign RFD900 radiomodem, 915–928 MHz band with a calculated EIRP of 30 dBm as configured with dual 6 dBi Yagi antennas. Licensed under *Radiocommunications (Low Interference Potential Devices) Class Licence 2000* Sch. 1 items 45 and 45A.
- Huawei 3G USB modem with an integrated antenna. Licensed under *Radiocommunications (Cellular Mobile Telecommunications Devices) Class Licence 2002*.
- Spektrum DX6i 2.4 GHz radio control transmitter, with integrated antenna. Licensed under *Radiocommunications (Radio-Controlled Models) Class Licence 2002*.

As all equipment is operated under ACMA class licences, no additional licences are required (*Rules* §§ 8.2, 8.3).

### 6.10 Flight termination

Flight termination uses the standard servo positions described in *Rules* § 5.6, modified for a flying wing airframe as follows:

- Throttle closed;
- Full down on the right elevon;
- Full up on the left elevon.

These positions have been tested in flight and were found to perform well; refer to § 7.2 (p. 18) for details.

Flight termination is activated via independently-powered sensor boards in response to fault conditions as outlined below, in response to a mission boundary crossing detected by the sensor board, or via a command from the GCS. Once activated, both sensor boards remain in the flight termination state until powered off (*Rules* § 5.6).

Flight termination conditions are represented visually in § 5.10 (p. 12).

### 6.11 Loss of data link

The loss of data link procedure (*Rules* § 5.5.2) is engaged after 10 seconds without heartbeat packets from the GCS, received via the primary telemetry link (RFD900) or via the backup telemetry link over the 3G cellular connection. Once engaged, the aircraft will nagivate directly to the "Comms Hold" waypoint and enter a holding pattern at that waypoint. After two minutes in the holding pattern, the aircraft will navigate to the "Airfield Home" waypoint and enter a holding pattern there. If the aircraft has not been brought under manual control via the 2.4 GHz RC link within two minutes of arriving at "Airfield Home", the flight will be terminated. This procedure is represented visually in § 5.10 (p. 12).

### 6.12 Loss of GPS

The loss of GPS procedure (*Rules* § 5.5.4) is engaged immediately if both GPS receivers in the aircraft lose position lock, or if the number of satellites tracked drops below 5. Once the procedure is engaged, the aircraft will enter a holding pattern at the current position; if GPS lock is not obtained within 30 s the flight will be terminated. If loss of GPS occurs while the aircraft is following the loss of data link procedure, the flight will be terminated immediately (*Rules* § 5.5.4). This procedure is represented visually in § 5.10 (p. 12).

### 6.13 Autopilot failure

The health of the autopilot is monitored by both sensor boards via a heartbeat packet transmitted every millisecond. If ten consecutive packets are missing or malformed, the sensor boards will terminate the flight (*Rules* §§ 5.5.6, 5.5.9). This procedure is represented visually in § 5.10 (p. 12).

### 6.14 GCS failure

Failure of the GCS (*Rules* § 5.5.7) is handled in the same way as a loss of data link, since the effect (from the perspective of the aircraft) is the same. A spare set of GCS equipment will be available at all times to enable a rapid change-over and re-establishment of the data link.

### 6.15 Motor, servo or control surface failure

In the event of a motor or servo failure while under automatic control (*Rules* § 5.5.3), the autopilot will attempt to stabilise the aircraft's trajectory and follow a shallow diving path until ground impact. If the aircraft is within visual range while this occurs, manual control will be activated and a dead-stick landing will be attempted.

### 6.16 Battery management

Lithium polymer batteries are used for motor and main electronics power in our aircraft. We have developed a set of battery handling procedures to mitigate the risks inherent in this class of battery. In addition, based on experimental results from ground impacts in excess of $30\ \mathrm{m\,s^{-1}}$ (58 kn), we have re-designed the internal layout of our aircraft to reduce the risk of a battery contacting sharp metal objects in the event of a crash (*Rules* § 5.17).

When not in use, batteries are stored in fire-proof bags specifically designed for the purpose. After each flight and prior to charging, batteries are inspected for surface damage which might indicate the structure of a cell has been compromised. Batteries are discharged to 80% prior to long-term storage to maximise cell life and reduce the risk of fire.

For mass distribution reasons, we use three 4S2P lithium polymer cells; these are advantageous from a safety perspective as well, since the lower mass reduces the risk of a puncture compared with a single large battery. The batteries are securely mounted adjacent to the forward foam bulkhead, which is reinforced by a carbon-fibre spar extending through both wings. In a nose-first crash, the forward compartment also acts to dissipate the kinetic energy of the batteries.

We have a Class ABE fire extinguisher available during test flights. While this cannot extinguish the primary lithium polymer fire, it is able to be used on any secondary fires until the lithium polymer fire self-extinguishes.

### 6.17 Payload release

Our payload release mechanism uses an electro-permanent magnet to secure the bottle. The mechanism is rated for accelerations up to 8 $g$—beyond the structural limits of the airframe—so the risk of uncommanded detachment during high-$g$ manoeuvres is very low. The mechanism retains full attachment force even with no external power applied, so electrical failure will not cause an uncommanded release.

The bottle is carried internally at the aircraft's centre of mass, resulting in very little change to flight dynamics during release. A major benefit of the magnetic attachment mechanism is an almost instantaneous release, with the payload being unobstructed by hatches or other restraining devices. This reduces the risk of entanglement between the bottle and the airframe.

During flights in which no release is planned, we carry the full payload but use fibreglass tape to secure it to the main spar and the bottom of the fuselage. This restrains the bottle even in a severe crash.

We use IP2-rated HDPE bottles, which are highly leak- and shock-resistant, so kinetic energy reduction options have not yet been fully explored; at this stage we expect moulded foam or composite cushioning will be sufficient to guarantee the bottle remains intact after drop. Due to the observed unreliability of alternate energy reduction mechanisms (*e.g.* parachutes) we consider that a high-speed impact with controlled deformation of the structure surrounding the bottle is the safest and most accurate approach.

# 7 Flight test results and discussion

Extensive flight testing has been performed using three identical aircraft. We have completed multiple flights longer than 30 min, and have integrated all on-board systems except for the downward-facing search camera.

## 7.1 Aerodynamic performance

The aerodynamic performance of the aircraft is in line with requirements, with an optimum cruise speed of 25 m $s^{-1}$. Flight tests have been conducted in a variety of conditions, and manual controllability has been confirmed in winds up to 15 m $s^{-1}$ (29 kn). Based on our range tests, we expect the aircraft will remain mission-capable in winds averaging 25 kn; above that speed the battery capacity may not be sufficient to complete the search.

We have found the yaw and roll stability of the aircraft to be sufficient but not ideal; this affects our search strategy as it will be necessary to fly a pattern with significant overlap between tracks in order to ensure full coverage of the search area. The performance of our AHRS is sufficent to ensure accurate georeferencing regardless of angular rates.

## 7.2 Flight termination performance

We have tested our failsafe device twice: once while under manual (2.4 GHz radio) control, and once while under automatic control.

In the manual case, termination commenced at cruise speed and an altitude of 40 m above ground level. Impact occurred approximately 3 s later after travelling 60 m horizontally, with a peak vertical speed of 22 m $s^{-1}$. Airframe damage was catastrophic, however most of the on-board systems survived. The batteries were undamaged.

In the automatic case, termination commenced at cruise speed and an altitude of 100 m above ground level. Impact occurred 4 s later, with a peak vertical speed of 35 m $s^{-1}$. The airframe and all on-board systems were destroyed, except the motor and ESC. Two batteries were dented but not scratched or punctured; one battery was pierced by the autopilot CPU heatsink and smoked briefly, but extinguished itself after less than one minute.

As a result of these tests we are constructing carbon-fibre and aramid honeycomb tub enclosures for the main electronics, which will provide significant protection for the PCBs as well as ensuring the batteries are not exposed to sharp metal objects in a crash.

## 7.3 Communications and electrical performance

All radio devices have been tested in flight. The RFD900 radiomodems work as expected with sufficient link margin available to reach an estimated 10 km range; the performance of the 3G modem will depend on local network conditions but is expected to be adequate. The range of the 2.4 GHz radio control transmitter has been tested and will be sufficient for local airfield use in the *Challenge*.

A number of interference and power stability issues have been observed in our prototype hardware; in some cases these can result in the lock-up of the autopilot CPU. We are currently awaiting delivery of the second revisions of our autopilot and sensor boards, which will resolve the power stability issues and dramatically reduce the number of cable assemblies connecting the main electronics; in addition, our enclosures will contain a layer of woven copper wire to reduce the impact of EMI.

### 7.4 AHRS performance

Using the 1000 Hz data logs and attitude estimates provided by our AHRS, we have been able to develop a reasonably accurate 6 DOF model of our aircraft's flight dynamics. This model is now used to improve the accuracy of the attitude and position estimates generated by the UKF, as well as the performance of the NMPC system.

The output of our AHRS and accuracy of our flight dynamics model (FDM) have been validated by comparing the UKF roll and pitch estimates with roll and pitch estimated by a machine vision system extracting the horizon orientation from a 240 frames per second on-board video recording. The results are as follows:

| | **° Error at percentile** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Pitch** | | | | **Roll** | | | |
| **FDM** | 50th | 75th | 95th | RMS | 50th | 75th | 95th | RMS |
| None | 4.0 | 6.6 | 13.4 | 6.5 | 4.5 | 7.8 | 14.6 | 7.3 |
| X-8 | 1.8 | 3.1 | 5.9 | 2.9 | 1.7 | 2.9 | 5.0 | 2.7 |

The 95th percentile pitch and roll error when using the X-8 model will result in a 95th percentile georeferencing error contribution of approximately 5 m, which will result in an overall 95th percentile error of around 15 m from a single pass.

### 7.5 Autopilot performance

Our autopilot system has been tested extensively using software-in-the-loop (SITL) and hardware-in-the-loop (HITL) techniques, and we commenced flight testing in March 2014. Simulation performance is excellent in winds up to 18 $\mathrm{m\,s^{-1}}$, exhibiting better stability and navigation performance than can be achieved by manual control.

In simulation, the autopilot is capable of recovering with minimal altitude loss from a variety of challenging aerodynamic configurations, including stalls and significant wind gusts. Flat spins are recoverable within 50 m altitude loss with approximately 30% probability.

If simulation results can be replicated in flight, the performance of our autopilot will be more than sufficient for the *Challenge* and should significantly reduce operational risk compared with off-the-shelf solutions. However, as we are at the initial stages of autopilot tuning, this remains a significant development risk to our entry.

### 7.6 Operational risk assessment

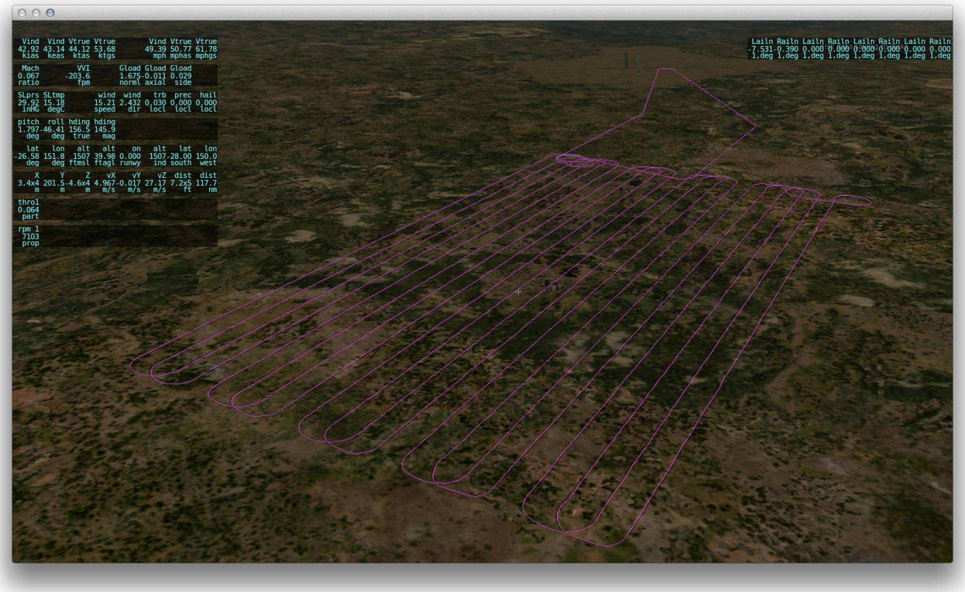
The issues identified during operation have been largely in line with the risk assessment included in our Deliverable 1 submission and summarised in § 6 (p. 13), and the mitigation measures we have taken have successfully prevented injury and property damage. All in-flight issues have been attributable to testing of new equipment (*e.g.* motor and propeller combinations) or configuration (*e.g.* the location of the centre of mass, antenna placement).

At the time of submission, our project plan calls for a freeze of the autopilot and sensor board / failsafe device hardware and software commencing June 2014. After that time, only critical bugs (those leading to flight termination or mission abort) will be addressed. This will ensure that we accumulate the full 5+ hours of autonomous flight time required by Deliverable 3 with hardware and software systems identical to those that will be flown in the *Challenge*.

## 8 Search strategy

While our search strategy may be modified as a result of empirical data from camera testing in flight, based on simulation results we intend to use a straightforward "lawnmower" pattern with strips oriented parallel to the longer boundaries of the search area. Based on our field of view calculations assuming an altitude of 122 m (400 ft), our search strips will be 80 m in width, with tracks spaced 130 m apart. Following the first pass, a second pass will be flown with a 65 m offset, yielding an overlap between strips of 45%.

A mission with these parameters run in our HITL simulator is shown below. Winds of 5–10 m s$^{-1}$ (10–20 kn) were used during the simulation.



```
 Vind  Vind Vtrue Vtrue        Vind Vtrue Vtrue
42.92 43.14 44.12 53.68       49.39 50.77 61.78
 kias  keas  ktas  ktgs         mph mphas mphgs

 Mach         VVI       Gload Gload Gload
0.067      -203.6       1.675-0.011 0.029
ratio         fpm       norml axial  side

SLprs SLtmp        wind  wind   trb  prec  hail
29.92 15.18       15.21 2.432 0.030 0.000 0.000
 inHG  degC       speed   dir  locl  locl  locl

pitch  roll hding hding
1.797-46.41 156.5 145.9
  deg   deg  true   mag

  lat   lon   alt   alt    on   alt   lat   lon
-26.58 151.8  1507 39.98 0.000  1507-28.00 150.0
  deg   deg ftmsl ftagl runwy   ind south  west

    X     Y     Z    vX    vY    vZ  dist  dist
3.4x4 201.5-4.6x4 4.967-0.017 27.17 7.2x5 117.7
    m     m     m   m/s   m/s   m/s    ft    nm

throl
0.064
 part

rpm 1
 7103
 prop
```

```
 Lailn Railn Lailn Railn Lailn Railn Lailn Railn
-7.531-0.390 0.000 0.000 0.000 0.000 0.000 0.000
 1,deg 1,deg 1,deg 1,deg 1,deg 1,deg 1,deg 1,deg
```

Total distance flown, including travel to and from the search area and navigation to the drop location, will be no more than 60 km. This is well within the range of our aircraft assuming no wind; with 10 m s$^{-1}$ (20 kn) winds parallel to the longer boundary of the search area, we would still expect to complete the search with at least 5 min and 20% battery capacity remaining.

Images captured during the search will be transmitted to the GCS via the 3G modem connected to our imaging processor. Target recognition will occur on board the aircraft, and images possibly containing Outback Joe will be flagged and prioritised so that drop approval can be requested. Thumbnails of the specific regions in which Outback Joe could be located will also be transmitted via the 915 MHz telemetry link to mitigate the effect of 3G network unavailability or modem failure.

## 9 Conclusions

During the development of our UAS, we have completed many flights under manual control in a variety of wind conditions, and have accumulated significant experience with our chosen airframe. We have commenced testing of automatic control and tuning of our flight dynamics model. All our mechanical, electronic and software systems with the exception of the main search camera have been fully integrated and flight tested.

The capability of our aircraft design to meet the requirements of the *Challenge* has been tested and demonstrated, and we believe our approach has resulted in the smallest, safest aircraft able to complete the mission over the required range of wind speeds. Our AHRS flight test performance compares favourably to off-the-shelf systems available for aircraft of this size, and although our automatic control system is in the initial stages of flight testing, positive results from extensive hardware-in-the-loop testing has validated the approach.

The procedures and checklists developed from our risk assessments have facilitated safe and efficient flight operations with no injury or damage, no "near misses", and no airframe losses under manual or automatic control except as a result of flight termination (which has been tested in both modes). We will continue to update our risk assessment matrix using further information from our flight tests, enabling continuous improvement of safety and reliability.

Our progress to date has been in line with our expectations, and we do not anticipate problems meeting the Deliverable 3 deadline or the scrutineering requirements of the *Challenge*. Although the testing and tuning of the automatic control system represents the highest-risk period of development, we do not foresee any time, cost or hardware availability constraints that would prevent us from accumulating the desired 10 hours of autonomous flight. So far we have constructed three identical aircraft, and expect to construct a further three during the remainder of the *Challenge* period to ensure tested spare parts are always available. We have sufficient inventory of our custom hardware to assemble six aircraft, and do not expect any further hardware revisions will be required.

We are confident in our continued ability to meet the requirements of the *Challenge* and the Deliverable 3 deadline, and look forward to participating in the *Challenge* event in September.