Towards Flight Trials for an Autonomous UAV Emergency Landing using Machine Vision

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Abstract

This paper presents the evolution and status of a number of research programs focussed on developing an automated fixed wing UAV landing system. Results obtained in each of the three main areas of research as vision-based site identification, path and trajectory planning and multi-criteria decision making are presented. The results obtained provide a baseline for further refinements and constitute the starting point for the implementation of a prototype system ready for flight testing.

1 Introduction

The team at the Autralian Research Centre for Aerospace Automation (ARCAA)[1] have been researching UAV systems to overcome many of current impediments facing the widespread integration of UAVs into civillian airspace. One of these impediments that the group identified in 2003, was how to allow a UAV to perform an emergency landing.

An emergency or forced landing (in the case of an un-powered landing), is where the aircraft is required to perform an unplanned landing due to the occurrence of some onboard emergency (eg: an engine failure). This capability is an inherent component of the benchmark performance for the manned aviation industry, therefore the group identified this as a key impediment to overcome to allow UAV operations over populated areas in civilian airspace (Fitzgerald, Walker et al. 2005; Fitzgerald 2007).

Hence, it is believed that UAVs must therefore be provided with the ability to safety terminate the flight through a range of emergency scenarios. A UAV plummeting uncontrollably into the middle of a busy freeway or a school yard is a risk that the public will be unwilling to except. A UAV emergency landing system will be an important component towards enabling routine missions in civilian environments.

To date no commercial system is available that allows a UAV to decide on the safest area to land in an unknown area autonomously. There are safety systems currently that can allow a UAV to fly towards a pre-defined safe landing area from a database of known safe landing locations. However, these systems must be programmed with up-to-date information, requiring a continuous communications link between a human operator and the air vehicle to ensure the UAV does not attempt to land at an area that has become unsuitable.

The solution is to have a system onboard the UAV that can think in a similar way to a human pilot in emergency situations that require the aircraft to land. Therefore, the objective of this research is to develop an onboard capability that allows the UAV to select a suitable landing site then maneuver the UAV to land at this location autonomously. If this functionality is realised, it will bring UAVs one step closer to flying in civilian airspace above populated areas.

The resarch in (Fitzgerald 2007) has reduced the technical risk for a vision based emergency landing system and thus in the past year a number of research programs have began at ARCAA to compliment this research. It is now proposed to develop a complete prototype system suitable for flight trials.

A range of flight test scenarios will be evaluated on the prototype system (range of altitudes and terrain), and will be conducted with the relevant approvals from the Civil Aviation Safety Authority of Australia.

1 ARCAA is a joint research centre between the Queensland University of Technology and CSIRO.

This paper will describe the different research programs and results to date, and how these will be combined together to form a complete prototype system ready for flight testing.

These research programs can be classified into the three broad areas of:

- Visual identification and classification of UAV forced landing sites;
- Guidance and navigation for autonomous aircraft forced landing; and
- Multilevel decision making for high-level reasoning during the descent

These form the basis of this paper and their use in developing a real time implementation and system for flight testing.

The remainder of the paper is as follows: a system overview of the approach including all subsystem components; and a system hardware overview of the UAV platform, onboard components and groundstation hardware.

2 System Overview

It is proposed to develop a complete emergency landing UAV system that will run in real time. To reduce the development time, the initial flight tests will have all algorithms ran at the ground station, and new commands to the autopilot sent to the UAV through the radio links. This will be discussed in section 3 along with the specific hardware being considered for these tests.

The software system will comprise of a number of modules that will be described in detail in this section. The following figure shows the interaction of these modules at a high level.

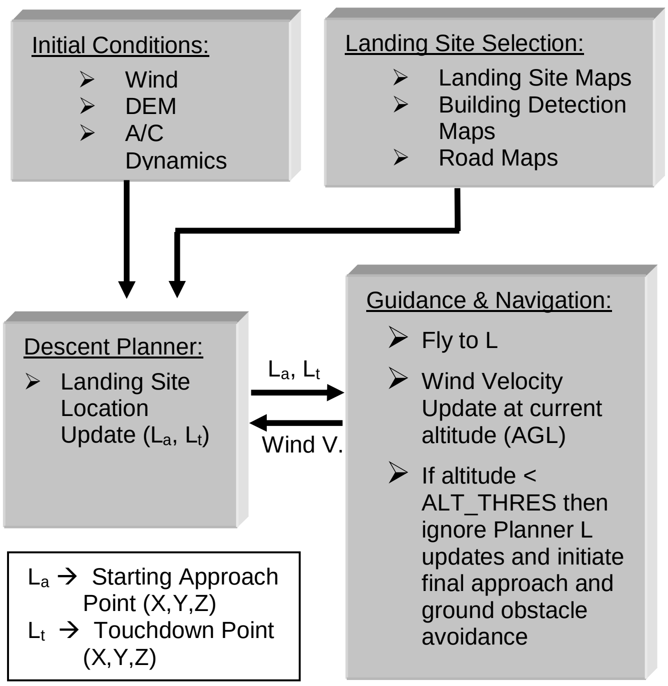

Figure 1 - Emergency Landing Software System

The remainder of this section will discuss these components in detail. Briefly, the Landing Site Selection module uses machine vision to output a number of maps of the area below the UAV. These maps provide information such as areas free of obstacles, surface type, slope, the locations of buildings and the location of roads. This information is then used by the Descent Planner module as well as wind information from the Guidance and Navigation module to come to a decision on the best landing site location based on multipe criteria and objectives. This landing location (L_t) is passed to the Guidance and Navigation module which is responsible for guiding the UAV to this landing site. This module must account for wind disturbances, changes in the final landing location throughout the descent and obstacle detection and avoidance on final approach.

2.1 Landing Site Selection Subsystem

Over a 3 year period a computer vision based architecture has been developed and optimised. This technique, which mimics human processes, identifies emergency landing sites that are obstacle free. More specifically, the landing sites are chosen based on their size, shape and slope as well as their surface type classification. Subsequent algorithms have been developed that allow automatic classification of the candidate landing site's surface (based on back propagation neural networks). Examples are shown in Figure 2 and all techniques and results discussed fully in (Fitzgerald 2007).

A series of flight trials were performed using a Cessna 172 aircraft with a 100% success rate for locating large open landing areas. 92% of these large open landing areas were considered to be completely free of obstacles, with only 8% having small obstacles such as trees. These obstacles were missed by the algorithm due to the resolution of the camera vs the current height above ground. As the UAV descends however, these obstacles would be detected and the descent planner could take the appropriate action.

The surfaces of these large open areas were also classified to accuracies of over 93% - for example grass, water, etc. This classification information will be used by the descent planner to select the most suitable landing site from the ones available.

The objective of finding areas for a UAV to land in that would minimize injury to people on the ground was achieved.

(Fitzgerald 2007) recommends that additional information be used to select the most appropriate landing area to compliment the research. Based on this recommendation, it is proposed that additional maps will be produced by the landing site subsystem to highlight *keep-out* areas. Two additional maps have been proposed in addition to the site selection map and slope map (Fitzgerald, Walker et al. 2005).

Figure 2 - Example Landing Site Selection Output

The first map will highlight where roads are in the image below. This is useful for a number of reasons. The first is as a coarse keep out boundary, that is, the UAV will not try to land on roads, as it is assumed that there is a higher probability of injury to persons and in causing damgage to property in these areas. The second reason is to infer the location of power lines, which is required high level knowledge in the decision for the landing approach phase. Smaller distribution powerlines are usually located close to and parallel to roads, therefore this high level information can be used to choose landing approach paths that minimise the chance of collisions with this type of powerline.

The other map will locate areas in the image with a high probabiltiy of containing buildings. There are a number of techniques in the literature such as (Azencott, Durbin et al. 1996; Chen and Blong 2002). These techniques are being evaluated for this application and tested on the flight data of the south east Queensland region that has been collected. The most promising approach will be used to provide *keep-out* regions in the area below, and again provide high level information to assist with the selection of an appropriate landing approach path.

All maps will be derived from computer vision techniques, and will not use stored databases onboard. It is believed that this is fundamental to the approach that will allow a UAV to make it's own decisions.

2.2 Descent Planning Subsystem

One of the most important aspects in the initial stages of a forced landing is to make the right decision at which site to land at and how to approach the chosen landing site. In fact, this decision will continue to be validated and changed throughout much of the descent if the decision from new information yields a more appropriate landing site.

Multiple Criteria

According to the Australian Civil Aviation Safety Authority's latest Visual Flight Rules flight guide (CASA 2001) there are seven criteria to selecting the best site for forced landing, which are:

- Wind;
- Surrounding,
- Size and Shape,
- Surface and Slope;
- S(c)ivilisation

These, coupled with the other critical factor of wind, both strength and direction, are the primary elements which a human pilot use when making decisions on where to perform a forced landing.

When applied in the context of UAVs, many of these factors still hold their significance, and a number of other variables also come into consideration which are not explicitly stated for piloted aircraft. These include, the aircraft dynamics, the uncertainty of sensor data and the wind estimation.

Also to be considered is the geometrical relationship between the various candidate sites. As the aircraft descends, the number of landing site options will rapidly decrease. Thus, it is generally better to glide towards several possible sites in close proximity than to one that is isolated, as this keeps multiple landing site options open for as long as possible. This is important so as to have several options if obstacles are detected on the candidate landing sites at lower altitudes.

The number of structures and the population density that lies in the descent path to each site must also be accounted for if applicable, as it would be safer to fly over empty terrain than a populated area, in case further mishaps occur.

These points, along with other factors which remain to be identified, will be evaluated to reach an optimal, verifiable decision on which candidate landing site the aircraft will aim for.

Further investigations will be conducted in order to identify any other influences that affect this decision process, possibly including surveys and simulations involving experienced pilots and/or UAV controllers.

Multiple Objectives

The complexity of the forced landing decision process due to multiple criteria is further increased by multiple objectives that must be met. In many cases, these objectives may be conflicting, and thus compromises must be made to accommodate the achievement of the most critical objective/s.

According to the Civil UAV Capability Assessment (Cox, Nagy et al. 2004), in the event of an emergency landing the UAV needs to be able to respond according to the following objectives in the following order:

1. Minimize expectation of human casualty;
2. Minimize external property damage;
3. Maximize the chance of aircraft survival; and
4. Maximize the chance of payload survival.

In many scenarios, the best landing site for meeting objectives 3 and 4 may compromise the more important objectives 1 and/or 2, or vice versa. This complex process of trading off between the risks and uncertainties involved with each possible choice is an example multiple objectives that the system must trade off between and is what makes this problem difficult.

Decision Making

The Descent Planning and Decision Making module will initially have preplanned contigency plans from map data to give fast, reflex responses to emergencies that guide the aircraft towards known landing sites initially, or large flat areas based on the slope map data.

The Guidance and Navigation module (discussed in the next section) will constantly make estimates of the wind speed and direction, which will be taken as input for decision making. The aircraft dynamics will also be known and necessary restraints applied when judging the feasibility of a decision.

As the aircraft descends, the visual Landing Site Selection module (refer Section 2.1) will continosly analyse the terrain the aircraft is flying over. Possible landing sites, buildings, and roads will be identified, including the associated uncertainties of objects in each map. With this information the Decision Making module will be able to continuously validate and update its decision in real time.

It is expected that uncertainties will reduce as the aircraft descends, however the options available will also reduce. It may be very likely that an initially selected landing site will eventually be deemed unsuitable by the Landing Site Selection subsystem, and an alternative must be sought after. It is the responsibility of the Decision Making subsystem to be prepared for such situations by maximizing the number of alternative choices available.

The research in this area is focussing on the development of a multi-agent based architecture, where multiple events require layered decision schemes. Different software agents that handle different events during the landing process will be in constant interaction and communication throughout the descent in order to handle all the different events.

2.3 Guidance and Navigation Subsystem

The development of a UAV platform capable of precision flight, addressing safety and reliability as main concerns, is the logical progression for future UAVs in civilian airspace. Achieving this realization will not be limited to designing advanced control laws and/or flight control systems, since these UAVs will be mainly used to support reconnaissance and surveillance roles. For these applications, computer vision can offer its potential, providing a natural sensing modality for feature detection, tracking and visual guidance of UAVs.

An important part of the fixed-wing aircraft forced landing problem is how to navigate to land on a chosen site in unknown terrain, while taking into account the operational flight envelope of the UAV and dynamic environmental factors such as crosswinds and gusts, small flying objects and other obstacles in the UAV glide path. Static obstacles such as buildings, telegraph/light poles and trees on the perimeter of the chosen landing site will also be considered as they may interfere with the approach glide path of the UAV.

Vision Based Navigation Literature

In order to command the aircraft to the desired landing site, visual information plays a crucial role in the control of the platform. Using the visual information to control the displacement of an end effector is refereed in the literature as *visual servoing* (Hutchinson, Hager et al. 1996). It is envisaged that the location of the candidate landing sites in the image should be used to command the aircraft while is descending.

Previously (Mejias, Roberts et al. 2006) has demonstrated an approach to command the displacement of a hovering vehicle using an Air Vehicle Simulator, AVS (Usher, Winstanley et al. 2005). This task required the development of suitable path planning and control approaches to visually maneuver the aircraft during an emergency landing. In this approach the vehicle had to navigate through a scale environment provided with power lines and artificial obstacles over the ground, avoid power lines and find a safe landing area over the ground.

Preliminary Results in Dynamic Path Planing using a Fixed-Wing UAV

Initial simulations have provided valuable feedback on the design of the control, guidance, path planning and navigation algorithms, before being implemented on the actual hardware.

In the current simulation, an AeroSim model of an Aerosonde UAV was modified and expanded to include blocks for flight controls, path planning, GPS waypoint navigation, wind generation, wind correction and an interface to FlightGear. By running MATLAB and FlightGear concurrently, the user is able to visualize the UAV flying in a manner as dictated by the Simulink model.

At present, the primary focus of this simulation is to evaluate the dynamic path planning capability for a UAV performing a forced landing in changing wind conditions. This simulation is intended to serve as a tool in the design and testing of a visual servoing and path planning system for automating a fixed-wing UAV forced landing. It will be further enhanced to model complex, uncooperative environments with hazards such as buildings, trees, light poles and undulating terrain, as well as machine vision for use in the feedback control loop.

Wind Compensation

In the current forced landing simulation, the initial wind velocities are given by uniformly distributed random numbers that are updated every 60 seconds. These numbers generate the initial W_{North}, W_{East} and W_{Down} components, which are then multiplied by a continuous square wave giving the profile shown in Figure 3. The values of $W_{N,}$ W_E and W_D were chosen based on the wind rose generated for Brisbane, Australia, and combined to give a maximum wind velocity of 60 kts, which can arise from any direction. A wind rose is a diagram that summarises the occurrence of winds at a location, showing their strength, direction and frequency. The wind rose used in the simulation represented wind measurements taken at 9 a.m. from 1950 to 2000, and are published on the Australian Government Bureau of Meteorology.

Note that gusts have not been modelled in the simulation, instead, the input wind is assumed to blow with a constant magnitude and direction for 60 seconds, before changing magnitude and direction for the next 60 seconds. Whilst this does not necessarily represent the wind conditions found in an actual descent, it does present a challenging wind shift scenario for the simulations to date. Future simulations will include wind gusts.

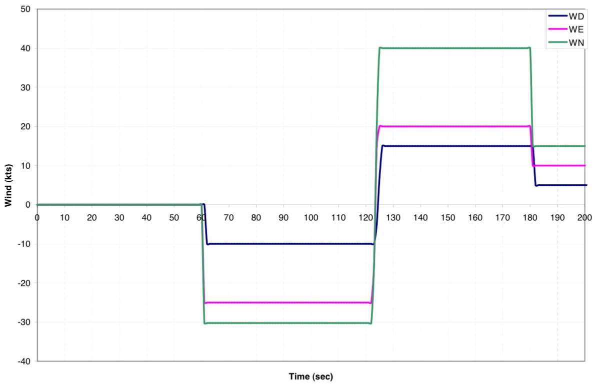

Figure 3 - Wind components (W_N: Green, W_E: Pink, W_D: Blue). These components are used to compute the resultant wind vector incident on the UAV.

Correction for wind is performed using principles of wind vectors to compute the wind correction angle, which is compared with the current aircraft heading and passed as input to the UAV flight planning subsystem. From Figure 4, suppose that waypoint B is 600m (0.32 nmi) north-east (045˚ true) of waypoint A and the UAV glides from A to B, maintaining a heading of 045˚ true and a constant True Airspeed (TAS) of 37kts. A wind velocity of 340˚/9.7kts coming from the south-east will cause the UAV to drift to the left.

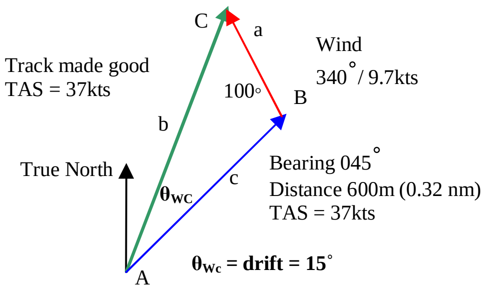

Figure 4 - Wind Triangle Calculations

This implies that the wind correction angle supplied to the flight planning subsystem must be 15˚ in the opposite direction, such that the “track made good” will converge on the “required track” to target.

Path Planning

In the current simulation, the path planning algorithm generates a series of waypoints, which form a flight path along which the UAV is guided to land at the chosen landing site. The waypoints were extracted from the forced landing circuit pattern as outlined in (CASA 2001). Table 1 gives the coordinates of the idealised waypoints for a right-hand circuit pattern, and Figure 5 shows their relationship to the landing site. Note that a similar pattern for a left-hand circuit pattern can also be generated.

Waypoint	Longitud (rads)	Latitude (rads)	Alt (ft)
High Key	0.4782	2.6725	2500
Low Key	0.4783	2.6722	1700
End Base	0.4786	2.6721	1200
Decision Height	0.4786	2.6723	670
Overshoot1	0.4787	2.6724	400
Aimpoint	0.4784	2.6725	13

Table 1 – Waypoints – Left-hand Approach Circuit Pattern

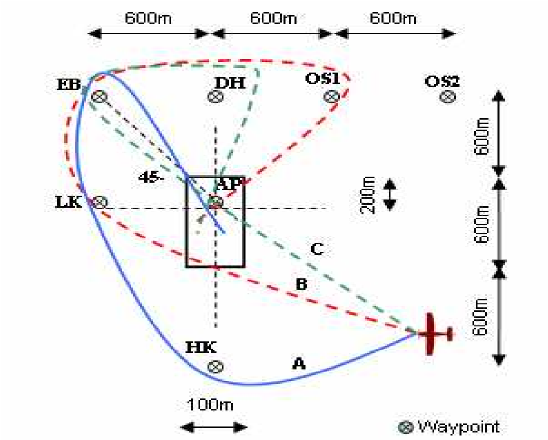

Figure 5 – Forced Landing Circuit Patterns. HK=high key, LK=low key, EB=end base, DH=decision height, OS1=overshoot 1, AP=aimpoint.

Based on the initial position of the UAV, the path planning algorithm then generates a modified table of waypoints which includes the aim point, and all or a combination of the other waypoints listed in Table 1. The UAV flies to these new waypoints using the great-circle navigation method defined in (Kayton and Fried 1997). Figure 5 depicts three possible flight paths generated using the planning algorithm described.

Fixed-Wing Simulation Results

To test the performance of the path planning algorithm, a Monte Carlo simulation consisting of 500 automated landings was conducted. The simulations were run with randomised initial aircraft positions, attitudes and wind velocities. In this simulation we observed that the majority of landings had a radial miss distance between 0 and 400m. These results can be attributed to several factors; the relative spacing between the waypoints, how the path planning algorithm selects the waypoints for the UAV to navigate to and the fact that the UAV is constrained to fly with a positive 3 degree pitch attitude. However, from these tests it was observed that 151 landings lay within the site boundaries, corresponding to approximately 32% of the total population. While this figure is not exemplary, it does present a baseline for subsequent refinements to the navigation and path planning algorithms to improve upon.

Figure 6 shows a top and 3D view of the aircraft trajectory during one landing maneuver simulation. The green arrows labelled show the direction of the changing wind affecting the aircraft during flight. The path described by the red line is the trajectory computed by the path planning algorithm, and the blue line is the actual path that the aircraft is flying. The designated landing area is ilustrated by a thick green line on the bottom.

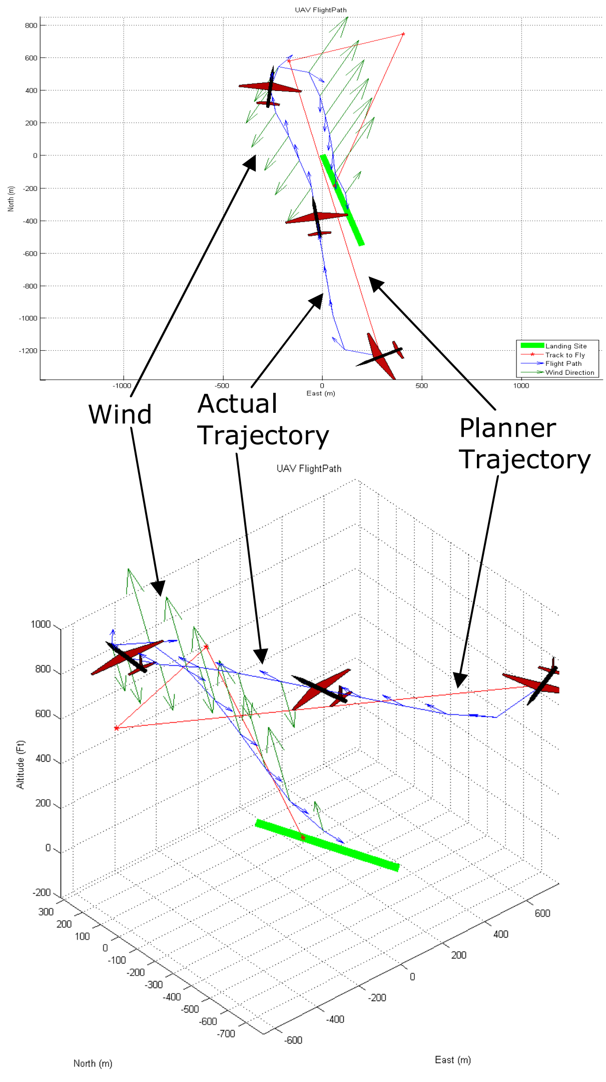

Figure 6 – Detailed View of the Forced Landing Simulations under Changing Wind. Green arrows indicate the direction of the wind.

Static and Dynamic Obstacle Avoidance

When vehicles navigate in complex and dynamic environment they need to acquire a global representation and understanding of objects and events affecting their performance. Traditionally sensors like sonar or laser range-finder has been used for obstacle avoidance purposes. As mentioned before, the constrained payload of most small-medium size UAVs makes in some cases prohibited the use of this type of sensor.

During the descending manoeuvre while the vision system is detecting landing sites, and commanding the aircraft to them. Obstacles can simultaneously be identified in the path by using complementary image processing algorithms. Power lines, trees or poles can be detected and this information will be sent to the planning and decision subsystem which will replan the route in real-time to the best suitable landing site.

The static and dynamic obstacle avoidance problem is an ongoing research area in the group.

3 Hardware

An overview of the experimental platform and associated hardware to begin flight testing of the protoype UAV forced landing system will be presented in this section.

The platform chosen for the initial experiments is a Boomerang 60 size model aircraft. The Boomerang comes *almost-ready-to-fly* and is an inexpensive option for the initial flight test experiments. Additionally, this aircraft has been chosen as it is large enough to carry the payload desired but small enough to keep the risk profile at an acceptable level during the initial flight testing campaign where this novel system will be first trialled. The platform is shown in Figure 7.

Figure 7 - Experimental platform for forced landing research

As discussed, the approach for initial testing and development of the software modules is to keep to bulk of the processing on computers at the ground station. This approach serves a number of purposes: the first being to keep the payload on board to a minium to reduce the cost to the project from any complete or partial losses of the aircraft which should be planned for in any experimental flight test; secondly, this in turn reduces the overall size of the UAV which is good from a safety point of view; also it places less restrictions on processing requirements onboard; and allows the development of novel algorithms as opposed to miniturising hardware which should be done at a later stage.

Specifically, the hardware onboard will include:

- An autopilot to accept waypoint and velocity

commands from the Guidance and Navigation module on the ground;
- A radio modem to accept communications from the ground and pass through commands such as the waypoint demmands to the autopilot;
- GPS and inertial sensors as part of the autopilot system for navigation and also used for georeferencing the target landing location;
- Long range laser altimeter for height above ground readings and included in georeferencing the target landing location;
- A high power analogue video link and camera to send imagery to the ground station for processing. The camera will have the ability to look directly down and also tilt forward for the approach phase of the landing; and
- Other associated equipment such as batteries and servos.

The groundstation components will consist of the radio modem transceiver, the receiver for the video link, antennas and suitable computer hardware to interface to the radio modem (RS-232/485) and input the analogue video. The software modules will run on the hardware and receive input data such as the UAV's current position, velocity, long range laser readings and air data information via the radio modem link. This data will be used along with the imagery from onboard to complete the tasks as defined in Section 2.

This hardware setup will allow flight testing of the forced landing algorithms through a range of altitudes and scenerios, providing the first steps towards a prototype UAV forced landing system.

5 Conclusion

A number of research programs have been presented in this paper and an overview of the software system and flight testing hardware has been provided. This overview aims to present the methodology for the development of a system capable of flight trials for a UAV forced landing.

Research in this area by the group over the past 3 years has seen the technical risk of an autonomous UAV forced landing system decrease, and the group is now confident that with the existing results and new research objectives, future flight tests will demonstrate this level of capability that is missing in UAVs today. The capability for a UAV to be able to land in an unknown environment with no human input is something that must be solved if UAVs are to fly above populated areas in civillian airspace.

It is believed that the approach presented will allow the progression of this novel UAV forced landing area from the development and simulation stages through to a prototype system that can demonstrate this important capability for UAVs to the research community.

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