Experiments in Integrating Autonomous Uninhabited Aerial Vehicles (UAVs) and Wireless Sensor Networks

Steven Teh*, **Luis Mejias***, **Peter Corke#**, **Wen Hu#**
*Queensland University of Technology
s4.teh@student.qut.edu.au, luis.mejiasalvarez@qut.edu.au
#CSIRO ICT Centre
{peter.corke, wen.hu}@csiro.au

Abstract

This paper is concerned with the integration and control of UAVs and wireless sensor networks, an approach that is useful in isolated areas where communication between ground nodes might be difficult. We present the preliminary design for a fixed-wing aircraft carrying a wireless sensor node which acts as a mobile gateway for information gathering. Experiments were conducted using a low cost UAV platform to measure the range and amount of data that can be exchanged between ground-based and airborne nodes. Field test results demonstrate the feasibility of this approach and the viability of a combined UAV air and ground wireless sensor network.

1 Introduction

We are interested in the application of unmanned systems to civil and commercial applications, leveraging a technology which has until now been largely applied to the military domain. Research in unmanned technologies and smart payloads will be key to the use of small and medium size Uninhabited Aerial Vehicles (UAVs) as an inexpensive tool for executing inspection and surveillance functions, potentially revolutionizing industry. Applications of UAVs include aerial surveillance, search and rescue, border patrol, facilities inspection, management of natural risks, environments, intervention in hostile environments and agriculture. In these applications UAVs and wireless sensor networks are complementary technologies. UAVs are mobile and have the ability to sense over a large area, but from a high altitude. Sensor network nodes make in-situ point measurements about a very small area. Sensor network nodes have radio communications capability, but with ranges of the order of 1km and at current unit prices they remain a prohibitively expensive approach to cover large areas. Instead we can use UAVs to upload information sensed in-situ by nodes on the ground or to deploy nodes, see for example [Ollero *et al.*, 2007] [Corke *et al.*, 2004].

Very little research to date has looked at the problem of controlling the flight platform using feedback from the node. Our research aims to provide, in the long term, an answer to the question: Can a UAV dynamically replan its trajectory based on the feedback received from each node in the sensor network? Our aim is for the flight control and trajectory planning system to re-task the mission in an adaptive manner, or switch the control mode or gains in the flight controller in order to achieve an optimal flight pattern with respect to the nodes on the ground. In this paper, we approach the first stage of this problem which is the characterization of the network communications with respect to range and also to demonstrate data muling between nodes. The work reported in [Allred *et al.*, 2007] is the closest in spirit to our approach. They use a "minimal" autopilot combined with a globally stable and convergent vector field guidance system on each vehicle. This provides a small, low-mass, and low-cost autopilot system that requires very little human interaction in the form of flight control or path planning. The operator or an overseeing algorithm provides the desired center of loiter coordinates and a loiter radius.

Sensor network nodes are devices that incorporate communications, processing, sensors and power sources within a small package. They have become a useful tool for research and real-world applications including habitat monitoring, health, education, structure monitoring, precision agriculture and military. Traditional WSN typically feature one or more base stations [Hu *et al.*, 2004], also called sinks or gateways, to which all the information collected by the sensor nodes will be forwarded. The base stations then forward the information to end users via the Internet. UAVs acting as mobile base stations can improve network performance measures such as energy consumption and traffic load balancing. UAVs can also serve as mobile sensing nodes, augmenting the network of fixed nodes with additional sensors, or the same sen-

Figure 1: Fleck 3 Wireless Sensor Node. The size of main board is 50x60mm.

sors temporarily at locations not currently sensed. The use of UAVs and sensor networks together will enable many novel applications, for example:

- ***Remote data muling***: in which a robotic agent moving through a large-scale network uploads data and carries it back to base. For example in [Vasilescu *et al.*, 2005], a robotic submarine serves as a mobile base station to collect information from a network of underwater sensors (AquaFleck). In this paper, we design and implement a WSN airborne mobile base station based on a UAV. The UAV base station can mule information from a WSN deployed in a remote area where conventional communication networks such as the Internet and mobile phone networks are not available.
- ***Urban pollution monitoring***: UAVs together with ground sensors can provide fine-grained three-dimensional sampling of a physical phenomenon. For example, a hybrid system of UAVs and ground sensors can be used to accurately sample pollution, such as CO2 levels over a large geographical area.
- ***Traffic monitoring***: acting as mobile camera sensors, a fleet of UAVs can be used to monitor traffic conditions on major roads during rush hours.

At CSIRO the wireless sensor network group is focusing on the development of robust and manageable wireless sensor networks, primarily for large-scale environmental monitoring. At the core of this project is the Fleck series of wireless sensor nodes, the latest of which is the Fleck 3 shown in Fig. 1. These devices incorporate a number of novel design features that set them apart from other devices on the market: a long-range radio for outdoor applications, solar-capable power supply, and an extensive range of sensors and sensor interfaces. The Fleck 3 has the functionality of the Fleck 1 family with additional on-board GPS, 3-axis magnetometer, 3-axis accelerometer, and an MMC socket for local bulk data storage. The uBlox GPS chip is capable of producing position fixes at 4Hz and supports differential corrections and various power-saving modes. A detailed description of the sensor can be found in [Glaser, 2004].

Autonomous Flight Search and Navigation (AFSAN) is an undergraduate final year project at Queensland University of Technology (QUT). The project started in 2007 with the aim of developing a flexible, reliable and low cost UAV platform. One of the main goals of AFSAN was to serve as an engineering educational platform for Aerospace Avionics students at QUT. In 2007 the project achieved a major milestone of autonomous flight control and navigation capabilities. In 2008, the AFSAN project saw a new student team and extended its scope by collaborating with the ICT Centre at CSIRO to develop full autonomous control and waypoint navigation for a UAV sensor network. The primary objective is to develop civilian applications based on UAVs and sensor networks. We explore and evaluate the use of UAVs as mobile gateways in sensor networks. Experiments performed with a small UAV and several sensor nodes demonstrate the feasibility of the control and navigation using feedback from the sensor nodes. The project represents the first implementation of CSIRO's sensor network technology on a UAV platform. This paper presents the experiments and results obtained using a low cost UAV platform and a wireless sensor network.

The remainder of the paper is organized as follows. Section 2 describes the system design and its constituent components. Section 3 describes the experimental setup and procedures, the results are discussed in Section 4. Finally, Section 5 presents our conclusions.

2 System Design and Approach

2.1 Airborne System

UAV design is a challenging task that must balance size, weight, flight endurance, payload capacity all whilst minimizing costs without compromising safety. The AFSAN system is the realization of a baseline design incorporating the knowledge and experience from prior UAV efforts. The design is intended to be cost-effective and reliable, utilizing as many off-the-shelf components as possible. The airborne system can be segmented into four main system areas: airframe, power and propulsion, avionics, and payload.

The platform chosen for the initial experiments is a Boomerang 60 model aircraft. The Boomerang comes almost-ready-to-fly and is an inexpensive option for flight test experiments. Additionally, this aircraft has

Figure 2: Standard TF4050 Boomerang trainer.

Figure 3: Modified Autonomous Boomerang.

been chosen because it is large enough to carry the desired payload, but small enough to keep the risk profile at an acceptable level during initial flight testing.

The TF4050 Boomerang, shown in Fig. 2, is a trainer aircraft, giving it good flight stability and control. This airframe is primarily constructed from balsa wood with an approximately 2m wingspan. Comparing Fig. 2 and 3, it can be seen that several additions are required to prepare the aircraft for autonomous flight. A pitot tube mount is constructed on the wing. Global Positioning System (GPS) antenna are positioned on top of the fuselage, as well as several other omni-directional antennas for avionics and payloads. Many modifications to the airframe itself are to improve its practicality in field operations: for example, the conversion from a high-wing (the wings are connected at the top of the fuselage) to a low wing (the wings are connected at the bottom of the fuselage) makes it easier to access the internal systems. Other modifications such as the relocation of the servos that manipulate the aircraft's control surfaces are chosen carefully to maximize the available room in the main fuselage area for other on-board systems.

The primary power system for the aircraft consists of two NiMH batteries: a 12 volt pack for avionics and a 6 volt pack for servo power. A separate battery for the servos is used as a safety mechanism to prevent electrical noise from the servos affecting critical avionics such as the autopilot. Each battery cell has a 2400mAh capacity, giving the avionics an endurance of at least 1.5 hours. Propulsion is provided by an OS Max91FX glow engine. A 710cc fuel tank provides up to 30 minutes of flight time. Engine vibration damping is achieved with two stages of fail-safe silicone polymer vibration isolation mounts. Without this vibration damping system, the autopilot's inertial sensors cannot operate correctly. The final platform used during the experiments is shown in Fig 3.

The main avionics consist of a Micropilot MP2128^{Heli} autopilot, a Microhard MHX920A radio modem, and a power supply system to deliver regulated power to various aircraft payloads. Support avionics for the autopilot include Global Positioning System (GPS), pitot tube for measuring airspeed, magnetometer (compass), analogue-to-digital converters (ADC) and an air-to-ground level (AGL) ultrasonic sensor for accurate measurement of altitude close to the ground. Finally, a Spektrum AR9000 receiver provides the manual radio control link. These system components are shown in Fig. 4.

The aircraft system has two scientific payloads, a CSIRO Fleck 3 and a pan-tilt camera. The camera is a basic 5.8 GHz wireless analogue camera with extended range using a tracking antenna on the ground. This camera system serves as a test bed for prototyping video applications on the UAV.

2.2 Sensor node: The Fleck 3

The Fleck 3 (Fig. 1) is a low power embedded sensor device that features an Atmega 128 microcontroller and a Nordic nRF905 radio transceiver [Corke, Jan 2008]. The micro controller works at 8 MHz and has 4 kbyte Random Access Memory. The nRF 905 transceiver operates in the 900 MHz Industrial, Scientific, and Medical (ISM) band and has four different transmission power levels (-10, -2, +6, +10 dBm). The Fleck has been integrated into the airborne system by separating the antenna from the main board via a SubMiniature version A (SMA) extension cable. The Fleck subsystem is housed within the aircraft's payload section. The antenna has been mounted externally on the airframe with an orientation to match the polarization of ground node antennas as shown in Fig. 5.

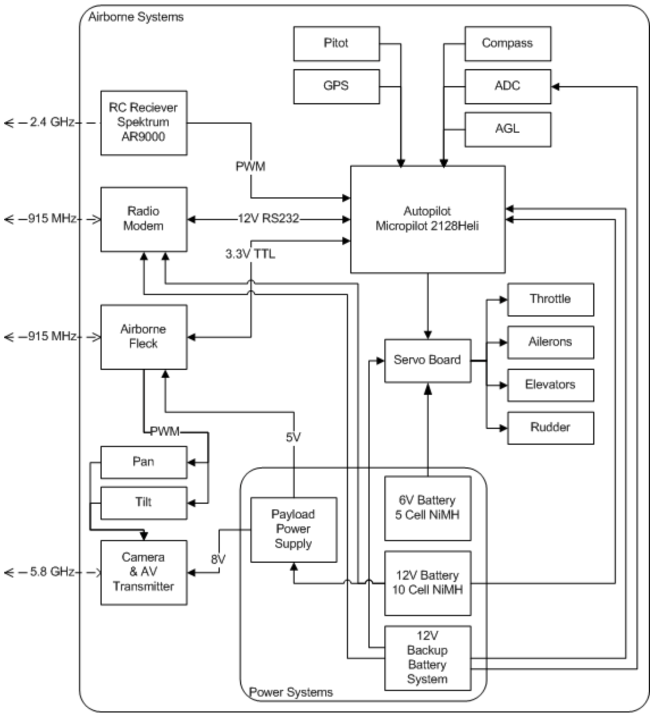

Figure 4: UAV System Architecture.

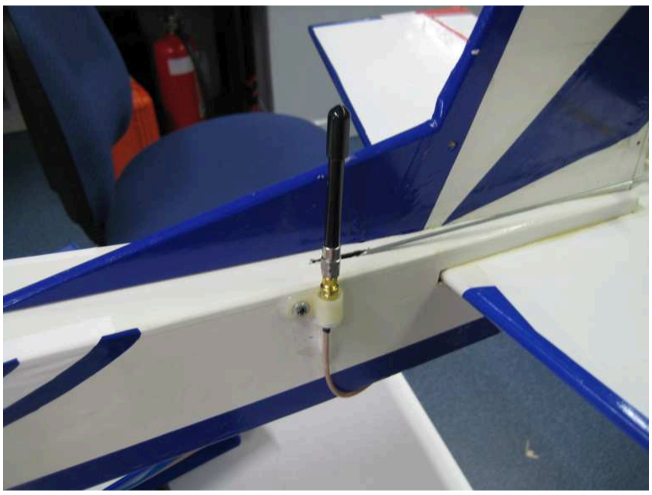

Figure 5: Airborne Fleck Antenna.

The payload section of the aircraft is large enough for multiple Flecks or expansion boards to be used on the airborne Fleck. Refer to [Dinh *et al.*, Oct 2007] for a detailed description of the hardware and software components in the Fleck 3.

2.3 UAV Control

The Micropilot MP2128^{Heli} autopilot has extensive capability for its size and weight. It can control both rotary and fixed-wing aircraft with autonomous waypoint navigation for up to 1000 waypoints. A 4 Hz GPS and optional magnetometer are the autopilot's navigational sensors. Micropilot's Ground Control Station Software, Horizon^{mp} provides real time flight information and allows the autopilot waypoints to be dynamically re-tasked. The AGL sensor can be integrated for autonomous take-off and landing capability. The MP2128^{Heli} can be further expanded with its ADC module, and up to three user-configurable serial ports. Finally, user-programmable fail-safes allow for control over flight or mission termination.

The autopilot utilizes 12 PID (proportional, integral, differential) feedback loops to stabilize and control the aircraft. The PID loops used change depending on the desired mode of flight: take-off, landing, climb or level flight. PID control is one of the most common controllers in modern autopilots [Chao *et al.*, 2007] due to its simplicity and accuracy.

For the autopilot to be able to control the aircraft, a PID tuning process must be completed. While theoretically possible to tune a PID controller analytically or via a simulation method this requires a good dynamic model of the aircraft which in turn requires considerable experimentation and analysis. Instead, a manual tuning method was used to configure the PID gains. This method involves observing the aircraft during flight operations and adjusting gains through trial and error until the aircraft is controlled sufficiently well.

This method is not as time consuming at it may first appear because Micropilot provides gains for a 40-sized trainer aircraft, similar in flight characteristics to the TF4050 Boomerang, which is an excellent starting point.

2.4 Fleck-Autopilot Integration

The Micropilot autopilot has the ability to configure unused servo board outputs into serial communication ports. This configuration option can be exploited to create two additional 3.3V CMOS serial interfaces. The Fleck serial ports are 12V RS232, an incompatible interface that would cause damage to the autopilot electronics. This was overcome through the use of a MAX3223CPP bus transceiver chip that converts the 12V signal from the Fleck to 3.3V level required by the Micropilot and vice versa. This hardware configuration

Byte 0	Byte 1	Byte 2	Bytes 3.. N-2	Byte N-1	Byte N
0xFF	Sequence #	Command Type Response Code	Command Data Response Data	Checksum	0xFE

Figure 6: Micropilot communications protocol format.

allows the Fleck to be integrated with the Micropilot without impinging on the baseline setup of the UAV.

The approach taken to the creation of the software interface between the Fleck and Micropilot is to conduct all communication using the Micropilot defined protocol format which is shown in Fig. 6. This format is used by the ground station control software for the autopilot and is reliable and robust. In this way, the Fleck will appear as another ground station computer from the autopilot side of the interface.

Communication with a Micropilot autopilot is a command and response system. The ground station (or in this case, the Fleck) always initiates communication by sending commands to the autopilot. The autopilot will reply with a response to the command some time later if required.

The Micropilot protocol is little endian in format, the least significant byte of a multi-byte value in a command or response packet is transmitted first. Start and stop packet characters are 0xFF and 0xFE which means byte stuffing is required for the data portion of a packet. The checksum used is the unsigned sum of all the bytes in the data portion. Sequence numbers are used to keep track of which responses belong to which commands. The command/response type in the packet specifies the layout of the rest of the data in a packet.

3 Experimentation

This section presents three major experiments in the development of a UAV platform integrated with a wireless sensor network. The first is an experiment in testing the communication range between airborne and ground network nodes with the initial hypothesis that the airborne wireless sensor nodes have improved communications range compared to its ground-based brethren. The second experiment was designed to demonstrate the data muling capability of the UAV. The third experiment is the software integration of the Fleck 3 wireless sensor node with the Micropilot autopilot of the UAV. The integrated sensor node-autopilot configuration is our approach to creating a dynamic flight planning and retasking autonomous system that can accept feedback from the sensor network to guide its mission. The setup and results for each experiment are discussed in the following sections.

All experiments involved the use of AFSAN's autonomous UAV described in section 2 with an integrated Fleck 3 payload. During the field tests a Fleck base station was used to monitor the airborne Fleck as well as start and stop the collection of data. Flight test mission areas were constrained to be within line of sight of the base station as well keeping the UAV within manual radio control range at all times.

3.1 Sensor Node Range Test

The sensor node range test experiments were designed to determine the range characteristics of the UAV system as a mobile sensor node. Field tests were conducted at Watts Bridge Memorial Airfield, and on a private aeromodelling airstrip at Boyland. The test area and setup for Watts Bridge is shown in Fig. 7. Four Fleck ground nodes were deployed in a line along the boundary of the mission area. The recorded flight path of the UAV during the test is also shown by the white line. The total experiment time was just under 20 minutes, predominantly spent in fully autonomous flight.

The airborne Fleck is configured to periodically broadcast beacon messages and log the reply messages from the ground nodes which function as transponders. The beacon message contains a sequence number and the power level at which the beacon is transmitted. Beacons are transmitted at different powers in the sequence: -10, -2, +6, + 10, -10, -2 dBm, etc. The purpose of the varying strength beacon messages was to obtain some increased precision in estimating the range between a beacon and the transponder.

The reply messages contains the sequence number and beacon power level copied from the beacon message, the address of the transponder node and its temperature and battery voltage.

The airborne Fleck uses GPS to track its position during the test and can thus record the location when each beacon messages was received. All data is timestamped and logged to a 1Mbyte flash chip on the Fleck. In this test, the ground nodes were only responding to beacon messages and not performing any other processing or ground network communication. The software pseudo-routines are depicted in Fig. 8.

This same experiment was repeated another three times at Boyland to collect sufficient data. Some modifications to the test setup were made however. The number of transponder nodes was reduced to one, and the mission area expanded to allow autonomous flight at longer ranges from the transponder on the ground. The results from all the test flights are summarized in Table. 1. The values in the table columns are the maximum, mean, median, and minimum ranges in meters respectively at which beacon communication was recorded. Tx0, Tx1, Tx2 and Tx3 (-10, -2, +6, +10 dBm respectively) are the transmission powers of the Fleck radio used in the beacon communication.

Figure 7: Watts Bridge test site and setup.

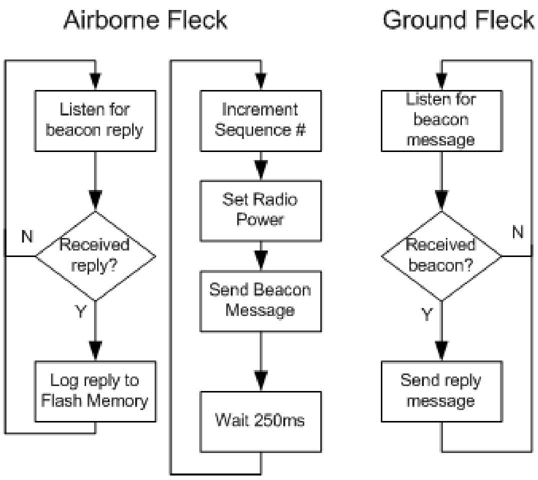

Figure 8: Software logic for range test.

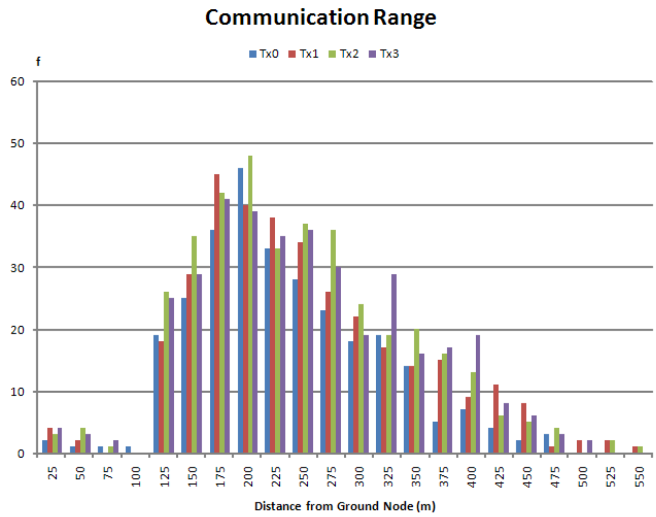

Figure 9: Histogram of beacon ranges by transmission power.

	Tx0	Tx1	Tx2	Tx3
max (m)	470	526	534	492
mean (m)	223	237	232	238
median (m)	205	219	220	226
min (m)	10	10	19	19

Table 1: Airborne sensor node range results.

Analysis of the data yielded the results in Fig. 9, which shows the frequency at which beacon message communication took place with respect to distance (taking into account altitude). The data is grouped by transmission power. Fig. 9 is the results from all of the experiments combined. Each beacon reply recorded by the airborne Fleck constitutes a received beacon for which the range between the aircraft and ground node that responded has been calculated. The distribution of the histogram is not intuitive. The total number of received beacons at ranges under 100m is low not because communication was unable to take place at that range, but simply because the aircraft spent little time flying in an area that distance from the ground nodes. This is not true on the other end of the scale however as experiment setup provided ample flight time at distances well beyond the maximum recorded communication range.

3.2 UAV for Data Muling

The data muling experiments were designed to demonstrate the feasibility of a fixed wing UAV as a platform for data muling between sensor nodes. Two separate field tests were conducted at Boyland. Fig. 10 shows the recorded flight path and setup from the first of these tests. During this test the UAV flew a figure 8 pattern autonomously for over 20 minutes.

The Fleck software configuration for this test was similar to the range test in the previous section. The airborne Fleck records the UAV's position during a flight while transmitting data request packets which are similar to beacon messages to listening ground nodes functioning as transponders. The data request packet causes the transponder to reply by sending a large number (2000) of data packets to the airborne Fleck. The airborne Fleck records the uploaded packets along with their timestamps. The software pseudo-routines are depicted in Fig. 11.

Analysis of the data from the data muling experiments was focused on quantifying two metrics: data throughput and delivery ratio. Fig. 12 shows the data throughput with respect to the distance the UAV was from the transponder. Fig. 13 shows the delivery ratio with respect to the same distance. Both figures show the raw data plot and the mean, maximum, and minimum values in distance bins of 20m. Other analysis efforts not included in this paper were the creation of similar plots of throughput and delivery ratio with respect to: aircraft heading, delta heading, velocity and heading difference between the UAV and the transponder. Analysis from these plots proved to be inconclusive and will be further discussed in Section 4. The results of the data mule experiment prove that the integrated Fleck UAV platform can indeed be used as a roaming data sink.

3.3 Fleck Dynamic Navigation

Fleck software was created to handle the communications format shown in Fig. 6 to create a dynamic navigation system for the UAV that can change the autopilot's GPS waypoints on the fly. This is achieved by modifying the values of waypoints in the autopilot's command buffer. Using Micropilot's own communication format and command structure makes this operation safe and able to be monitored by the Micropilot ground station control software. The dynamic navigation system can be

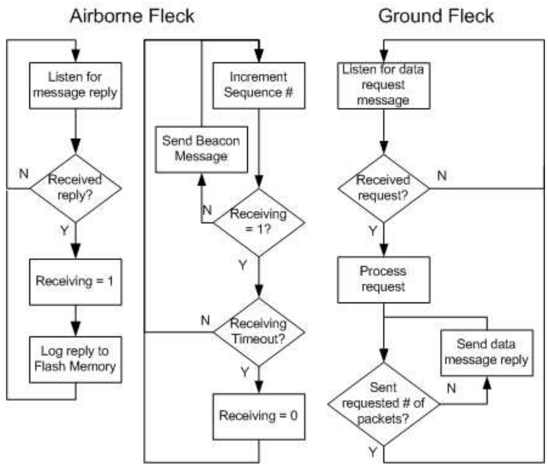

Figure 11: Software Logic for data mule.

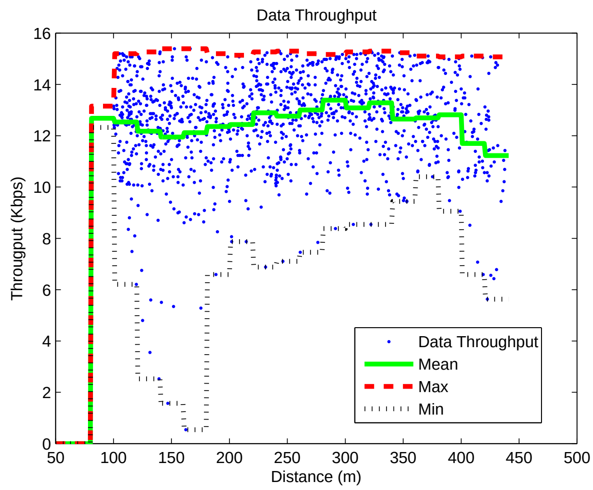

Figure 12: Data mule throughput.

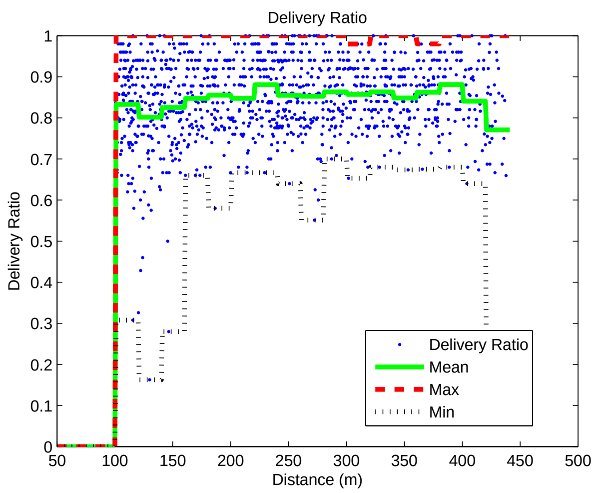

Figure 13: Data mule delivery ratio.

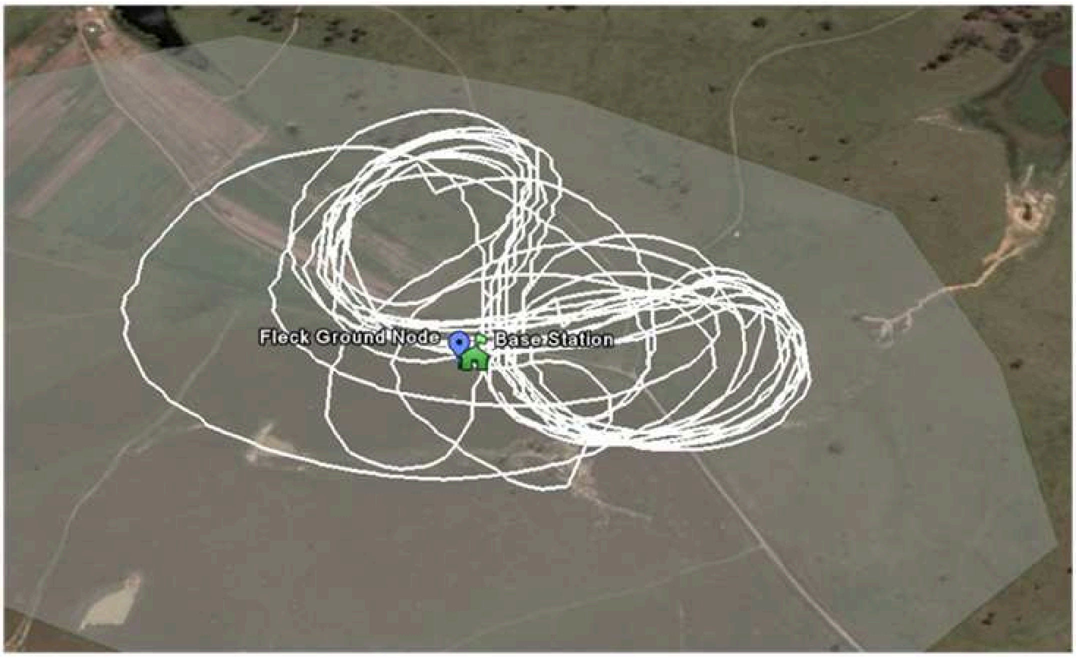

Figure 10: Data mule Boyland test site and setup.

used to autonomously create dynamic flight plans for the UAV in a data muling scenario where the optimal flight path can only be calculated in the field or from changing sensor network feedback.

A test application that created a virtual pathline for the Fleck-directed UAV to follow was created as an initial experiment in answering the long term question proposed by this paper in Section 1. The software pseudo-routines are depicted in Fig. 14.

This test application was validated in laboratory testing, however field testing is part of our future work.

4 Discussion

The results from the range test flights were not as expected. Data (Table. 1) from the three flight tests show that the maximum communication range achieved is around 500m, about half of the expected minimum. Closer examination of the test flight setup and system architecture (Fig. 4) can explain some of the results.

A potential factor in the Watts Bridge test is the density of the ground node deployment. It is conceivable that at any one time, all four of the ground nodes were attempting to reply to a beacon message from the airborne Fleck. Although the Fleck MAC layer checks the channel before transmitting the system may suffer from the hidden terminal problem. The radio path loss between air-ground nodes is significantly smaller than the path loss between ground-ground nodes [Allred *et al.*, 2007], it is common that the airborne Fleck can hear two ground Flecks; however, the two ground Flecks can

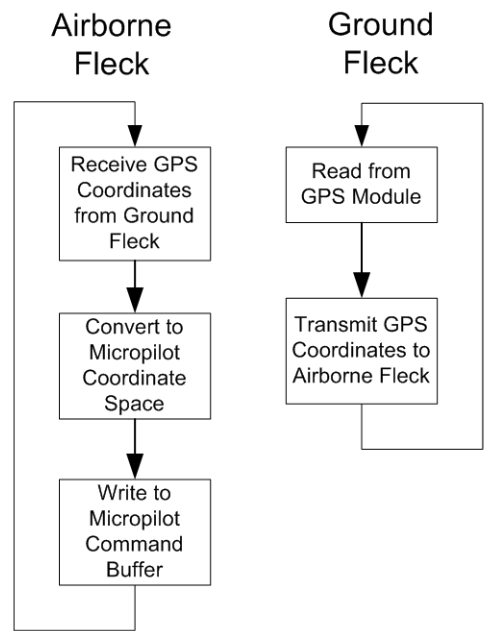

Figure 14: Software logic for dynamic navigation.

not hear each other. It suggests that either conventional Request To Transfer (RTS) and Clear To Transfer (CTS) found in IEEE 802.11 protocol is necessary, or we need to introduce longer random back-off intervals to reduce transmission collision probabilities.

Another likely cause can be seen with scrutiny of (Fig. 4). The Fleck and UAV radio modem both use the 900 MHz ISM band. While both radios are spread spectrum and can clearly operate together, it is possible that the radio modem is causing interference with the Fleck. The Microhard MHX920A radio modem has a maximum power output of 1000mW, 100 times greater than that of the Nordic nRF905 on the Fleck.

Surprisingly, the results show that transmission power appears to have little overall effect on the range of communications when in theory, every 6dBm power increase should double the line of sight range.

We believe these results demand further flight trials. Firstly, control experiments should be conducted with the UAV radio modem off. However, this would require manual piloting of the UAV and this limits the range of the experiment. Additionally, further experimentation should be done with the antenna configuration on the airborne platform. Different orientations and the inclusion of a large ground plane for the antenna are part of our future work.

The results from the data muling experiments are promising for the fixed wing UAV, they show that within 400m range the airborne Fleck is able to receive data from a ground Fleck with a high delivery ratio. The 400m radius is several times greater than the smallest turning radius the UAV can autonomously achieve. Analysis of the data muling experiments also included attempts to characterize the communication performance with respect to parameters of the UAV's flight, such as heading, velocity, etc. Results from this analysis were inconclusive. It is likely that the communication performance is affected by many factors other than distance (though this is believed to be a strong factor) and these factors have a multiplicative affect on the final observed results.

5 Conclusions

In this paper we have presented initial experiments on the integration of UAVs and wireless sensor networks. These experiments will lead to the development of a fully integrated network of wireless nodes and UAVs with the capability of dynamic flight plan re-tasking based on feedback from ground nodes. The AFSAN UAV system has proven to be fully capable of autonomous flight operations. The baseline design is scalable to larger airframes for longer flight endurance, and able to carry additional or larger payloads than a single Fleck 3. The AFSAN UAV was fully tuned for autonomous waypoint navigation and flight in only three flight tests (separate from the experiments presented in this paper). Each test targeted various control loops to incrementally build the autonomous capability of the aircraft: wings level flight, waypoint navigation and finely tuned throttle control were the main steps.

Our experiments are inconclusive in completely characterizing the airborne Fleck network communications with respect to range. However, the feasibility of UAVs as mobile wireless sensor nodes has been proven.

Future work will include tuning the autopilot for autonomous take off and landing, further range testing and data muling experiments (currently being undertaken) and the field testing of the integrated on-board Fleck-autopilot dynamic navigation system in order to allow the wireless sensor nodes to provide feedback to the UAV and re-task the flight plan.

Acknowledgments

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