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Autonomous collection of ground truth data by unmanned aerial vehicles instructed using SMS text messages

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***Abstract*—This paper describes a solution to increase the efficiency of collecting agricultural ground truth data by the use of one or more off-the-shelf drones to autonomously collect high quality RGB image data at low level, through the incorporation of a bespoke smartphone application that receives routing path-planned location data in the form of Short Message Service (SMS) text messages.**

***Index Terms*—Autonomous ground truth, Android Application**

I. Introduction

Current agricultural surveying increasingly involves the use of Unmanned Aerial Vehicles (UAVs) to collect standard (Red, Green, Blue) RGB image and multispectral image data [12], [13], which is then processed using algorithms to produce index maps specific to the area of interest. An example of the process is described in “Evaluating Multispectral Images and Vegetation Indices for Precision Farming Applications from UAV Images” [1].

The value of such survey output is increasingly reliant on the objective accuracy of machine learning [14], [15] within the process to produce tailed index maps. This in turn requires example data to train and improve algorithms especially where algorithm’s initial development was from lower resolution satellite imagery data, as described in “Ground truth information is necessary for evaluating products and services under various settings and physical or weather conditions” [2], and to provide supportive information for “enhancing the existing tasks of management and decision/ policy making by context, situation and location awareness” [6]. Ground truthing comprises of close examination of crop canopy typically achieved by agricultural specialists visiting a number of locations within fields of crops. Information gained can include aspects such as growth stage, disease type, and insect presence identification.

Whilst automation of analysis of ground truth data is desirable, there is still significant human interest in the specific health of crops. Providing close proximity data that is easy to analyse can provide agricultural decision makers with the information they need to give them the confidence to make manual and confirm machine derived decisions as automation increases.

Current ground truthing methods have the following disadvantages though:

- It is a manual process that requires people visiting identified locations
- It can take many hours for large fields and farms
- It is a relatively slow process which can fail to spot fast spreading issues being identified quickly enough
- Carbon dioxide / particulates are emitted farm vehicles travelling to locations
- Specialist agricultural knowledge is required at the locations to interpret data

Methods for identification of areas of interest for ground truthing, allocating tasks to UAV’s and carrying out path planning are not discussed within the scope of this paper, but are fundamental and therefore do require consideration with respect to automated ground truth solutions. This paper describes an autonomous solution to minimise or eliminate the aforementioned disadvantages.

II. Automated Ground Truth Method Requirements

A number of factors were considered in defining a solution to automate a ground truthing process.

- The type of data to be collected at locations of interest
- The means of transmitting data to a specialist for interpretation
- The speed and quantity of locations of interest that can be visited
- The cost of development, and potential future purchase, operation, and maintenance
- The effect of the environment on the method
- The impact of the method on the environment
- The safety of the method
- The potential ease of adoption within establish process workflows

- The transferability to other (non-agricultural) processes benefitting from ground truth data

Upon initial review of these factors, it was apparent that a UAV-based solution could be appropriate, and as such was considered in more detail against these factors.

A. Data Type and Transmission

Given a solution was to be a proof of a concept it was decided to keep data collection to a single and widely understood format, and so high quality RGB photo imagery was selected.

Fig. 1. image of crop captured with 20-megapixel camera and at 3X magnification

Given a solution was to be a proof of a concept it was decided to keep data collection to a single and widely understood format, and so high quality RGB photo imagery was selected. Modern UAV-based camera system include 'Auto' camera settings, which optimise colour, contrast, and brightness per photo taken. From a height of $10m$ above ground level, a 20-megapixel camera can capture images with a ground spectral density (resolution) of $0.23cm$ per pixel. With the drone camera field of view (FOV) of 77^o the crop area captured within a photo taken from a $10m$ height is $14x8m$. An example image of crop at this resolution and at 3 x magnification shown in fig. 1

Photos can be transmitted electronically via email and FTP, and do not require post processing or localisation in order to be interpreted. Photos can also be geotagged such that location and capture height data is included within the file metadata along with date and time of capture. This in turn aids subsequent analysis and archiving.

B. Speed and Path Length

Camera equipped consumer / prosumer UAVs can typically operate at speeds of up to $20m/s$ with effective flight times of 25 minutes [3]. This gives the potential for location (waypoint) survey paths of up to $30km$. In practice, it would be expected that paths would be shorter due to the need to limit speed whilst capturing data due to potential camera motion blur.

C. Cost

To keep cost to a minimum, use of standard off-the-shelf UAVs (consumer / prosumer style drones) was highly desirable, and that required bespoke functionality be added by incorporation of UAV-to-operator integration software, where possible. This approach harnesses the benefit of the fast-paced technological developments in commercially available UAV products.

D. Environmental Consideration

As with all aircraft based operations, adverse weather can reduce the quality of data captured and on occasion prevent flights from taking place. The captured image quality will be affected by poor light conditions and so time of day and weather will affect results. Survey flight times will be reduced where UAVs have to accommodate stronger winds. Airborne data capture eliminates the risk of damage to crops compared to walking in fields, and battery powered UAVs do not produce emissions at the point of operation.

E. Safety

Given the regulative framework within the UK [4] operational safety is a fundamental consideration when operating UAVs especially with autonomous functionality. As such, the system's architecture has to ensure that:

- Legal operational requirements are complied with at all times
- An operator (safety pilot) must take full responsibility for safe conduct of the flight, be able to maintain Visual Line of Sight (VLOS) throughout the flight, and be able to abort the flight safely in the event of an emergency.
- The system must provide the operator with the necessary situational awareness information to meet the requirements of preceding points.
- Adequate security within the system is required to prevent unexpected autonomous behaviour, unsafe operation, and illegal operation.

Also considered was the potential for UAV situational awareness with respect to collision avoidance. It in increasingly common for consumer drones to include camera and ultrasonic-based systems to prevent collision occurring from controlled flight into obstacles. This functionality is often now available in 3-axis providing spherical collision avoidance protection.

F. Ease of Adoption

In order to effect change to established procedural workflows, new procedures need to be easy to use and easy to integrate. Consideration was given at the system architectural definition stage as to how users could and would be prepared to interact with the system.

G. Technology and Application Transfer

Whilst the nature of this case study focused on the collection of agricultural image data, this fundamental approach to instructing UAVs to collect ground truth image data is application agnostic. Other applications such as search and rescue of missing persons may benefit from this approach where urgent ground truth identification of newly identified locations is required, especially where there are large survey areas with human resource constraints.

III. Solution Identified

Whilst not mandatory to function, many consumer style drones operate with the inclusion of a smartphone or tablet computer into the operator's controller. Typically, this is to provide a human machine interface (HMI) to the drone in order to be able to view a live feed from an on-board camera together with reviewing essential flight telemetry data such as height, speed, and position data on a moving map. A smartphone connected to a consumer drone controller is shown in the following fig. 2. Given the widespread use of smartphones,

Fig. 2. Smartphone connected to the operator's controller

a bespoke smartphone application was identified as an ideal method of providing an autonomous receipt of waypoint data and conversion into an autonomous drone ground truth UAV missions.

IV. Development Approach

A smartphone application software development company, Apadmi Ltd.[9], was selected to produce the application, and a requirement specification produced to define the scope and functionality.

The application was designed to run on readily available hardware to enable potential future development and commercialisation opportunities. Android applications can be loaded directly onto a smartphone without mandatory release through a proprietary 'App Store'. This allowed development iterations to be quickly loaded and tested, and removed any requirement to meet additional App Store quality and privacy requirements. This approach was appropriate given that commercial release of this application was not within scope of the project.

The application was developed and tested using a Samsung Galaxy S9 smartphone and a DJI Mavic 2 Pro quadcopter consumer drone. The smartphone was running Android version 9 and the drone firmware version $V01.00.0400$.

A. Functional Flow

The application essentially carries out three primary functions in the order as shown in fig. 3.

Fig. 3. Functional Flow

B. Data transmission format, selection, and receipt

Due to the desire to incorporate standard off-the-shelf smartphone hardware as part of the ground truth data collection system, only well established and existing data communication formats and protocols were considered. The Short Message Service (SMS) protocol is a well-established means of sending small amounts of ascii data (160 characters) over Global System for Mobile (GSM) networks and was selected accordingly. Other means of data transmission were not considered for this aspect of overall intra-system communication due to the need for bespoke hardware and possible additional infrastructure.

SMS messages were generated from a ground control station comprising of a computer running a Matlab program to carry out task allocation and individual drone path planning, together with a GSM module connected as a means to transmit SMS messages. Waypoints, and the order in which to visit them, were defined as an output of this program.

To ensure integrity and security of SMS data transmission, the application requires the sender's number to be entered in the settings. Multiple SMS messages are required for multiple waypoint missions. These SMS text message mission 'bundles' require a mission number to be entered during the sending process, and are subsequently given a unique serial number. Each waypoint is sent as an individually numbered SMS text message. The positional format of the waypoint is decimal Latitude / Longitude in accordance with the WGS 84 coordinate system. The last SMS message contains a checksum. This checksum recognises the number of messages within the mission and therefore allows the applications to wait for any missing SMS messages. This is necessary due to the possibility that SMS messages may be received in a different order to which they are sent.

An example mission bundle containing three waypoints requires transmission and receipt of six SMS messages as shown in fig. 4

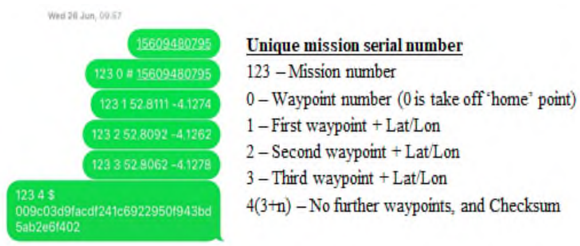

Fig. 4. SMS messages contains waypoints

C. Planning

DJI, a large manufacturer of consumer and commercial drones produces a Mobile Software Development Kit (Mobile SDK) [6] to allow third party creation of applications for interacting and controlling their drones. This application was developed to be able to communicate with compatible DJI drones using their Mobile SDK. The application scans incoming SMS text messages from the sender's number that has been entered in the application settings. It ignores all other SMS activity and databases.

The mission planning functions by compiling received waypoint data together with referencing manually configurable flight information settings contained within the application. The configurable information is flight height (above take off level, m), return to home height (from last waypoint back to home point, m), flight speed (m/s), maximum flight height (m), and maximum flight radius (m). The mission is compiled and is executed such that it will visit all the waypoints at the single specified height, pause at each waypoint to take a photo with the camera orientated nadir (pointed directly downwards), before returning to the take off point at the additionally specified height, then landing automatically and stopping the propellers. The return to home (RTH) feature, including autonomous landing as used within the application is a standard feature of DJI drones and can also be initiated manually and directly on the drone's controller. The maximum height and maximum flight radius settings provide the operator with a means to 'geo-fence' the flight to prevent the drone from exceeding safe and legal distance limitations.

D. Mission Upload

Once the mission has been compiled by the application it is uploaded to the drone through interaction with the Mobile SDK. The drone is then ready to execute the mission. Real-time telemetry data is displayed by the application running on the smartphone.

E. Modes of Operations

Whilst the ultimate aim is for a fully autonomous solution, for testing purposes an additional semi-autonomous mode was included within the application, which enables users to manually initiate the autonomous flight. This feature helped check functionality prior to flight both during desktop and outdoor flight testing.

F. Multiple Instances

Given that there could be many potential areas of interest requiring ground truth inspection, the system architecture has been designed such that it can be duplicated in multiple instances. The application works independently of any other instances of the application running and of any other drones operating locally. This is beneficial in that it provides a scalable and distributable architecture enabling multiple independent ground truth mission to be flown concurrently, all whilst being instructed from a single control station. However, this does place full responsibility for drone-to-drone deconfliction in flight on the task allocation and path planning algorithms running on the control station. Many of the DJI drone models that are compatible with the Mobile SDK incorporate collision avoidance systems; however, these are intended to prevent collision with static ground-based objects only.

The schematic in fig. 5 shows the functional breakdown and information flow within the application.

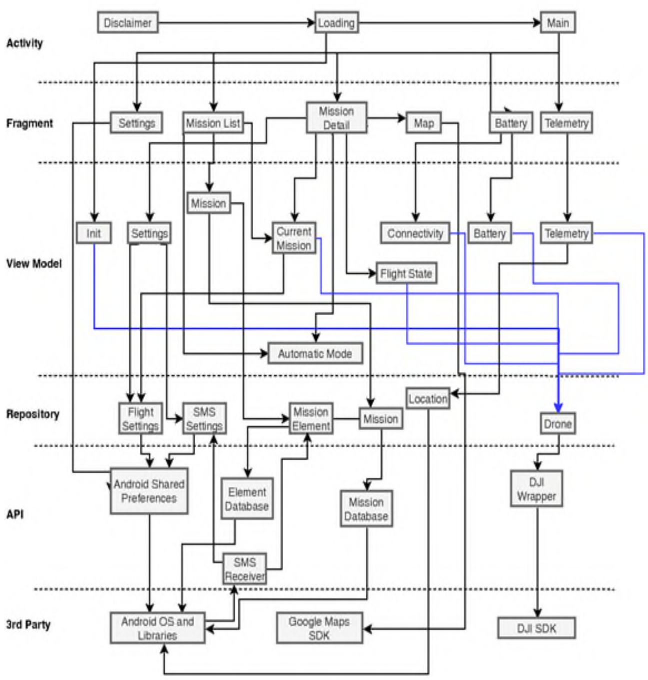

Fig. 5. Modes of Operations

V. Experimental Testing

Experimental testing was conducted to confirm the integrity of SMS as a control station to drone communication method, and to confirm achievable positional accuracy of waypoints visited. The application was developed in a four-week period. Significant desktop based testing was conducted during the development of the application, which is not covered within this paper.

The application shows displayed a user interface as shown in the image in the following fig. 6. Note that whilst displayed during operation, the drone's take off and current position are not shown in this particular image. The switch at the bottom right of the user interface is used to set the fully autonomous mode. When set, the 'Launch Mission' green icon is not displayed; instead, the progress of the mission transmission then subsequent mission completion status is shown.

Due to the short development and experimental nature of the application, testing involving outdoor drone flight was carefully planned to mitigate the risk of unexpected behaviour such as the drone unexpectedly flying away.

In order to mitigate the risk of unexpected behaviour, testing was carried out incrementally, as follows:

Fig. 6. App shows the waypoints in map

- Pre-testing of the drone in a standard configuration using the manufacturer's smartphone application (DJI Go 4) to check it flies correctly and that its standard safety features, primarily that the return to home function, operate correctly.
- Outdoor ground based telemetry connection functional check to ensure the application has two-way data access to the drone through the Mobile SDK.
- Airborne telemetry data check whilst flying manually to confirm key positional information is relayed accurately to the application to aid pilot situational awareness.
- Semi-autonomous mission operation from confirming receipt of SMS messages through to manual initiation of autonomous mission, to confirm autonomous mission are executed as expected.
- Initiation of manual mission abort both through switching to manual flight and manual initiation of the return to home function during flight, to ensure the operator can take control at any time and end the mission.
- Fully autonomous mission operation including SMS message receipt, mission compilation and transmission to the drone, take off, flight to waypoints, return to home, and landing, in order to confirm full autonomous system functionality.
- Individual testing of the application with other DJI drones compatible with the DJI Mobile SDK (models tested were the DJI Inspire 1 and DJI Matrice 100 drones), to confirm wider Mobile SDK compatibility.
- Multiple instance testing of three DJI drones flying simultaneous deconflicted mission paths, to confirm multiple drones and of different DJI types can be instructed to operate fully autonomously from a single control station via SMS text message.

A. *Waypoint accuracy*

In order to ascertain how accurately the drone could capture ground truth images, a positional comparison has been made comparing the waypoints transmitted by the control station with the positional information stored in the image file's' metadata captured from the drone's GPS system during flight. This information is shown in the table in Table I.

TABLE I
WAYPOINT ACCURACY

Waypoint	Format DD	Position	Image location	Error (m)
1	Lat	52.8111	52.8110931	1.4543
	Lon	-4.1274	-4.1274184	
2	Lat	52.8092	52.8092026	0.5692
	Lon	-4.1262	-4.1261926	
3	Lat	52.8062	52.8062036	0.4243
	Lon	-4.1278	-4.1277979	
Hovering Accuracy spec. (DJI) = 1.5 m				

The positional accuracy of a location specified in decimal degrees (DD) to four decimal places, at a Latitude of 52^0N, could not be expected to be less than $5m$. From Table I it is shown that the drone was able to navigate to an accuracy greater than that inherently dictated by the positional format of the mission waypoints, was within its published specification, and hence there was no significant additional degradation in accuracy introduced by the drone's navigation system. In the example of capturing image data at a height of $10m$, the positional accuracy noted is approximately 10% of the FOV of the camera.

VI. Conclusion

It has been demonstrated that multiple off-the-shelf drones can be autonomously sent on simultaneous autonomous missions by means of instructions received by SMS text messages in an application running on smartphones connected to a drone's' controller, as a method of collecting ground truth image data at identified locations.

This can be achieved whilst observational safety pilots are fully aware of the drone's' locations and progress throughout the mission due to displayed situational awareness information within the application, in addition to maintaining visual line of sight of the drone and maintaining compliance to UK UAV regulations.

Due to the successful use of SMS text message as a means of waypoint communication, this solution can harness the growing install base and coverage of GSM infrastructure, both land satellite based, hence enabling extensive global usage potential. Images captured provide useful ground truth data at the locations visited. The positional accuracy of transmitted waypoint locations is adequate but could be easily increased to seven decimal points in order that the location accuracy of image data is not unnecessarily limited.

Further potential development of the smartphone application and ground station control, including for non-agricultural purposes, could include: a) Capturing image-based data closer to crops using a means of UAV-ground proximity management, b) Performing contact measurements such as for soil moisture and temperature, c) Collecting samples for subsequent analysis, d) Capturing non-contact additional data types such as passive infrared intensity and hyperspectral images

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