31st Congress of the International Council of the Aeronautical Sciences
Belo Horizonte, Brazil; September 09-14, 2018

GROUND AND FLIGHT TESTING OF A MULTI-SENSOR OBSTACLE DETECTION AND TRACKING SYSTEM FOR RPAS SITUATION AWARENESS

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Keywords: *RPAS, Sense and Avoid, Electro-Optical, Infrared*

Abstract

Unmanned Aerial Vehicles (UAVs) – including Remotely Piloted Aircraft Systems (RPAS) – are becoming increasingly common, in applications ranging from search and rescue and surveillance, to package delivery and powerline inspection. In order to ensure that UAVs can operate safely around other aircraft – both manned and unmanned – it is essential that they are equipped with appropriate Sense and Avoid (SAA) technology.

This paper discusses the design of a test campaign for a system which uses Electro-Optical (EO) and Infrared (IR) cameras and an Automatic Dependent Surveillance – Broadcast (ADS-B) receiver to enable a UAV to detect and track other aircraft. In addition, the results of the test campaign – consisting of a number of ground and flight tests – are presented and discussed.

1 Introduction

The Unmanned Aerial Vehicle (UAV) industry is booming and the number of UAVs is on the rise, with applications that include: surveillance, search and rescue, product delivery, and infrastructure inspection. However, there are various challenges and safety concerns related to UAVs, including: obstacle Sense and Avoid (SAA), command and control security threats, and lack of government regulation.

1.1 Sense and Avoid (SAA)

The ability of a UAV to detect and avoid obstacles – including terrain, man-made structures, and other aircraft (whether manned or unmanned) – is very important. There are two main types of obstacle SAA: collaborative and non-collaborative.

With collaborative SAA, UAVs are typically equipped with systems (such as a transponder) which allow them to exchange information with each other (such as their current position, heading and speed). Thus, the UAVs can cooperate in order to detect threats and avoid each other. For instance, in the RAID project [1], collaborative SAA, through the use of Automatic Dependent Surveillance – Broadcast (ADS-B) technology, is used to detect and resolve conflicts between a remotely-piloted aircraft and a manned aircraft. Similarly, ADS-B technology is proposed in [2] for threat detection and avoidance for small UAVs.

With non-collaborative SAA, a UAV is equipped with one or multiple sensors which are capable of detecting obstacles irrespective of the equipment on other aircraft. Thus, the UAV can detect and avoid obstacles independently of other aircraft and can also detect other types of obstacles such as terrain and man-made structures. Sensors for non-collaborative SAA include vision-based sensors [3], laser scanners, and millimeter wave radar [4].

Naturally, a UAV can be equipped both with collaborative and non-collaborative SAA. A system based on an ADS-B collision avoidance radar, which can detect both cooperative and non-cooperative targets, is described in [5]. The system detects cooperative traffic by receiving ADS-B messages from other aircraft and can also use the echo of its own transmissions to detect non-cooperative targets. Carrio A. *et al* [6] propose a system for small UAVs which integrates a thermal IR camera with an ADS-B receiver.

1.2 Proposed obstacle detection and tracking framework

For this work it was desired to have an obstacle detection and tracking system for UAVs that combines collaborative and non-collaborative SAA and which is able to detect commercial aircraft at a distance of up to 2 NM. A block diagram of the proposed system is shown in Figure 1.

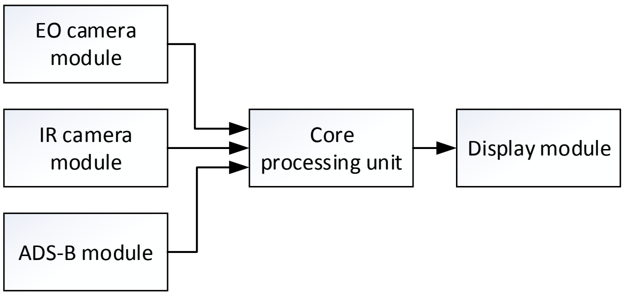

Figure 1. Block diagram of proposed obstacle detection system

The proposed system has three sensors: an Electro-Optical (EO) camera module, an Infrared (IR) camera module and an ADS-B receiver.[1] The ADS-B receiver is an off-the-shelf piece of hardware whereas the EO and IR camera modules were custom-built for this application. Each of the camera modules is mounted on a 3-axis gimballed platform which stabilizes the camera and allows it to scan in the horizontal plane, effectively increasing the camera Field of View (FOV). Each of these sensors transmits obstacle information – including target position – to the core processing unit (a Raspberry Pi module). Then, the core processing unit uses this information to determine whether a conflict exists between the UAV and any detected targets and outputs any threat information to a remote display module to alert the (remote) UAV pilot. The display module is a Linux-based 4.5” display.

For detailed information about the complete system, including the obstacle detection and tracking algorithms, the reader is referred to [7]. The rest of the paper is organized as follows. Section 2 describes the test campaign which was carried out to validate the proposed system. Section 3 presents and discusses the results of ground and flight testing. Finally, Section 4 highlights the conclusions of the paper and identifies potential areas for future work.

2 Design of the test campaign

In order to validate the complete system, a test campaign – consisting of a series of ground and flight tests – was carried out.

2.1 Test objectives

The high-level objective of the test campaign was to assess the ability of the overall system to detect and track light and commercial aircraft in a typical operational environment. This objective was met by focusing on a number of low-level objectives, including:

- Determining the accuracy, detection rate and detection range of the sensor modules
- Assessing the performance of the gimballed platform
- Testing the communication link and data transfer between each sensor and the core processing unit
- Verifying that the display module showed obstacle information correctly and in real-time
- Verifying that the system logged data correctly and completely (for post-test analysis)

2.2 Test scenarios

Due to the complexity of the proposed system and the risks, costs and logistical challenges associated with flight testing, it was decided to test the system incrementally and to carry out a series of ground tests before proceeding with the flight tests. This allowed the team to gradually gain confidence in the system and to identify and

[1] The system can also cater for additional sensors.

resolve any component and integration issues prior to the flight tests. The key test scenarios are described in Table 1.

Table 1. Test scenarios

#	Description	Target
1	Ground testing of EO camera module and ADS-B receiver	Commercial and light aircraft
2	Ground testing of IR camera module and ADS-B receiver	Commercial and light aircraft
3	Flight testing of EO camera module and ADS-B receiver mounted on a light aircraft	Light aircraft
4	Flight testing of EO camera module and ADS-B receiver mounted on a multi-rotor UAV	Light aircraft

As can be observed from Table 1, the EO and IR camera modules were tested separately during the ground tests. Also, due to time constraints, only the EO camera module and ADS-B module were flight tested.

2.3 Ground tests

A total of about 10 outdoor ground tests were carried out at various locations around Malta International Airport (MIA) in different time and weather conditions. Specific test sites were selected to provide the opportunity to test the system on various landing and departing aircraft (both light and commercial) as well as aircraft flying in the vicinity of the airport. In addition, the sites provided good visibility of aircraft from the ground, with minimal cluster and obstructions. One of the test sites – located to the left of Runway 31 – is marked in Figure 2.

For the ground tests, the EO and IR camera modules were mounted on a tripod as shown in the example given in Figure 3. The orientation of the camera modules was initially controlled by the gimballed platform in order to verify that the platform was working as expected. However, in the latter ground tests, the gimbal was disabled and the orientation of the camera was controlled manually in order to be able to aim it directly at a particular aircraft. This was necessary to facilitate testing since both cameras have a narrow FOV[2]; otherwise, it would have been very difficult to gather enough obstacle test data.

Figure 2. One of the locations for ground testing

Figure 3. Setup for ground testing of EO camera module

A laptop was connected to the core processing unit in order to read the data packets received by the processor (from the individual sensors) and to display that data to the user in real-time. This was done for debugging purposes and to easily determine when an aircraft was being detected by the system. In addition, during the latter tests, threat information was displayed on the remote display module.

When testing the IR camera module, a dedicated display was used to output the raw camera

[2] The EO camera lens has a horizontal FOV of 2.8° and a vertical FOV of 2.1°.

images to the user. Unfortunately, the display of a live camera feed was not possible when testing the EO camera module. All of the data generated by the sensors (including the raw camera images) and the core processing unit in each ground test was recorded for post-test analysis.

2.4 Flight tests

2.4.1 Flight test with system mounted on a manned aircraft

The first flight test consisted of two light aircraft flying in formation – a Cessna 172N, acting as the *Leader* and *Ownship*, and a Tecnam P.2006T, acting as the *Follower* and *Target* (Figure 4). The system under test – including the EO camera module, gimballed platform, ADS-B receiver, core processing unit and a GPS receiver – was mounted on a tripod which was secured to the back of the Ownship as shown in Figure 5.

Figure 4. Ownship (top) and Target (bottom)

As in the case of the ground tests, the remote display module and a laptop were connected to the core processing unit in order to display obstacle information and to monitor the system throughout the flight (Figure 6). The laptop was used to record data for post-flight analysis, including all sensor data and the output of the remote display module. In addition, a video camera was mounted inside each aircraft to capture footage of the complete flight.

Due to the risks associated with formation flying, a full safety risk assessment was carried out in the months leading to the flight and all of the stakeholders – including the pilots, Air Traffic Controllers (ATCOs) and the civil aviation authority – were engaged well in advance of the flight.

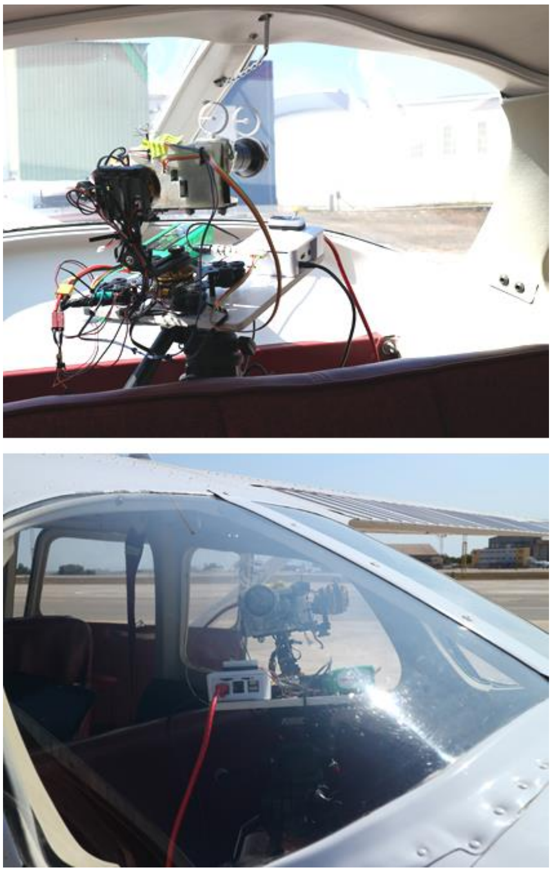

Figure 5. View of the system under test from inside the aircraft (top) and outside the aircraft (bottom)

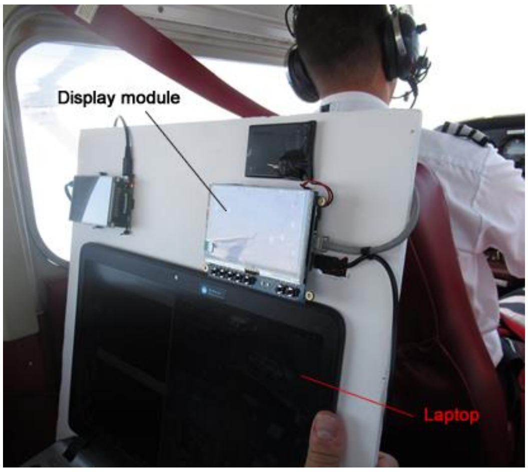

Figure 6. Display module and laptop

The formation flight was carried out along the coast of the Maltese islands for a duration of approximately 33 minutes. During the flight, the Target was flown on the left (port) side of the Ownship and slightly behind. The distance between the two aircraft was varied from approximately 2 km to a few hundred meters in order to test the system over its full operational range. A photo of the Target taken from the Ownship is shown in Figure 7 whereas the trajectory of the formation flight (excluding takeoff and landing) is shown in Figure 8.

Figure 7. View of the Target aircraft from the Ownship aircraft

Figure 8. Trajectory of the formation flight

2.4.2 Flight test with system mounted on an UAV

The second flight test was carried out on the west coast of Malta. For this flight, the system under test was mounted on a hexacopter UAV platform as shown in Figure 9. A wireless link was set up between the UAV and the laptop and remote display module in order to allow sensor data to be recorded and to display any detected obstacles to the user during the flight. Then, the UAV was flown in hover mode while the Target (a Cessna 172M) was flown at a safe distance from the UAV along a straight line path, such that it repeatedly crossed the FOV of the EO camera, as shown in Figure 10.

Figure 9. System under test mounted on an UAV

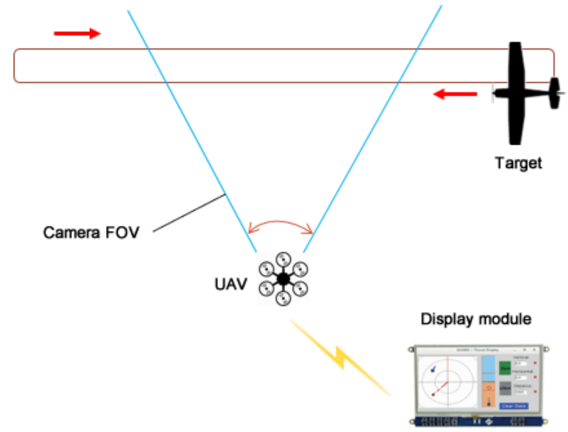

Figure 10. UAV test setup

3 Results and discussion

3.1 Ground testing

Figure 11 shows examples of aircraft detected by the EO and IR camera modules during one of the ground tests. In the case of the EO camera view, it can be observed that although clouds are present in the image, the camera module is able to distinguish the aircraft from its surroundings.

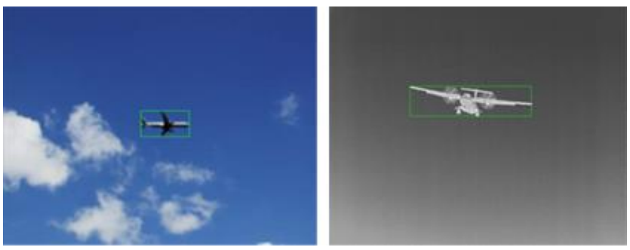

Figure 11. Aircraft detected by EO camera module (left) and IR camera module (right)

Figure 12 and Figure 13 are plots showing how the distance measurements obtained by the EO and IR camera modules compare to the readings obtained by the ADS-B receiver for two image sequences of commercial aircraft captured from the ground. In these image sequences, the aircraft is more than 1.6 km away from the camera. The IR camera module tends to under-read the actual distance and is less accurate than the EO camera module. The main reason for this result is that the IR camera lens has a wider FOV than the EO camera lens. Each camera module calculates the obstacle distance based on the intrinsic camera parameters and the size of the obstacle (in pixels) within the captured images and, therefore, a position error of one pixel in the detection of an aircraft with the IR camera has a bigger impact on the range estimation than the same error obtained with the EO camera.

One reason for the distance error observed in both camera modules is that the aircraft may be occluded or may not lie completely within the camera FOV, thus appearing smaller (and further away from the camera) than it actually is. Another reason for the distance error is that the image processing algorithms assume that the aircraft has particular dimensions. Therefore, errors may result if the actual aircraft dimensions differ from those expected by the system.

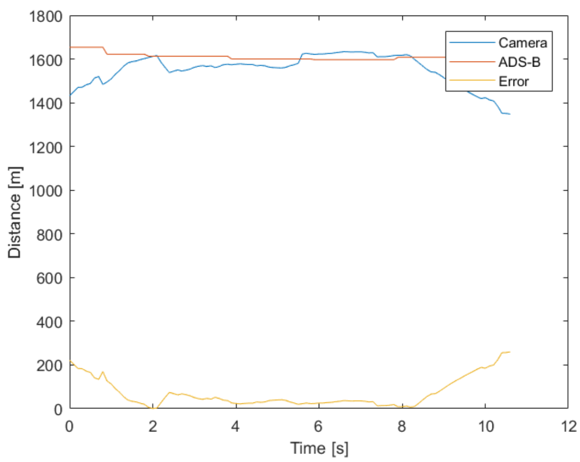

Figure 12. Distance measurements obtained by EO camera module and ADS-B receiver

Figure 14 is a plot of the range measurements obtained by the EO camera module for an image sequence of an aircraft approaching to land. In this case, the camera was located close to the landing runway as shown in Figure 2. The camera initially detects the aircraft when it is approximately 3.1 km away. The camera detects the aircraft consistently and it can be observed that the plot approximates a straight line (which corresponds to an aircraft approach speed of approximately 143 knots), with the exception of a few error spikes towards the end of the sequence.

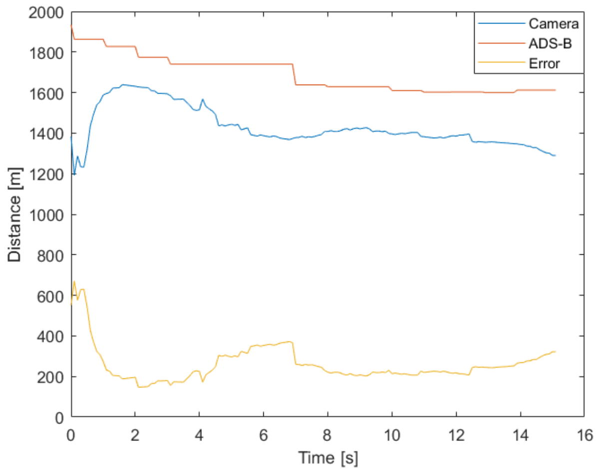

Figure 13. Distance measurements obtained by IR camera module and ADS-B receiver

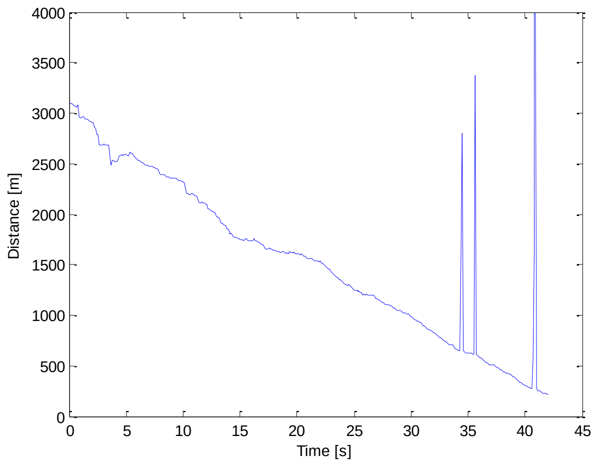

Figure 14. Range measurements obtained by EO camera module for a landing aircraft

One of the reasons for the error spikes is that, as the aircraft was coming in to land, the camera was pointed closer to the ground and, therefore, some ground clutter entered the camera FOV, resulting in erroneous obstacle detections and distance measurements. Another reason is that as the aircraft gradually approached the runway, it occupied an increasingly larger portion of the image and hence it became more and more difficult to keep it within the FOV (considering that the camera was being pointed towards the Target manually).

Two main issues were encountered during ground testing. The first was caused by the fact that the EO camera did not have any automatic exposure and was therefore unable to detect aircraft in different lighting conditions. This problem was solved during the ground tests by implementing an algorithm to adjust the camera exposure automatically.

The second issue was that the EO camera lens has a narrow FOV and the EO camera module does not output a live camera feed. This made it difficult to capture targets manually by pointing the camera towards an aircraft. Thus, in order for the team to be able to aim at an aircraft with greater precision, cross-hairs were mounted on the camera lens (refer to Figure 3).

3.2 Flight testing

Figure 15 shows an image of the remote display module during the first flight test (with the manned aircraft). The section on the left provides a top-view obstacle map. The center of the map corresponds to the Ownship's position whereas the red points indicate the lateral position of the detected obstacle (i.e. the Target) relative to the Ownship during part of the flight. The section in the middle indicates the relative vertical position of the detected obstacle. The section on the right outputs the obstacle elevation ("Vertical"), azimuth ("Horizontal") and the distance of separation between the Ownship and the obstacle ("Distance"). In this instance it can be observed that the EO camera module successfully detected the Target at a distance of 1,620 m. The reason why obstacles were detected in just one direction is that the camera has a narrow FOV and its orientation was kept fixed during the flight.

Due to the limited FOV of the camera, one of the main challenges of the first flight test was to fly the Target precisely in such a way as to keep it within the camera FOV as much as possible without compromising flight safety. This required constant radio communication and coordination between the crew of both aircraft. An analysis of the log files after the flight showed that the Target was never within the camera FOV for more than a few seconds at a time. For this reason, a lens with a wider FOV was used for the second flight test (with the UAV).

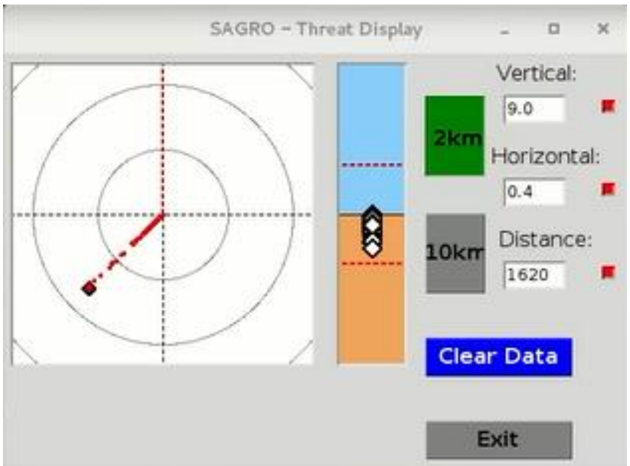

Figure 15. Threat display

Figure 16 is a plot of the distance measurements obtained with the EO camera module for a 10 second image sequence of the second flight test. From this image it can be observed that the camera module successfully detected the Target; however, the measurements are noisier and less accurate than those obtained during the ground tests. This was mainly due to the wider FOV of the camera lens used in the second flight.

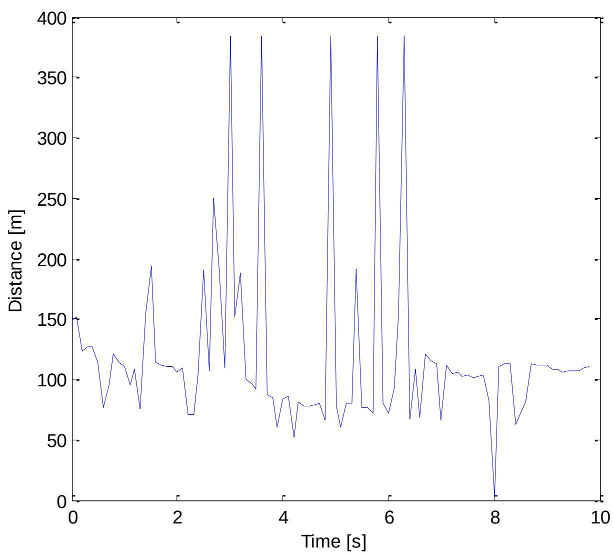

Figure 16. Sample of measurements obtained by EO camera module during UAV flight test

4 Conclusion and areas for future work

This paper discussed the design and execution of a test campaign for a multi-sensor obstacle detection and tracking system for UAVs. The system relies on three independent sensors for obstacle detection (an EO camera module, an IR camera module, and an ADS-B receiver), a core processing unit, and a remote display module. The system was first validated through a series of ground tests, before being tested on a manned aircraft and a UAV platform.

Overall, the results of the tests were positive and confirmed that the system is able to detect light and commercial aircraft in different scenarios, with the EO and IR sensors capable of detecting (and estimating the distance to) aircraft up to a few km away.

The following are some potential areas for further research:

- The image processing algorithms can be updated to cope with any type of aircraft, without having to make assumptions about aircraft type *a priori*;
- The measurements of the individual sensors can be fused in order to improve the performance and robustness of the overall system;
- Conflict resolution algorithms can be developed to process the data related to any detected targets and to send commands to the UAV's autopilot in order to mitigate any threats.

Acknowledgements

The work presented in this paper was conducted as part of SAGRO, a project financed by the Malta Council for Science and Technology through the National Research and Innovation Programme (Grant Agreement R&I-2013-042). The authors would like to thank Malta Wings Co. Ltd. for providing the aircraft and pilots required to conduct the flight tests.

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