FLIGHT TRIAL OF AN ELECTRO-OPTICAL SENSE-AND-AVOID SYSTEM

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Keywords: *Detection algorithms, Filtering techniques, Filter banks,Obstacle avoidance, sense-and-avoid.*

Abstract

This paper presents the flight trials of an electro-optical (EO) sense-and-avoid system onboard a Cessna host aircraft (camera aircraft). We focus on the autonomous collision avoidance capability of the sense-and-avoid system; that is, closed-loop integration with the onboard aircraft autopilot. We also discuss the system's approach to target detection and avoidance control, as well as the methodology of the flight trials. The results demonstrate the ability of the sense-and-avoid system to automatically detect potential conflicting aircraft and engage the host Cessna autopilot to perform an avoidance manoeuvre, all without any human intervention.

1 Introduction

One of the key enabling technologies required for safe and seamless integration of Unmanned Aircraft Systems (UAS) within civilian airspace is a certified 'sense-and-avoid' system mirroring the human pilot 'see-and-avoid' capability. A survey of potential approaches to address the sense-and-avoid issue for UAS was presented in Karhoff et. al. [1]. This study concluded that a visual/pixel based sense-and-avoid solution offered the best chances for regulator approval. However, other studies have shown (BASI [2]) that it is actually difficult to detect and avoid a collision using the human visual system. To date, public domain hardware implementations of vision-based sense-and-avoid systems have been limited to a small number [3], with the most significant development made by Utt et al. [4].

We have previously investigated vision-based target detection and control onboard aerial platforms [5, 6, 7, 8, 9, 3]. These past studies have focused primarily on the 'sensing' aspect of collision avoidance; that is, real-time implementation of image processing algorithms and collection of image data for analysis of detection ranges. The literature on vision-based collision detection algorithms is relatively extensive focusing mainly on the 'sensing' aspects of the collision avoidance problem. (see [3] for a survey of studies over the past decade reporting detection range results). However, the 'avoidance' aspect in realistic flight scenarios have received little attention in the literature. The closest work to that presented in this paper is by Korn and Edinger [10], where an aircraft provided with radar and an onboard 'sense and avoid' system demonstrated autonomous avoidance manoeuvres based on the sense and avoid algorithms.

Since our preliminary approach [11], our control concepts have matured and in this paper we are now able to consider the performance of a complete closed-loop sense-and-avoid system with fully integrated detection and control elements allowing autonomous airborne collision avoidance. This system is the outcome of several years of research and is part of an ongoing project that aims to develop collision avoidance technologies for manned and unmanned aircraft. The main contribution derived from this paper is in the experimental procedure and field report under realistic conditions that demonstrate the technology readiness level of this approach towards its maturity.

2 Aircraft Detection and Control

2.1 Detection Approach

The detection of other aircraft is based on the premise that it will appear as a dim point-like feature in the sensor field-of-view (FOV). Our detection approach exploits a pre-processing stage that applies morphological operations to highlight point-like features. This is followed by a hidden Markov model (HMM) based temporal filtering approach to detect and track persistent features (targets) in a sequence of image measurements. The performance characteristics of this morphological-HMM detection approach are considered in [9, 8, 5, 3]. Once the target is identified and its location in the image estimated, this is used to generate a control command to autopilot as described next.

2.2 Avoidance Approach

After detection and tracking has occurred, target position estimates on the image plane are passed to a vision-based controller that manoeuvres the aircraft away from the detected target. This is achieved by generating a command signal that is proportional to the location of the target in the EO sensor FOV (vision-based control). The command signal is translated to a series of avoidance waypoints that is then tracked by the aircraft autopilot. Details on the estimation of the parameters to perform the control can be found in [6].

3 System Implementation

The experiments reported in this paper were performed using two Cessna aircraft. One aircraft

Fig. 1 Cessna 172 camera aircraft.

was equipped with a forward-looking camera and our sense-and-avoid system (camera aircraft), the other aircraft served as target (target aircraft). This aircraft was fitted with a position logging system for posterior data consolidation and analysis.

The list of specific hardware components installed in the camera aircraft is:

- Camera Sensor: Basler Vision Technology Scout Series camera @15Hz (model scA1300-32f) fitted with a Computar 5mm lens (H0514-MP) with 2x extender.
- GPS-INS Sensor: NovAtel SPAN (iMAR IMU-FSAS coupled with NovAtel OEMV-3).
- Primary Flight Computer: Backplane Systems Technology MI910 Mini-ITX with an Intel Core 2 Duo 2.4GHz processor, 2GB SDRAM.
- Secondary Flight Computer: Digital-Logicő SM855 PC/104 with an Intel Pentium M 1.8GHz processor, 1GB SODIMM DDR RAM.
- Storage Device: OCZ Technology SATA II 2.5" Solid State Drive 120 GB.

Figure 1 illustrates the custom modified Cessna 172 host aircraft [12] onboard which the sense-and-avoid system was fitted. Figure 2 illustrates the system's externally mounted EO sensor housed in a specially designed pod. The implementation of the sense-and-avoid system represents a fusion of commercial-off-the-shelf hardware with real-time detection and control algorithms. Graphics processing unit (GPU) based

Fig. 2 EO sensor pod mounted on wing support strut.

hardware was exploited to enable computationally intensive image processing algorithms to achieve throughput rates of up to 15 frames per second.

4 Flight Trials

To evaluate the performance of the sense-and-avoid system under realistic operating conditions, we designed flight experiments that placed the camera aircraft and a target aircraft on near-converging flight paths (for safety reasons, the aircraft were separated vertically by at least 500ft at all times). The flight paths were chosen to recreate *head-to-head* and *tail-chase* collision scenarios.

The head-to-head scenario corresponds to a geometry where the aircraft are approaching from opposite directions (Figure 3). The tail-chase scenario describes an overtaking situation where a faster aircraft approaches a slower aircraft from behind (Figure 4). The motivation for investigating the head-to-head scenario comes from the time critical nature this encounter (due to the relatively high closing speed). Likewise, the tail-chase scenario was motivated by the high incidence of mid-air collisions that occur from behind [13].

In the head-to-head scenario the experiment begins at time T_0 when both aircraft have concurrently arrived at their starting waypoints, as shown in Figure 3. The experiment is conducted with the aircraft flying straight and level and maintaining a constant altitude separation of 500 feet as they converge. The experiment ends when the target aircraft is beyond the camera FOV, approximately at time T_2. After this point, both aircraft begin returning to their respective holding patterns in preparation for a repeat of the experiment. In our head-to head experiments the distance between the starting waypoints was approximately 20 nautical miles, and the ground speed for both aircraft was 100 knots. This translates to a closing speed of 200 knots, with the aircraft crossing over approximately 6 minutes into the experiment.

In the case of the tail chase scenario one aircraft gradually approaches another aircraft from behind to replicate a low-speed overtaking collision situation. In this scenario the two aircraft are heading in the same direction with one leading the other, but the trailing aircraft is travelling slightly faster. Figure 4 illustrates this scenario. The experiment begins at T_0 when both aircraft have concurrently arrived at their starting waypoints. In this scenario an initial horizontal lead distance is defined between the aircraft at the beginning of the experiment. Similar to the previous scenario, the experiment is conducted maintaining a constant height separation of 500 feet.

The experiment ends when the target aircraft is beyond the camera FOV, approximately at time T_2. At this point, the aircraft perform coordinated rate-1 turns in opposite directions (one turns left and the other turns right) in order to return to their respective holding areas.

In our tail-chase experiments, the closing speed was approximately 15 knots (based on nominal target and camera aircraft speeds of 85 knots and 100 knots, respectively), and the initial target aircraft horizontal lead distance was about 3.5 nautical miles. In this paper, particularly we report on two cases, however we have performed in excess of 27 target scenarios. These outcomes will be reported in future work.

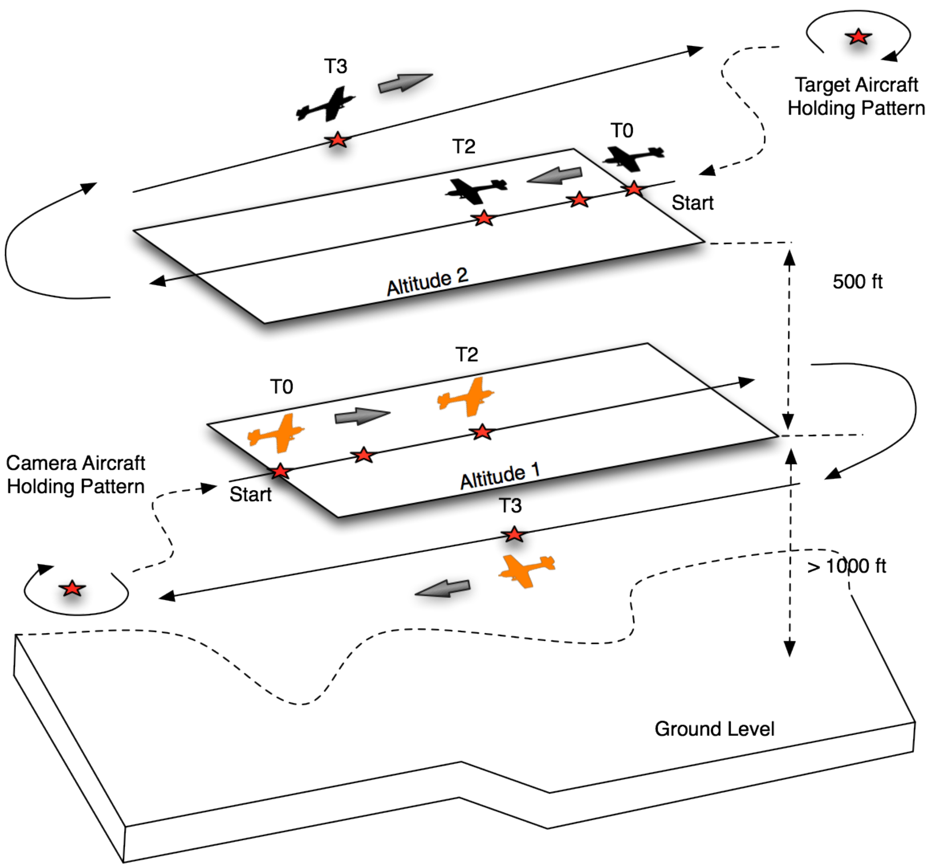

Fig. 3 Head-To-Head flight collision scenario

4.1 Results

Figure 5 illustrates the control response of the sense-and-avoid system during a tail-chase collision scenario.

The flight paths (solid lines) of the camera aircraft (dark aeroplane) and the target aircraft (bright aeroplane) are shown, as well as the aircraft positions at 4 time instances. Shortly after time t_2, the sense-and-avoid system onboard the camera aircraft detects the target aircraft, triggering the generation of avoidance waypoints indicated by the 3 cross ($\times$) markers. The camera aircraft autopilot automatically tracks these waypoints to avoid a potential collision with the rear of the target aircraft. A similar control response can be seen in the head-on collision experiment illustrated in Figure 6, where detection occurs shortly after time t_3 and the camera aircraft can be seen to track the avoidance waypoints at times t_4 and t_5. The control commands are generated following the approach described in [6] where the position of the target in the image is used to generate a desired heading command that is proportional to the target location.

5 Conclusions

In this paper, we have presented the outcomes of a end-to-end passive sense and avoid system. This system is the outcome of several years of research and is part of an ongoing project that aims to develop collision avoidance technologies for manned and unmanned aircraft. We have described the experimental design, test and validation of an approach that has been reported previously. Therefore, the contribution derived from this paper is in the experimental procedure and field report under realistic conditions that demonstrate the technology readiness level of this approach towards its maturity.

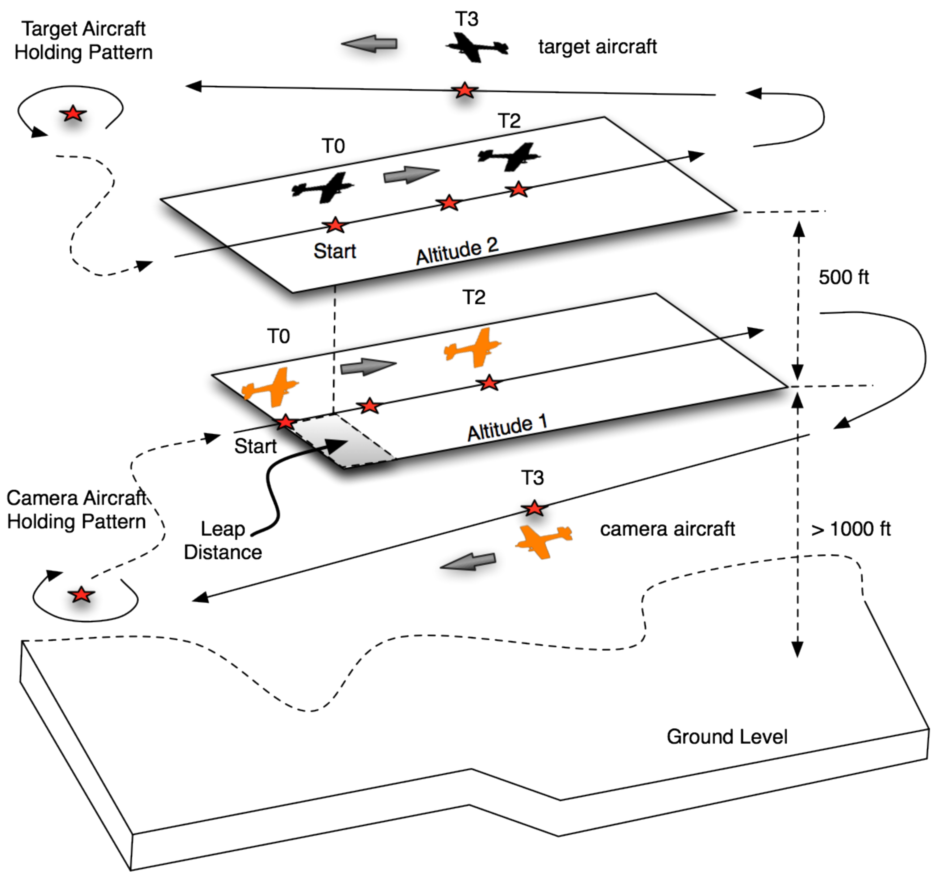

Fig. 4 Tail-Chase flight collision scenario

6 Acknowledgement

This research was supported under Australian Research Councils Linkage Projects funding scheme (project number LP100100302) and the Smart Skies Project, which is funded, in part, by the Queensland State Government Smart State Funding Scheme.

The authors would like to thank all flight pilots (Rhys Mudford, Duncan Greer, and Felipe Gonzalez), and test engineers (Scott McNamara, Chris Turner, and Richard Glassock) involved in conduct of the reported flight tests and the construction of the specialised equipment. We also thank Reece Clothier, Brendan Williams, and Geoff Casey for their assistance with risk management and experimental planning stages.

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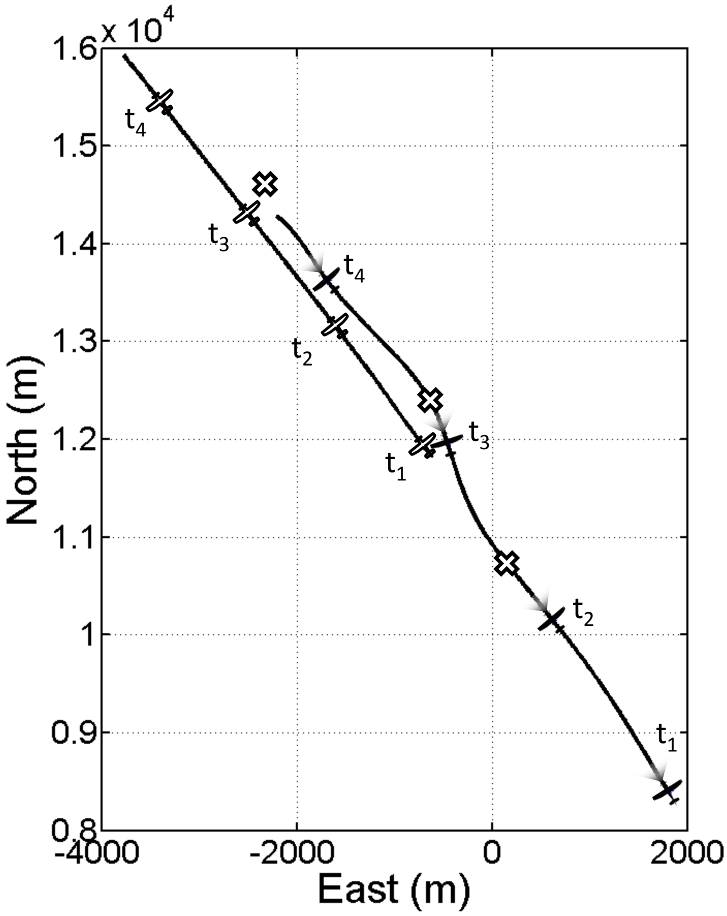

Fig. 5 Aircraft flight paths (solid lines) during a tail-chase collision avoidance experiment (overhead view). The host Cessna and target aircraft positions are indicated by the dark and light aeroplane markers, respectively. The crosses (×) mark the locations of avoidance waypoints issued by the sense-and-avoid system.

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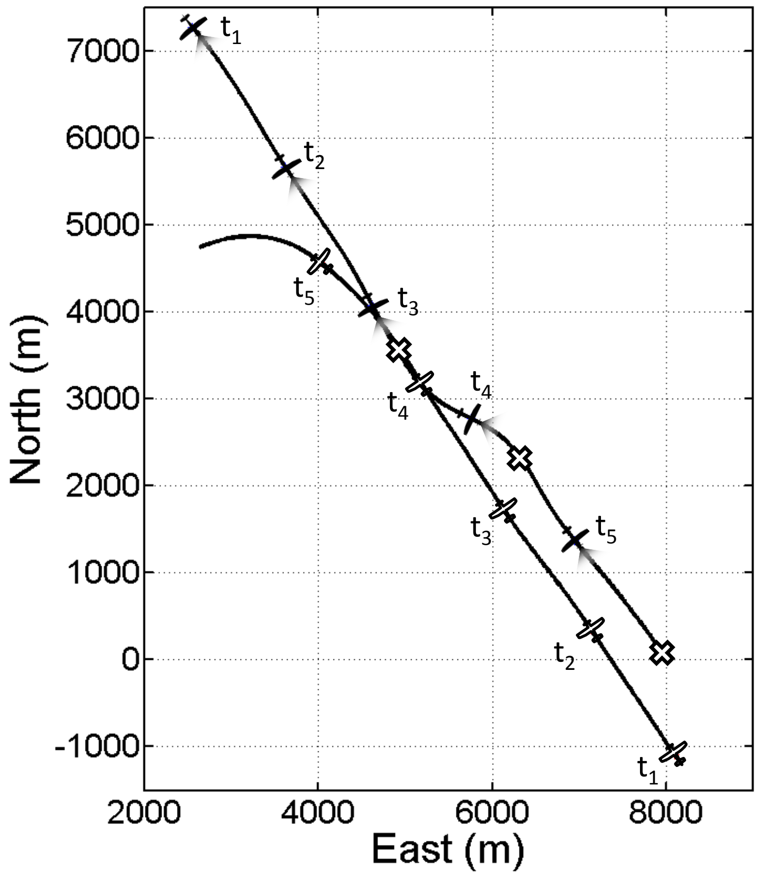

Fig. 6 Aircraft flight paths (solid lines) during a head-on collision avoidance experiment (overhead view). The host Cessna and target aircraft positions are indicated by the dark and light aeroplane markers, respectively. The crosses ($\times$) mark the locations of avoidance waypoints issued by the sense-and-avoid system.

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