DEVELOPMENT AND TEST OF AN INTEGRATED SENSOR SYSTEM FOR AUTONOMOUS COLLISION AVOIDANCE

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Abstract

Unmanned Aerial Vehicles will have a safe access to the Civil Airspace only when they will be able to avoid collisions even with non cooperative flying obstacles. Thus, they need to replace the capability of human eye to detect potential mid-air collisions with other airframes and the pilot expertise to find an adequate avoidance trajectory. This paper deals with sensors and logics required on-board to achieve the necessary situational awareness. In particular, it refers to the research activities carried out by the Department of Aerospace Engineering of the university of Naples “Federico II” in collaboration with the Italian Center for Aerospace Research in the framework of TECVOL project. An integrated multi-sensor system is described which is comprised of a Ka-band radar, two visible and two thermal infrared cameras, and two processing units. Ground hardware-in-the-loop tests and images from first preliminary flights confirm the system potential which was estimated in past studies by off-line simulations.

1 Introduction

In recent years, Unmanned Aerial Vehicles (UAVs) have experienced a great worldwide diffusion. While the current use of these systems is mainly in the military field, there has also been a growing interest in using UAVs for civil purposes, as they are suited for many applications: their potential uses range from border and coastal surveillance, to drug interdiction, to checking the status of oil pipelines and power systems, to environmental surveillance and support during emergencies, crop assessment (farming), automotive and vessel traffic surveillance, and sky based communication networks. While autonomous control and payload technologies can be considered mature, the basic problem that hinders the use of UAVs in civil scenarios is represented by flight safety and relevant regulations in terms of collision risk with respect to other aircrafts.

The need to overcome this problem led to a remarkable increase in worldwide research for integration of UAVs in the Civil Airspace [1-3]. Several organizations for the development of standards were involved in writing the guidelines to allow UAVs a safe access to flight [4, 5]. This effort was sponsored by Federal Aviation Administration (FAA) and was developed by important regulatory agencies such as ASTM and RTCA. Also the European Union with project USICO [2], Japan, and Australia were involved in this field of research.

FAA 7610.4 regulation [6], stated that UAV flight in the Civil Airspace is allowed only if it guarantees “…an equivalent level of safety, comparable to see-and-avoid requirements for manned aircraft”, both in the controlled and in the uncontrolled airspace.

At present, UAV autonomous anti-collision systems are at an experimental level and research studies are being carried out to focus requirements and solutions [7-9].

This paper is focused on the situational awareness aspect of the problem. All the study has been conducted in the framework of project TECVOL (Technologies for Autonomous Flight) carried out by the Italian Aerospace Research Center (CIRA). CIRA holds the Italian Aerospace Research Program (PRORA) funded by the Italian Government. This program involves the realization of a High-Altitude Long-Endurance (HALE) UAV. Within this program, the TECVOL project aims at the development and flight demonstration of the technologies needed to support the HALE UAV flight autonomy, and will realize a hardware/software prototype that integrates the following functions:

- Autonomous Flight Path Execution;
- Autonomous Approach and Landing;
- Obstacle Detect See & Avoid (DS&A);
- Autonomous Runway Search and Lock;
- Enhanced Remote Piloting.

Regarding the sense and avoid function, the Department of Aerospace Engineering (DIAS) of the University of Naples “Federico II” has been in charge of developing and testing the anti-collision sensing system and logics.

The system prototype has been initially installed onboard a manned laboratory aircraft equipped for automatic control so that flight tests are verifying the adequacy of attained performances for supporting fully autonomous flight. The optionally piloted laboratory aircraft is a Very Light Aircraft (a TECNAM P-92) and has been named FLARE, which means Flying Laboratory for Aeronautical Research. It is shown in figure 1.

Fig. 1. FLARE at landing

FLARE is equipped with an integrated hardware configuration that includes:

- A set of navigation sensors (Attitude and Heading Reference System, Laser Altimeter, Standalone GPS, and Air Data Sensor);
- Sensors and Processing Units for Obstacle DS&A;
- Electro-optical sensors for enhanced Remote Piloting;
- A Flight Control computer.

All these systems were installed respecting the stringent weight and size requirements imposed by the airframe type and by the presence of the human pilot, who is always present for safety reasons.

Sense and avoid flight tests are currently being performed where a single intruder enters the Field of Regard (FOR) of obstacle detection sensors. Initial tests are verifying the capability of the designed system to detect and track the intruder, in different approaching geometries and weather/illumination conditions. Subsequently, Collision Avoidance tests will be performed.

This paper provides a complete description of the whole obstacle detection and tracking system and is organized as follows. The second section describes the installed obstacle detection sensors. Measurements from multiple different sensors are fused in real time to compensate the lack of performance of single sensors. Sensor fusion requires a proper hardware architecture which is addressed in the third section. Then, the flight test system is pointed out, also considering the intruder and the necessity to coordinate FLARE and the obstacle in order to fly selected collision scenarios. Ground-based hardware-in-the-loop tests are briefly described and preliminary flight data are reported and discussed in the last part of the paper showing the high quality of electro-optical sensors’ images and the negligible disturbance caused by the aircraft in terms of vibrations and thermal noise.

2 Obstacle Detection Sensors

Obstacle detection sensors were selected on the basis of requirements assessed in terms of achievable field of regard, range and angular resolution, detection range (which is connected to the time-to-collision by means of approaching speed) and system data rate.

The process of understanding the requirements was carried out in previous studies and is illustrated in [10]. The focus was on mid-air flight, thus maximum considered approaching speed was 500 kts. The all-time all-weather requirement was also considered. In its initial configuration, TECVOL aims at demonstrating the capability to avoid one non cooperative flying obstacle in the search volume. In the final configuration, the system should be able to avoid up to four obstacles.

One key point of sensor selection for autonomous collision avoidance is that no single sensor was found that is capable to fulfill all the requirements.

For example, radars guarantee adequate detection range and all-time all-weather performance, but angular accuracy is unsatisfying and data rate is of the order of 1 Hz. On the other hand, EO sensors provide accurate angular measurements at high frequency, but do not measure range directly and the detection process is strongly influenced by weather and illumination conditions, and by background. Thus, a multiple sensor approach was selected by using sensors based on different technologies (i.e. active microwave, passive infrared, and visible cameras) in order to compensate the lack of performance of single sensors.

The selected radar was the AI-130^{TM} OASys^{TM} (Obstacle Awareness System) model produced by Amphitech^{TM}. It is a pulsed radar operating with a carrier at 35 GHz and has been already used for UAV anti collision flight tests in NASA-ERAST flight tests [11]. Selected carrier frequency provides a good compromise between antenna dimensions, angular accuracy and sensitivity to rain and fog.

The radar is the main sensor and provides the all-time all-weather capability. In order to improve angular accuracy and data rate, auxiliary electro-optical sensors have been considered, and in particular two visible cameras, one panchromatic, one color, and two infrared cameras (figure 6).

The visible cameras are the Marlin^{TM} F145B2^{TM} and F145C2^{TM}, produced by Allied Vision Technologies GMBH^{TM} (AVT). The former is a panchromatic camera, whereas the latter is a color (Bayer tiled) camera. Both communicate via an IEEE1394 IIDC interface and are capable of producing color/panchromatic images up to 1392x1040 pixels. Furthermore, they can acquire images up to 10 Hz at full scale, with a resolution depth of 8/10 bits per pixel. They were equipped with MV618T^{TM} optics realized by AVT, with focal length of 6.5 mm and thus a field of view (FOV) of approximately 52.9° x 40.8°.

The two visible cameras are installed parallel to the aircraft longitudinal axis to get simultaneously a high resolution panchromatic image and a color one of the same region. While the panchromatic camera was chosen basically for fusion with radar data, the color camera was selected for obstacle identification, which will be tested in the second part of TECVOL project.

The infrared (IR) cameras are two Thermocam A40V^{TM} produced by FLIR^{TM}. They have a detector with 320 X 240 pixels, can acquire images up to 50 Hz, and are equipped with optics with focal length 35 mm, so that their FOV is 24 ° X 18 ° and the instantaneous field of view (IFOV) is of 0.075°. Thermal resolution is 0.08 °C at full frequency. The sensor is a Focal Plane Array (FPA), that is a non-cooled micro-bolometer. The imaged spectrum is in the thermal infrared field: from 7.5 μm to 13 μm. It is worth noting that the IR wavelength choice is due to the fact that spectral radiance has a broad peak in this region for temperatures near 300 K. In any case, the camera can cover a temperature field from -40 °C to 500 °C. Due to their limited angular aperture, the IR cameras are pointed slightly eccentric to get an azimuth field of view comparable to visible cameras.

3 Integrated system architecture

Sensors' layout is shown in figure 2. It was designed to allow for a compact installation of the sensor system, and in order to minimize vibration effects. The radar is mounted in central position with respect to the EO cameras. All the sensors pack is installed on the top of the aircraft wing (figure 3).

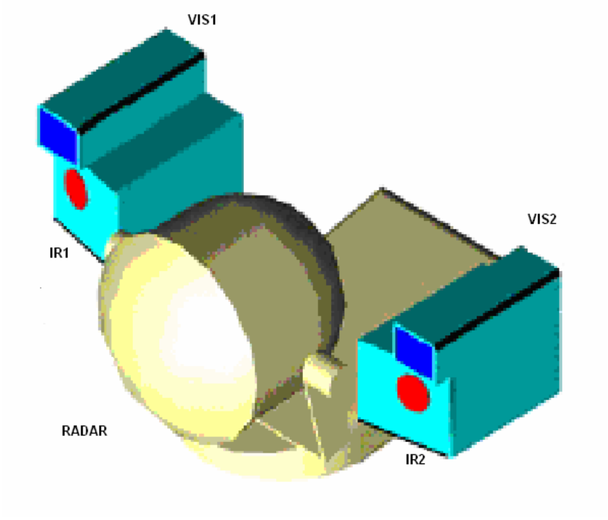

Fig. 2. Sensors' layout

Fig. 3. Obstacle detection sensors mounted on-board FLARE

The whole DS&A System hardware architecture (including the flight control computer with sensors and actuators) is reported in figure 4. Considering the sensing system, which is the subject of this paper, it is made up by two separate processing units, which implement different functions with different operating systems (OSs). The Real Time Computer is based on a deterministic OS. It is directly connected with the radar sensor via an Ethernet link and the TCP/IP protocol, performs tracking (and identification in the future), and exchanges data with the Guidance, Navigation, and Control (GNC) system by a deterministic data bus, which is the Controller Area Network (CAN) bus. The EO sensors are connected via a Firewire link to the Image Processing Computer, based on a conventional OS, that has to process the visible and infrared images to find estimates of intruders' position and shape (in view of the identification function).

Basically, the sensor fusion architecture is central-level: in fact, tracks are not produced at sensor level and minimally processed data are combined in a unique Kalman filter-based tracking algorithm [12]. However, detection function is in some way decentralized, and a hierarchical sensor architecture is considered.

This choice derives from the consideration that radar measurements are less sensitive to atmospheric effects and typically offer larger detection range with respect to EO cameras.

Thus, while target detection by radar is performed autonomously with a search in the whole sensor field of view, the object detection process is carried out in EO images on the basis of cues by the tracking module, considering a search window centered in the foreseen obstacle position. In particular, only firm tracks (generated on the basis of radar measurements) are used for EO object detection, in order to keep a reasonably low false alarm rate. The EO detection process is schematically described in figure 5.

From a hardware point of view, the two computers exchange data by an Ethernet connection and the User Datagram Protocol (UDP). In particular, firm tracks are sent in one direction, target estimates (in case of reliable detection) are sent in the other. The separation of the two processing units allows a reduction of the computational load on both systems. The two processing units are physically mounted in a single compact configuration to save volume (figure 6).

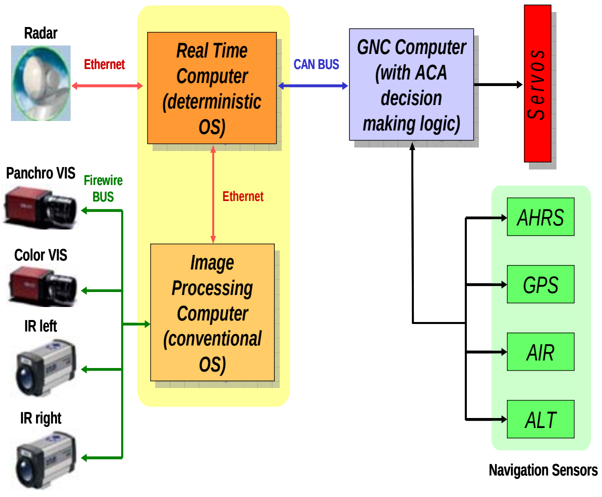

Fig. 4. DS&A System hardware architecture

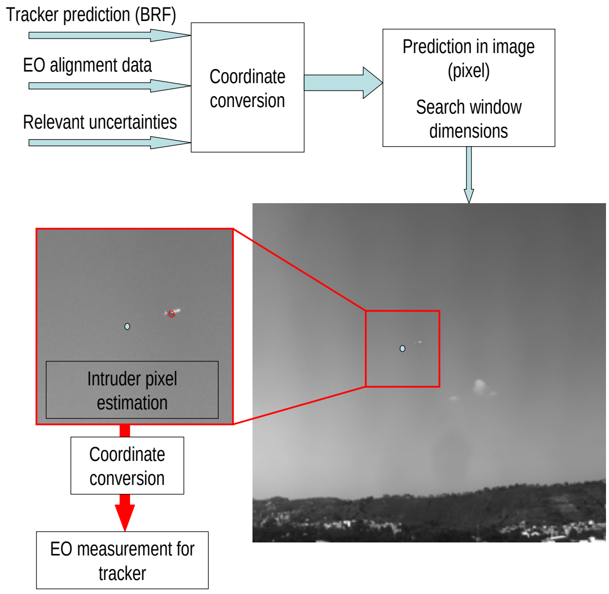

Fig. 5. EO detection process

Fig. 6. Obstacle detection and tracking on-board system

4 Flight test system and ground tests

A dedicated system has been developed to ensure execution of collision avoidance flight tests. The ground control station is comprised of a number of workstations which are connected on an Ethernet bus and communicate by means of the UDP protocol. In particular, a workstation is dedicated to obstacle detection and tracking experiments monitoring. The obstacle detection ground station sends commands and receives data in real time from a computer which acts as the ground communication controller. The latter is devoted to communication with FLARE. In fact, it communicates with an on-board communication controller by means of a full duplex Radio Frequency (RF) data link. This latter computer communicates with the flight control computer and the real time computer by means of the CAN bus.

Correct execution of obstacle detection and collision avoidance flight tests also requires that the intruder is properly synchronized with FLARE in order to realize the desired approaching geometries. Thus, also the intruder is equipped with a GPS receiver, a processing unit to store flight test data, and a RF transmitter to download position data to the ground station. In this case the obstacle sensing workstation is directly connected with the intruder, as shown in figure 7. Intruder and ground GPS data are stored to apply differential corrections in post-processing phase so as to have a ground truth for evaluating tracker performance.

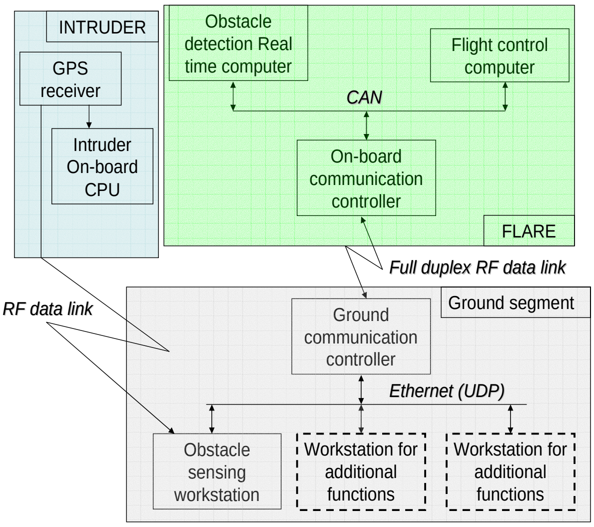

Fig. 7. Physical architecture relevant to obstacle detection function

Ground station software is used by the flight test engineer to monitor test status by means of information reported in graphical displays and numerical output, and to send commands to the flight system and in particular to the radar. It reports intruder position with respect to FLARE considering both GPS data, radar raw measurements and tracking algorithms outputs. Of course, all these data must be converted in real time to the same reference frame on the basis of estimates from navigation sensors. A preliminary version of the graphical interface is depicted in figure 8.

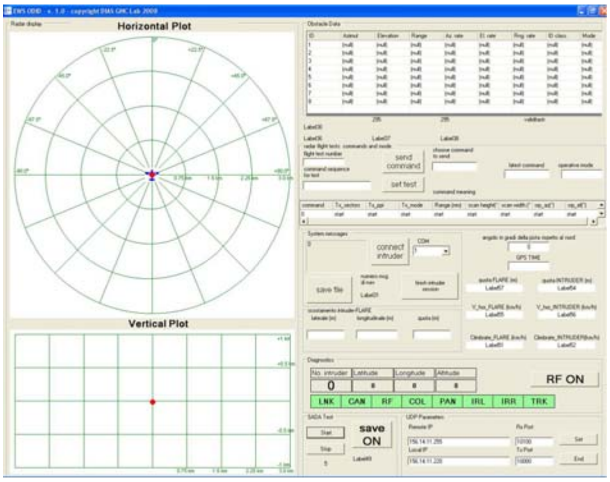

Fig. 8. Graphical interface for ground station software

The development process of the collision avoidance system has foreseen different phases, starting with selection of algorithms and software detailed design and off-line verification. Developed methods and numerical validation of both obstacle tracking and collision avoidance algorithms have been described in detail in [13].

Then, the on board software development process has been performed, with different approaches and languages for the real time computer and the image processing computer. Hardware-in-the-loop tests have been later performed to test the on board and ground system, regarding in particular reliability and latency of communications. It is worth noting that latency in data exchange between the flight control computer and the real time computer plays a key role for the sense and avoid function. Though the average data rate is in the order of only one tenth of CAN bus throughput (1 Mbps), data are transmitted in burst mode at a frequency of 10 Hz and the bus has to solve collision phenomena between packets. Tests with nominal data traffic have shown latencies in the order of a few ms. Figure 9 reports loop times (for the on-board data chain) for data packets with different priorities.

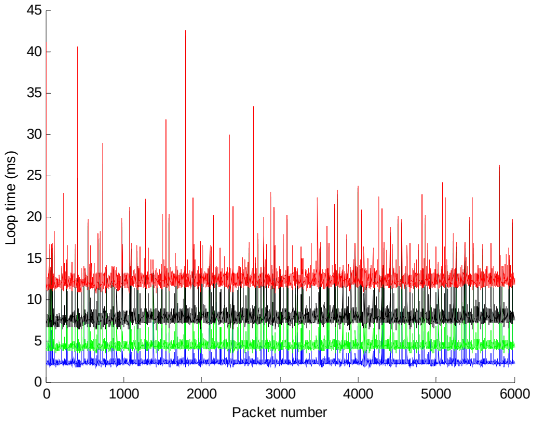

Fig. 9. Loop times on CAN bus for messages with different priorities

A further improvement has been observed by introducing an inter-message time in the order of tenths of ms. This slight transmission delay does not impact significantly the time required for sending all the messages but allows to reduce collision phenomena between packets, thus reducing latencies, as shown in figure 10.

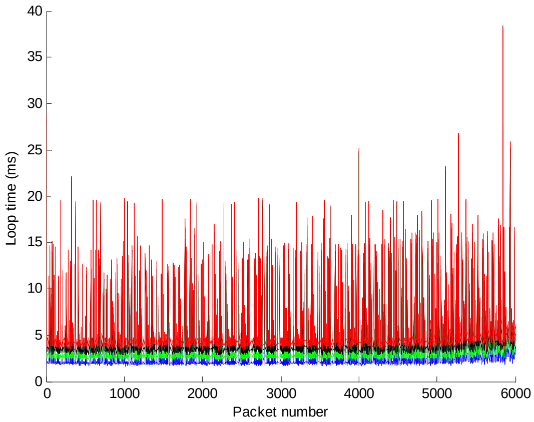

Fig. 10. Loop time for messages with different priority with introduction of a small inter-message time

5. Preliminary flight data and collision avoidance tests planning

As already anticipated sense and avoid flight tests are currently in progress. However, some flight activities were carried out in past months to provide functional verification of EO sensors. In particular, the interest was in evaluating the impact on image quality of vibrations and in general of all the disturbances due to the aircraft. For the infrared cameras, there was a particular interest in evaluating the thermal influence of aircraft engine, and the image quality in sunlight. Figures 11 and 12 show a color and a panchromatic image acquired at about 4 pm during a left turn (sun in lateral geometry), while figure 13 reports the grass runway as seen with the sun in the back. It is interesting to note that the grass runway is undetectable from the rest of the image, on the basis of the intensity information, in color (and panchromatic) images, even with a favorable geometry with respect to sun. Propeller appears as a still object in figure 12, due to very low shutter time. In the same aperture conditions, it “spreads” a little when it appears in color images due to Bayes filtering and consequent longer shutter time required for a given level of absorbed electromagnetic energy.

Fig. 11. Image taken by the color camera during a left turn

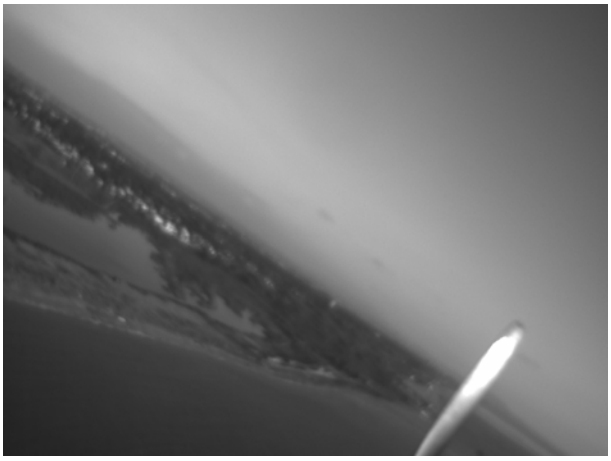

Fig. 12. Image taken by the panchromatic camera during a left turn (same point of previous image)

Fig. 13. Grass runway as seen by the color camera

The previous images show the high quality of images, with negligible effects of vibrations. They all refer to geometries with the sun in back or in lateral position. With the sun in front about 30% of the visible images is completely saturated with minimum aperture and thus is useless for obstacle detection. Detection range as a function of visible sensors orientation with respect to the sun is being evaluated in flight tests with the intruder aircraft.

As for the infrared cameras, all the gathered images showed high quality and contrast in daytime hours and in any orientation with respect to sun. Some images are reported in the following. In all the images, the small rectangle on the upper-left part of the figure represents mean image intensity. For example, figure 14 shows a low altitude image while figure 15 (taken with the sun in front though not in the FOV which is narrow if compared to visible cameras) shows that the grass runway is detectable and that contrast is not affected by sun.

Fig. 14. Low altitude image taken by the infrared camera

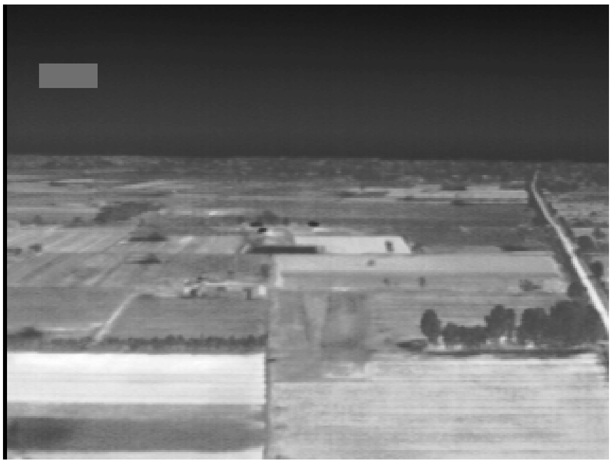

Fig. 15. Grass runway as seen by the infrared camera with the sun in front

As for the propeller effect in IR images, because of the shutter time required by the sensor, the propeller spreads in the image. Thus, the main effect for obstacle detection is a (small) reduction of signal-to-noise ratio in a part of the image. However, applying the required mounting angle, propeller impacts only a very small part of the IR sensors FOV.

The following two figures are very important in view of the collision avoidance application. Figure 16 shows a TECNAM P-2002 during take-off. The engine area is very bright compared to the rest of the aircraft. It is believed that engine temperature will be very important for intruder detection, although in near collision geometries. The same result is confirmed in figure 17, where a P-92 is imaged during landing. The engine temperature makes it detectable even on a cluttered background. Detection of an intruder flying over the horizon is a more favorable situation since, as observed in all the images, the sky appears as a dark background in any geometry with respect to sun. In summary, preliminary flights gave high confidence on the possibility to use EO sensors information for obstacle detection and tracking in the designed radar-driven anti-collision system.

Fig. 16. A TECNAM P-2002 during take-off in an image taken by the IR camera

Fig. 17. A TECNAM P-92 during landing in an image taken by the IR camera

Sense and avoid flight tests are being performed with the following logic. First of all, flights for radar acceptance are performed. These tests require that the entire architecture described in this paper is properly installed on board FLARE, except for the EO sensors. The radar is remotely commanded from the ground station, by means of the radio link, the CAN bus and the real time computer. A proper ground/on board software has been developed for these flights. Different tests allow the different operating modes for the radar to be validated, and the detection range for a VLA intruder to be evaluated.

As for sense and avoid flight tests, they are divided in two main categories: obstacle detection and tracking flight performance assessment, combined autonomous collision avoidance.

In the first category automatic control is not activated and tests are repeated for several weather and illumination conditions.

In a subsequent phase, collision avoidance tests will be performed. In these tests, FLARE, with all systems on, will fly several near collision trajectories with a single intruder in its field of regard. On the basis of detection and tracking system estimates, flight control computer will generate and follow in real time a proper escape trajectory in the case of a predicted collision.

6 Conclusions

This paper presented the sensing section of the Autonomous Collision Avoidance System developed by the Italian Aerospace Research Center (CIRA) for its project on innovative technologies for UAV systems named TECVOL. It is based on a sensor set (radar and EO) and two real-time processing units. The system is all-time all-weather and provides large detection range and accurate range measurements, while also offering the potential for high data rate estimates and fine angular resolution at smaller distances. The prototype was installed on a VLA named FLARE, and flight demonstration is being performed. The paper described the whole ground and on-board architecture, regarding both FLARE and the intruder.

Extensive hardware-in-the-loop tests were performed to estimate latency in data exchange and accuracy of real time performance. In particular, latency in the communication via CAN bus between the obstacle detection real time unit and the flight control computer was estimated to be of the order of a few ms. It is largely compatible with application requirements.

Preliminary flights were performed for electro-optical sensors functional verification. Acquired images show that disturbances induced by the platform are negligible, in terms of vibrations, propeller impact, and thermal noise for the infrared sensors. Visible images taken with the sun in the back or in lateral position show high detail and contrast. Instead, the effect of sun presence in the field of view makes completely useless for obstacle detection about 30% of the image. Infrared sensors performance in any geometry with respect to sun are largely satisfying in terms of contrast and radiometric resolution. Thus, the flight data confirmed the good potential of electro-optical sensors for target detection, especially for intruders flying over the horizon. Future works will present the operation of radar, the electro-optical and radar data fusion, the sense and avoid flight results and the lessons learned.

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