Hardware-in-the-loop validation of a sense and avoid system leveraging data fusion between radar and optical sensors for a mini UAV

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Keywords: Sense And Avoid, Unmanned Aerial Vehicles, Hardware in the Loop, Data Fusion

Abstract. The present work illustrates the results obtained at the conclusion of the three-year project TERSA (Tecnologie Elettriche e Radar per Sapr Autonomi), involving the aerospace section of the Dept. of Civil and Industrial Engineering (DICI) of the University of Pisa and its industrial partners. The project aimed at the design and development of a fully autonomous Sense and Avoid (SAA) prototype system, based on data fusion between optical and radar sensors data, for a tactical lightweight surveillance UAV (MTOW<25Kg). The problem of non-cooperative collision avoidance is well known in literature and is currently a central theme of investigation within the aeronautical industry, considering the growing UAV traffic and the consequent need to employ autonomous self-separation technologies in the market. Several past works have investigated the most varied solutions for the Sense problem utilizing optical, acoustic, electro-magnetic signals or a combination of the previous. Likewise, the Avoidance problem has been successfully tackled in literature by means of a wide variety of different approaches ranging from rule-based methods, strategies based on game theory, force field methods, optimization frameworks leveraging genetic algorithms and nonlinear programming techniques and geometric methods. Yet, to the knowledge of the authors, no previous work found in literature has successfully demonstrated and validated the real-time simultaneous interaction of both sense and avoid functionalities within a highly integrated simulation environment. The present work describes the implementation of a complex, nonlinear, simulation environment conceived in order to perform real-time, Hardware-in-the-Loop (HIL), testing of the effective cooperation between sense and the avoid algorithms constituting the core of the SAA system developed within the context of the project. The system effectiveness has been validated by means of complex dynamic simulations, comprising an accurate, fully nonlinear, flight mechanic model of the aircraft, a graphic rendering engine of the scene, proper video capture and transmission pipelines, computer vision algorithms and collision avoidance logics running on the target hardware (Nvidia Jetson Nano) and tailored noise resilient data fusion algorithms. Results show the effectiveness of the system in detecting impending collisions and performing last-resort resolution manoeuvres with high computational efficiency and update frequencies compatible with real world applications in Unmanned Aircraft Systems (UAS).

Introduction

Unmanned aircraft systems (UAS) undoubtedly represent the future of the aeronautic world. The growth in popularity of these highly autonomous aircraft system is driven by the numerous potential applications, their inherent flexibility, lower maintenance cost w.r.t to manned aircraft and the current general willingness to achieve a greener and more sustainable aviation industry. UAS, due to their inherent lower weights, represent indeed the ideal field of application to test innovative electric propulsion systems, characterized by lower emissions. Furthermore, the disruptive military potential of UAS proved itself beyond any doubts in the ongoing Ukrainian conflict, where, for the first time in history, UAS and small drones have been massively used in order to carry out hundreds of thousands of sorties on both sides since the start of the hostilities. For civil applications however, the non-trivial problem of integrating autonomous aircraft systems into non segregated airspace still presents to date a combination of technical and regulatory challenges to solve. Under the general and widely accepted principles that a UAS shall comply with existing regulations and procedures, its operations shall not increase the risk to other users and its integration shall not force other users to carry additional equipment, the development of a suitable Sense and Avoid (SAA) is considered a fundamental milestone towards the future integration of UAS into non segregated airspaces. Said system, should allow the UAS to perceive and avoid obstacles as a human pilot does, effectively empowering the aircraft with separation provision and collision avoidance capabilities. When it comes to the physical implementation of a SAA system, taking into account the dimensional and ponderal constraints of mini-UAVs which often hinder the applicability of more conventional systems (such as ADB-S or TCAS), multisensory architectures seem to be the most prominent solution widely investigated in literature. In particular, SAA system based on data fusion between RADAR and optical sensors have been the subject of several studies [1, 2, 3] which have outlined the benefits of a solution that allows to compensate for the shortcomings of each sensor type, reducing noise and increasing at the same time system robustness and accuracy. During the design phase of such a complex system, simulation models are helpful to validate system requirements and predict system response before actual flight tests can take place. Unfortunately, the simulation of the interaction between the avoidance and the sensing algorithms of a multisensory SAA system is no simple matter. The nontrivial dependency between the source data fed as input to the sensing algorithms (optical data from the camera and range information from the radar) and the attitude and position states of the aircraft (which in turn depend on the output of the avoidance algorithms) give rise to an interconnected problem, to address which, a dedicated HIL simulation environment was developed in the laboratories of the aerospace section of the Dept. of Civil and Industrial Engineering of the University of Pisa. The present work shortly describes the architecture of the SAA system developed within the context of TERSA project and focuses on the description of the nonlinear, HIL, simulation framework specifically created to test the effectiveness of the system utilizing an accurate dynamic model of the aircraft, with aerodynamic data provided by courtesy of Sky-Eye-Systems (SES). The last section briefly describes the simulation conducted and comments on the results.

System Overview

The SAA system has been developed following a multisensory architecture approach that leverages data fusion between a radar, which provides target distance and velocity reading, and Electro Optical (EO) sensor which allows for an accurate angular reconstruction of the target within the field of view of the camera [4, 5]. An High level diagram of the system architecture is presented in Fig. 1; Fig. 2 shows the prototype of the system built by the aerospace section of DICI, in partnership with Echoes [6] within the scope of TERSA project, that was successfully tested at the airfield of Tassignano (Lucca) using a Rapier X-25 aircraft as a moving target [7].

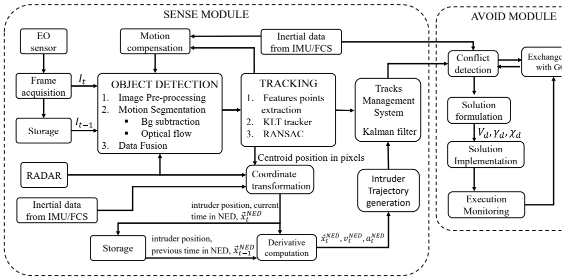
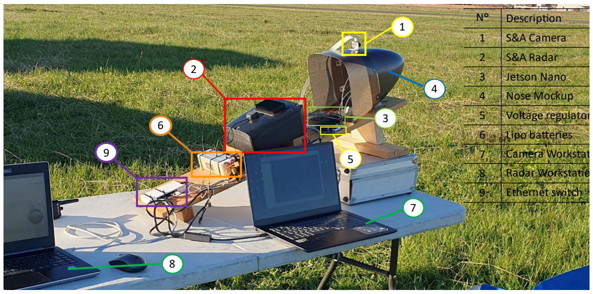


Fig. 1: SAA system architecture



N°	Description
1	S&A Camera
2	S&A Radar
3	Jetson Nano
4	Nose Mockup
5	Voltage regulato
6	Lipo batteries
7	Camera Workstat
8	Radar Workstatio
9	Ethernet switch

Fig. 2: SAA prototype

In a nutshell, both radar and the optical sensor, continuously scan the air space in front of the aircraft in search of a potential non cooperative intruder. The detection algorithm for the optical sensor is based on an implementation of Single Gaussian Models (SGM) background subtraction algorithm. Motion compensation schemes are employed in order to greatly reduce the noise caused by the ego motion of the camera. Specifically, at each iteration step, the background model is continuously warped (updated) according to an homography matrix which is iteratively obtained via a RANSAC procedure, where matching points between current frame and background model are fed as input. Such correspondences between points are computed by an efficient matching algorithm (i.e. pyramidal implementation of the KLT tracker), while feature points are extracted by means notorious Harris Corner algorithm. Various blobs obtained from the detection stage are then collapsed into single tracks using an implementation of Connected Component Analysis (CCA). Validation based on statistical criteria are then applied to the track readings, in order to make sure that such tracks exhibit a certain regularity in terms of position within the field of view (FOV) and dimension of the visual track itself to further suppress background noise. Once tracks are validated, the pixel position of the intruder aircraft centroid within the FOV is transformed into elevation and azimuth angles in a body fixed reference frame using geometric relationships involving intrinsic parameters of the camera. Such angles, together with the distance reading provided by the radar and the attitude, position/velocity states of the UAV are fed as input to an Extended Kalman Filter (EKF) which performs data fusion and outputs the position and velocity states of the target aircraft in an inertial reference system. These states in turn, constitutes the input to the avoidance routines which continuously check for impending violations of the self-separation condition. When a collision is predicted (meaning that at a certain future time the relative distance between UAV and intruder aircraft will be less than a certain safety threshold), a geometric conflict resolution approach based on the strategies discussed in [8, 9], transforms the dynamic problem into a relative static kinematic problem and computes the tangency solution (i.e. a trajectory which results in the UAV being tangent to the safety bubble at the point of closes approach). The system has been extensively tested in a simulation campaign detailed in the following sections.

Simulation Framework

Initially, a simplified simulation model was devised in order to test avoidance algorithms independently from computer vision part. A Simulink model has been created featuring a realistic 6 DOF, nonlinear, data base driven model of the reference UAV, where the aerodynamic database and the FCS laws has been provided by courtesy of SES. The model features an automatic trim routine leveraging gradient descent optimization, that computes the initial inputs in terms of control surface deflections and engine settings in order to trim the aircraft at various conditions. Avoidance algorithms have been implemented by means of tailored "m-functions", together with the EKF and a waypoint follower block for the trajectory recovery after the end of the avoidance manoeuvre. The position states of the intruder aircraft are considered known in advance, albeit injected with gaussian noise in order to simulate sensor noise. System effectiveness has been tested for a variety of initial conditions in terms of relative position w.r.t to the intruder aircraft ($\Psi_0 =$

$0^{\circ} \div 45^{\circ}$) and intruder speed ($V_0^{Intr} = 22 \div 42\ m/s$), which is assumed to be constant during the simulation, see Fig. 3; the initial heading angle of the intruder aircraft Ψ_{Intr} is precomputed taking into account each aircraft relative initial position and speed magnitude to ensure that a collision will always take place. The avoidance manoeuvre is accomplished by means of a coordinated turn in the horizontal plane. The effectiveness of the manoeuvre is evaluated according to a series of performance metrics (Fig. 4) together with the respect of safe envelope boundaries in terms of load factor limits, maximum bank angle and control saturations.

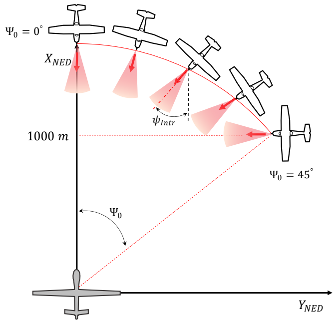


Fig. 3: Simulation initial conditions

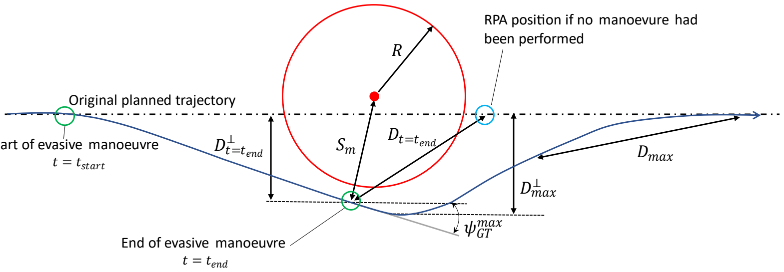


Fig. 4: Evaluation metrics

After the verification of the correct behaviour of the avoidance algorithms and the correct operation of the EKF, more complex simulations have been conducted inserting computer vision algorithms in the close loop, with the aim of validating the simultaneous interaction between sense and avoid modules. This time, intruder aircraft states are no longer assumed known beforehand but only the relative distance is known in a body fixed reference frame. Once again, this measure is injected with gaussian noise. Position states are reconstructed in real time based on the output of the computer vision algorithms that process a realistic rendering of the scene produced by the Open-source flight simulator *Flight Gear (FG)*.

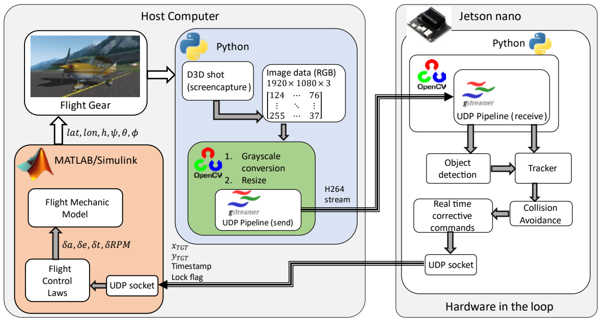
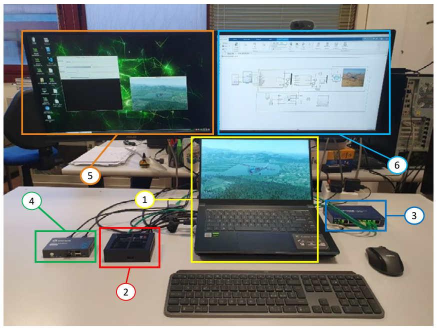


Fig. 5: Scheme of the HIL simulation framework



N°	Description
1	Workstation
2	Jetson nano
3	Ethernet switch
4	KVM switch
5	Jetson Display
6	Workstation 2nd Display.

Fig. 6: HIL Simulation setup of the SAA system

Basically, as shown in Fig. 5, the Simulink model outlined above, drives an instance of the FG software, running on the workstation which in turn generates a realistic 3D scene comprising accurate weather, lightning conditions, background settings etc. Being an open-source software, tailored modifications have been implemented in order to setup a camera view positioned in front of the aircraft (as to replicate the real EO sensor of the SAA system). Likewise, FG is also configured to display an intruder aircraft model, following a pre-cooked trajectory. Proper synchronization functions make sure that both the Simulink model, the intruder aircraft and FG rendering output are in sync. The workstation screen where FG is opened is captured at a high rate by a dedicated Python module; the obtained frames are then packed into a video stream leveraging the Gstreamer framework and sent to the Video Processing Unit (VPU), Jetson Nano embedded platform, where, thanks to extensive optimisation efforts in the design of the algorithms, object detection and tracking algorithms run in real time (~25Hz) together with avoidance routines. When a collision is predicted and a real time corrective manoeuvre is computed, the prescribed heading angle is fed back in real time to the UAV's FCS in the Simulink model via a dedicated UDP port. This allows for the generation of a realistic synthetic imagery representative of the scene, which evolves according to the dynamic manoeuvre of the aircraft. The simulation setup implemented at the laboratories of the DICI is shown in Fig. 6.

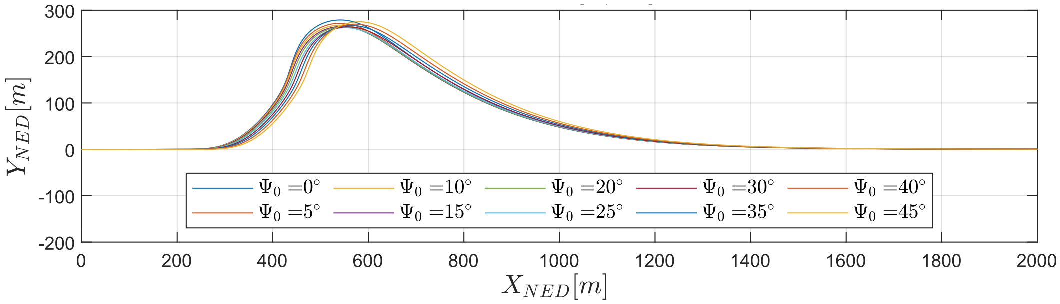


Fig. 7: Avoidance trajectory at various initial intruder positions

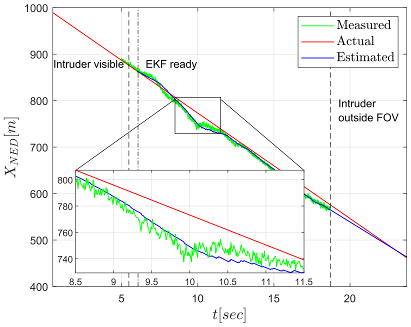


Fig. 8: Intruder position state X

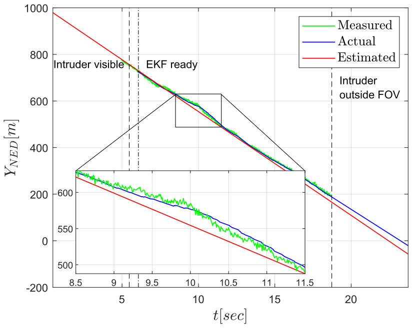


Fig. 9: Intruder position state Y

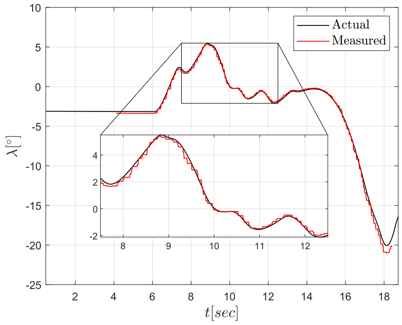


Fig. 10: Intruder elevation angle

Fig. 11: Rendering # 1

Fig. 12: Rendering # 2

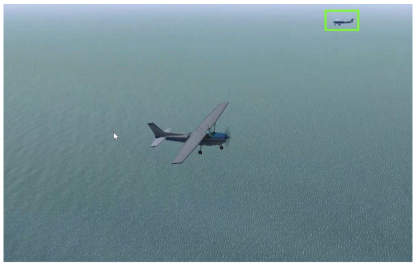


Fig. 13: Rendering # 3

Simulation Results

Fig. 7 shows the evasive manoeuvre (seen from above) for various values of Ψ_0 for the highest intruder speed ($V_0^{Intr} = 42\ m/s$) obtained with the simplified simulation model. Fig. 8-9 instead show the position state X, Y of the intruder aircraft (Cessna 172p), reconstructed by the EKF in the complete simulation with the Jetson Nano as hardware in the loop (intruder approaching from port side, @ 52 m/s). Fig. 10 shows the intruder elevation angle reconstructed by the computer vision algorithms plotted against the actual one, while Fig. 11-13 depicts the actual rendering of the scene generated by FG. Plots of the performance parameters of the evasive manoeuvre are omitted for brevity. However, simulation have shown that the system satisfies the requirements for all the tested initial conditions, without invalidating the safe boundary limits. Minimum distance to the intruder is never violated and the evasive manoeuvre is conducted correctly.

Conclusions

The present work has illustrated the complex simulation environment implemented at the Fly-by-wire laboratories of the DICI of the University of Pisa, within the context of the TERSA project which has proved a crucial and invaluable tool for the preliminary validation of a multisensorial Sense and Avoid system. The framework has allowed the verification of the correct simultaneous interaction between avoid and sense algorithms as well as the verification of the requirements of the chosen hardware in terms of available computational power.

Funding & Acknowledgements

This research was co-funded by the Italian Government (Ministero delle Imprese e del Made in Italy, MIMIT) and by the Tuscany Regional Government, in the context of the R&D project “Tecnologie Elettriche e Radar per SAPR Autonomi (TERSA)”, Grant number: F/130088/01-05/X38.

The authors wish to thank Sky Eye Systems (Italy) for the support to the research activity and for providing the UAV aero-mechanical data and FCS laws that allowed the creation of an accurate dynamic simulation model.

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