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PRELIMINARY DESIGN AND VALIDATION OF THE AUTOMATION LOGIC SUPERVISOR MODULE FOR AN INTEGRATED MISSION MANAGEMENT SYSTEM

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Abstract

This paper is focused on the design, implementation and validation, in the MATLAB/Simulink/Stateflow environment, of a software prototype, named Automation Logic Supervisor (ALS) module, for the internal execution logic automation of the various systems constituting an Integrated Mission Management System (IMMS). The Automation Logic Supervisor module has been developed by CIRA as a part of a thesis work within the international project COAST (Cost Optimized Avionics System), funded by the European Union in the framework of the Clean Sky 2 - Systems ITD Programme, in which CIRA is a core partner. In the paper, after an introduction about the operational framework and motivations of the ALS design, it is described the preliminary conceptual design of the module, emphasizing the various considered logical states and their connections and associated transition conditions. Then, the implementation of the ALS as preliminary software prototype in Matlab/Simulink/Stateflow environment is outlined. Finally, the numerical validation of the ALS model is described, by outlining the considered test scenarios, which have been on purpose defined to stimulate all the ALS finite state machine modelled transitions, and reporting the results of the numerical simulations that show the correct behavior of the ALS, whose development successfully reached TRL 3.

Introduction

The Small Air Transport (SAT) is emerging as the most suitable transportation means in order to allow efficient travel over a regional range, in particular for commuters, based on the use of small airports. The vehicles that are comprised under the SAT domain are usually fixed wing aircraft with 5 to 19 seats or similar cargo vehicles, belonging to the EASA CS-23 category. In order to ease the growth of the SAT business domain, the availability of new technological solutions allowing reduction of the related operative costs represents a challenge of capital importance. Several benefits, in comparison with the use of larger commercial vehicles on the same routes, are associated with the introduction of the SAT category in the Air Transport System (ATS), such as reduced fuel consumption, reduced turnaround times, increased economic viability. These benefits are particularly evident when considering the possibility of implementing regional transportation in countries where the economic development level and/or the geographical constraints prevent the use of other competitive transportation means, such as trains. lt has to be considered, indeed, that the construction of railways on a regional extent is far more expensive than the use of small even if remote airports, especially where the geographic morphology is an additional obstacle for the implementation of railways [1]. In the SAT framework, the COAST project develops both individual technologies (Tactical Separation System [2][3], Flight Reconfiguration System [4] and

Advanced Weather Awareness System [5][6][7]) and the Integrated Mission Management System enabling autonomous mission management in all flight phases for Small Air Transport (SAT). The IMMS [2][8] aims to implement and extend the functions of individual technologies into a unique integrated system. It is conceived both as a support system for the pilot in normal conditions and as an emergency system in case of pilot's incapacitation (for instance, if he/she has sudden health problems during the flight and is therefore unable to operate the aircraft).

The IMMS allows communication among the single functions and supports the pilot during the flight. Such a support is of paramount importance under single-pilot operation in emergency conditions, where the pilot is incapacitated to perform his/her tasks. The IMMS is a system of systems, including several individual systems that need to cooperate and to be sequenced in a logical and ordered way. Therefore, it is needed that the IMMS internal systems are coordinated and sequenced in an appropriate logical way. This is the aim of the ALS whose preliminary design and validation is addressed in this paper.

ALS conceptual design module

The ALS design process included the conceptual design and the software implementation. This section describes the conceptual design, starting from the IMMS architecture shown in Figure 1.

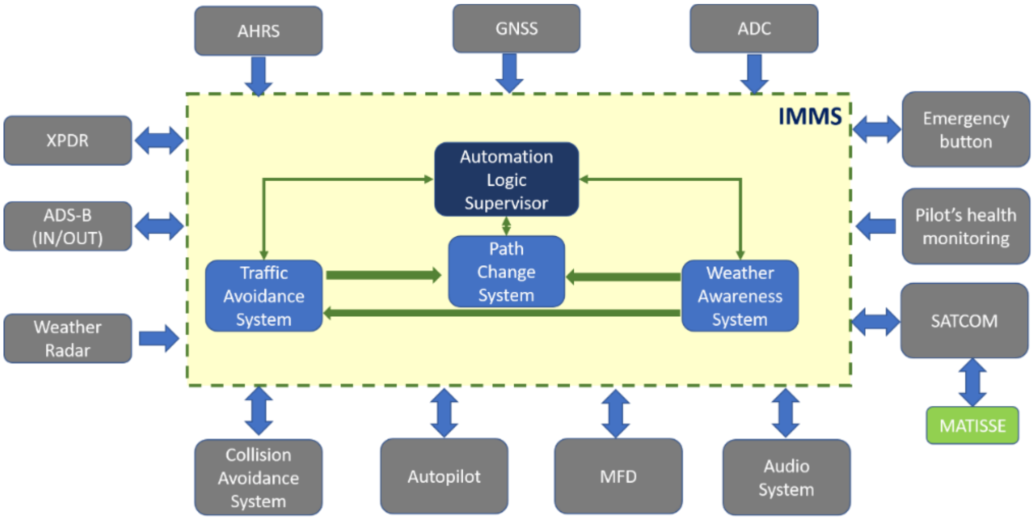

Figure 1. IMMS high-level architecture and boundary diagram.

The high-level architecture of the IMMS and of its related interactions with the external systems emphasizes that the ALS role is to allow proper working, according to specified logic, of the systems internal to the IMMS system of systems, as well as to allow proper triggering of IMMS internal states, based on the information provided by the external systems.

As illustrated in Figure 1, the IMMS consists of the following systems:

- Traffic Avoidance System,
- Path Change System,
- Weather Avoidance System,
- Collision Avoidance System.

Traffic Avoidance System is a functionality carried out by the Tactical Separation System (TSS, already developed and tested in the COAST project for the En-Route phase which will be extended also

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in TMA phase) and it is primarily intended to provide the elaboration of the resolution maneuver with respect to only the most dangerous conflict (i.e. the most dangerous vehicle posing loss of separation risk with respect to ownship), thus preventing emergency collision conditions in the traffic picture. Indeed, in order to become a threat (i.e. a vehicle posing collision risk), a vehicle needs first to be a conflict (i.e. a vehicle for which potential loss of separation is detected). Therefore, by supporting the pilot in restoring the safe separation minima with respect to the conflicts, the TSS [2][3] prevents that they become threats.

Emergency System is a functionality carried out by the FRS [4]: it will be in charge not only of the automatic route planning and of the aircraft guidance to the arrival airport, in the event of the pilot's incapacitation, but also of providing support to less experienced pilots, for adequate flight management towards the destination airport.

Weather Avoidance system is a functionality carried out by AWAS [5][6][7]: it provides observed and forecasted data concerning meteorological hazards having potentially not negligible impact on the aircraft. The system provides weather conditions along the path, integrating multiple data sources, including an advanced and user-friendly visualization.

The Collision Avoidance System is the last barrier that will be in function before a collision occurs.

The ALS model here described and developed by CIRA starts from the avionics technologies developed within the COAST project and introduces the operational distinction between two phases of flight (TMA phase, in addition to the En Route one) and the possibility of changing the assigned path. In this way, the combination of possible states and associated transitions between the systems included in the IMMS defines a complete conceptual scheme of the ALS model. In Figure 2, a conceptual graph of the Moore finite state machine associated to the ALS model is illustrated; it represents the first step towards the implementation of the ALS model in the Matlab / Simulink / Stateflow environment.

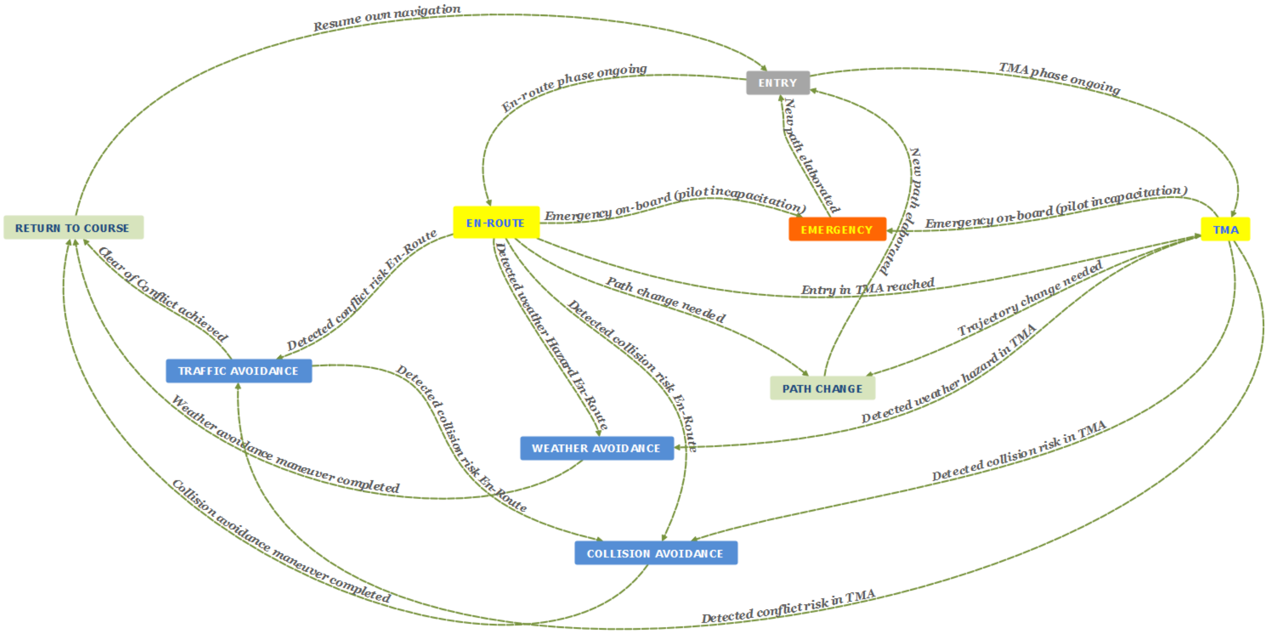

Figure 2. Automation Logic Supervisor conceptual graph.

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As depicted in Figure 2, the possible states of the IMMS are as follows:

- Entry,
- EnRoute,
- TMA,
- Emergency,
- CollisionAvoidance,
- TrafficAvoidance,
- WeatherAvoidance,
- PathChange,
- ReturnToCourse.

Table 1. Identification of ALS states, associated transition conditions.

(input variables) and outputs

State	Input Variable	Output Variable
Entry	NewPathElaborated	0
	ResumeOwnNavigation	
EnRoute	EnRoutePhase	1
TMA	TMAphase	2
Emergency	EmergencyOnBoard	3
CollisionAvoidance	CA_Hzd	4
TrafficAvoidance	TA_Hzd	5
WeatherAvoidance	WA_Hzd	6
PathChange	PathChangeNeeded	7
ReturnToCourse	CA_ManeuverCompleted	8
	ClearOfConflictAchieved	
	WA_ManeuverCompleted	

All the above-mentioned states have been collected in the Table 1, where for each ALS state the input variable/s are specified, and the value of the ALS machine output variable associated with the considered state is indicated.

Starting from this table, the software implementation of the previous conceptual model is developed in the Matlab/Simulink/Stateflow environment, as described in the following section.

Software prototype implementation

Once the ALS conceptual model was defined, as shown in previous section, it was implemented in the Matlab/Simulink/Stateflow design environment. The various states and the connections between them have been built, by properly setting the transition conditions, priority and output values.

As a first step, similar functions have been collected into macro states, as it can be already seen in the conceptual scheme of Figure 2, in which the same color has been associated with states with similar functions. Starting from what reported above, the following macro states have been created:

- Avoidances,
- FlightPhase.

The first macro state (i.e. Avoidances) includes Collision Avoidance, Traffic Avoidance and Weather Avoidance states, as shown in Figure 3.

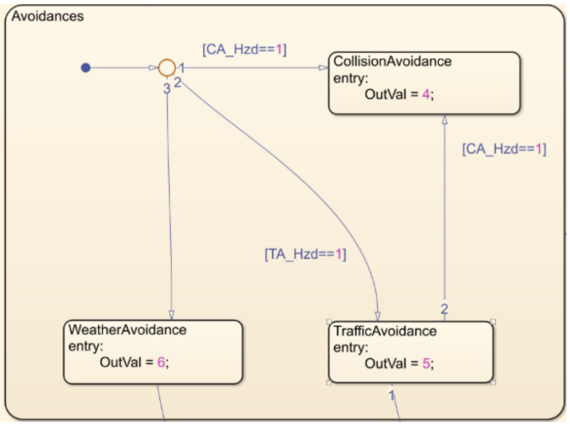

Figure 3. Avoidances macro state.

To enter in the Avoidances macro state, at least one of the three transition conditions implementend in OR logic must occur: CA_Hzd == 1 OR TA_Hzd == 1 OR CA_Hzd == 1. Within the Avoidances macro state, based on the occurring transition condition, it is possible to entry in the Collision Avoidance or Traffic Avoidance or Weather Avoidance state. Furthermore, the transitions have an assigned execution priority and this can be seen from the numbers placed at the junction output: in case of simultaneous events, the one with the smallest number is executed first. In fact, the Collision Avoidance is the highest priority state (number 1 on transition), because it intervenes on a smaller time scale and safety volume than Traffic Avoidance.

The FlightPhase macro state collects the EnRoute and TMA states, as shown in Figure 4.

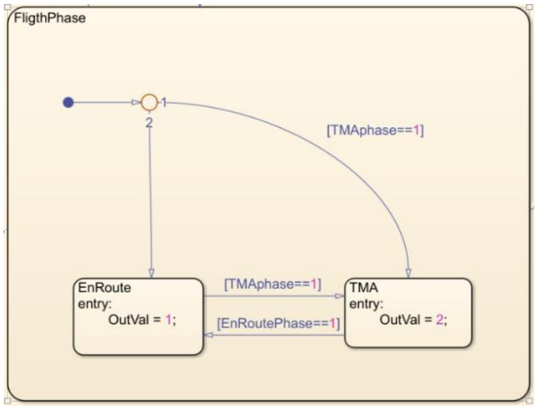

Figure 4. FlightPhase state.

Within the FlightPhase macro state, to entry in the EnRoute or in the TMA states the respective transition condition must occur. Also in this case, the transitions have an assigned execution priority, as it can be seen from Figure 4, with the TMA transition having priority over the EnRoute transition; anyway, they are mutually exclusive and the assigned priority is only a protection against possible erroneous evolution of the input variables behaviors. As it can be seen in Figure 11, according to the Stateflow rules the standard transition when entering the FlightPhase macro state is the transition into the EnRoute state (the associated transition from the entry node to the EnRoute state is not subject to condition), unless the TMA entry condition applies (TMAphase==1). Then, the transition from one state to the other is ruled by the associated transition conditions occurrence.

The complete ALS software implementation model with all states is shown in Figure 5.

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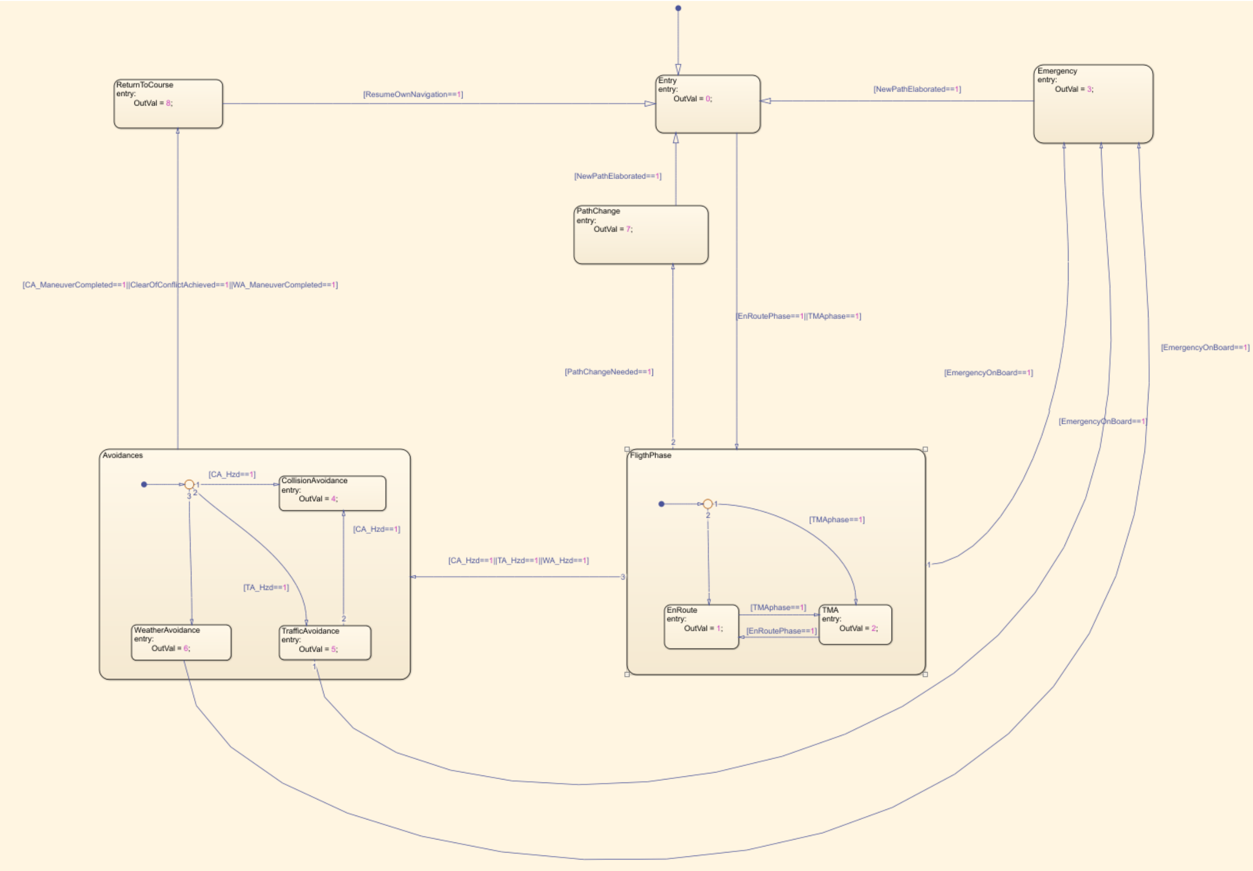

Figure 5. ALS Stateflow model.

The Staeflow model consists of all the states reported in Table 1, with the related transition conditions from one state to another. As depicted in Figure 5, each arc represents the connection between one state and another of the system and on each arc there is the transition condition which allows the state change.

The conditions of transitions in the macro states (Avoidances and FlightPhase) have been implemented with a logical OR of the transition conditions inside the macro state. The assignment of priority to the various transitions is essential to create a coherent sequence of states: the logic adopted is based on both the time horizon of the event (for instance, the CA_Hzd priority wrs TA_Hzd) and the associated flight safety (for instance, if an emergency occurs on board, it has priority on TA_Hzd and WA_Hzd, but not on CA_Hzd, being the CollisionAvoidance functionality automatic).

Once the ALS model has been consolidated, the numerical validation of the model has been performed. To this aim, a set of flight scenarios has been designed, first in the form of purely descriptive scenarios and then translated into a path generator, in order to trigger the ALS state transitions and verify their correct behavior. Moreover, an exemplary scenario from fast-time simulations of the developed TSS within the COAST project has been applied, in order to include the actions performed by the TSS downstream of the TA_Hzd into the ALS model. All these aspects will be reported in detail in the following section.

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Numerical validation and results

For the numerical validation of the ALS model designed and implemented in the Matlab/Simulink/Stateflow environment, it was necessary to simulate the input variables (Table 1) to the ALS.

In Figure 6 the ALS module and its input variables in Matlab/Simulink environment are represented. As already anticipated, in order to feed the ALS module for the validation campaign execution, some specific flight test scenarios have been first elaborated and then converted into dedicated logic tables, in which the logic state associated to each input variable is reported, also indicating the associated timing during the simulation execution. Based on this test scenarios design, an input variable generator has been implemented, to stimulate the ALS finite state machine and trigger the state transitions to be verified.

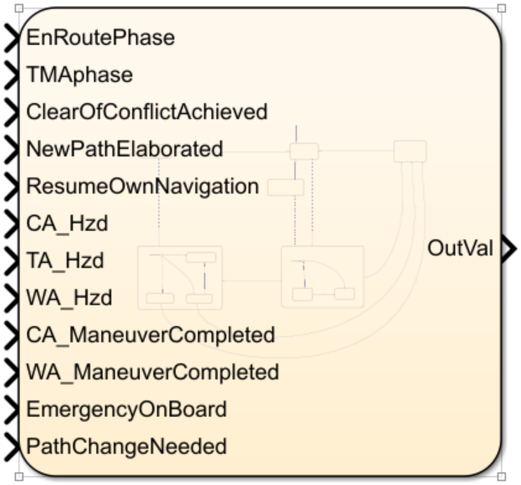

Figure 6. ALS module in Matlab/Simulink environment.

A total number of 4 flight scenarios has been created with the aim of stimulating the ingress/egress to/from all the possible states included into the ALS and to test all the included transition conditions. The scenarios have been elaborated in a way that is deliberately exaggerated in terms of events, in order to stress the ALS transitions using a limited number of tests.

A fifth scenario, then, has been taken from fast time simulations for the EnRoute validation of the TSS system as designed, developed and tested within the COAST project, in order to illustrate the ALS behavior in the framework of a wider simulation environment specific of the COAST project where the ALS is expected to be integrated.

The evolution of the flight scenario #1 is as follows:

- Flight number XX123, an A320 aircraft, takes off from LIRF - Roma-Fiumicino "Leonardo da Vinci" and flies towards EDDM - München International Airport Franz-Josef Strauss.
- After takeoff, the ascent phase begins to reach the assigned flight level.
- Once the aircraft has reached the assigned flight level, it begins the en-route phase.
- During the en-route phase, a collision threat is detected by the Collision Avoidance system, and consequently the evasive maneuver begins.
- Once the evasive maneuver is finished, the aircraft returns to the en-route path.
- During the reestablished en-route phase, probably due to the imminent risk of collision just experienced, the pilot starts feeling bad and causes the activation of the emergency system on board.
- When the pilot is able to come back to the control of the aircraft, the emergency condition is terminated and the aircraft is ready to begin the descent phase towards the destination airport.
- Unexpectedly, during the descent phase, the weather radar detects heavy rain along the assigned path trajectory and consequently the Weather Avoidance system is activated and a new descent path is generated.
- The aircraft finally safely lands at the destination airport.

The simulation pattern of the flight scenario #1 is depicted in Figure 7, whereas the output of the simulation is shown in Figure 8, in which the various logical states assumed by the ALS during the flight are reported.

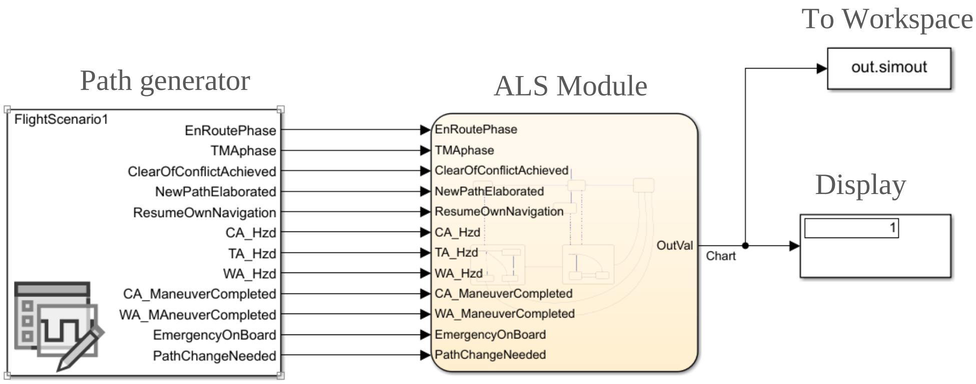

Figure 7. Flight Scenario #1 simulation configuration.

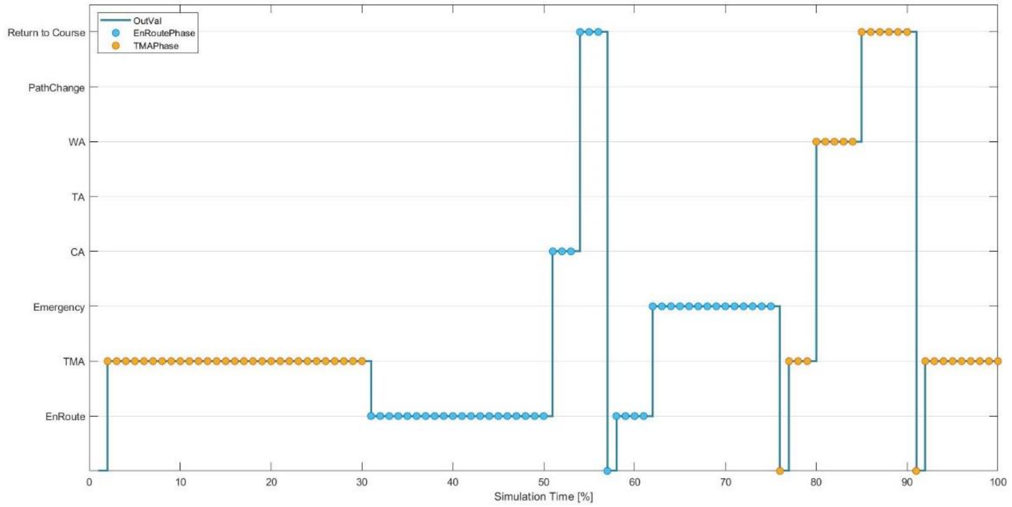

Figure 8. Simulation output of Flight scenario #1.

With reference to Figure 7, the Simulink block on the left is the path generator, set on FlightScenario1, which feeds the ALS module of the overall IMMS that is the Stateflow chart on the right side. A display block has been connected to the ALS output, to indicate the output variable value during the simulation (see Table 2). In addition, a To Workspace block (namely out.simout) has been implemented, in order to save the output data during all the simulation time and plot them in a graph in post simulation data analysis (see Figure 8). As expected, the ALS output is compliant with the flight scenario described: to better identify the active flight phase, cyan and yellow circles have been used, indicating the en-route and TMA phase, respectively (see Figure 8).

Table 2. ALS state association to the output variable.

IMMS State	Output Variable
Entry	0
EnRoute	1
TMA	2
Emergency	3
CollisionAvoidance	4
TrafficAvoidance	5
WeatherAvoidance	6
PathChange	7
ReturnToCourse	8

The same architecture is used for all the simulations, where of course for each scenario the corresponding flight scenario is activated in the path generator through a dedicated drop-down menu allowing the user to choose the scenario to be simulated.

The flight scenario #5 is related to a fast-time simulation for the validation of the TSS developed in the COAST project and for the EnRoute phase only (the TMA phase devoted TSS module has not yet been developed). For the above reasons, the TMA phase is not present in the simulation output.

The evolution of the flight scenario #5 is as follows:

- Flight no. AA127, a PZL M28 aircraft, is flying over Brno airport towards Wroclaw airport.
- The aircraft AA127 is cruising at the assigned flight level (FL198).
- During the cruise phase, the Traffic Avoidance system onboard provides a TA Hazard alert (at 500 s) with respect to a traffic aircraft coming from the right side.
- The TA system provides a resolution horizontal maneuver which deviates the current track of 25 deg.
- Once the conflict situation is resolved, the TA system declares the Clear of Conflict condition (at 781 s) and the AA127 aircraft restores the original track towards a trajectory parallel to the original one (at 802 s).
- The aircraft returns to its undisturbed levelled flight in cruise phase.

In Figure 9 to Figure 12 the simulation evolution is represented in details in terms of trajectories. The simulation starts with the flight in Enroute [at 500 s], as shown in Figure 9; a TA_Hzd is detected and the TSS performs the maneuver to restore the tactical separation; when the clear of conflict is declared [at 781 s], as shown in Figure 10, the aircraft returns on track towards a trajectory parallel to the original one [at 802 s], as shown in Figure 11 and in Figure 12.

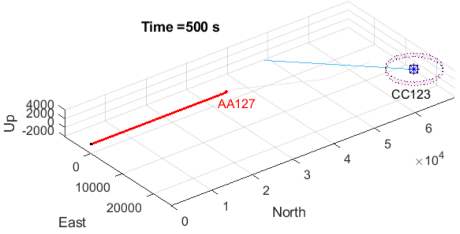

Figure 9. Loss of tactical separation between AA127 and CC123 aircraft.

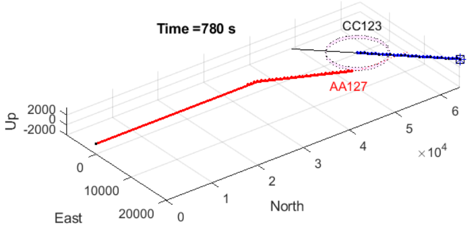

Figure 10. TA maneuver.

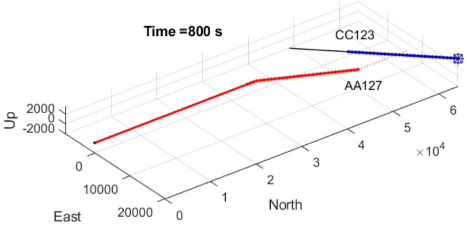

Figure 11. The aircraft AA127 resume own navigation.

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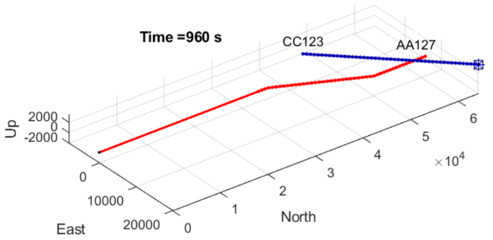

Figure 12. The Aircraft AA127 return to original track towards a trajectory parallel to the original one.

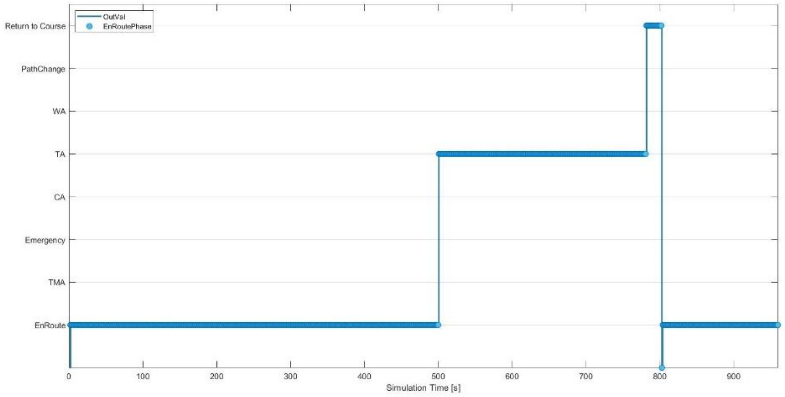

Figure 13. Simulation output of Flight scenario #5.

Conclusions

The developed system, named Automatiom Logic Supervisor (ALS), has been designed starting from the consideration of the specific functions implemented by the individual systems integrated in the IMMS and from the consideration of the intended concept of operations of the IMMS. The activities included the analysis of the individual enabling technologies for single pilot operation developed in the COAST project by CIRA (i.e. the Tactical Separation System and the Advanced Weather Awareness System) and by Rzeszów University of Technology and Institute of Aviation (i.e. the Flight Reconfiguration System) and the definition of the high-level architecture of the IMMS and of its interactions with the surrounding cockpit avionics environment. Based on that, the conceptual design of the ALS has been carried out, identifying first of all the logical states to be included in such a finite state machine and the related transitions. Once consolidated the conceptual design, the ALS has been designed and implemented in the form of a Stateflow module, in the Matlab/Simulink/Stateflow design and verification environment. Such software prototype has been finally validated through numerical simulations, based on a validation plan encompassing proper simulation scenarios that have been designed in this work to assure full coverage of all the states and transitions included in the ALS. From the analysis of the simulation results, it emerged that the ALS prototype demonstrated to behave as expected and it is now considered as developed up to TRL 3.

The ALS is therefore ready for further development in the framework of the IMMS design activities that are ongoing in the COAST project.

Future work will address: the refinement of the ALS logic based on the detailed additional functionalities that are going to be implemented in the IMMS systems devoted to Traffic Avoidance, Weather Awareness and Path Change; the implementation of the ALS integrated with the final version of the other systems included in the IMMS; the validation of the IMMS, including the ALS, first in fast-time simulation environment (TRL 4) and then in real-time simulation environment (TRL 5). Finally, the IMMS is expected to be demonstrated in-flight on the EVEKTOR EV 55 aircraft in 2023, finally reaching TRL 6.

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