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Formal Intent Based Flight Management System Design for Unmanned Aerial Vehicles

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Abstract— **This paper presents a formal intent based Flight Management System (FMS) hardware and functional structure utilising multi-level autonomy modes. The novel advanced capabilities added to the UAV autopilots are envisioned to meet the requirements of the future flight operations of the UAVs integrated into national airspace. The proposed FMS structure integrates new functionalities such as a) formal intent based information exchange and collaborative tactical planning utilising air-to-air and air-to-ground data links and, b) decentralised immediate sense-and-avoid. The collaborative nominal operation mode enables the ground operator to build "shared intelligence" with the UAV through the intent sharing. In this mode, the intent sharing process benefits from the advantages of formal intent languages at different levels of abstraction and data-links. The air-to-ground data link allows the ground operator to update/modify/re-plan the flight intent (FI) of the UAV(s) in any phase of the operation according to evolving situations through ground station. The air-to-air intent sharing also continues between the surrounding aircraft through the aircraft intent (AI) ("machine-to-machine" level) communication which makes unmanned systems to be visible. The sense-and-avoid mode, the FMS recursively computes and observes the probabilities of potential immediate collisions with the other aircraft and terrain. Whenever the immediate response needs, the FMS executes the generated 3D avoidance maneuver. For technology demonstration purposes, an experimental FMS hardware has been deployed in a quadrotor UAV, and a ground operator station with GUI has been designed enabling envisioned operational experiments.**

I. Introduction

Over the last 20 years, unmanned aerial systems for civil applications are being operationally more efficient, cost effective, and having high-end capabilities. The new functionalities come into UAV flight management systems allow ground operators to focus on higher level tasks including not only operating single vehicle but also managing the entire operation with large scale UAV fleet. The current practice of the UAV operations is to segregate certain areas of the airspace for their use. However, growing demand in both use of UAVs and commercial air traffic will make unfeasible existing procedures and will require to build joint airspace structure. Future intensive use of UAVs for civil applications will require appropriate integration into general aviation

The *FAA Modernization and Reform Act of 2012* [1] mandates for full integration of UAS into the NAS by 2015, but according to [2], issues of lack of UAS interaction links with Air Traffic Management System, and non-standardised performance/behavioural characteristics still continues as major challenges in integration of UAVs into the national airspaces. Therefore, next generation UAV flight management systems should contain additional data links in order to make themselves visible in 4-dimension for both ground systems and other aircrafts. In addition to this, they should have also own sense-and-avoid system operates independent from both ground and air systems for safety redundancy.

In this paper, the authors propose a novel UAV Flight Management System (FMS) structure that integrates two-level autonomy modes in order to meet the operational requirements of the future UAV operations. In a nominal flight operation, the FMS operates in a collaborative manner where UAVs exchange their intent with ground systems and other aerial vehicles using a formal intent description language through air-to-air and air-to-ground (e.g. ATC and C2 segments) data links. These data links using formal intent languages enable ground segment (human) to "talk" with aircraft (machine), and convey their diverting command at different levels. Whenever the ADS-B equipped FMS detects a potential collision (immediate-term) with other aircraft and terrain obstacles generates and executes an 3D evasive maneuver in order to solve the issue. The FMS handles switching these safety modes considering the required response time. For technological demonstrations and operational validations, an

Fig. 1: On-board camera capture from flight tests of the quadrotor UAV testbed

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Fig. 2: Graphical User Interface screen on the ground station during flight test

experimental prototype of the FMS has been deployed on a Quadrotor testbed, and a command and control (C2) station has been built. Due to page limitation, the paper mostly covers hardware and software design considerations of the FMS, and leaves the algorithmic and implementation details to the future publications.

In order to enhance the predictability of the aircrafts's future path, trajectory planners have begun to utilize a wide range of information including reference intention. In algorithmic side, a formal methodology has been introduced in [3] and applied into small UAV. In [4], intent information prediction by observing aircraft motion has been studied, and in addition to modal estimation, [5] has also utilised flight plan information. In the similar fashion, [6] has presented a probabilistic myopic intent estimation method for an intruder UAV with uncertain goals and motivations. The intent based probabilistic trajectory planning method using a hybrid model has been proposed in [7]. In application side, Intent based approaches have begun to appear in air traffic management, for example, in ground based systems. These tools require almost complete knowledge of the aircraft intents and assume that aircraft follow the advisories of air traffic controller (ATC) and standard flight rules. However, the picture of the future airspace with various type of aircraft (e.g. private aircrafts, commercial planes, UAVs etc.) is envisioned that flight plan and reference trajectory continue to evolve over time in order to meet the dynamic constraints and achieve changed objectives[8], [9]. To address this issue, both the aircraft and ground systems will be handling shared flight data to build a ”shared situational awareness” on trajectory evolution. Through these considerations, Boeing Research and Technology Europe has studied on the trajectory synchronization problem between the different trajectory planners and proposed three-level formal description languages (AIDL, ICDL and FIDL). These languages have enabled to efficiently define an action sequence of the aircraft dynamics or the flight plan with different levels of detail, fully or partially specifying some aspects of the aircraft motion. [10].

In the flight operations, the multi-layer safety structure plays a major role in ensuring safety especially in the high level autonomous systems such as UAVs. Through new concepts of the future use of airspace that redefines responsibility, aircraft must also be equipped with multi-layer safety automation where at least one must work independently from the ground or air [9]. This structure will reduce dependence to the ground and isolate the system from common mode failures such that single data error would invalidate the entire system. By considering these facts, nonintent-based collision avoidance (i.e. Airborne Collision Avoidance or Sense-and-Avoid Systems), which does not require any knowledge on the aircraft intent, will still be crucial when the collaborative separation assurance process fails. The limitation of this method is that the prediction error tends to grow quadratically with time; therefore, these types of tools will still remain in the domain of the immediate to short-term collision avoidance. The method in [11] which is a modal-based probabilistic short-term collision avoidance has been integrated in this system.

The rest of the paper is organised as follows: Section II introduces Flight Management System and Ground Station functionalities and hardware architecture. Section III gives details about collaborative nominal operation and trajectory planning module and explains the intent sharing/negotiation process. Decentralized sense-and-avoid module for collision avoidance and its algorithmic structure is given in Section IV.

II. ONBOARD FLIGHT MANAGEMENT SYSTEM FOR UAVS: EXPERIMENTAL QUADROTOR TESTBED

The integrated system is envisioned to integrate two layers of safety mode into the onboard flight management system (FMS) of the aircraft in order to meet the requirements of the future UAV flight operations. The FMS handles switching these safety modes considering the required response time. The ”required response time” term is defined as the min time for creating an appropriate response (includes comprehending, evaluating and reacting) to solve the occurring and evolving situation. These two process cycles at different autonomy levels are represented with *Intent Based Planning* and *Sense-and-Avoid* modules where both are involving different procedures and algorithms. Figure 8 demonstrates this entire integrated functionalities and its add-on modules.

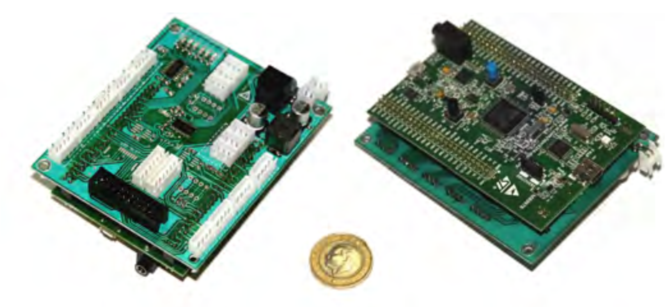

Fig. 3: Custom flight control computer (FCC) hardware

In the mid-term horizon (in couples of minutes) processes are operated in a collaborative manner. In this domain, it is expected that the aircraft cooperates with the ground command and control systems. This module incorporates all tactical level information (i.e. weather data, intent data, user preferences data and traffic data) obtained from both on-board sensing (including air-to-air data link) and air-to-ground data exchange. In this mode, *Replanning Request (ReP)* can be initiated by either the UAV or the ground system. The ground based ReP request may emerge in some circumstances such as drastic change in operational constraints, conflict detection, emergency situations or detection of an aircraft does not conform to the anticipated behaviour. Similarly, the UAV may also create an ReP request cycle when the on-board *Conflict Monitoring* detects a potential conflict. *Trajectory Computation Infrastructure* (TCI) which its details will be given in the following section, automatically validates the feasibility of the given intent data, and *Conflict Monitoring* block checks potential conflicts between the predicted trajectories. This structure allows low-level intent sharing between the aircraft in the surrounding traffic through the air-to-air data link (see the Figure 8). This low-level intent sharing is the ”machine-to-machine” communication, which inherently makes unmanned systems visible for also commercial aircraft, envisions to integrate the UAVs into the national airspace. This function provides the aircraft to have more accurate information about near airspace than the ground systems. Furthermore, in an efficient manner, aircraft can monitor the conflicts more frequently than the ground systems for the interested local region. Specifically, potential conflict may be detected on-board while ground based system can not yet detect the same situation due to the lack of accurate local information.

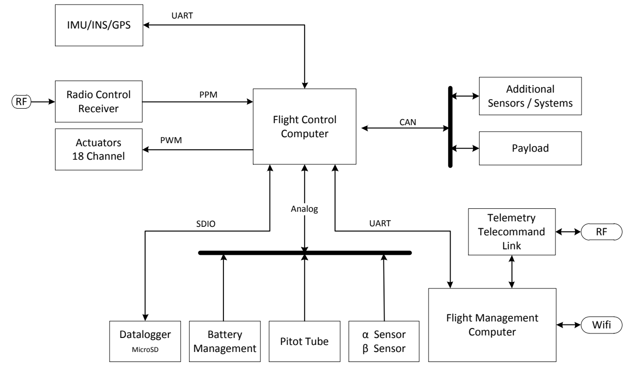

Fig. 4: Hardware architecture of Flight Management System

The Sense-and-Avoid module (seen in the Figure 8) is an isolated system from the intent data exchange and works independently. Thus, it provides redundancy in the aircraft. This module only uses position data of the aircraft in the surrounding traffic obtained via ADS-B based onboard sensing. The *Sense-and-Avoidance* block persistently monitors occurrence probabilities of potential collisions with other aircraft and terrain obstacles for bounded local region. The conflict detection algorithm uses worst case approach and takes into account both uncertainties in position measurement and aircraft actions (e.g failure in control). Whenever the immediate threat(s) is/are detected (i.e. immediate response is required), the autopilot system executes evasive behaviour to solve the issue with required 3D avoidance maneuvers which is generated by *Sense-and-Avoidance* block. These avoidance maneuvers including recovery generate small deviations where their impacts on the entire flight route is minimized.

General architecture of the FMS is illustrated in Figure 4. The Flight Management System (FMS) includes flight control computer (FCC), flight management computer (FMC) and sensor package. While flight control computer is executing low level control processes with on-board sensors, flight management computer handles high level navigation processes. The Flight Control Computer (FCC) is a custom board (seen in Figure 3) with STM32F4 microcontroller which is based on 32bit ARM Cortex M4 floating point processor (168 MHz clock rate and has 192kB Ram).

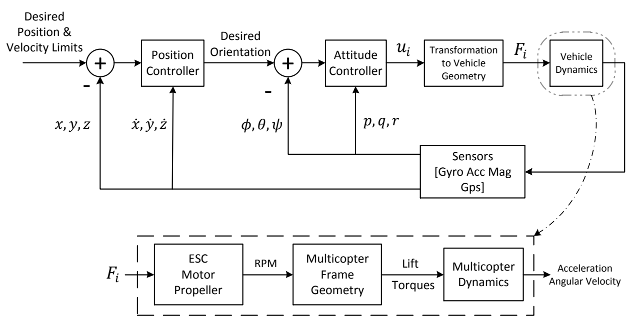

Fig. 5: Position and attitude control loops in the Flight Control Computer

The FCC includes different analog and digital interfaces such as; serial inputs/outputs, PWM outputs, PPM encoders, CAN and ADC inputs/outputs. The serial interfaces such as RS232, UART, SPI and SDIO are used to communicate with IMU/INS/GPS, data logger and Flight Management Computer (FMC). Large number of PWM outputs enables to build a generic autopilot that suitable for most UAV concepts such as helicopter, plane, multicopter or even hybrid systems. Two channel PPM encoders are reserved to get inputs from traditional RC controller, where one of them is designed for master operator while the other is for trainee function. Moreover, the FCC board includes many ADC channels to interface with analog sensors such as pitot tube pressure sensor and alpha-beta sensors. The CAN interface, which is based on standard automotive communication protocol ensuring high electrical and electromagnetic noise immunity, has been reserved for an expansion port needs of additional sensors or payloads.

Flight Management Computer (FMC) executes high level guidance and navigation algorithms including aircraft intent language transitions. This computer is a Linux based Raspberry Pi which has 720MHz clock speed and 512MB ram. The aircraft intent (AI) output of the flight management computer transferred to the flight control computer through a serial interface. Telemetry and telecommand communication module is also linked to the flight management computer. The Xtend RF transponders (seen in 6) operating at 900Mhz emulates ADS-B transponders for sense-and-avoid application. In addition to RF link, a wireless network with higher-speed but short range communication is utilised for remote debugging of the flight control computer through on-chip debugger abilities of the flight management computer.

For in-flight inertial measurements, Xsens Mti-G-700 Inertial Measurement Unit (IMU) is used. This IMU combines embedded accelerometer, gyroscope, magnetometer measurements (up to 100 Hz rate) for flight control purposes. In addition to this package, concept-specific sensors such as pitot tube, alpha-beta sensors has been equipped into FCC.

The Figure 5 demonstrates the control cycles of the autopilot system. As seen in the figure, the desired position and maximum velocity limits are generated by FMC, while other low level control loops run in flight control computer. The FCC evaluates required actuator signals to steer the aircraft. Position and Attitude Controllers are mainly based on cascaded Proportional and Integral (PI) controllers with washout filter. For position control, the outer PI controller loop derives the desired velocity for the Position Controller, while the washout filtered inner PI holds the aircraft at desired velocity. The same applies to attitude controller. The outer PI controller derives desired angular rates while the second PI with washout filter keeps the vehicle in the desired angular rate to achieve controlled turns. Washout filtered PI controller limits the velocity control signals within the desirable region. Otherwise, growing velocity generating errors as time passes cause undesirable control signal biases. On the other words, washout filter provides more smooth and stable flights. The control signals generated by the Attitude Controller drives another block consisting transformation matrixes associated with vehicle actuator geometry. The transformed signals are then conveyed to the actuators which are each driven by electronic speed controllers.

A portable ground station with graphical user interfaces (GUI) enables the operator to manage and monitor high-level flight operations through 900 MHz RF and wireless network links. RF modems are pre-programmed for working in broadcast mode to communicate with all transponders in the field. For test and validation purposes, wireless link is used for data-link experiments based on intent language; and RF links are integrated as enabling ADS-B implementations.

Graphical User interface consists of two separated screens. The primary flight display provides with real-time video and flight data such as orientation, battery status, navigation accuracy, altitude, speed, control inputs, and telemetry status. The operator can choose to monitor any information at the required level. The GUI also includes a second screen demonstrating an operational map overlay which enables to view vehicles' location as shown in figure 2. The vehicles which are equipped with transponders can also be located on the operational map of operator GUI. Using this screen, the

Fig. 6: Xtend 900Mhz transponders for hardware emulation of ADS-B

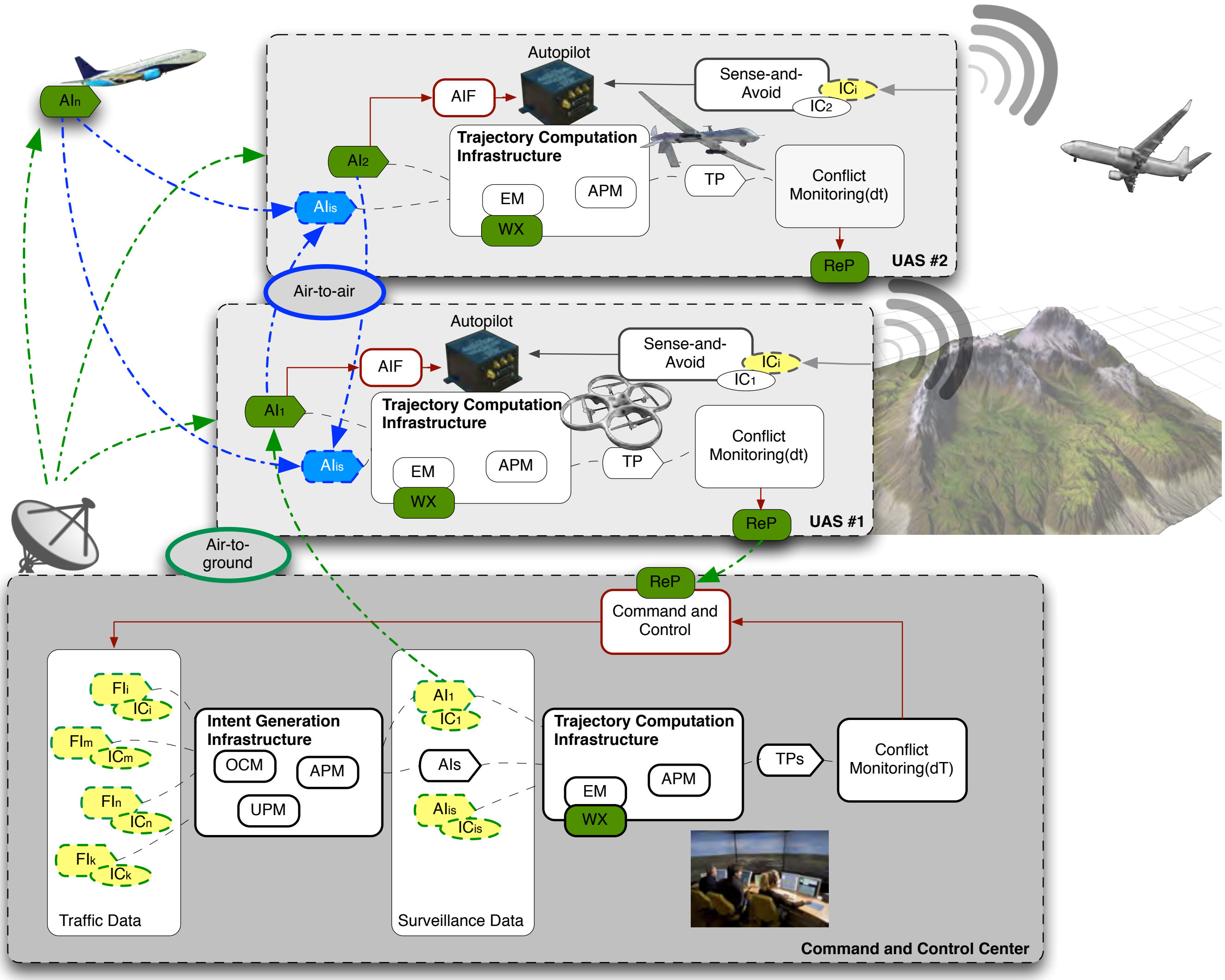

Fig. 8: Flight/Aircraft intent planning data handling with command and control, and intent exhange procedures

operator can create a flight intent sequence (similar to the flight plan) or modify the existing one on-the-fly. Through the data-link, the operator can update flight intent sequence for evolving operational needs. The details of this process are given in the next section. In addition to real-time camera broadcast, the GUI also provides with synthetic vision suite (seen in Figure 7) using synthetic 3D map and earth terrain model. This add-on mode enables operating the vehicle in low visibility conditions such as foggy weathers and even night flights.

III. Intent Based Nominal Operation and Trajectory Planning

Formal intent based planning module is envisioned to integrate effective command and control functionalities, and efficient intent data sharing capability into the unmanned aerial systems through a standardised intent language. This module utilizes two-level formal description languages such as flight intent and aircraft intent. One of the pretty mature formal intent language set, Flight Intent Description Language (FIDL) and Aircraft Intent Description Language(AIDL) are developed by Boeing Research and Technology Europe in order to efficiently synchronise the trajectories between the trajectory planners [10]. In our experimental testbed, a similar but simplified version has been implemented into command and control structure of unmanned aerial vehicle for technological demonstration purposes. These type of languages enable to define an action sequence of the aircraft dynamics (aircraft intent) or a sequence of the flight plan (fligh/mission intent) with different levels of detail, fully or partially specifying some aspects of the aircraft motion and leaving others open for later optimization/specification/planning considering the constraints and the objectives.

The Aircraft Intent (AI) language is a low level formal description employed to model the basic commands, guidance modes or control strategies for managing the aircraft on autopilot level. The AI instructions basically fill each degree of freedom of the mathematical description model describing

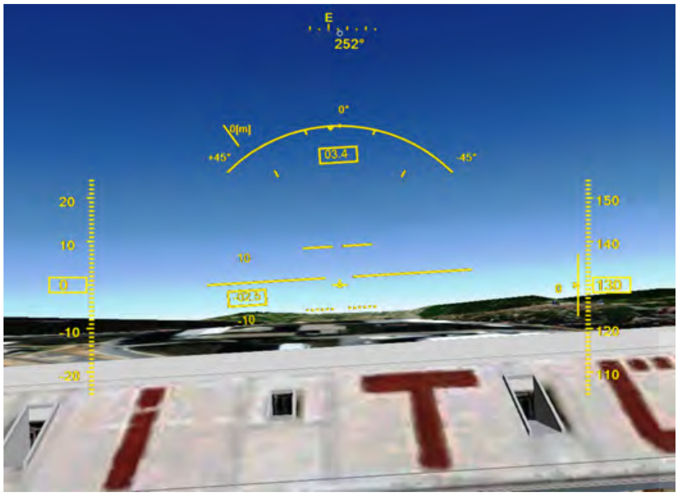

Fig. 7: Synthetic vision screen capture from a real flight.

the aircraft motion. The instructions set including different primitive modes of operation that an aircraft may employ has been derived from a detailed analysis and simulations. Any valid combination of predefined instructions (e.g. Hold Cruise Speed, Hold Altitude etc.) with their specifiers and execution intervals (bounded with end-triggers) describes the motion control objectives of the aircraft which are accepted by FMC of the UAV. The AI language grammar is subjected to set of lexical and syntactical rules in order to create a valid sequence.

The higher level language, Flight Intent (FI) language, is seen as a approximate mission plan of the UAV where the details to be satisfied by the limitations and objectives. A FI sentence provides a high level directions (flight segments or composite AI templates) on how a flight will be operated, and includes operationspecific constraints and objectives. In general, the flight intent does not determine a unique trajectory. A basic example for FI instruction is given in Figure 9 where flight segment primitives defines certain waypoint sequence tracking with their constraints and objectives associated with airspace rules and operational preferences. Flight Segment (FS) instructions may also include additional details about the lower level operation of flight if some aspects of the aircraft behaviour are defined. These are represented by the composites which are the template representation of a set of AI compositions such as *Level Flight, Descent, Level Thrust Deceleration*.

The Figure 8 demonstrates whole data handling processfor theintent based command and control and intent data sharing through the air-to-ground and air-to-air data links respectively. In this structure, mission interpretation and management procedures are handled through FI language that is the higher level language enabling the human operator (operation/mission manager) to easily manage, interpret and modify. The ground based *Conflict Monitoring* and *Command and Control* blocks represent management functions including all autonomous and decision support tools for managing flight operation at tactical level. The *Intent Generation Infrastructure* is a tool introduced in [12] including *Aircraft Performance Model* (APM) and a pair of databases, one storing a *User Preferences Model* (UPM) and one storing an *Operational Context Model* (OCM). The UPM involves the preferred operational strategies directing the aircraft such as the preferences of an mission manager [12]. The OCM involves standard constraints on the use of airspace. The *Intent Generation Infrastructure* accepts a FI sentence (including flight segments, constraints and objectives), and Initial State (IC) as inputs; then processes with UPM, OCM, APM in order to translate into a compatible AI sentence.

The peripherals of the aircraft FMS also includes functionalities enabling similar capabilities of *Trajectory Generation Infrastructure* for trajectory planning and intent based control handling. In addition to routine automated data exchange, any intervention (ReP; replanning request) can be initiated through air-to-grounddata-link when it is needed. The *Conflict Monitoring* functions in both air and ground segment monitor potential loss of separation situation within the prescribed time interval through predicted trajectories (TPs). These trajectories may also include uncertainty factors in a set of parameters (e.g. in aircraft performance, position, weather etc.) and their "what-if" extensions (e.g. considering unexpected behaviours) in a probabilistic manner. The *Command and Control* function operates this intervention from the ground by attaching new constraints or objectives to the pre-planned FIsequencewhen it requires. The textitTrajectory Generation Infrastructure translates updated FI sequence into AI sequence and broadcast to the aircraft.

The aircraft can also request re-planning (ReP) when the on-board *Conflict Monitoring* detects apotential conflict. The AI data sharing is the low-level "machine-to-machine" communication where the autopilot of the UAV can fully understand and execute through the *Automated Intent Flight – AIF*. Similarly, air-to-air intent data exchange procedure is also handled through AI language. In this case, the

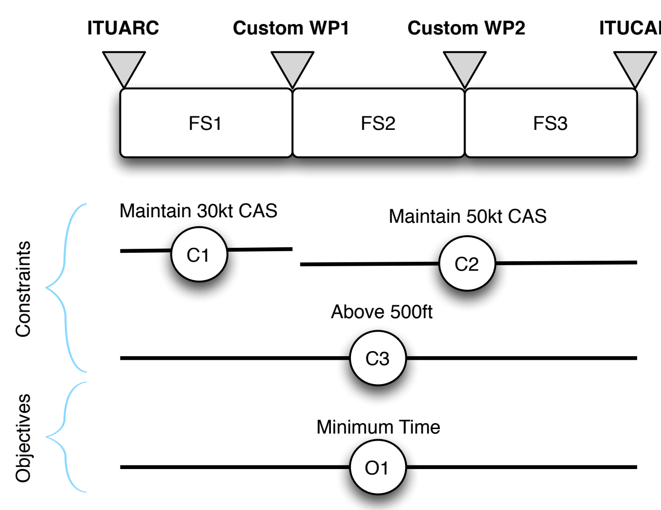

Fig. 9: Example FIDL instance with flight segments, constraints and objectives

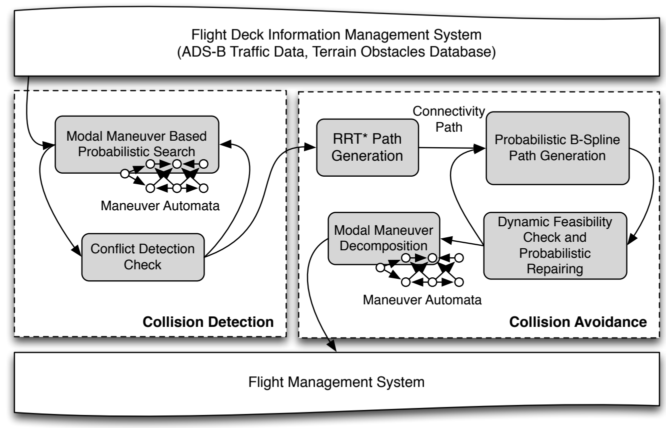

Fig. 10: Funtional architecture of Sense-and-Avoid algorithm

on-board *Conflict Monitoring* blockmonitors the potential conflicts between the predicted trajectories of the aircraft in the surveillance traffic through the *Trajectory Computation Infrastructure*.

The *Trajectory Computation Infrastructure* translates an AIDL sentence into unique predicted trajectory (TP). In this level, it is expected that different trajectory computation tools would result in the same predicted trajectory if they use the same inputs and models such as a) aircraft intent (AIDL) b) Initial conditions (IC) (aircraft state at the initial position and environmental condition at this altitude), c) Aircraft Performance Model (APM), d) Environmental Model (EM), and e) similar trajectory computation algorithms. Event though these premises may not be unattainable in practice, sharing the aircraft intent significantly contributes to achieve partial trajectory synchronization [13].

IV. Autonomous Sense-and-Avoid

The Sense and Avoid module is a decentralised independent safety assurance system in the unmanned system for immediate to short-term collisions with aircraft and terrain objects. This module does not require intent sharing or time-consuming negotiation process, and immediately intervenes when the mid-term separation assurance process fails. Envisioned approach involves recent algorithmic advances based on probabilistic models of aircraft behaviour and information uncertainty in order to improve existing logics of the collision avoidance system.

The sense and avoid module of the UAV uses two types of information; surrounding traffic information and terrain database. *Terrain Obstacle Database* stores spatial model of the earth objects with their locations and heights in certain resolution. The traffic information is obtained from ADS-B (Automatic Dependent Surveillance-Broadcast) transponders of surrounding aircraft. This module enables both ADS-In and ADS-B Out applications where allow data transmission between aircraft themselves and ground segments respectively. This data including a set of GPS-derived states of the aircraft is automatically broadcasted and received through equipped transponder emulators. The hardware emulators of the ADS-B transponders which allow multi-vehicle data communication can be seen in Figure6. For simplification of the implementation, the experimental ADS-B transponders always use exact same operation mode and simplified data structure which is illustrated in Figure 11.

The collision detection algorithm is based on the idea of spatial search phenomena for potential collisions with aircraft and terrain obstacles. This search method relies on the creatingof probabilistic flight trajectory envelopes (for constant time windows) for every aircraft in the surrounding traffic. These envelopes also include uncertainty factors due to the uncertainty in measured position, weather effect and performance models. Trajectory envelope generating process hinges on using multi-modal approach utilising distinct flight maneuver modes can be performed in the short-term domain. This multi-model approach strongly connected with the concept of hybrid systems. The algorithm generates bundle of probabilistic action patterns by sampling finite maneuver mode set and their parameter domains respectively[11]. Through this probabilistic search, this random sampling inherently embeds the stochastic nature of the rational or irrational behaviour of the aircraft (managed by human operator or machine). The Figure 12 was captured during *Collision Detection and Resolution* (CD&R) algorithm running. The Conflict Detection system recursively computes and observes the probability of collisions, and delays to issuing alert until the conflict probability exceeds the predefined thresholds.

The collision avoidance method based on closed-loop planning where theprocess generates an action sequence that minimizes cost by accounting future actions, and update likelihoods upon the new information availability. The algorithm hinges on solving first relaxed forms of the problem and then gradually refining it using the previous approximate solutions. This simplification enables the process to obtain a real-time solutionfor required response maneuver in the order of seconds. In the first step, the algorithm rapidly explores the airspace with a modified version of Rapidly Exploring Random Tree (RRT*) algorithm [14],

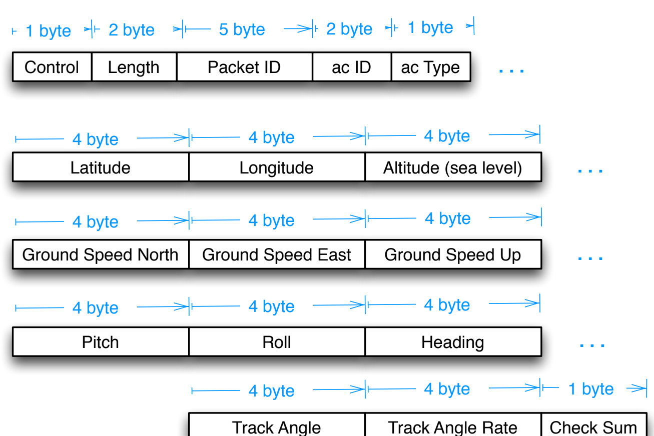

Fig. 11: Simplified ADS-B data structure for traffic information sharing

which generates approximate conflict-free route (ensuring asymptotic optimality). In the second step, this approximate path (including recovery to the original track) is enhanced with the Probabilistic B-Spline algorithm [11] in order to create smoother path. The generated path is further iteratively verified for collision and dynamic feasibility considering dynamic performance model of the aircraft. After obtaining the feasible flight trajectory with executable velocity and acceleration sequence; maneuver decomposition algorithm readily decomposes the flight trajectory into a feasible sequence of maneuver modes primitives and evaluates their flight-specific parameters. The overall functional architecture of the algorithm can be seen in Figure 10. The details of this algorithmic phenomena had been first introduced in the previous work of the authors [11]. The generated modal sequence is then translated into navigation inputs to provide the Flight Management System (FMS) for avoidance maneuver (with its recovery) implementation (as seen in the Figure 8). These avoidance maneuvers including recovery generate small deviations where their impacts on the entire flight route is minimised.

Fig. 12: Running of sense-and-avoid algorithm with probabilistic modal maneuver search

V. Conclusion

In this paper, a multi-mode Flight Management (FMS) structure is presented through the two add-on modules. The collaborative nominal operation module involves collaborative flight operation functions such as intent sharing implementations performed in the tactical level. In this mode, the required response time mostly permits the ground operator to maintain time consuming decision making processes at high-level. Therefore, this module aims to synchronise information with the ground systems and other aircraft through the intent sharing processes by benefiting from formal intent languages (AIDL and FIDL). The air-to-air intent sharing between the surrounding aircraft through the aircraft intent (AI) communication makes unmanned systems to be visible for the other vehicles including commercial aircrafts. This is envisioned to fully integration UAVs into national airspace without segregating. The Sense-and-avoid module incorporates probabilistic methods and monitors probabilities of potential short-term collisions. By considering the required response time, if FMS decides that an immediate response is needed, it immediately executes the generated avoidance maneuver to solve the situation. Through probabilistic search, it embeds uncertainty factors in both aircraft positions (obtained from air-to-air data link) and aircraft actions due to the disturbances. These two modules build a multi-level safety structure in the FSM, where if the sense-and-avoid unit issues an alert, it means that nominal collaborative separation assurance process has failed before. In the nominal operation mode, the operator is provided with real-time camera feed or synthetic vision through ground station GUI. In intent sharing process, the operator GUI allows the operator to modify/update/re-plan the flight plan using flight intent formal language (FI). For test and validation purposes, an experimental FMS hardware has been deployed in a quadrotor UAV testbed; a custom ground station with GUI has been designed; and envisioned operational experiments have been performed.

As the future work, this research aims to improve the introduced algorithms that are amenable to the rigorous certification process implemented and executed by the aviation agencies in the U.S. and in Europe. Regarding uncertainties, errors on GPS based measurement have been considered in the algorithm implementation, but needs to further improved with multi-vehicle communication conflicts. The another future objective is to build a human factor test and evaluation platform to improve the ground operator GUI.

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