An Ontological Approach to Autonomous Navigational Decision Making in Aircraft Systems

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Abstract

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Aircraft systems are becoming increasingly complex, and automation increasingly necessary for safe aircraft operation. Current industry trends are encouraging either a reduction of crew numbers or complete elimination. After surveying the evolution of aircraft automation systems, pilot tasks and situational awareness, we argue that a hurdle to crew reduction is that of autonomous navigation. In this thesis, we put forth an ontology based approach for defining autonomous navigational decision making. The ontology is designed to capture elements representing the environment in which aircraft operate; the “air environment”. An expert system is then programmed and uses the ontology as its knowledge base. Combining the environmental ontology with a second one describing a generic air vehicle, the expert system is programmed to make navigational decisions based on environment, vehicle state and mission. Case studies show the functionality of the implementation, and a validation study demonstrates the feasibility of the solution. The thesis closes by relating it to other research and recently released industry avionics solutions.

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1 Introduction

The history of aircraft automation can be linked to changes in technology, infrastructure and regulation. Innovations in communication and navigation equipment simplified core tasks performed by flight crews. The implementation of these innovations required infrastructure such as air route traffic control centers be built, and necessitated updates in airworthiness, training and operations regulations. A significant impact of automation on aircraft operations has been the reduction of crew numbers, or de-crewing. Technological advances in automated systems have made it possible to reduce the number of crew required to operate a commercial aircraft from 5 in the 1940's to 2 today. A current focus of the aerospace research and development community is to develop enabling technologies for single pilot operations (SPO).

Research concerning single pilot operations does not always support the implementation of a completely un-crewed or autonomous aircraft (excluding remotely piloted aircraft (RPA)). While increased vehicle autonomy is central to SPO, the technological advances are still centered around a "human-in-the-loop" approach. This implies that the air vehicle interfaces with its environment through human perception and decision making. While pilots obtain their situational data primarily through vision, tactile and auditory cues, autonomous vehicles interact with their environment differently from piloted vehicles, with the "machine-environment" interface being the primary difference. Research in support of un-crewed air vehicles and their introduction into a shared airspace must focus on autonomous situational awareness and the interface between the vehicle and the environment in which it operates.

There may be more similarities between autonomous ground and air vehicles than there are between SPO aircraft and autonomous air vehicles. Both need to acquire information about their environment without a human interface, process this information, and implement navigational decisions while maintaining awareness of changes in the operational environment. In fact, the environment in which an autonomous air vehicle operates is simpler than the autonomous ground vehicle environment, with more regulation, more data available and substantially less unanticipated activity. In this research, we demonstrate that given the current state of existing technologies, the difficulty in attaining a safe fully autonomous aircraft lies in obtaining the required design assurance level in the integration of existing technologies, rather than in the developement of new and innovative hardware and software.

This thesis investigates the environment in which air vehicles operate; the data that is currently available to inform the user about the state of that environment; how the data is processed for the human pilot; and how it could be effectively made accessible to an autonomous air vehicle. Validation is provided through case studies developed for an autonomous vehicle operating in a shared airspace.

This thesis is organized in chapters, where Chapter 1 is the introduction. Chapter 2 is a review of the relevant literature that begins in Section 2.1 with a brief history of aerospace vehicle automation and communication/navigation systems. Section 2.2 introduces the concept of "de-crewing" and reviews literature on current research efforts aimed at enabling single pilot operations (SPO). In Section 2.3, the motivation for integrating the un-crewed air vehicle (UAV) into a common airspace is presented, and the tasks to be performed by autonomous technologies for UAV operation are presented. Section 2.4 introduces the topic of situational awareness and how it manifests itself differently for piloted aircraft, un-crewed aircraft and autonomous cars. Situational awareness is discussed in terms of risk, task, information and automation management. Differences between the ground and air environments are highlighted. The navigational decision-making process that follows from situational awareness is presented in Section 2.5, and a number of approaches to the automation of navigational decision-making are presented for the air environment. Section 2.6 introduces the topic of expert systems in aviation and discusses several applications. Chapter 2 concludes with a presentation of the objectives of the study, centered on the use of ontological methods to describe the air vehicle environment, the use of existing data for the purposes of simulating that environment in a systematic manner, and how to use that data for navigation. Chapter 3 presents the methodology developed to define the ontology and build the decision-making system. Chapter 4 discusses how the method is implemented in software, and Chapter 5 presents the results of the software validation through case studies for a number of different flight scenarios. Chapter 6 discusses the research more broadly and Chapter 7 concludes and provides suggestions for future work.

2 Literature Review

2.1 A brief historical background of automation and autonomy in aviation

The concept of “pilot assistance” has existed since the beginning of aviation. In 1898, Sir Hiram Maxim filed a patent named "Improvements in Aerial or Flying Machines" in which he described a system that “counteract[s rolling] by the automatic action of a weighted pendulum which, when the machine rolls to one side, cuts the supply of motive fluid from the motor on the side which is higher and opens wider the supply valve of the motor on the lower side.” [67]. This was five years before the Wright brothers successfully flew their machine in Kitty Hawk, North Carolina in 1903. In 1908, Sir Hiram Maxim published a book named “Artificial and Natural Flight” in which he described a gyroscopic system to keep a flying machine “on an even keel in flight” [66]. These two systems, which maintained the wings level and the pitch constant were refined by Lawrence Sperry who demonstrated their functionality in France in 1914 by standing up, hands on his head in the cockpit while his mechanic walked along the wing, all while the aircraft maintained a straight trajectory [37]. In 1930, a Ford Tri-Motor flew for over three hours on its way to Washington DC automatically, further establishing the feasibility and pilot confidence in autopilots [72].

World War II pushed the need for technological innovation. If bombers and fighters could land in all-weather and black-out conditions, greater operational flexibility could be gained over their opponents. In 1941, Captain Köster of the Luftwaffe made an automatic landing in zero-zero conditions. Tests in Allied B-17 and B-24 bombers also showed promise [52]. By 1959, Bill Lear had developed and matured the F5 autopilot which was capable of auto-landing aircraft including the C47, C54, Convair 440 and the F89/86 [52]. Radio communications and navigation technologies matured in tandem with autopilot systems. Wireless Morse code transmission systems developed in 1911 [39] evolved into systems capable of transmitting voice by radio waves, which could also be used to navigate. In 1930, Cleveland airport opened the first radio-equipped control room, and two years later, the US department of commerce installed 83 navigation radio beacons across the country. In 1936, Newark, Cleveland and Chicago were designated operating Air Route Traffic Control Centers (ARTCC) to control en-route air traffic [71]. These advances in technology and infrastructure were accompanied by corresponding regulations. In 1941, the United States’ former Civil Aeronautics Board issued regulations for type certification of radio equipment [29]. In 1960, the FAA amended Part 20 of the Civil Air Regulations to mandate that private and commercial pilots be trained in “radio communication and navigation procedures” [16].

2.2 De-crewing and Single Pilot Operations (SPO)

As a result of technological advances and the evolution of infrastructure and regulations, the tasks of communication and navigation could be performed by pilots, rendering the communication and navigation flight crew unnecessary [82]. The 1940’s crews of 5 were reduced to 3; a pilot, co-pilot and flight engineer. While the pilot and co-pilot managed the flight, navigation and communication, the flight engineer managed the on-board systems [46]. The Lockheed L-1011 TriStar is often regarded as the culmination of this technological innovation. Its flight control system and autopilot were highly integrated, and in 1978 it became the first aircraft to receive FAA certification for category IIIb Instrument Landing System (ILS) procedures, allowing operators to land with a zero ceiling and in near zero visibility conditions [31, 56]. The Hawker Sidley Trident followed soon after, and in 1979 received its category IIIc approval for zero-zero landings [56].

The Douglas DC-9-80 represents the next step in de-crewing with a reduction from 3 to 2 pilots

[59]. Technological advances were such that much of the systems management task could be automated. The Douglas design philosophy, aimed at reducing crew workload, was that "if you know what you want the pilot to do, don't tell him, do it" [31]. In 1981, the DC-9-80 was certified for 2 pilot operations.

The gradual crew reduction from 5 to 2 was equipment-driven. As improved radios and navigation equipment became available, radio operators and navigators were no longer required. As the computational power of computers increased, management of aircraft systems could be largely automated. Task complexity has been modified and in part reduced to the extent that 2 pilot crews can today fly the worlds most advanced and heavily automated airliners. For example, during a typical transatlantic flight, B777 pilots reported hand-flying for about 7 minutes, and A320 pilots only half that time [64]. Today, a pilot's principal tasks are communicating with ATC, evaluating routings, programming and configuring the aircraft, and managing abnormal situations. In effect, today's pilots manage the flight by delegation [31]. They request actions by programming the aircraft through the flight deck interface, and automated systems are responsible for executing them. This is a human centered approach.

There are compelling commercial reasons to move to air-carrier SPO, particularly for smaller operations where crew costs account for 15% to 35% of direct operating costs [87]. Pilot shortages are another important factor, with Boeing estimating that by the year 2038, the world will need an additional 804,000 qualified pilots [30]. SPO is authorized under FAA's Part 135 but, due to the risk-based approach to certification, the operations are limited in frequency and size of the aircraft in which they can be conducted. High workload situations such as ILS category II and III approaches are also prohibited [8]. A technology recently developed to address the landing minimums is the Enhanced Flight Visual System (EFVS) [19], which enables properly equipped aircraft and trained crews to land and rollout entirely by reference to the EFVS display, without looking out the window. Innovations like the EFVS are important enablers for SPO, which allows a single pilot to accomplish a landing in category IIIc conditions, which otherwise requires two pilots. Part 135 operators may be granted permission [22] by the regulator to use such a system which is currently installed on Gulfstream aircraft [7, 50] certificated for operations with a minimum crew of 2 [27]. A human factors study has shown that the workload using the EFVS is almost identical for a crew of two as it is for a single pilot [62]. This system is poised to be offered as an option on the B737MAX and B787 airliners operated by major airlines around the world [36].

The evolution of de-crewing as established in the literature is founded on technological advances in communication, navigation and systems management. These equipment-based advances are designed to assist the pilots in the accomplishment of their tasks. In contrast, the "un-crewed" or autonomous air vehicle (excluding RPA since a remote human is in the loop) is fundamentally different from any version of crewed vehicle. This research is based on the observation that the technologies required for un-crewed aircraft are different from those for de-crewed aircraft. The requirements for un-crewed flight are centered on the interface between the vehicle and the environment in which it operates, rather than the interface between the pilot and the aircraft. It is observed that the technologies for autonomous flight either exist or are at a mature stage of development. However, research into the technologies for the acquisition and processing of the data necessary to provide a functional interface between un-crewed air vehicles and the environment in which they operate are lagging and are inadequate to enable the safe and effective integration of un-crewed aircraft into a common airspace.

2.3 Unmanned Aerial Vehicles (UAV – i.e. un-crewed aircraft)

UAVs have generated a lot of recent interest, particularly in the Unmanned Air Mobility (UAM) or "on-demand mobility" market. Uber's white paper, "Fast-Forwarding to a Future of On-

Demand Urban Air Transportation" [58] calls for autonomous aircraft operation and has served as the impetus for many novel aircraft designed for the 'air-taxi' mission. Other UAV applications include aerial firefighting, search and rescue, surveying and agricultural applications. For example, if unconstrained by human pilot limitations, firefighting aircraft could operate by night and for longer periods of time [60]. Search and rescue operations would also benefit from the use of autonomous aircraft in much the same way. Regardless of their mission, un-crewed aircraft must be capable of autonomous decision making. According to NASA's autonomous systems taxonomy, autonomy is "the ability of a system to achieve goals while operating independently of external control" [92]. The following terms are defined as follows:

- "external control" is taken to be synonymous with any form of "human pilot"
- "goals" vary along the flight, and are blocks of acheivable actions, which when executed lead to a desired outcome. Goals are further discussed in Sections 3 and 4.
- "system" is an abstraction. It refers to the integration of software and hardware capable of accomplishing goals.

"Un-crewed" is taken to be synonymous with "autonomy". The NASA taxonomy defines four elements of autonomy: situation and self-awareness; reasoning and acting; collaboration and interaction; engineering and integrity. This research presents solutions to the first two in the context of autonomous decision making for navigation; situation and self-awareness, and reasoning and acting. These "navigational decisions" are made as a result of data acquired describing the environment and their assessment in the context of air vehicle mission and performance. For the case study validation presented here, decisions include: adjusting a route for weather avoidance, determining if an airport is suitable for diversion purposes and selecting appropriate published procedures.

2.4 Situational awareness

The FAA's Pilot Handbook of Aeronautical Knowledge (PHAK) defines four risk elements: pilot, aircraft, environment, and external pressures [24]. In the case of autonomous vehicles, the pilot and external pressure elements are not considered. The "aircraft" risk element originates from any parameter relevant to the air vehicle performance capabilities provided by its on-board systems. This includes information such as how long can it fly, how high can it go, how slow can it travel, can it fly through ice, etc. The "environment" risk element refers to the environmental factors that surround the machine including parameters such as the weather, the nearest usable fields, ATC delays, etc. The environment has a direct and non-negotiable impact on how the machine uses its on-board systems to navigate and complete its mission. An example of the non-negotiable nature of the environment is that if the aircraft detects a severity of icing it is not equipped for, then it must react to those conditions.

In addition to the risk elements described above, the PHAK defines risk, task, information and automation management as the factors that combine to create and maintain situational awareness about the aircraft and the environment. In this context, "information management" is the process of acquiring information about weather, airports, aircraft capability, and frames the current and future situation [24]. Given a complete picture of the current flight situation, the risk management process is used to systematically identify hazards and to define the best course of action, which is then put into practice with task management. Tasks are executed by proper management of the automated systems. In reality, the process described above is not linear, and situational awareness involves juggling numerous management items in order to safely navigate the aircraft through the environment.

2.4.1 Situational awareness and autonomous cars

Technologies such as Tesla's autopilot, Uber's self-driving taxis or Alphabet's Waymo taxi service have been under extensive testing, demonstrating the feasibility of autonomous self-driving cars. Like aircraft, self-driving cars require situational awareness in order to safely navigate their environment. A component of information management, referred to as 'perception' by Schwarting et al. [96], deals with interpreting the nature of the objects surrounding the vehicle. A method termed "mediated perception" [32, 96] uses "semantic segmentation", where image pixels are classified as belonging to different classes of objects including cars, pedestrians and street signs. Neural networks identify the object classes, distances, speeds and directions, while an algorithm establishes navigation constraints according to established policies. Using task management, an appropriate path is then planned for the automated systems to execute. The neural networks rely on large amounts of data to generalize semantic segmentation well enough in different environments because the road environment is highly variable. Traffic signs may be partially obstructed and lane painting covered by snow. Pedestrians are all different in appearance and behavior, and no one vehicle, cyclist or building is identical. Manually labeled datasets such as Cityscapes Dataset are used to feed the neural networks with pre-established segmentation data for learning purposes [35]. A second approach, "behavior reflex approach" teaches a neural network to extract steering angles directly from camera images, bypassing semantic segmentation [63] and effectively combining the information and task management tasks. This simpler and computationally lighter approach has been implemented in off-road obstacle avoidance [98] and has been shown to be able to learn the tasks of lane and road following [63].

A second component of situational awareness relates to the smooth integration of self-driving cars into a shared road environment. The algorithms must be capable of deducing other drivers' intentions, and of understanding and abiding by the "unspoken rules" of road etiquette, termed by the research community as "socially compliant driving" [96]. Ulbrich et al. discuss lane changes and merging as a ubiquitous driving task that requires cooperation from at least two vehicles at the same time [91]. Several methods have been applied to address this challenge, including game theory, probability, and machine learning approaches. Lenz et al. [38] apply a Monte-Carlo tree search algorithm to determine the "next best" action for lane changes, while Wei et al. [61] use a probabilistic Markov decision process. Vallon et al. [34] tackle the same issue using machine learning techniques. The common thread between these approaches is that they attempt to make safe decisions in an uncertain environment where no two-lane change situations are the same. For example, vehicles that are expected to yield way may not do so, and algorithms must have the flexibility and level of abstraction required to deal with unpredictable behavior on the part of human operators.

2.4.2 Situational awareness in the FAA National Airspace System (NAS)

Aircraft must also consider a large amount of information about the environment they operate in. Airport information such as runway data, altitude, and navigation and communication frequencies must be known. Departure procedures, waypoints and en route airway information must be available. Air traffic and expected weather along the route are important pieces of information required to establish situational awareness. The FAA regulates the dissemination of information such that essential information is known to pilots. Chart supplements are updated every 56 days [15] and list airport, navaid and airspace information. Notice To Airmen (NOTAM(s)) are used to distribute information not known sufficiently in advance to be publicized by other means [20]. The Coded Instrument Flight Procedures (CIFP) is updated every 28 days and encodes departure, arrival and approach procedures, airway and runway information, etc. A complete list of information coded in the CIFP can be accessed at the FAA website [18]. The Aviation Weather Center (AWC) distributes weather information at regulated intervals to describe weather throughout the United States. Advisory Circular (AC) 00-45 [14] comprehensively outlines all weather services, dissemination intervals and what information is provided. Recent Automatic Dependent Surveillance Broadcast Out (ADS-B) requirements 14 CFR 91.225 and 14 CFR 91.227 [23] provide the air traffic position reporting required to support the FAAs NextGen National Airspace System (NAS), which requires all aircraft in controlled airspace be ADS-B equipped. ADS-B equipment broadcasts aircraft identification, position and trajectory parameters, among many others [44]. Flight plans may be retrieved from online services such as FlightAware.com and data from Enhanced Mode-S [44] or Automatic Dependent Surveillance Contract (ADS-C) can be used to obtain intent data on flight route and expected position at a later time [9, 83].

2.4.3 The Air Environment vs. the Road Environment

The air environment is described by a wealth of data, the content of which is tightly controlled by regulatory authorities. In comparison, the road environment is subject to a greater level of uncertainty and is characterized by unpredictable events that cannot be programmed into a database. Automated systems must be highly adaptive in order to correctly perceive and react to the world around them. Autonomous road vehicles share their environment with cars, pedestrians and other street users in close proximity, so require robust decision making to avoid and cope with unexpected and hazardous situations. Aircraft, on the other hand, have the benefit of Air traffic Control (ATC), which maintains a global picture of all aircraft positions and trajectories to organize and sequence air traffic. Aircraft do not have to deduce the intention of other users of their environment in the same way as autonomous ground vehicles because of the existence of intent data and ATC. Aircraft operations are subject to strict operational regulations under the FAAs Part 91 which dictates Flight Rules including, but not limited to, speed limits, airway and airspace rules, and communications procedures [23]. Under normal (non-emergency) flight conditions this makes air vehicle behavior very predictable because, unlike the road environment, the air environment is a scripted, rule-based space.

2.5 Navigational decision making

To make informed navigational decisions, aircrews must have a mental picture of the flight situation, the aircraft state and the environment in which they are operating. Automated navigational systems have been researched for many years. In 1948, Anast [53] described a system that could configure and navigate an aircraft automatically. Flight was separated into 12 distinct phases; given distance, altitude, localizer and glide path information, the system used pre-programmed values to determine when a flight phase was over to automatically switch to the next one. Aircraft configuration items such as landing gear and flap position were automatically set for takeoff and landing, and performance parameters were automatically updated. A more recent autonomous navigational implementation was described in 2017 by Fallast [4] where an automated emergency landing system was developed and flight tested in a Diamond DA42 aircraft (Part 23 certified). The system is capable of selecting the best landing site when an incapacitated pilot is detected. The site is selected according to a “risk-based approach” and considers environmental elements including distance to airfields, runway dimensions, crosswinds at runways and aircraft endurance. The system correlates aircraft capability (endurance) to the environment conditions to make the safest possible navigational decision, and is capable of not only selecting the appropriate field, but can also fly the full approach and land the aircraft without pilot input. Although the research was focused on the emergency situation of pilot incapacitation, the paper closes by stating that “[a] second future implementation may target the task of flight planning without an emergency situation solely for convenience”, such as flying into a canyon too narrow to turn around, or re-routing flight around hazardous weather.

Meuleau [70], like Fallast [4], focused on aircraft emergency situations and selects the best suited landing field based on risk. The flight trajectory is divided into 4 elements (en route, approach, runway, airport) for which environmental elements are scored based on risk. The "en route" phase considers icing and turbulence, "approach" population density, "airport" emergency services, and "runway" dimensions and surface conditions. Aircraft capability is considered when calculating the best (lowest risk) path. The research described uses a defective aileron as an example to indicate that the aircraft can fly more effectively to the left, making left crosswinds more favorable than right crosswinds, and left turns more favorable than right turns. The algorithm then calculates the best trajectory based on these parameters, "fusing" performance information with environmental information in order to make the best navigational decision. A difficulty mentioned in the paper is that of determining the degraded flight characteristics of the aircraft. McCrink [65] demonstrated this problem is solvable through machine learning techniques. Armanini [88] proposed a belief-desire-intention (BDI) system for detecting ice and deciding on the next best action. His research considered aircraft fuel quantity, current flight conditions, aircraft state/performance and meteorological and atmospheric information. Environmental and aircraft capability information are combined to make a navigational decision based on whether or not the aircraft has the capability of handling the current environmental conditions. These studies have all considered an aircraft centric approach to navigation.

In contrast, Vela [84] used an ATC centric approach to discuss aircraft routing around hazardous weather at and around airports to sequence departing and arriving traffic. His research looks at the problem space in a single dimension where altitude and flight plan are constants and only aircraft speed is variable for the purposes of sequencing aircraft. Kuenz [6] made the case that individual aircraft capability must be considered when routing in order to make efficient use of the airspace, and suggests that ATC could use this planning approach to allow aircraft to share the NAS more cooperatively, thus reducing flight and holding times. Kuenz uses icing as an example and explains that aircraft capable of flight into known icing conditions do not need to be routed around areas of icing, while aircraft with no ice protection do. The case study explains that the way in which ATC sequences aircraft should be a function of their individual capabilities, rather than indiscriminately sequencing them on the same trajectory. These two approaches capitalize on the fact that ATC maintains a global picture of all aircraft in their area.

Though both approaches provide navigational solutions in a broad sense, they differ in what is achievable. The aircraft centric approach allows for system feedback. For example, if icing is detected, an equipped aircraft can activate anti-icing measures to remain on trajectory and adjust accordingly if system failures occur. The ATC centric approach would need prior knowledge of every aircraft profile to know what environmental factors need or need not be avoided on an individual basis, without having the ability to re-plan routings based on on-board system status. This research focuses on the aircraft centric approach, since system feedback is essential to full vehicle autonomy.

2.6 Expert systems in air vehicle autonomous research

A common theme across all the above reported aircraft centric research is a focus on route planning given aircraft capability and environmental conditions. Boskovic et al. [55] propose an architecture to design autonomous intelligent controllers for uncrewed aerial vehicles composed of 5 layers, which communicate with each other:

1. decision-making based on mission
2. environment and system health
3. path planning

4. trajectory generation
5. inner-loop control for monitoring system health.

With the exception of Armanini [88], all of the research presented in section 2.5 assumes that the decision to divert or otherwise alter a trajectory has already been made and does not address point 1 in Boskovic's list.

Decision making tools have recently been proposed by several authors. The Cockpit Hierarchical Activity Planning and Execution (CHAP-E) system by Benton et al. [54] looks at "the problem of real-time monitoring of all phases of flight from takeoff to landing, and providing feedback to the pilots when actions are overlooked or are inappropriate, or when the conditions of flight are no longer in accordance with the objectives or clearance." The system must be aware of aircraft variables such as speed and altitude, and has internal representations of phases of flight describing knowledge about how they should be carried out. The authors study the example of executing an Instrument Landing System (ILS) approach and define rule-based actions to be carried out by the system. Koczo et al. [90] discuss the Traffic Aware Strategic Aircrew Requests (TASAR) Electronic Flight Bag (EFB) which "seeks to identify and recommend candidate trajectory improvements for consideration by the pilot that have higher probability of ATC approval" based on own-ship performance data, route, airspace, winds, traffic, and other environmental constraints. A third implementation is that of MITREs Digital Copilot (DC) [68], which aids general aviation pilots in situational awareness. An iPad implementation follows the flight track, is voice configurable by the pilot, aids in checklist execution and provides pertinent flight information at desired times. For example, when approaching an airport, the system will provide a briefing of the airport environment such as frequencies, runway lengths and weather. Like CHAP-E, the DC must have programmed conceptual knowledge to know when to provide what information to the pilot.

The CHAP-E, TASAR and DC systems described above exhibit behaviors comparable to that of a Belief, Desire, Intention (BDI) agent, a term used in robotics. According to Rao et al. [2] and Fox [57], such agents must first hold beliefs representing what the agent knows about the environment around it. In the case of TASAR, CHAP-E, and the DC, beliefs include wind, airport locations and regions of weather. In the case of CHAP-E and the DC, assumptions on how flight phases differ from each other are also held, reflected by which information the system decides is relevant to the crew. These agents must also have goals or desires which define their sense of purpose. TASAR desires to optimize trajectory, CHAP-E to ensure pilots follow all the appropriate procedural steps, and the DC to make sure the pilot has all the pertinent information at hand and executes procedures at the right time. Finally, the "intentions" constitute how the agent plans on accomplishing its desires. These three systems differ from BDI systems in that they are "human-in-the-loop" approaches and rely on their human operator for execution.

A popular method for planning execution is by production-rule systems. Santorro [33] implements an Erlang framework for robotic control, which serves as an implementation platform for BDI languages [1]. Caesar, the Erlang robot that competed in the Eurobot 2007 competition, is capable of sensing its environment, navigating and accomplishing goals such as picking up trash and placing it in appropriate bins [33]. The Erlang framework uses the ERESYE inferencing engine [33] which is at the heart of the behavior exhibited by the robot. The inferencing engine allows the robot to react to the environment to accomplish its goals by executing rules based on sets of preconditions [3], where rules combine sensory information with goals to produce achievable actions. In this example, production rules not only plan and execute actions, but also characterize the environment around the robot. For example, a rule may specify that if another robot is detected and is in the way, then the action will be to avoid it. A planning algorithm may then be called to determine how the trajectory should be altered to avoid a collision. Another rule may define the knowledge required to know to place batteries in the battery recycling bin, and the leftover lasagna into the compost bin, and not the opposite.

These "production rule" or expert system (ES) reasoning systems have also been used in aviation for planning purposes. HaiQiang et al. [97] identifies the need and discusses the design of a Pilot-Assistant Navigation Expert System (PANES) programmed in PROLOG and PASCAL, capable of "navigation calculation, situation estimation [and] decision-making recommendation". PANES ingests the state of the environment and of the aircraft to assist the pilot in achieving a given plan. A similar system to the EREYSE inferencing engine, the C Language Integrated Production System (CLIPS) [94], has been used for satellite navigation to configure navigation software to achieve desired orbits as well as to determine the current satellite maneuver [95]. CLIPS was also found to work well when used for navigation of an autonomous underwater vehicle (AUV) [93]. Rao et al. [2] describe OASIS, an air traffic management system which uses procedural reasoning built on declarative rules to optimize air traffic throughput in real time. In this case, production rules are used to plan and direct many converging aircraft trajectories.

Expert systems in aviation have also been used in diagnostics. Cochran [48] discusses expert system development for real time diagnostics of fuel and electrical system failures using the CLIPS ES shell. The system was able to accurately diagnose 95% of failures and reconfigure the on-board systems in real time accordingly. Similarly, Long et al. [51] use the CLIPS ES shell to design a fuel system failure diagnostics system for aircraft capable of suggesting corrective actions to human users. Dreyer [89] and Liu et al. [99] have studied the implementation of expert systems for aircraft system diagnostics in general, with the former applying the method to helicopters and the latter to UAVs. Dreyer highlights the fact that such systems work well only if they have organized "interrelated data" to work with. Liu et al. also recognize that the amount and quality of the data fed to an expert system directly impacts its ability to solve problems. In their application, they design a system capable of diagnosing over two hundred different faults.

2.7 Research objectives

The research presented in this thesis is concerned with providing a functional interface between un-crewed air vehicles and the environment in which they operate. The study focuses on methodologies for situational and self-awareness, and reasoning and acting on the part of autonomous air vehicles. The methodologies do not depend on visual, tactile or auditory cues, but rather access data directly describing their environment. Decision-making for the purposes of navigation is accomplished based on data acquired and assessed in the context of air vehicle performance parameters. The study has four main objectives:

1. The development of an ontology to describe the air vehicle and the air environment, suitable for the development of a data-based situational and self-awareness system, independent of human-in-the-loop, auditory, tactile or visual cues.
2. The use of the ontology to develop a software environment that accurately reflects a real-life shared airspace in which an autonomous air vehicle must navigate.
3. The development of an expert system to represent an autonomous aircraft, with generic variables that can be adjusted to represent a range of aircraft performance parameters. The aircraft model will be implemented in, and navigate through, the environment described in objective 2.
4. Validation of the software model and proof-of-concept demonstration using case studies involving a self-aware, decision-capable air vehicle using information from publicly accessible sources.

✈

3 Methodology

Taxonomies and ontologies are means for representing a domain and are used to group different concepts and entities to show how they relate to each other. The principle objective of a taxonomy or ontology is to provide a common, referenceable grouping of entities for the purpose of communicating concepts in a consistently understood manner. A taxonomy can be seen as a simple ontology, where entities are grouped in a hierarchical manner according to categories and sub-categories. A taxonomy classifies objects according to consistent and unambiguous rules, where sub-categories generally define more specific concepts that are of the same type as the main category. For example, “Airbus” may be a category, and “A320” and “A380” may be sub-categories.

An ontology allows for more complex relationships between entities than does a taxonomy. It formalizes a world through the definition of concepts, properties and their relationships to each other [69], and is therefore well suited to define a complex system. To build on the Airbus example, instead of defining separate categories for A320 and A380, a variant property is assigned to the concept “Airbus”, and that variant property may have different values such as “A320” and “A380”. Similarly, “number of engines”, “engine type” or “maximum takeoff weight” are other properties that can be assigned to “Airbus”. In this way, a single concept “Airbus” can be instantiated to define several different kinds of airbus’ without having to redefine the properties multiple times.

An ontology should also describe a domain in such a way that useful tasks can be performed based on that description. In the case of the current research, the domain of interest is the aircraft operational environment, and the ontology is developed as a tool to enable the aircraft to navigate within that environment. For the purpose of defining the concepts and properties, the domain is referred to as the “Air Environment” for the rest of this thesis.

This chapter describes the approach used to create the ontology for the air environment. The approach begins with a taxonomic examination of a typical air environment using a case scenario as described in section 3.1. It is shown that, as the taxonomy becomes larger, the interactions between individual entities are increasingly complex, and the hierarchy is increasingly difficult to maintain. In Section 3.2 the taxonomy is used as the basis for the development of an ontology. Section 3.3 presents the expert system that is used to represent the autonomous air vehicle that will be deployed in the Air Environment.

3.1 A Taxonomy for Defining the Air Environment

A selected case study was used to examine the Air Environment and initialize the development of an appropriate taxonomy to describe the distinct elements from which it is composed. The pipeline inspection flight shown in Figure 1 was used for the first iteration. The blue line in the figure shows the path of the pipeline, as well as the assumed flight path of the inspection aircraft. The flight path crosses both urban and rural areas, and includes several different classes of airspace. The flight begins inland, flies through mountainous terrain and ends beside the sea. In the summer time, a pilot may expect to encounter weather phenomena such as rain, thunderstorms, turbulence, or wind; in the winter, snow and ice are possibilities.

Figure 2 is an example of a simple air environment taxonomy that could be extracted from the elements observed or anticipated during the pipeline inspection flight in Figure 1. The taxonomy has little detail and does not anticipate the relevance of the individual entities to the mission being flown. Nor does it consider the nature of the interaction between the aircraft and the entities that compose the environment. For example, if the aircraft is capable of vertical flight, fields are potential landing sites and therefore relevant to the mission. In the case of a firefighting mission, rivers become relevant because they can be used to replenish water reserves. In this way, the case study is being used as a reference state from which to observe and capture the entities within the domain.

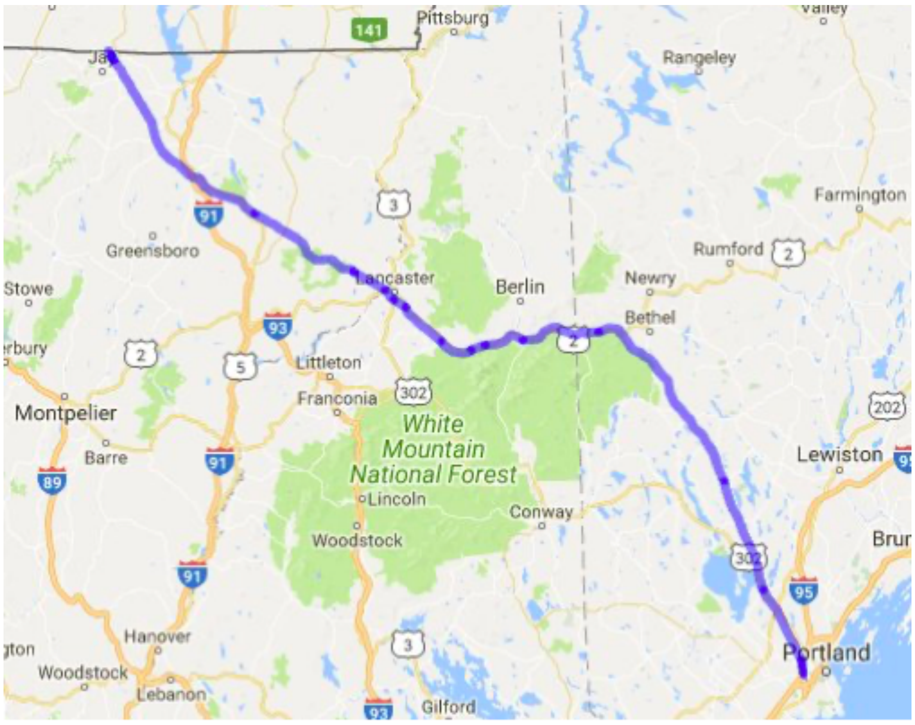


Figure 1: Montreal - Portland pipeline (blue)

The entities depicted in Figure 2 must be combined, forming a complete description of the environment along the flight path at any point in time, for the taxonomy to be useful.

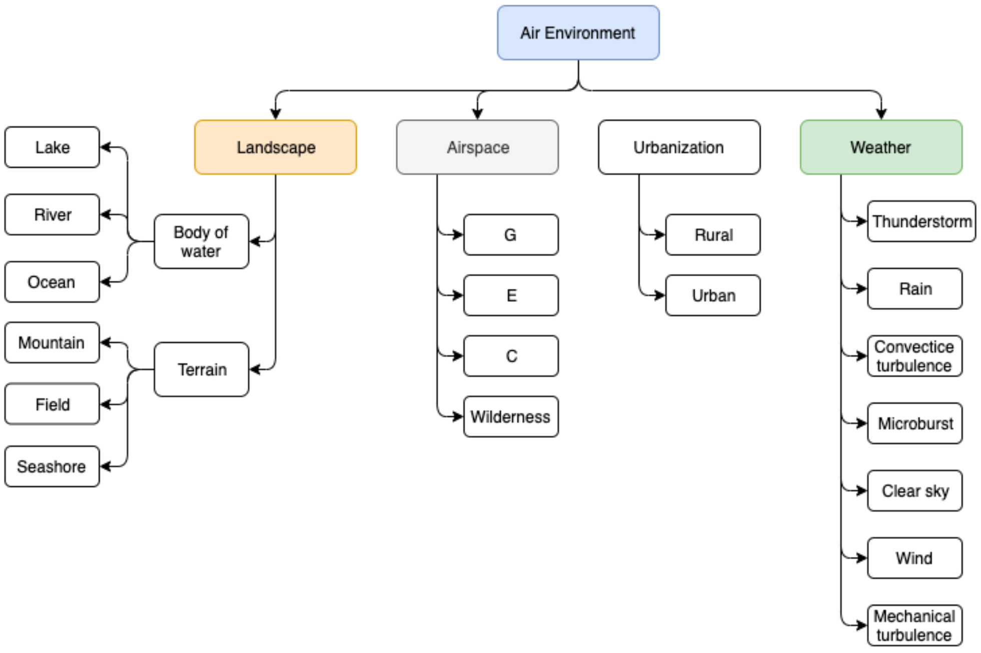


Figure 2: Pipeline inspection Air Environment taxonomy

Figure 3 is an example of the use of the taxonomy to describe environments that may be encountered by the inspection aircraft as it moves along its flight path. The three Venn diagrams in the figure are used to represent different flight environments, where each diagram is associated with a type of airspace. In the case of this example, class G, C and wilderness areas are represented separately, and for each airspace, a set of potential environmental conditions are depicted in the diagram. Each diagram has four possible combinations of environmental entities, each denoted by a letter. Using all possible combinations of the environmental entities listed in Figure 2, several hundred descriptions of possible air environments could be generated.

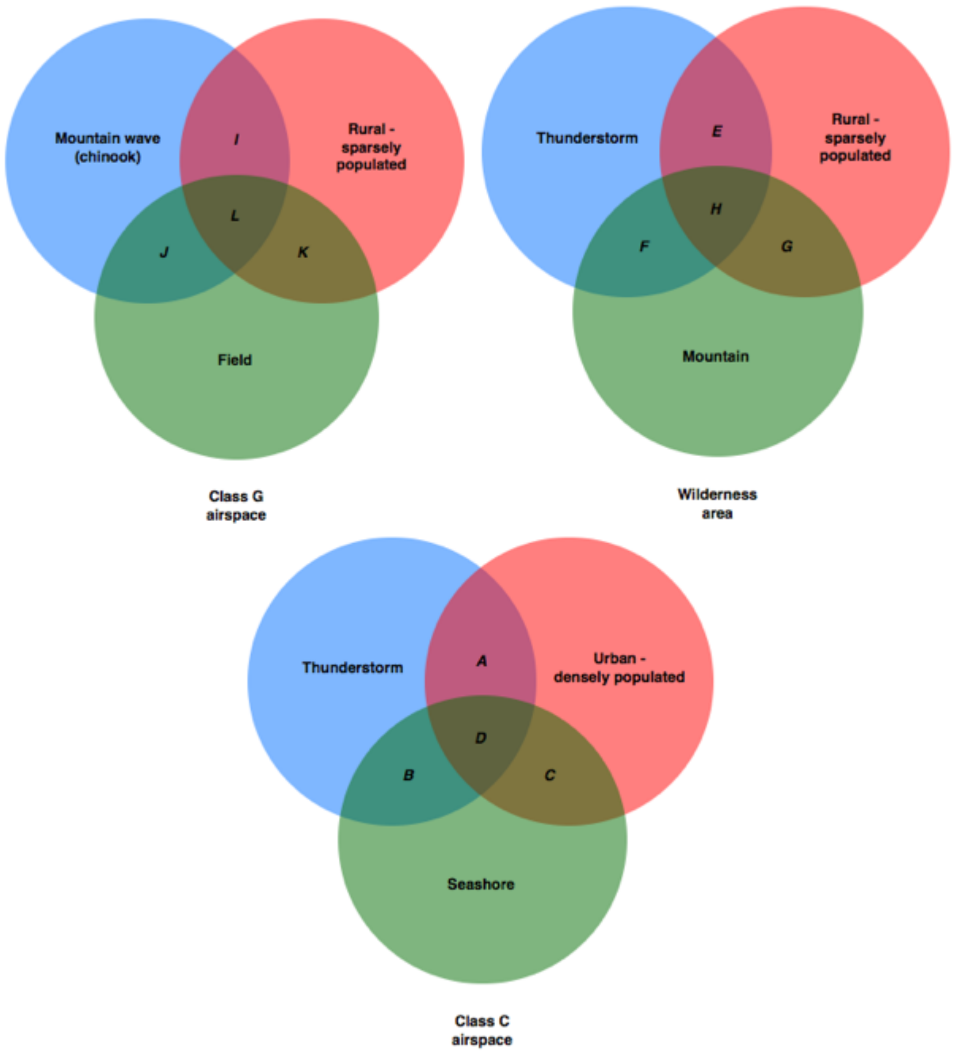


Figure 3: Flight situation Venn diagram examples

The problem with this approach is the difficulty in visualizing the relationships between entities as the number of categories and sub-categories increases. The other difficulty with the taxonomic approach is communicating the relationship between the various entities of the air environment and the air vehicle itself, such as the fact that a helicopter may land in a field while an aircraft requires a runway. In order for the taxonomy to be employed in a useful manner, this relationship must somehow be embedded in the taxonomy itself. For example, the pipeline route shown in a Google Maps setting in Figure 1 is useful for visualizing the route with respect to geographical features such as mountains, rivers and coastline; and urban features such as highways and large urban centers.

In the case where the operator of the aircraft requires more detailed topographic information, visual checkpoints, and information about infrastructure such as navigational aids, airports and airspace boundaries, the map shown in Figure 4 is more representative of the data that needs to be accessed. Produced by the FAA, sectional aeronautical charts are one of the primary navigational reference media used by the aerospace community. They contain topographic and checkpoint information including populated areas, drainage patterns, roads, railroads, and other distinctive landmarks. Aeronautical information on the charts includes visual and radio aids to navigation, airports, controlled airspace, restricted areas, obstructions and related data. The map indicates the geographic limitations of airspace, as well as special use airspaces (SUA) such as military operations areas (MOA). Sectional charts are prepared by the FAA, primarily for use by slow to medium-speed aircraft operating under Visual Flight Rules (VFR) at lower altitudes, and are updated every 6 months. The information shown in Figure 4 is an example of a group of air environment entities that would need to be accessed and their relationship defined for the same Montreal-Portland pipeline inspection mission depicted in Figure 1.

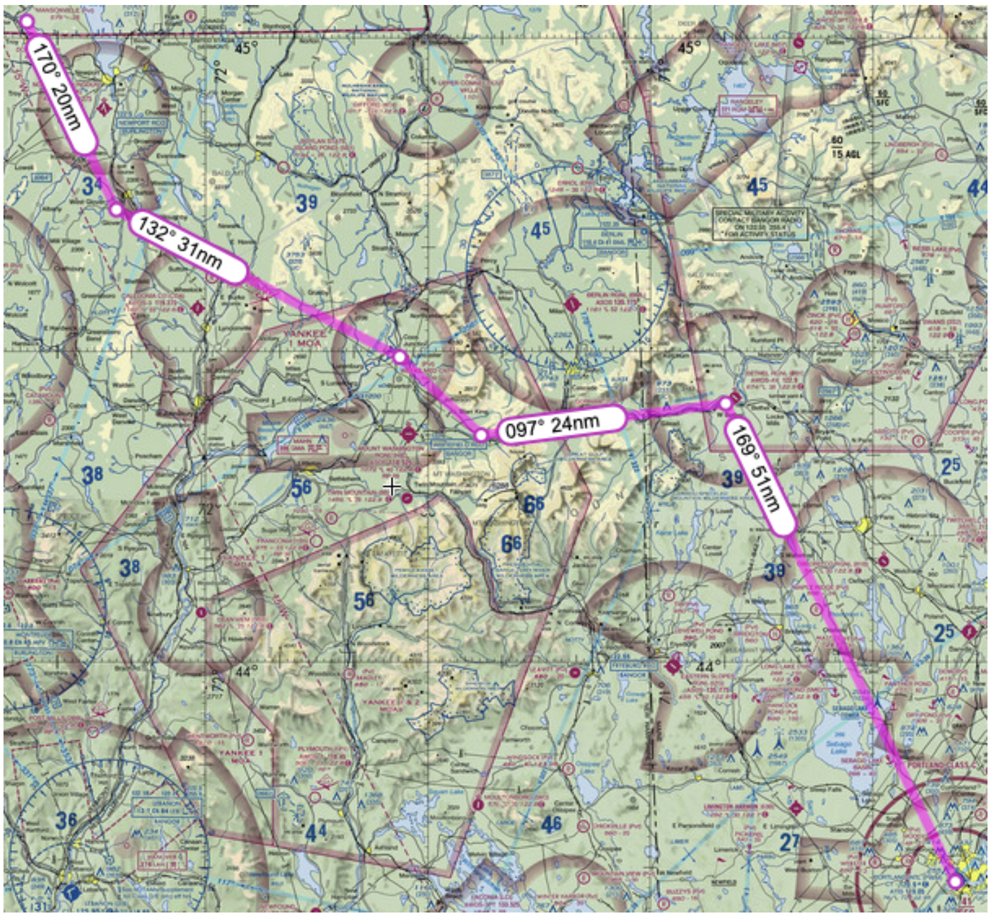


Figure 4: Montreal - Portland pipeline (sectional chart)

While the sectional chart in Figure 4 provides information for the VFR pilot who relies primarily on visual cues, aircraft operating under Instrument Flight Rules (IFR) rely on a different set of data, rather than visual references, for navigation. The En-route Aeronautical Navigation charts are provided by airworthiness authorities such as the FAA in the United States and provide navigational information in the form of data that may be entered into computer-based navigational systems for the purpose of planning and executing flight routes. En-route charts are available in both low and high altitude versions and contain information on radio navigation aids (navaids) such as VORs and NDBs, navigational fixes (waypoints and intersections), standard airways, airport locations and minimum altitudes. Information not directly relevant to instrument navigation, such as visual landmarks and terrain features, is not included. Figure 5 shows the same pipeline inspection route shown in Figure 1 and Figure 4 plotted in the context of a low-altitude en-route chart. The black lines in Figure 5 denoted “Vxxx” are designated Victor routes used for navigation. The routes are analogous to a highway system in the sky. The high-altitude version of the map is used to plot jet routes.

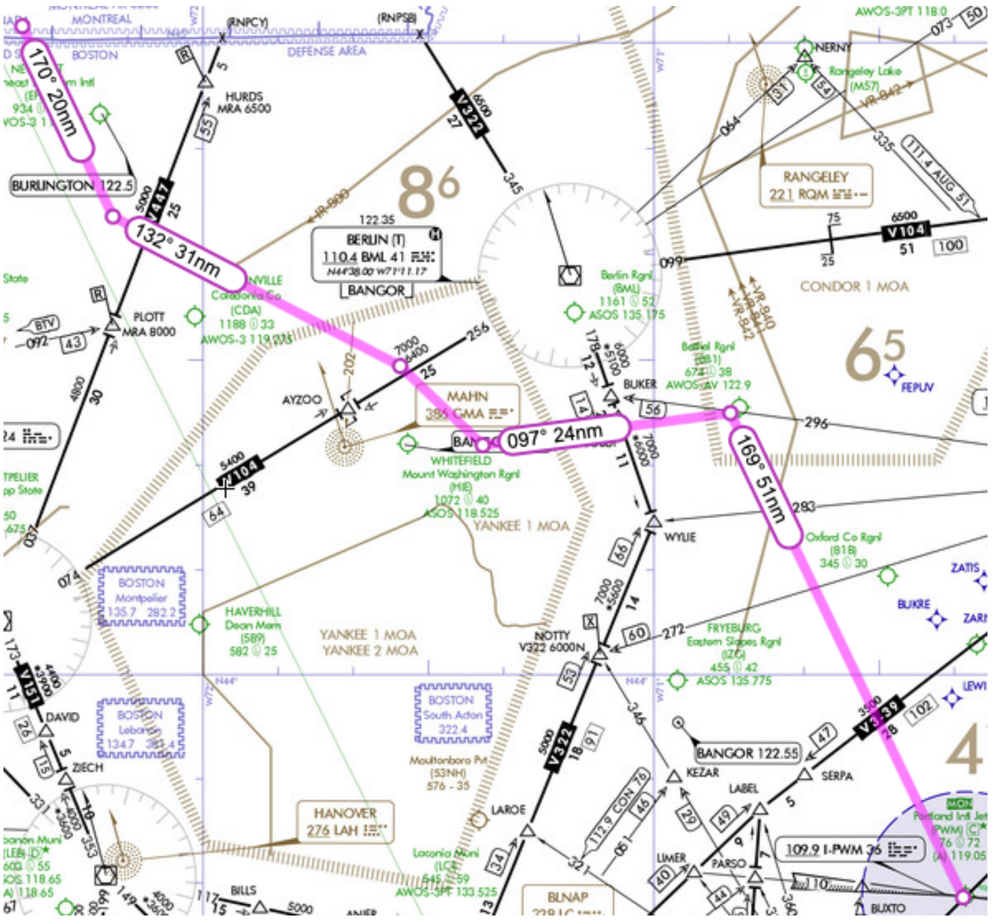


Figure 5: Montreal - Portland pipeline (low altitude en-route chart)

While the taxonomy from Figure 2 could be expanded to include navigational facilities, airfields, ATC and air traffic as shown in Table 1, the result is cumbersome for the stated purpose of communicating a common understanding of the air environment. All three maps show the pipeline inspection route and in a global sense, could be used as a basis for a single taxonomy. In fact, the different maps lend themselves to very specific uses. For example, the map in Figure 1 would be useful to provide information on the routing and length of the pipeline, and its location with respect to major roadways and urban infrastructure for an individual that wished to bid on a contract for the pipeline inspection and was interested in general information regarding the environment. However, an individual wishing to fly the pipeline inspection in an aircraft flying under VFR conditions would find the information provided in Figure 4 more useful for planning and executing the inspection. A third individual wishing to fly a portion of the route under IFR conditions would not find the map in Figure 4 adequate, and would require the data provided in Figure 5 in order to complete the mission. While a taxonomy is adequate to present a hierarchical ordering of entities, it is unable to express complex relationships and does not consider the relationship between the choice of entities and the planned use that is to be made of the information such as flight operations.

The example provided above demonstrates that, while a taxonomy can be used as a general categorization, the taxonomical approach is limited by the hierarchical relationship between cat-

Table 1: Pipeline inspection Air Environment taxonomy

Airspace	Landscape	Weather	Navigational Facilities	Airfields	Urbanization
G	Seashore	Thunderstorm	VOR	Airport	Rural
E	Field	Rain	NDB	Heliport	Urban
C	Lake	Turbulence	VOR/DME	Seaport	
Wilderness area	River	Clear sky	TACAN		
Victor route	Hill	Microburst	VORTAC		
Jet route	Mountain	Wind			
	Ocean				

egories and sub-categories. It is perhaps more appropriate for classification purposes than as the basis for the development of an expert system. As additional sub-categories are defined, the domain representation in Table 1 quickly becomes convoluted and increasingly difficult to interpret. For example, airfields have frequencies, but so do navigational aids, leading to the necessity to define "frequency" at least twice with different definitions and belonging to two different sub-categories. Altitude restrictions are another example. They could be correctly understood as the spatial boundaries shown in Figure 6, where aircraft within those boundaries are subject to specific rules and regulations. On the other hand, in Figure 5, "altitude restrictions" must be interpreted in the context of airways, where they imply obstacle clearance, navigational aid (Navaid) reception, etc. This example demonstrates the contextual interpretation and relationship between the entities in the Air Environment.

Ontologies differ from taxonomies in that they can be used to describe a domain in terms of both content and relationships. Ontologies lend themselves to the description of intricate and complex relationships between entities and are more easily maintainted as the domain they describe evolves over time. The example described above suggests that the taxonomy should be used as the basis for an ontology in support of this expert system development.

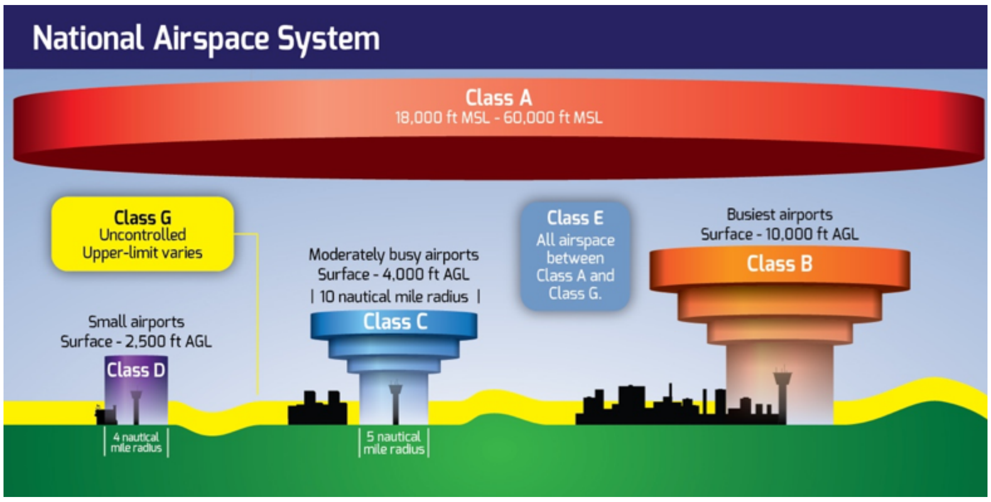


Figure 6: NAS airspace structure [45]

3.2 An ontological approach to defining the Air Environment

A complete description of the environment requires the selection and organization of data describing a large number of entities and the interactions between them. Accessing this data and turning it into useful information is essential to the navigation effort. The methodology proposed in this thesis is an ontological approach to knowledge representation. It is used to structure information for processing by both humans and machines. Although there is no clear consensus on the definition of “ontology”, the research presented here adopts the definition from Kendall and McGuiness [40]:

“The primary reason for developing an ontology is to make the meaning of a set of concepts, terms, and relationships explicit, so that both humans and machines can understand what those concepts mean. An ontology specifies a rich description of the

1. *terminology, concepts, nomenclature;*
2. *relationships among and between concepts and individuals; and*
3. *sentences distinguishing concepts, refining definitions and relationships (constraints, restrictions, regular expressions)*

relevant to a particular domain or area of interest.”

The intent is to demonstrate that, through a precise definition and organization of terms, an Air Environment ontology will define a comprehensive picture of the environment in which aircraft operate. This definition can be used as a foundation for autonomous navigational decision-making in a shared airspace. The study uses a descriptive logic approach where the ontology is specified in terms of concepts (classes), roles (properties or relationships) and instances (individuals). This structure provides a means of accessing and communicating the data that exists within the environment in a form that is useful for expert systems. The terms that are used in the study are defined below:

1. Domain: A subset of “All Things” (ie. the super-class or highest possible level of abstraction). In this case, the domain is the “Air Environment”.
2. Class: A concept in the domain. Classes can be connected to other classes through relationships, or object properties. Classes may also have attributes described by datasets and are called data properties. In an ontology, classes are organized in a hierarchical sub-class/super-class manner.
3. Property: used to further refine class definitions in an ontology. They typically describe the characteristics and features of the members of a class, as well as link that class to others. Properties are divided into two types; object properties (relationships between classes and individuals that are members of those classes) and data properties. Data properties are used for simple attributes that typically have primitive data values (e.g., strings and numbers).
4. Individual: A specific named instance of a class.

The approach to developing the ontology is adapted from Kendall and McGuinness [40] and employs the following steps:

1. Select a subset of a domain, identify use cases and prepare a list of terms;
2. Research existing ontologies/vocabularies to determine reusability;
3. Identify concepts and preliminary relationships between them;
4. Identify and extend concepts in existing ontologies/vocabularies that they are appropriate for our use case;
5. Connect concepts through properties (relationships); and

6. Conduct a basic verification test.

Domain and use case selection

The domain of study is the Air Environment. The ontology produced enables a computer to make navigational decisions in the context of the aircraft mission. For this reason, an additional ontology is added; the Air Vehicle (AV). The Air Vehicle ontology, when reconciled with the Air Environment, provide the necessary elements to make navigational decisions. The use cases are described in section 5. The data properties defining specific class individuals are stored externally in SQL databases and the relationships between all objects is by nature defined in the ontology.

Identifying existing ontologies

The concept of an Air Environment ontology has been considered by a number of organizations. Keller describes NASA's air traffic management ontology, the development of which was driven by a need to "integrate heterogenous forms of aviation data for use in aeronautics research." [86, 85]. It contains concepts that relate to all aspects of the national airspace such as flight information, aircraft and manufacturers, infrastructure, airlines, and NAS facilities. The ontology produced in this thesis builds on Keller's work and maintains a consistent terminology by retaining those concepts relevant to in-flight navigation and removing those that are not.

The European Organization for Safety of Air Navigation (EUROCONTROL), the FAA and IATA have also collaborated to generate industry-wide standards for data interoperability. The goal is to address the increasingly large amounts of data that are becoming available by facilitating communication between data suppliers (for example the FAA or NOAA) and consumers such as pilots and aviation data providers. The collaboration has yielded three different models which can be downloaded for free as XML files: Aeronautical Information Exchange Model (AIXM), Flight Information Exchange Model (FIXM) and Weather Information Exchange Model (WXXM). The AIXM provides data including airspace routes and boundaries, procedures, navaids and airports [41]; FIXM data is related to individual flights [42]; and WXXM provides meteorological information [43]. All three models are highly granular and complex. For the purpose of this thesis, concepts are taken from the AIXM and WXXM, but the terminology is adapted.

Identifying concepts and preliminary relationships

The Air Environment domain maps the concepts describing the environment in which the Air Vehicle operates for the purpose of in-flight navigation. Preliminary classes selected to describe the Air Environment domain include weather, navigational facilities, airfields, airspace, air traffic, terrain, and Air Traffic Control (ATC). The following sections provide a non-exhaustive description of these concepts and class descriptions. The full ontology, complete with all classes, is linked at the end of Section 4.2.

3.2.1 Weather

A survey of all FAA weather Advisory Circulars (AC) was performed to source weather properties for the ontology. AC00-6 [12] provides information on weather phenomena and their mechanisms; AC00-45 [13] on where and when what information can be found; and AC00-30 [17], AC00-54 [25] and AC00-57 [21] provide heuristics on how to detect the possibility of and manage encounters with clear air turbulence, wind shear and hazardous mountain winds, respectively. Based on these documents, the weather class is divided into four sub-classes: icing, precipitation, convection and wind. This subclass selection is meant to represent a high level of abstraction from which many other weather phenomena can be defined. Tables 2 through 5 show the sub-classes, properties, and data sources used to define individuals stored in external databases.

Table 2: Wind Sub-classes

Sub-class ('is-a' relationship)	Properties ('has-a' relationship)	Individual Data Sources
Low level wind shear (LLWS)	has-altitude, -latitude, -longitude	AIRMET T, SIGMET, SIG WX
Surface wind	has-altitude, -latitude, -longitude	AIRMET T
Mountain wave turbulence	has-altitude, -latitude, -longitude	AIRMET T, GTG
Clear air turbulence	has-altitude, -latitude, -longitude	AIRMET T, GTG
Temperature	has-altitude, -latitude, -longitude	FD, METAR/SPECI, TAF
Wind speed	has-altitude, -latitude, -longitude	FD, radar VWP, METAR/SPECI, TAF
Wind direction	has-altitude, -latitude, -longitude	FD, radar VWP, METAR/SPECI, TAF

Table 3: Convection Sub-classes

Sub-class ('is-a' relationship)	Properties ('has-a' relationship)	Individual Data Sources
Convection line	has-altitude, -latitude, -longitude, -probability	CCFP
Convection area	has-altitude, -latitude, -longitude, -probability	CCFP
Cumulonimbus	has-altitude, -latitude, -longitude	SIG WX (mid/high-level)
Cloud top	has-altitude, -latitude, -longitude	SIG WX (mid/high-level), SIGMET
Cell movement	has-altitude, -latitude, -longitude	SIGMET
Thunderstorm	has-altitude, -latitude, -longitude	SIGMET, PIREP

Table 4: Icing Sub-classes

Sub-class ('is-a' relationship)	Properties ('has-a' relationship)	Individual Data Sources
Freezing level	has-altitude, -latitude, -longitude	FD, SIG WX (low-level), SIGMET, AIRMET Z
Severity	has-altitude, -latitude, -longitude	AIRMET Z, PIREP, SIG WX (mid/high-level), CIP/FIP
Probability	has-altitude, -latitude, -longitude	CIP/FIP
SLD potential	has-altitude, -latitude, -longitude	CIP/FIP
Freezing drizzle	has-latitude, -longitude	METAR/SPECI, TAF
Freezing rain	has-latitude, -longitude	METAR/SPECI, TAF
Sleet	has-latitude, -longitude	METAR/SPECI, TAF

Table 5: Precipitation Sub-classes

Sub-class ('is-a' relationship)	Properties ('has-a' relationship)	Individual Data Sources
Rain	has-altitude, -latitude, -longitude, -intensity	Radar, PIREP, METAR/SPECI, TAF
Snow	has-altitude, -latitude, -longitude, -intensity	Radar, PIREP, METAR/SPECI, TAF

3.2.2 Navigational Facilities, Airfields and Airspace

Concepts related to infrastructure are grouped together. Properties pertaining to those concepts are sourced from documents available to pilots, namely sectional maps, IFR low and high en route maps, the airport/facility directory (A/FD) and the terminal procedures publication (TPP). Table 6 provides examples of sub-classes, properties and data sources for the Airport Infrastructure Component class.

Table 6: Airport Infrastructure Component Sub-classes

Sub-class ('is-a' relationship)	Properties ('has-a' relationship)	Individual Data Sources
Airspace	has-Airspace-Area	Sectional chart
Approach	has-Approach-Procedure	TPP
Runway	has-Runway ID	AF/D
Standard Terminal Arrival Route	has-STAR-Procedure	TPP
Standard Instrument Departure	has-SID-Procedure	TPP

3.2.3 Air Traffic and Air Traffic Control

Traffic properties are taken from what can be obtained from an ADS-B Out message. Given the FAA's recent requirements for ADS-B equipment and that the rest of the world is also adopting ADS-B, it is assumed that aircraft will be properly equipped and hence, that the following data is available [44].

Table 7: Air Traffic Class

Properties ('has-a' relationship)	Individual Data Sources
has-Heading	ADS-B Out
has-Callsign	ADS-B Out
has-Time since last report	ADS-B Out
has-Speed	ADS-B Out
has-Altitude	ADS-B Out
has-Vertical speed	ADS-B Out
has-Longitude	ADS-B Out
has-Latitude	ADS-B Out
has-On ground status	ADS-B Out
has-Squawk	ADS-B Out

3.2.4 Terrain

Terrain details are obtained from results of the NASA Shuttle Radar Topography Mission (SRTM), which freely provides topographical data of 30m resolution [28]. Terrain is described as sets of discrete points for which there are elevation, latitude and longitude figures.

3.3 The Air Vehicle

The *Air Vehicle (AV)* is the ontological domain used to describe a generic form of aerial vehicle. In the current study the Air Vehicle ontology is populated with the minimum amount of information necessary for a specific navigational use case in the Air Environment. Two types of classes are specified; systems and system state.

The AV is understood as a "collection of systems", where a "system" is a physical construct that provides a function or collection of functions. The system functionality relates directly to system health or state. Specific examples of generic air vehicle systems and their functions are listed below:

1. The anti-ice system is a collection including pipes, reservoirs (TKS) and pumps that enables the AV to remove ice from the airframe.
2. The flight control system (FCS) is a collection including moveable surfaces and actuators that enables the AV to maintain control.
3. In the case of hydraulically actuated controls, the hydraulic system is a collection including pipes, pumps, and reservoirs, and is related to the FCS.

Each system has properties to describe its functionality, as well as a group of classes to define that functionality. For example, the Class 'TKS anti-ice system' can have subclasses including 'OperationalState', 'FluidQuantity', and 'FluidFlowRate'; and Properties including 'has-OperationalState", 'has-a-FluidQuantity', and 'has-a-FluidFlowRate". These anti-ice system classes, individuals and properties can be used to define the anti-ice system performance of the Air Vehicle in terms of available flight time in icing conditions. Similarly, if an AV is equipped with high lift devices (HLD), the “landing distance” performance parameter depends on the functionality of the HLD.

The anti-ice system description demonstrates how “system” and “functionality” combine to define “performance”, or the ability of the AV to interact with the air environment. Figure 7 provides examples of how system functionality and performance are linked.

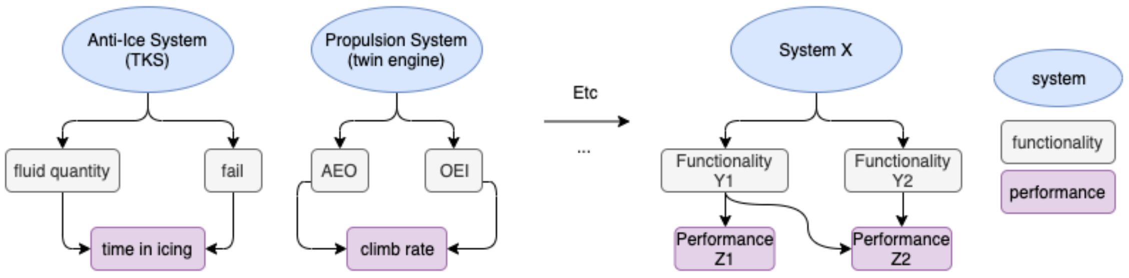


Figure 7: Examples of systems, functionality and state

3.4 Establishing Context

Context frames the goals by gathering all ontological concepts; the AV performance, functionality, and the environment. The first step in establishing context is to determine what is achievable by the AV, which considers both the functionality of the systems and the air environment. This consideration results in a flight mode which reflects the intent of the AV. For example, if the AV is flying in icing conditions and the anti-icing system fails, the intent of the AV is to exit the icing conditions. Flight mode, performance and environment are then combined to determine which actions reflective of the intent should be carried out to navigate the environment. This flow is shown in Figure 8. In the icing scenario, the AV may opt to increase airspeed and climb to exit the hazardous flight situation, or it may choose to do nothing if it is already descending towards its destination. To make these decisions, the AV must consider its available performance. Ontologically, flight modes are described by short expressions such as “avoid ice”, “degraded cruise”, or “diversion”.

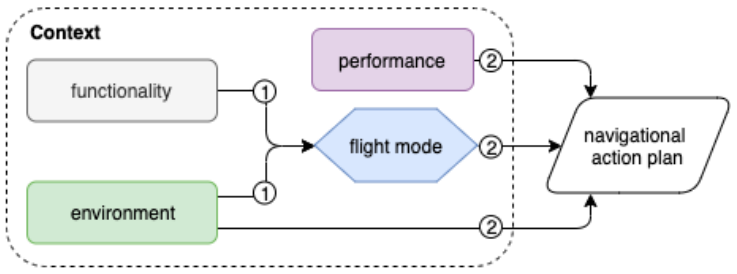


Figure 8: Context

Figure 9 shows an example of a possible icing context and gives examples of the kinds of environmental and performance elements the AV must consider when making a decision. In the context of avoiding ice, there are three possible actions; climb, descend or otherwise alter the trajectory.

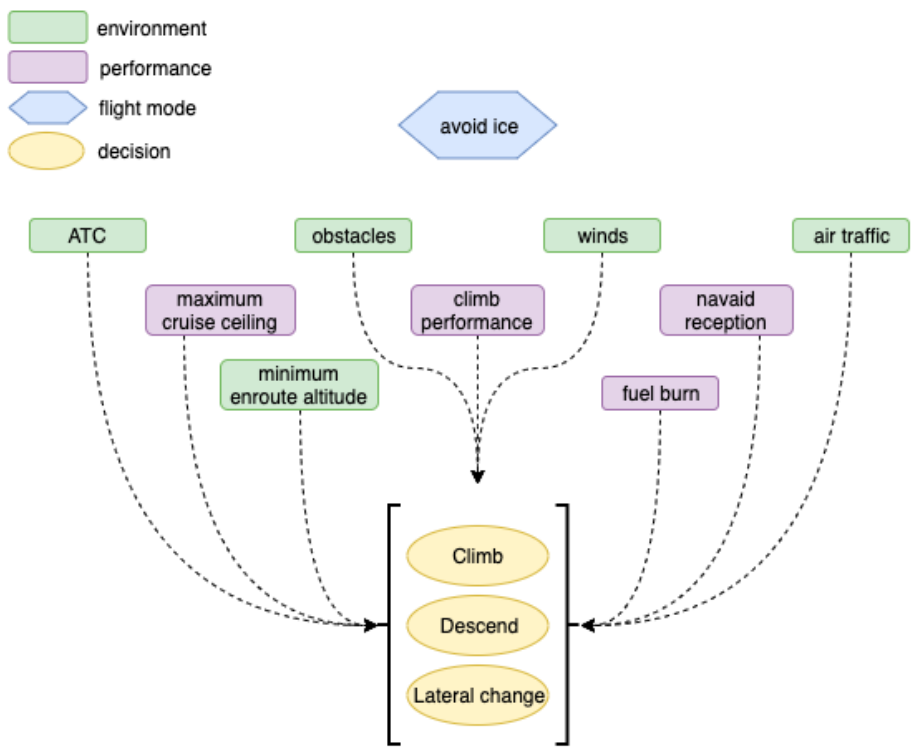


Figure 9: Icing context

3.5 Decision-making

The decision-making process is iterative and considers the environment, the AV, and the flight mode. It aims to determine if the current context is maintainable, or if it must change. The decision-making cycle also recognizes that the state of the environment is a variable that cannot be changed by the AV, it is non-negotiable. The process is shown in Figure 10 and built of three main questions:

1. Given the state of the environment and the flight mode, are the AV systems capable?
2. Given the state of the environment and the state of the AV systems, can the AV systems be reconfigured to maintain the current flight mode?
3. Given the capabilities of the AV systems and the flight mode, how can the environment be navigated?

The following Sections 3.5.1 and 3.5.2 provide examples of how the decision-making process unfolds for two specific scenarios. Section 3.5.1 describes the process for the case of an icing event, and Section 3.5.2 for the case of an in-flight engine failure.

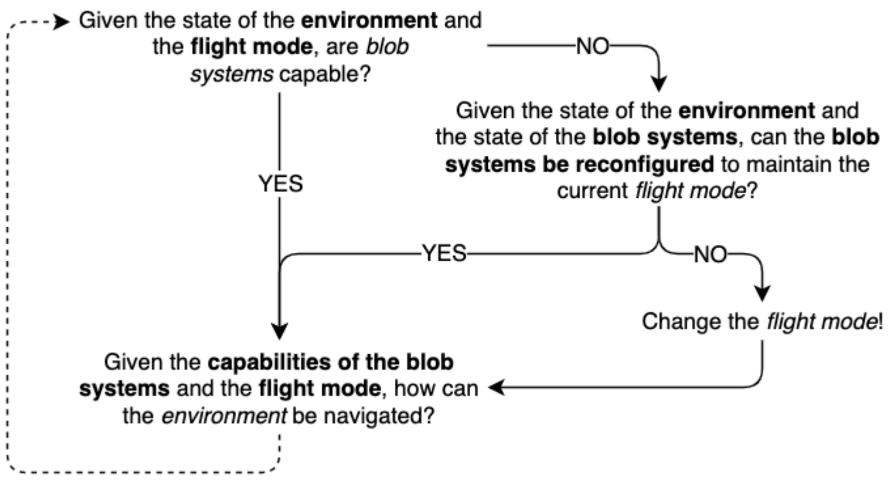

Given the state of the **environment** and the **flight mode**, are *blob systems* capable?
NO
YES
Given the state of the **environment** and the state of the **blob systems**, can the **blob systems be reconfigured** to maintain the current *flight mode*?
YES
NO
Change the *flight mode*!
Given the **capabilities of the blob systems** and the **flight mode**, how can the *environment* be navigated?

Figure 10: Decision making question cycle

3.5.1 Scenario 1: Icing Encounter

The air vehicle is configured as a twin-engine, piston-powered Part 23 aircraft certified for flight into known icing conditions, equipped with a TKS ice protection system.

Initial conditions:

1. The aircraft is cruising at altitude when icing conditions on the planned flight path are detected.
2. The flight mode is “cruise normal”.
3. All aircraft systems are performing normally and the anti-ice system is off.

Iterative decision-making process:

1. Q: Given the state of the environment and the flight mode, are the AV systems capable?
   A:**No**, because icing conditions have been detected and the anti-ice system is off.
2. Q: Given the state of the environment and the state of the AV systems, can the AV systems be reconfigured to maintain the current flight mode?
   A: **Yes**, and the required reconfiguration is to turn on ice protection.
3. Q: Given the capabilities of the AV systems and the flight mode, how can the environment be navigated?
   A: Evaluate how long the TKS system can operate to determine range on TKS. If insufficient fluid is on-board to traverse region of icing, then find a new altitude, alter the route, fly faster, etc. . .
4. Return to step 1.

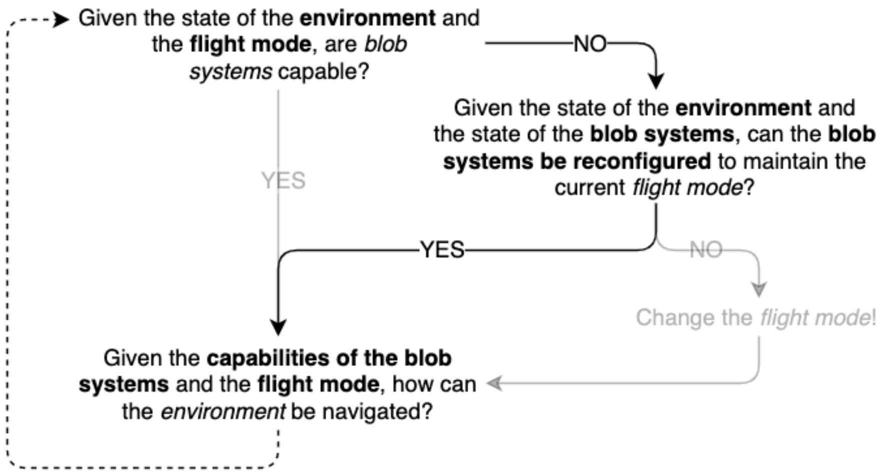

Given the state of the environment and the flight mode, are blob systems capable?
NO
Given the state of the environment and the state of the blob systems, can the blob systems be reconfigured to maintain the current flight mode?
YES
YES
NO
Change the flight mode!
Given the capabilities of the blob systems and the flight mode, how can the environment be navigated?

Figure 11: Icing encounter question flow

3.5.2 Scenario 2: Engine Failure

The air vehicle is again configured as a twin-engine, piston-powered Part 23 aircraft certified for flight into known icing conditions, equipped with a TKS ice protection system.

Initial conditions:

1. The aircraft is cruising at altitude when an engine failure is detected.
2. The flight mode is “cruise normal”.

Iterative decision-making process:

1. Q: Given the state of the environment and the flight mode, are the AV systems capable?
   A: **No**, because an engine has failed
2. Q: Given the state of the environment and the state of the AV systems, can the AV systems be reconfigured to maintain the current flight mode?
   A: **No**, because the engine cannot be restarted. Decide to change the flight mode to “degraded cruise” and “divert”.
3. Q: Given the capabilities of the AV systems and the flight mode, how can the environment be navigated?
   A: Find the nearest suitable field and fly to it.
4. Return to step 1.

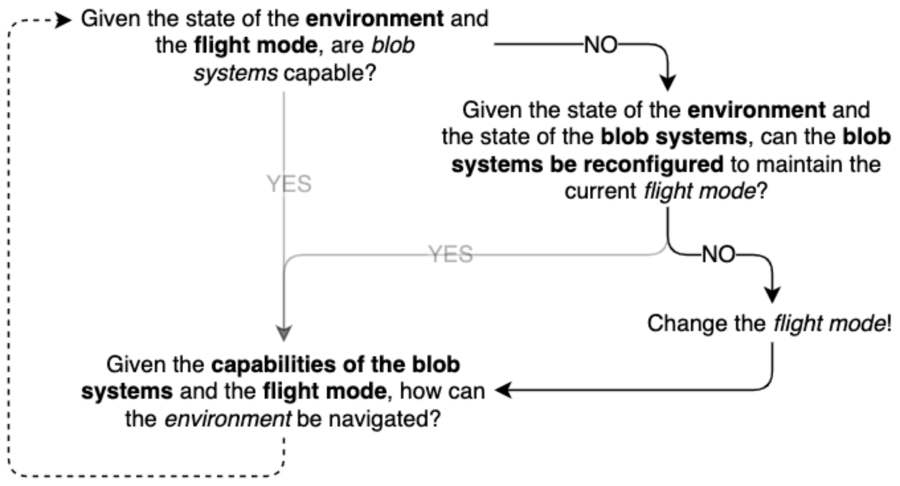

Given the state of the environment and the flight mode, are blob systems capable?
NO
YES
Given the state of the environment and the state of the blob systems, can the blob systems be reconfigured to maintain the current flight mode?
YES
NO
Change the flight mode!
Given the capabilities of the blob systems and the flight mode, how can the environment be navigated?

Figure 12: Engine failure question flow

4 Implementation

4.1 Ontology

The ontology was implemented in Protégé (Stanford University, USA), a free open-source platform for opening, building and visualizing ontologies. Its ability to open a wide array of formats, and user-friendly interface lends itself well to quick development. Protégé can also be used to open existing ontologies such as AIXM and NASA ATM to better understand how they are constructed. A final ontology was built for the purpose of navigation in the air environment.

The ontology in Figure 13 contains the following classes; *Environment, FlyingBlob (the AV), TimeSlice*, and *Value*. *TimeSlice* introduces the concept of time, necessary because the state of the air environment depends on time. *Weather* is highly dynamic since conditions are constantly changing, and even though the airspace infrastructure changes slowly, it does change over time. For example, airports may extend runways or navigational aids may be taken out of service. *Value* is added as a mechanism to create sequential or non-sequential groups of elements. For example, airport weather reports can at times report sequences of cloud layers. *Value* is used to group them together into a single sequential element. This helps keep the ontology organized.

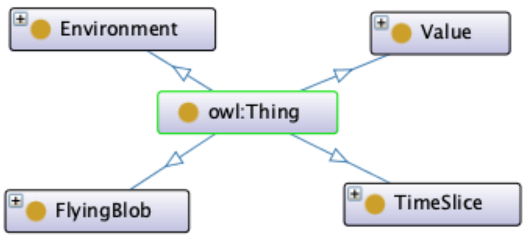


Figure 13: Ontology high-level concepts

4.1.1 The Environment

The environment is divided into terrain, National Airspace System (NAS), weather, air traffic and regulations as shown in Figure 14. A Regulations concept is included because the air environment is a regulated domain and depending on the context, aircraft decisions depend on what is permitted by operational regulations. The NAS concept groups sub-classes including airports and airspace.

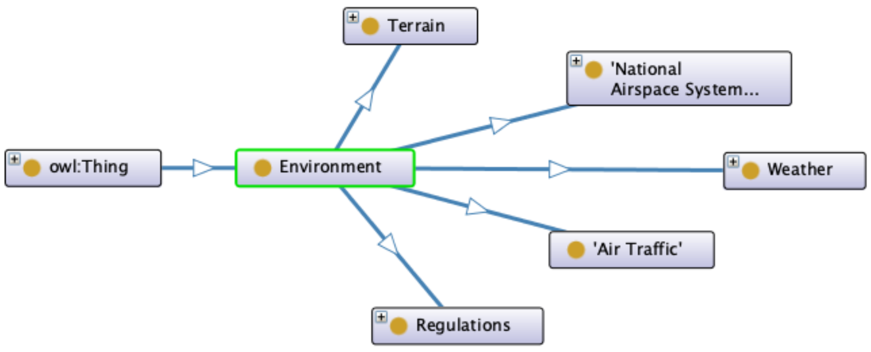


Figure 14: Environment concepts

4.1.2 The Air Vehicle (aka FlyingBlob)

The air vehicle is defined by several sub-classes depicted in Figure 15. *Performance* and *SystemHealth* are related in that performance depends on the state of the systems. For example, an aircraft which has a failed engine will not climb as well as if it had all engines operating. *Route* represents the air vehicle's flight plan. Air routes, airports, waypoints and other such information are contained in the Route class. *Blobaroo* is an instance of the *FlyingBlob* class, and defines concrete values for performance, route, mode and system health that are specific to *Blobaroo*.

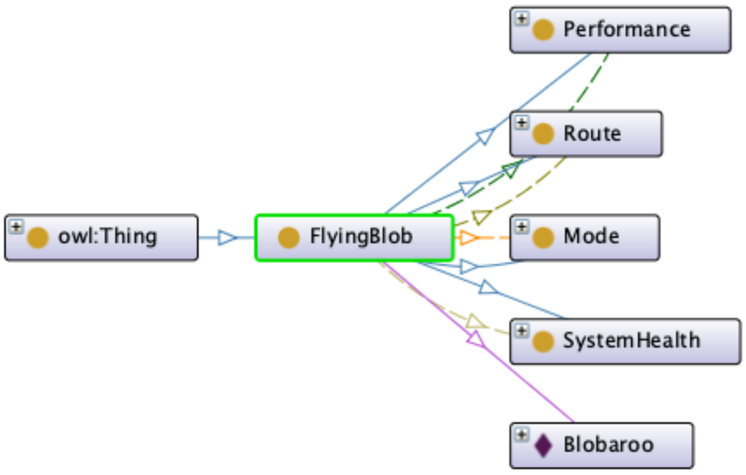


Figure 15: Air Vehicle concepts

4.2 The Route Class

This section describes the route class to explain how the ontology is implemented in Protégé, which uses properties to define relationships between classes. Data properties are used to specify allowable class property values. This mechanism builds the ontological web.

Further expanding Route reveals the following object properties, shown in Figure 16 by dashed arrows. The object properties connect other classes to the Route class. Object property relationships are denoted by <>.

1. <hasPlannedArrivalRunway>
2. <hasPlannedSID>
3. <hasPlannedSTAR>
4. <hasPlannedApproach>
5. <hasPlannedArrivalAirport>
6. <hasPlannedDepartureAirport>
7. <hasPlannedDiversionAirport>
8. <hasPlannedRoute>
9. <hasPlannedDepartureRunway>

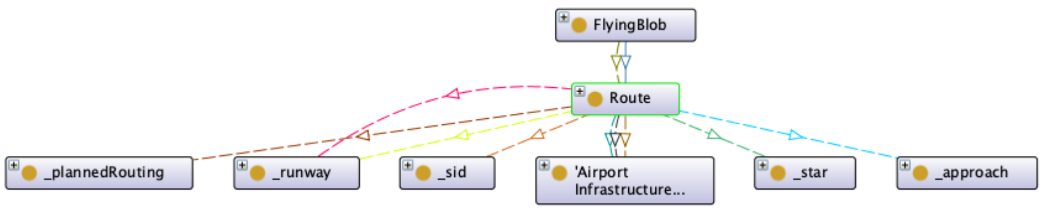


Figure 16: Route object properties

Inspecting the _runway object reveals the following:

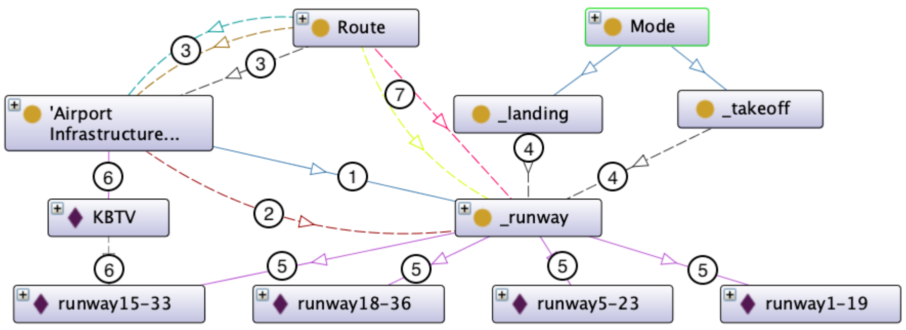
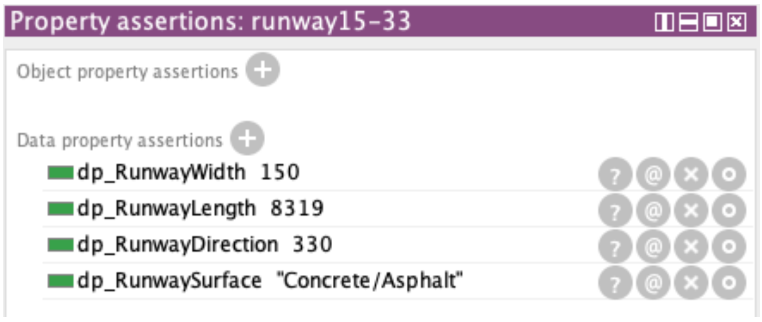


Figure 17: Runway object

1. _runway is a subclass of Airport Infrastructure Component
2. Airport Infrastructure Component <hasRunway >_runway
3. Route <hasPlannedDepartureAirport>, <hasPlannedArrivalAirport>and <hasPlanned-DiversionAirport>which are of class Airport Infrastructure Component
4. Flight modes _takeoff and _landing <hasActiveRunway>_runway
5. _runway has 4 defined instances (purple diamonds); runway15-33, runway18-36, runway5-23 and runway1-19
6. Airport Infrastructure Component has an instance KBTV which <hasRunway>runway15-33
7. Route <hasPlannedArrivalRunway>and <hasPlannedDepartureRunway>which are of class _runway

Class instances are referred to as individuals (or objects). Each runwayXX-XX individual is a concrete definition of a runway in the domain. For example, runway15-33 is defined by the following data properties: dp_RunwayWidth, dp_RunwayLength, dp_RunwayDirection, dp_RunwaySurface. All data properties are prefixed by “dp_”.


Property assertions: runway15-33

Object property assertions

Data property assertions

🟩 dp_RunwayWidth 150

🟩 dp_RunwayLength 8319

🟩 dp_RunwayDirection 330

🟩 dp_RunwaySurface "Concrete/Asphalt"

Figure 18: runway15-33 object data properties

The complete ontology can be viewed here:
http://www.visualdataweb.de/webvowl/#iri=https://sigur.ovaltofu.org/paul.public/website/environment.owl

4.3 Databases

Before implementing the concepts previously listed (weather, navigational facilities, airfield, airspace, air traffic, terrain, ATC, Air Vehicle), internet searches were performed to determine what data are openly available. Results of those searches indicate that the United States provides many data. The implementation is however not limited to the United States, as long as data from other countries is available. Data describing the United States is taken for the study because it is plentiful and easily accessed.

The following tables list the associated data sources. This list is not exhaustive, and pools links from the National Oceanic and Atmospheric Administration website, since it is open access and easily accessible.

Table 8: Weather Data Sources & Formats

	Icing	Wind	Precipitation	Convection
CIP/FIP	GRIB 1 [73]			
Airmet Z	BUFR [74], XML [81]			
Sigmet	BUFR [75], XML [81]	BUFR [75], XML [81]		BUFR [75], XML [81]
PIREP	XML [81]	XML [81]		XML [81]
Sig Wx	BUFR [75], XML [81]	BUFR [75], XML [81]		BUFR [75], XML [81]
TAF	XML [81]	XML [81]	XML [81]	XML [81]
METAR	TXT [76], XML [81]	TXT [76], XML [81]	TXT [76], XML [81]	TXT [76], XML [81]
GTG		GRIB 1/2 [73]		
Airmet T		BUFR [77], XML [81]		
Radar		BIN [78]	BIN [79]	
CCFP				TXT [80]

Table 9: Weather Data Sources & Formats

	Navigational Facilities	Airports	Airspace
Airports		JSON [10]	
Runways		JSON [26]	
Routes			JSON [11]
CIFP	ARINC 424-18 [18]	ARINC 424-18 [18]	ARINC 424-18 [18]

The CIFP is entered as a row of its own because it contains many data. Listing them individually would be too exhaustive.

Air Traffic data is obtained from the ADS-B Exchange website [44], which provides a python API. The API returns traffic data in JSON format.

SRTM terrain data is downloaded as a binary data file. Each file carries discrete points for a 1 degree of latitude by 1 degree of longitude tile. Each file contains a series of 16-bit integers giving the altitude of each cell. Each tile is separated into a grid of 3601 by 3601 cells for a total of 12967201 cells. Each 16-bit integer can then be associated to the correct latitude and longitude, since the coordinates of the first cell is known.

Since the data come in seven different formats, Structured Query Language (SQL) databases are coded. This not only unifies all data into one format but is also useful to efficiently search for data.

Data is coded into four distinct databases: CIFPRev12.sqlite, environmentRev8.sqlite, IcingRev3.sqlite and srtm3.sqlite. Each database contains tables that each contain data describing the air environment. Table 10 lists what SQL tables are contained in each SQL database.

Table 10: SQL Databases

CIFPRev12.sqlite	environmentRev8.sqlite	IcingRev3.sqlite	srtm3.sqlite
Airspaces	airfields	IcingInfo1	N44W073
AirwayRoutes	airports	IcingInfo2	N44W073_LR_1in10
Approaches	runways	IcingInfo3	N44W073_LR_1in3
Runways		...	N44W073_LR_1in50
SIDs		...	N44W074
STARs		...	N44W074_LR_1in10
Waypoints		IcingInfo30	N44W074_LR_1in3
			N44W074_LR_1in50

Notes:

1. Airfields and airports are different from each other because the “airfields” table does not contain any runway information. “airports” table combines “airfields” and “runways”
2. IcingInfoXX contains icing information for 1000 feet increment. For example, icing information at 3000 feet is contained in table “IcingInfo3”
3. NxxWxxx contains topographical information for a tile of 1 degree latitude and longitude. LR abbreviates “low resolution”, and 1inX means the table in question contains 1 in X points from the original table. For example, N44W073_LR_1in50 contains 50 times less points than N44W073. Certain flight modes may require a certain resolution. For example, an aircraft on approach needs access to high resolution terrain data, while one cruising at 30000 feet may not need any at all.

4.4 Programming Implementation

Python is the programming language used to integrate the different program components. It is used as the interface to join CLIPS, SQL and OpenGL. The CLIPS python binding CLIPSPy brings CLIPS 6.30 capabilities into the program and is used as the expert system shell. OpenGL runs a graphical interface to display the data in real time, and SQL stores and provides an interface to quickly query the data.

Since most of the data queries are geographical queries, a means to quickly search 3D space is needed. Operations to determine icing severity around the AV within a certain radius at a certain altitude, the locations of nearest airports, or if the AV is in a given type of airspace are examples of computations that need to be efficiently calculated during short time intervals. SpatiaLite [5] is an open-source library intended to extend the SQLite core to support spatial SQL capabilities, and is seamlessly integrated into SQLite. SpatiaLites' spatial computational abilities depend on geometries, which exist as BLOBs (Binary Large OBject) in SpatiaLite terminology. For that reason, several SQL tables in the databases described above have BLOB columns. The data contained in those columns are repackaged human readable data (latitude, longitude and altitude) into the binary format required by SpatiaLite.

4.4.1 The Python Route Class

Pythons object-oriented programming paradigm lends itself well to recreating the Protégé ontology.

To compare the Protégé ontology with the python class structure, this section looks at how the Route class is implemented in python code. The Route class is defined by properties and instance methods. The properties are the python analogues to the Protégé <has_>possessives. The instance methods provide a mechanism to build the individuals and their possessive links at runtime.

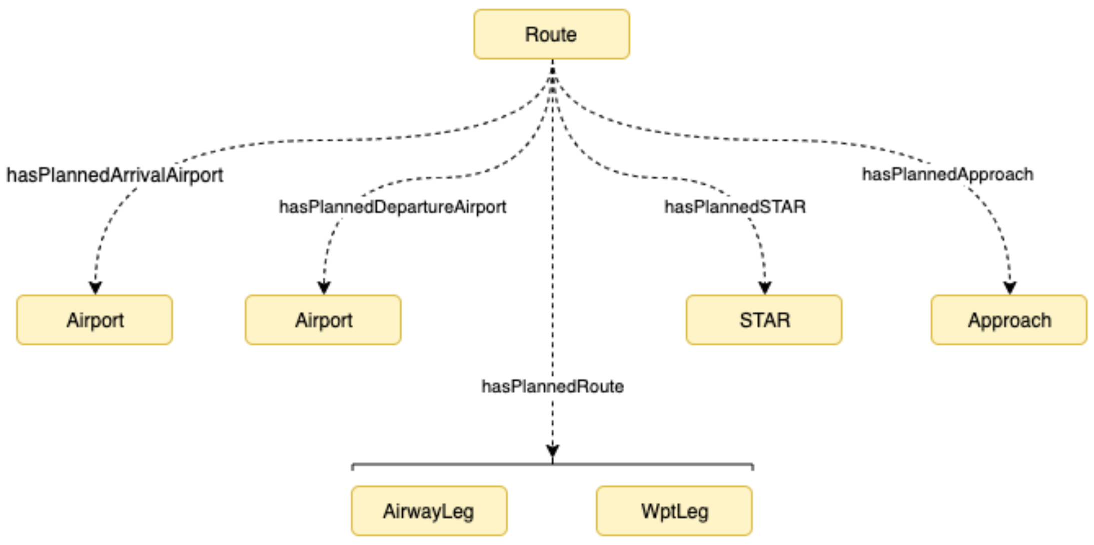


Figure 19: Python route class

The Python Route class contains many of the Protégé possessives. The following differences are noted and explained:

1. Missing <hasPlannedDiversionAirport>. Though the object structure does not explicitly include one, the python implementation includes a function that searches for the nearest usable diversion field when one is required. The criteria for a field to qualify as usable are context dependent, and rely on required landing distance, fuel range, wind, etc. Since the program only uses a diversion airport when it is required, it is not included in the object structure. This is a design choice, and it would have also been acceptable to provide it a placeholder in the Route object structure.
2. Missing <hasPlannedSID>. Standard Instrument Departures are left out because the SID data in the CIFPRev12.sqlite database have not been formatted into SpatiaLite BLOBs.

3. Missing <hasPlannedDepartureRunway>and <hasPlannedArrivalRunway>. It is redundant to include runways in the Route object since the STAR and Approach objects specify the selected arrival runway as a property. Therefore, Table 11 marks <hasPlannedArrivalRunway>as included, even though it is not shown in Figure 19.

4. <hasPlannedRoute>_plannedRouting is implemented by AirwayLeg and WptLeg classes. Both objects build route legs along airways or a succession of waypoints, respectively.

Table 11: Route Object: Protege vs. Python

Protégé	Python
<hasPlannedArrivalRunway>	✔
<hasPlannedSID>	✘
<hasPlannedSTAR>	✔
<hasPlannedApproach>	✔
<hasPlannedArrivalAirport>	✔
<hasPlannedDepartureAirport>	✔
<hasPlannedDiversionAirport>	✘
<hasPlannedRoute>	✔
<hasPlannedDepartureRunway>	✘

Each class has methods to build the object properties during initialization, and to modify them at runtime. For example Route has a method called "buildAirwayLeg". By calling "buildAirwayLeg(["MPV", "V447", "PLOTT"])", the function searches the CIFP database for all points along victor route 447 starting at MPV and ending at PLOTT. All other objects in the python code follow a similar methodology.

4.4.2 CLIPSPy – A Python CLIPS Binding

CLIPSPy is central to the decision-making process. It depends on an internal representation of the environment, the *knowledge base*, which is distinct from the Python object structure. The knowledge base is made up of facts and rules which define what CLIPS knows as "true" about the world, and what to "do" given a state of truth. Since environmental parameters such as Routing and weather are stored in Python objects, python listeners are used to detect changes in environment state, so that the CLIPS internal representation (facts) can be updated accordingly. This ensures that the CLIPS knowledge base identically mirrors the Python object individuals. For example, if the next active waypoint in the Route object updates because the AV has sequenced to the next point in the flight plan, listeners update the CLIPS knowledge base to reflect the change. Additionally, because navigational decisions are made by CLIPS but are executed by python, listeners are also used to determine what navigational action plans need to be performed by python given a CLIPS truth state. The CLIPSPy binding makes this seamless. Finally, all AV system configurations are managed internally by CLIPS. Figure 20 visualizes this method.

Figure 20 shows that:

1. The CLIPS knowledge base Weather knowledge listens for changes in weather data

2. The CLIPS knowledge base Flight plan knowledge listens for changes in active waypoint from the python flight plan object (the route object).

3. Python listens to the CLIPS knowledge base Flight Mode to determine which navigational action plan should be executed.

4. Changes in data and flight plan are rendered in an OpenGL window. This window exists to accomodate the human user, who may be monitoring the system. The program does however work indepentently of the display, and it is not required.

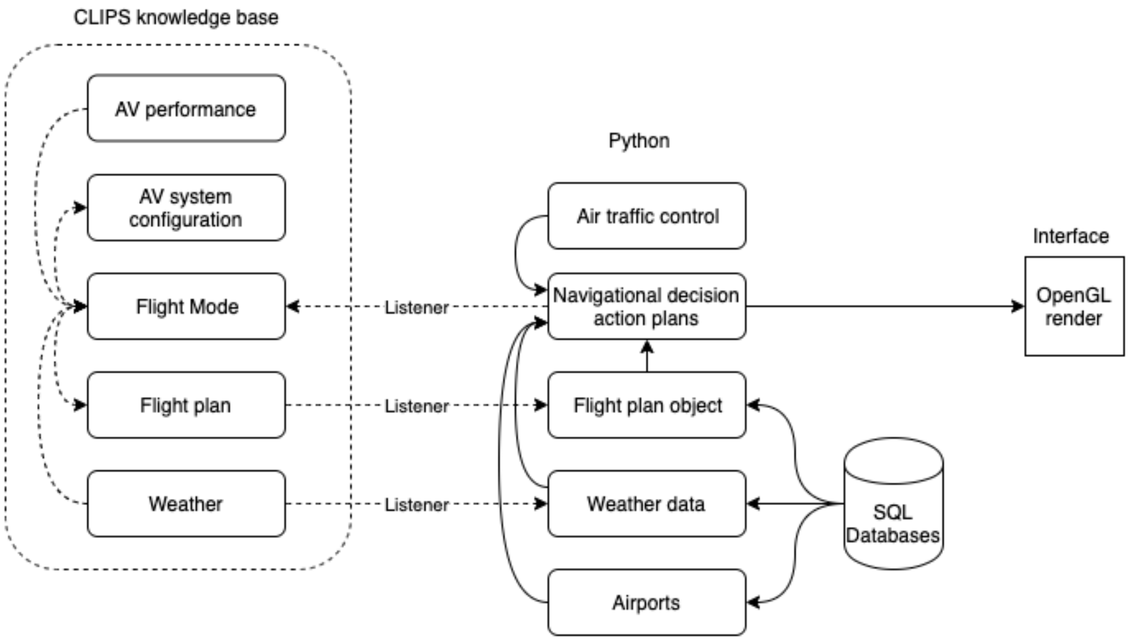


Figure 20: CLIPS Python integration

Various combinations may lead to changes in flight mode, for which python listens to. If a flight mode has a corresponding navigational action plan, then python executes it. The second method for python to execute a navigational action plan is through air traffic control commands, which are implemented in python by means of hotkeys.

Figure 20 also shows that in the CLIPS knowledge base, Weather and AV performance impact Flight Mode, but that the relation does not go in the other direction (ie these are 'non-negotiable' elements of the world). Flight plan and AV system configuration have a bi-directional relationship with Flight Mode. This is also described in 3.5 Decision-making.

The knowledge base is composed of the following facts and rules:

- Facts:
  - BlobPerf: AV performance information
  - BlobSystem: AV system status information
  - FlightMode: current flight mode
  - NavWaypoints: next active flight plan waypoint information
  - NavApproach: airport approach information
  - EnrouteWx: enroute weather information
- Rules:
  - Engine_failure_diversion: diversion action
  - Anti_ice_system_on: manage anti-ice system
  - Anti_ice_system_off: manage anti-ice system

- Anti_ice_fail_climb: anti-ice failure
- Anti_ice_fail_cruise: anti-ice failure
- Approach_fight_mode: switch to approach flight mode
- Landing_gear_down: when to lower the landing gear

If the decision-making process impacts the routing or the altitude, the OpenGL render reflects those changes. The terminal window displays the CLIPS knowledge base. Each time the knowledge base is updated, the terminal window reprints the entire knowledge base, as well as what change was detected, and what decision if any, was made.

✈

5 Results

This section presents results of two simulated scenarios and introduces a validation exercise performed on-board an aircraft. All scenarios take place on a flight between Burlington airport (KBTV) and Newport State airport (KEFK). For the simulated scenarios, a twin-engine aircraft with anti-ice capability is assumed, represented in the program render by a red dot and follows a simulated trajectory.

The waypoints on the flight plan are in order and plotted on a sectional in Figure 21:

1. PLOTT
2. LUNFI
3. YISXI
4. AHTON
5. ROMUW
6. KEFK (Northeast Kingdom): this is the destination airport

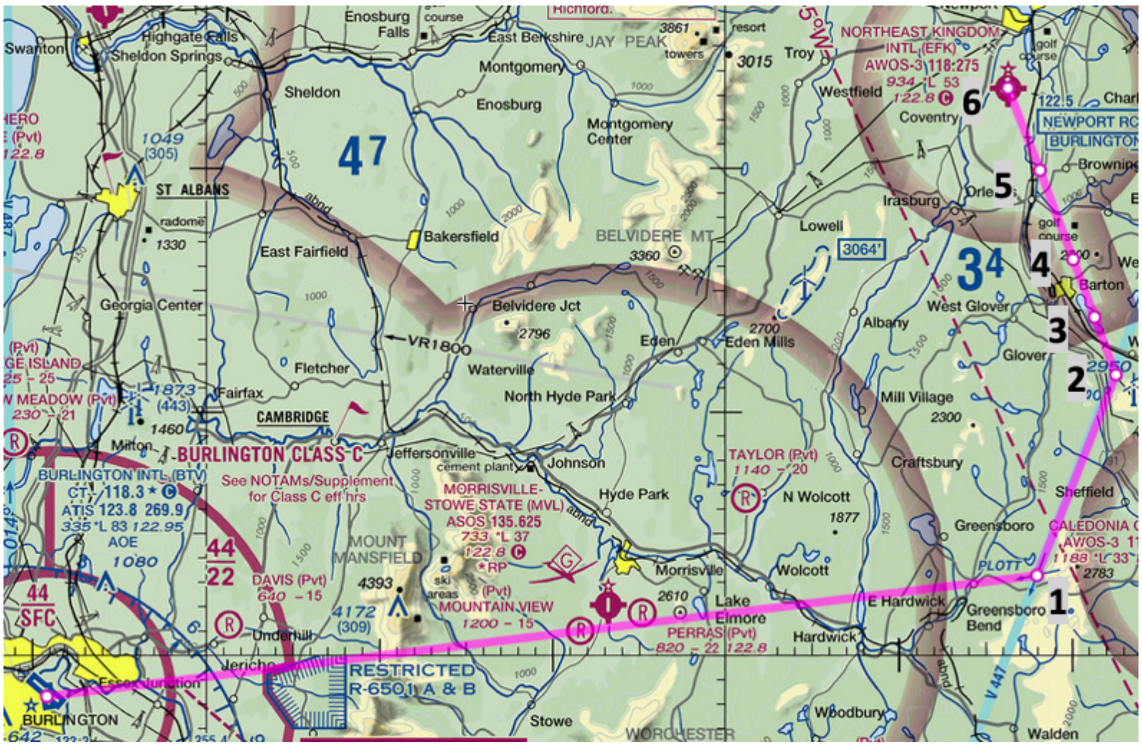


Figure 21: KBTV to KEFK routing (purple)

5.1 Scenario 1: Anti-ice activation/de-activation and approach mode

In this scenario, the anti-ice activation rules are tested, as well as the transition to "approach" flight mode. As changes in ice severity are detected, the status of the anti-ice system is adjusted internally by CLIPS. The following sequence of figures demonstrates how the program works.

5.1.1 Departing Burlington (KBTV)

After departing Burlington, the AV initiates a climb to 7000 feet. Initially, the AV is not in a region of ice. The terminal displays the CLIPS knowledge base. Each fact holds a representation of what is true, and CLIPS bases its decisions on those facts. Each fact discussed in 4.4.2 CLIPSPy is displayed below:

```
~~~~~~~~~~~~~~~~~~~~ Environment Current State ~~~~~~~~~~~~~~~~~~~~
(initial-fact)
(Blob_systemS (engine1 "run") (engine2 "run") (anti_ice "off") (landing_gear "up"))
(Flight_modE (diversion "FALSE") (phase "CRUISE NORMAL"))
(Nav_approacH (type "") (frequency -999.0) (FAFname "") (FAFLon -999.0) (FAFLat -999.0) (FAFAlt
-999))
(Blob_perfF (altitude 1000) (speed 250) (reqdLdgDist 2000))
(EnrouteWX (ice_sev 0) (ice_prob 0.0) (SLD_prob 0.0))
(Nav_waypointS (nextPointName "PLOTT") (nextPointType "Enroute") (nextPointAlt -999) (nextPointSpd
-999) (nextPointLon -72.200731) (nextPointLat 44.554983))

Event: ['altitude'] [2000]
```

This information indicates that all systems are running normally, the AV is climbing through 2000 feet and is headed to the PLOTT waypoint. The OpenGL render is shown in Figure 22, with the AV represented as a red dot.

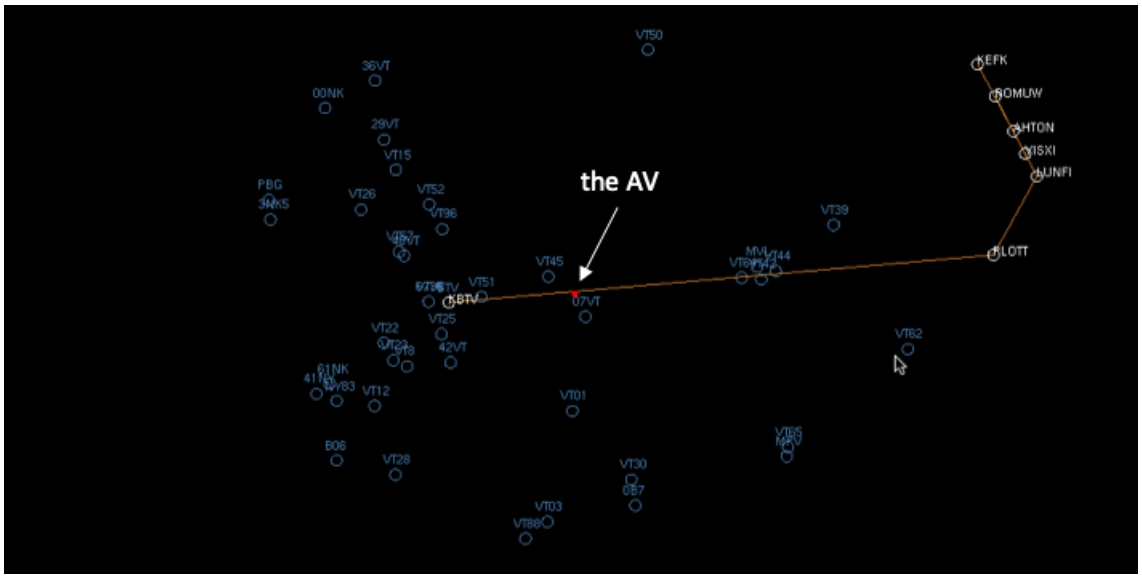


Figure 22: OpenGL render - Climb to 7000 ft departing Burlington

5.1.2 Encountering Icing Conditions

Upon reaching 3000 feet, the system encounters icing of severity 4, rendered as purple squares. The icing scale ranges from 0 to 5, 5 being the most severe. At this point, the flow of Scenario 1 in the methods section is executed. In Python, the flow is as follows:

1. Weather data is obtained from the SQL icing database and updated in the Python object

structure

2. Highest icing severity in the area is updated to the CLIPS knowledge base by listeners
3. The icing severity triggers a response from the CLIPS knowledge base: at icing severity 4, anti-ice systems must be turned on.
4. CLIPS turns on the anti-ice system. Since the system has not failed, no change to the flight plan is required and the AV continues on to PLOTT.

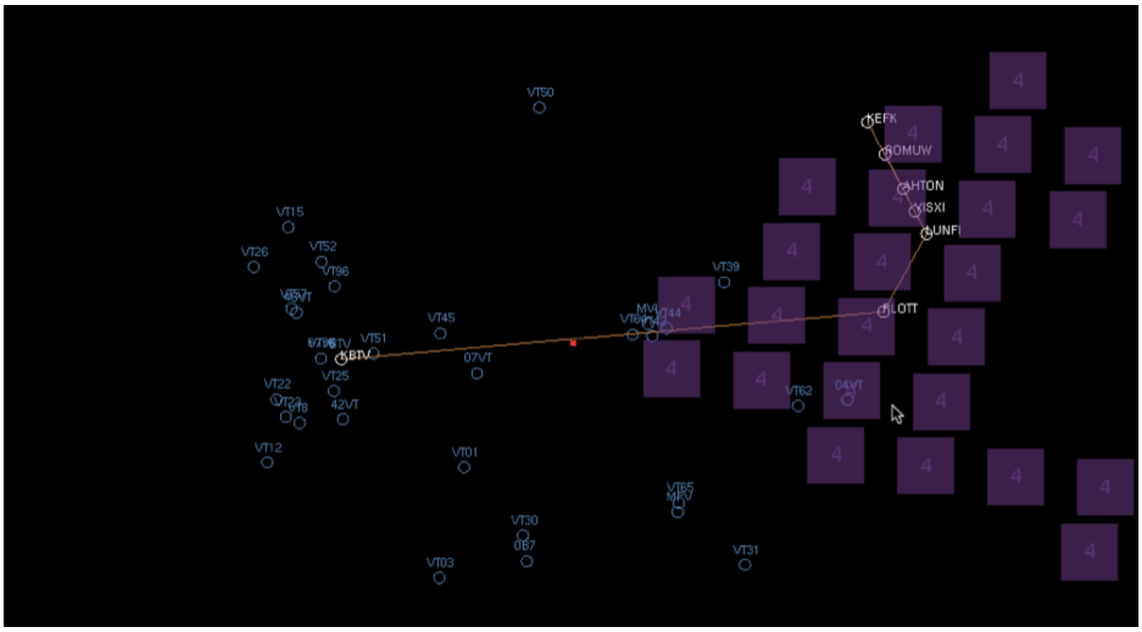


Figure 23: OpenGL render - Icing encounter

After passing PLOTT, the AV turns north to LUNFI, which is part of the GPS 36 approach into Newport. The system switches to "approach" flight mode, which in turns lowers the landing gear. CLIPS displays any change in the environment by declaring "Event:" and announces any decisions by declaring "Decision:". CLIPS then re-prints the updated truth state to the terminal window. The terminal displays the following:

```
Event: ['nextPointName', 'nextPointLon', 'nextPointLat', 'nextPointType', 'nextPointAlt'] ['LUNFI',
-72.124903, 44.692344, 'Approach', 4800.0]
Decision: Switching to flight mode approach
Decision: On approach, lowering landing gear

~~~~~~~~~~~~~~~~~~~~ Environment Current State ~~~~~~~~~~~~~~~~~~~~
(initial-fact)
(Nav_approacH (type "") (frequency -999.0) (FAFname "") (FAFLon -999.0) (FAFLat -999.0) (FAFAlt
-999))
f-11 (Blob_perF (altitude 3000) (speed 250) (reqdLdgDist 2000))
f-12 (EnrouteWX (ice_sev 4) (ice_prob 0.0) (SLD_prob 0.0))
f-14 (Nav_waypointS (nextPointName "LUNFI") (nextPointType "Approach") (nextPointAlt 4800.0)
(nextPointSpd -999) (nextPointLon -72.124903) (nextPointLat 44.692344))
f-15 (Flight_modE (diversion "FALSE") (phase "APPROACH"))
f-16 (Blob_systemS (engine1 "run") (engine2 "run") (anti_ice "on") (landing_gear "down"))
```

This information indicates:

- the Blob is in flight mode “Approach”
- the anti-ice system is “on”
- the landing gear is “down”
- the Blob is flying to waypoint “LUNFI” which is an approach waypoint.

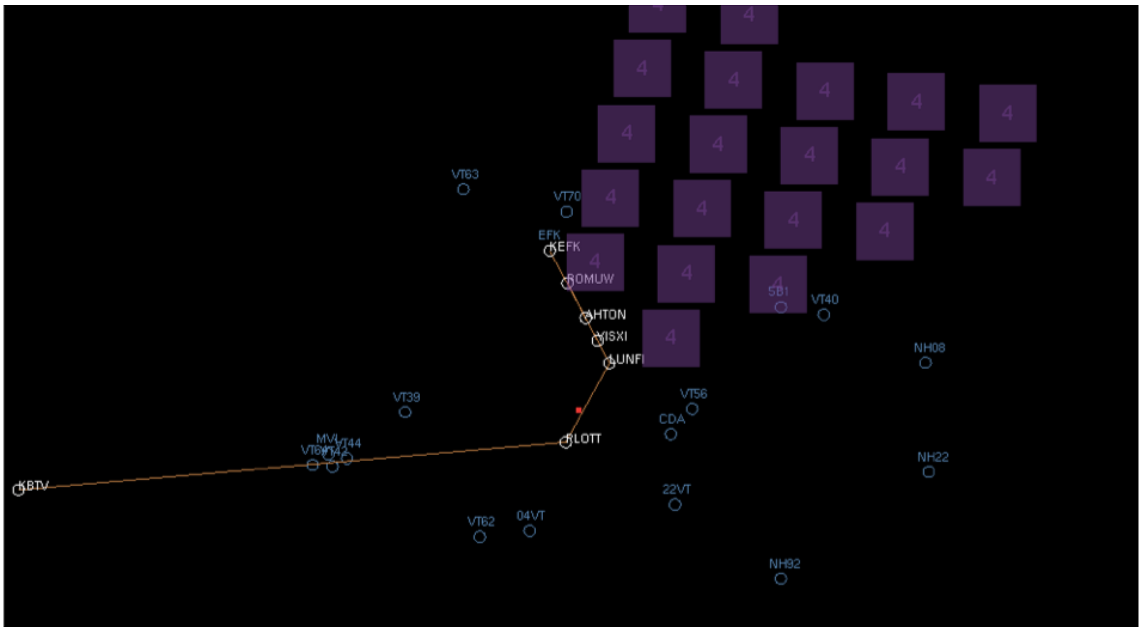


Figure 24: OpenGL render - Sequencing to waypoint LUNFI after passing waypoint PLOTT

5.1.3 Arrival Into Newport (KEFK)

As the AV continues its descent into Newport, it eventually descends below the icing layer, and subsequently turns off the anti-ice system. This change in icing severity is also reflected in the OpenGL render, with the absence of purple “icing squares”. The terminal outputs the following:

```
Event: ['ice_sev'] [0]
Decision: turn off anti-ice

~~~~~~~~~~~~~~~~~~~~ Environment Current State ~~~~~~~~~~~~~~~~~~~~
(initial-fact)
(Nav_approacH (type "") (frequency -999.0) (FAFname "") (FAFLon -999.0) (FAFLat -999.0) (FAFAlt
-999))
f-15 (Flight_modE (diversion "FALSE") (phase "APPROACH"))
f-17 (Nav_waypointS (nextPointName "YISXI") (nextPointType "Approach") (nextPointAlt 3000.0)
(nextPointSpd -999) (nextPointLon -72.145486) (nextPointLat 44.731783))
f-18 (Blob_perF (altitude 4000) (speed 250) (reqdLdgDist 2000))
f-19 (EnrouteWX (ice_sev 0) (ice_prob 0.0) (SLD_prob 0.0))
f-20 (Blob_systemS (engine1 "run") (engine2 "run") (anti_ice "off") (landing_gear "down"))
```

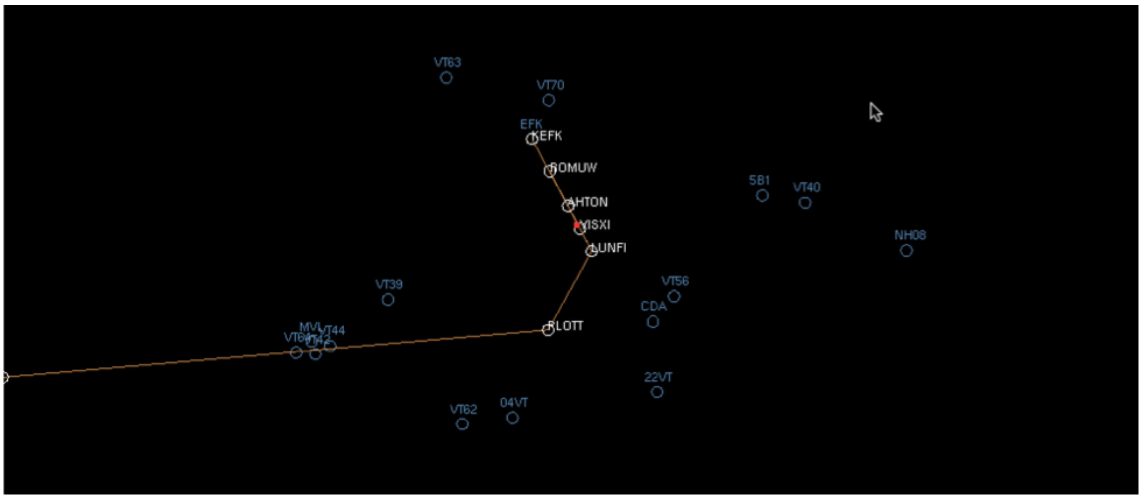


Figure 25: OpenGL render - AV descending below the icing layer passing YISXI

5.2 Scenario 2: Engine failure

The AV is on the same flight presented in scenario 1, but experiences an engine failure on its way to PLOTT. At this point, the flow of Scenario 2 in the methods section is executed. In Python, the flow is as follows:

1. Engine failure is updated in the CLIPS knowledge base
2. This triggers a response by CLIPS to change the flight mode to “Degraded Cruise”, and to “Diversion True”
3. This change in flight mode is listened to by Python, which then executes the appropriate navigational action plan; a diversion.
4. The action plan searches for the nearest usable airfield based on required landing distance and obtains real time weather at the airport from the NOAA website. It then modifies the flight plan to direct the AV towards the new destination, in this case Morrisville (KMVL). At the time the simulation was run, KMVL was reporting light winds out of the north and light snow.

```
Event: ['engine1'] ['fail']
Decision: diverting to nearest usable field

~~~~~~~~~~~~~~~~~~~~ Environment Current State ~~~~~~~~~~~~~~~~~~~~
(initial-fact)
(Nav_approacH (type "") (frequency -999.0) (FAFname "") (FAFLon -999.0) (FAFLat -999.0) (FAFAlt
-999))
(Nav_waypointS (nextPointName "KMVL") (nextPointType "Diversion") (nextPointAlt -999) (nextPointSpd
-999) (nextPointLon -72.614001) (nextPointLat 44.53437))
f-17 (Blob_perF (altitude 7000) (speed 250) (reqdLdgDist 2000))
f-18 (EnrouteWX (ice_sev 2) (ice_prob 0.0) (SLD_prob 0.0))
f-19 (Blob_systemS (engine1 "fail") (engine2 "run") (anti_ice "on") (landing_gear "up"))
f-20 (Flight_modE (diversion "TRUE") (phase "DEGRADED CRUISE"))

Diverting to:
Airport: 'KMVL'
Runway: '01'
Runway length: '3700'
BLOB required landing distance: '2000'
Runway surface: 'ASPH'
Weather METAR: 2019/11/20 18:54
KMVL 201854Z AUTO 34006KT 9SM -SN BKN042 OVC050 01/M03 A2998 RMK AO2 SNB31 SLP163 P0000 T00061028
```

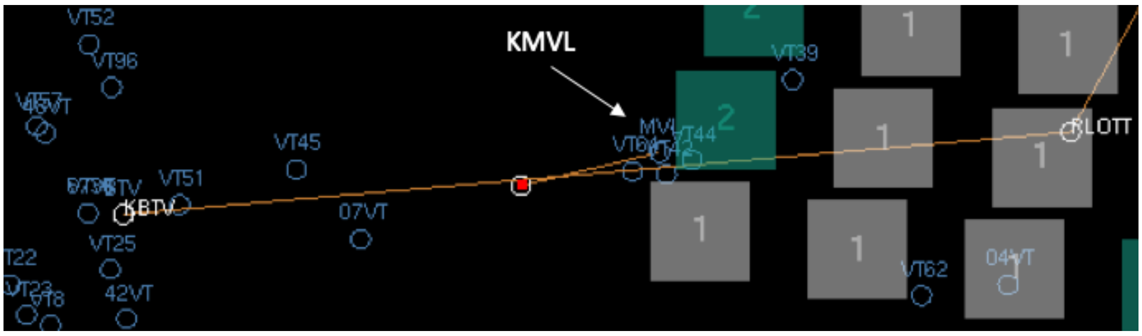


Figure 26: OpenGL render - AV diverting to KMVL after an engine failure

5.3 Validation Exercise

The validation exercise is carried out in a Cessna Cardinal CE-177-B. Even though the Cardinal is not a twin engine piston aircraft with anti-ice capability, it serves as a proxy for the exercise. The objective is to demonstrate that:

1. The data used in the program corresponds to data used by the Garmin 430W, a widely used certified GPS navigation system. Examples of data contained by the Garmin 430W are data describing the airport infrastructure component, terrain, and airspace among others.
2. The program is designed in such a way that it is suitable for making decisions in real time based on GPS location and the data contained in the SQL databases previously discussed.

Both scenarios discussed in this section compare the program output to the Garmin 430W output. The included videos show how the tests were carried out, as well as their results.

5.3.1 Position Determination

Since the program is to be tested in the real environment in an actual aircraft, the simulated trajectory position used in the simulated tests discussed in sections 5.1 and 5.2 needs to be substituted for actual GPS position. To obtain actual position (latitude, longitude, altitude), the Vk-162 USB GPS chip is used. The chip transmits information as per a standard defined by the National Marine Electronics Association (NMEA) in the form of sentences [47].

The two time-stamped sentences used in the program are labelled “GNGGA” and “GNRMC”. “GNGGA” carries latitude, longitude and altitude while “GNRMC” carries speed and course. As the GPS measures these parameters, the python program reads the sentences and updates the latitude, longitude and altitude values in the program, effectively replacing the simulated trajectory by actual GPS position. That way, position, speed and heading are updated every second and changes are reflected in the OpenGL render. This program configuration is referred to as “real flight mode”.

Figure 27 shows the aircraft flown during the tests, and figure 28 the specific GPS chip used. Figure 29 is the in-flight setup. The left seat is occupied by the safety pilot and the right seat by the pilot in command. The image also depicts the laptop running the program, the Garmin 430W and the Vk-162 GPS chip, which is not visible since it is placed on the dashboard to have satellite visibility.

[redacted]

Figure 27: Cessna Cardinal CE-177-B flown in the validation flights

Figure 28: VK-162 GPS chip

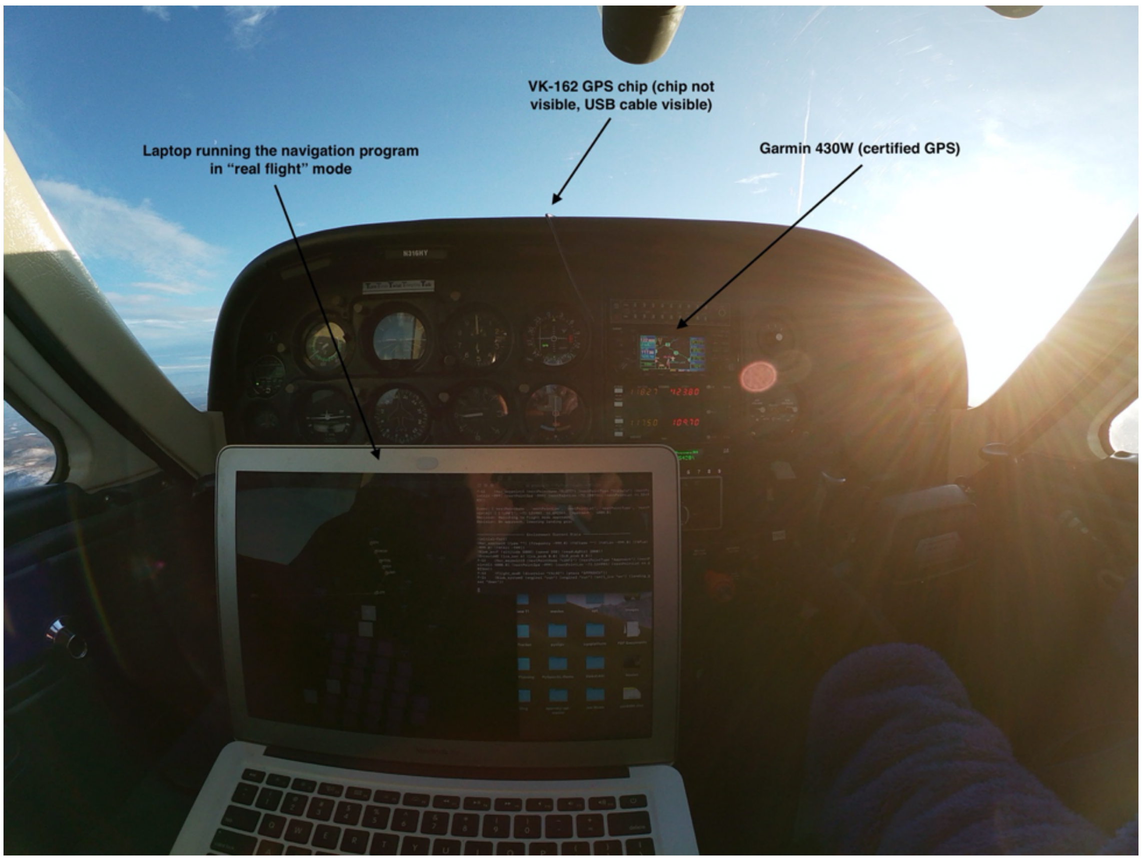

VK-162 GPS chip (chip not visible, USB cable visible)
Laptop running the navigation program in "real flight" mode
Garmin 430W (certified GPS)

Figure 29: Setup used in flight

Two scenarios are presented; an engine failure and a normal flight from Burlington to Newport. The ADS-B track for the flight from Burlington to Newport is obtained from flightaware.com and is shown in Figure 33. Waypoints PLOTT and LUNFI are added to the map to help situate the reader.

5.3.2 Engine Failure Scenario

In the following in-flight scenario, the aircraft is positioned southwest of waypoint PLOTT, northwest bound. Prior to the simulated engine failure, the terminal displays the following:

```
~~~~~~~~~~~~~~~~~~~~ Environment Current State ~~~~~~~~~~~~~~~~~~~~
(initial-fact)
(Blob_systemS (engine1 "run") (engine2 "run") (anti_ice "off") (landing_gear "up"))
(Flight_modE (diversion "FALSE") (phase "CRUISE NORMAL"))
(Nav_approacH (type "") (frequency -999.0) (FAFname "") (FAFLon -999.0) (FAFLat -999.0) (FAFAlt
-999))
(Blob_perF (altitude 5000) (speed 250) (reqdLdgDist 2000))
(EnrouteWX (ice_sev 1) (ice_prob 0.0) (SLD_prob 0.0))
(Nav_waypointS (nextPointName "PLOTT") (nextPointType "Enroute") (nextPointAlt -999) (nextPointSpd
-999) (nextPointLon -72.200731) (nextPointLat 44.554983))
```

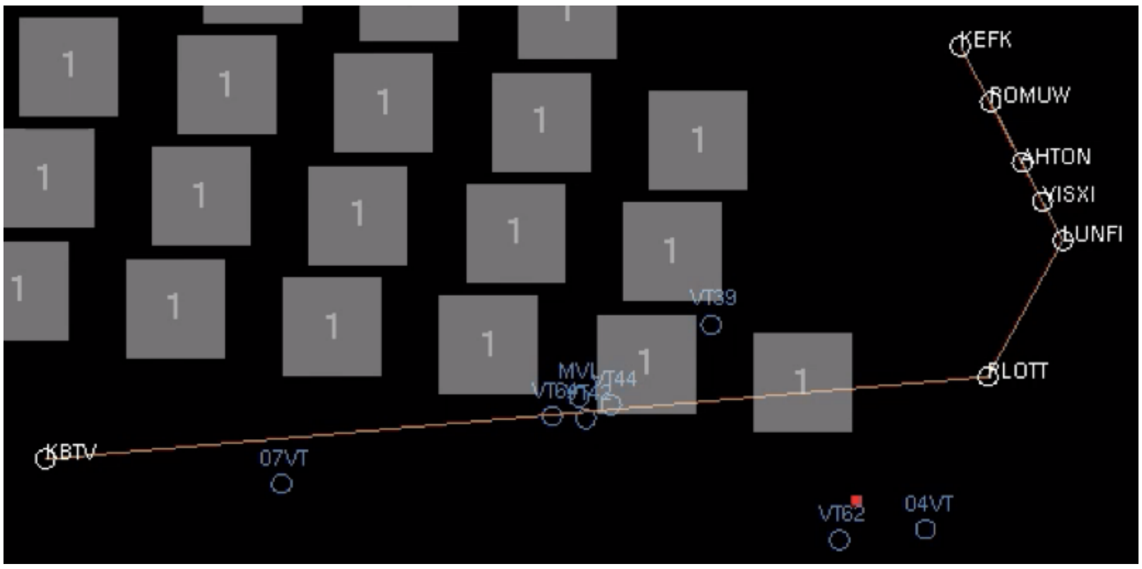


Figure 30: Engine failure scenario initial position

At an arbitrary point in time, an engine is failed in the python program. The terminal now displays the diversion airport, and updates the air vehicle system state:

```
Event: ['engine1'] ['fail']
Decision: diverting to nearest usable field

Diverting to:
Airport: 'KMVL'
Runway: '01'
Runway length: '3700'
BLOB required landing distance: '2000'
Runway surface: 'ASPH'
Event: [‘nextPointName’, ‘nextPointLon’, ‘nextPointLat’, ‘nextPointType’, ‘nextPointAlt’] [‘KMVL’,
-72.614001, 44.53437, ‘Diversion’, -999.0]

~~~~~~~~~~~~~~~~~~~~ Environment Current State ~~~~~~~~~~~~~~~~~~~~
(initial-fact)
(Nav_approacH (type "") (frequency -999.0) (FAFname "") (FAFLon -999.0) (FAFLat -999.0) (FAFAlt
-999))
f-17 (Blob_perF (altitude 5000) (speed 250) (reqdLdgDist 2000))
(EnrouteWX (ice_sev 1) (ice_prob 0.0) (SLD_prob 0.0))
f-11 (Blob_systemS (engine1 "fail") (engine2 "run") (anti_ice "on") (landing_gear "up"))
f-12 (Flight_modE (diversion "TRUE") (phase "DEGRADED CRUISE")
f-13 (Nav_waypointS (nextPointName "KMVL") (nextPointType "Diversion") (nextPointAlt -999)
(nextPointSpd -999) (nextPointLon -72.614001) (nextPointLat 44.53437))
```

The render now shows the calculated diversion trajectory and updated flight plan to Morrisville airport (KMVL):

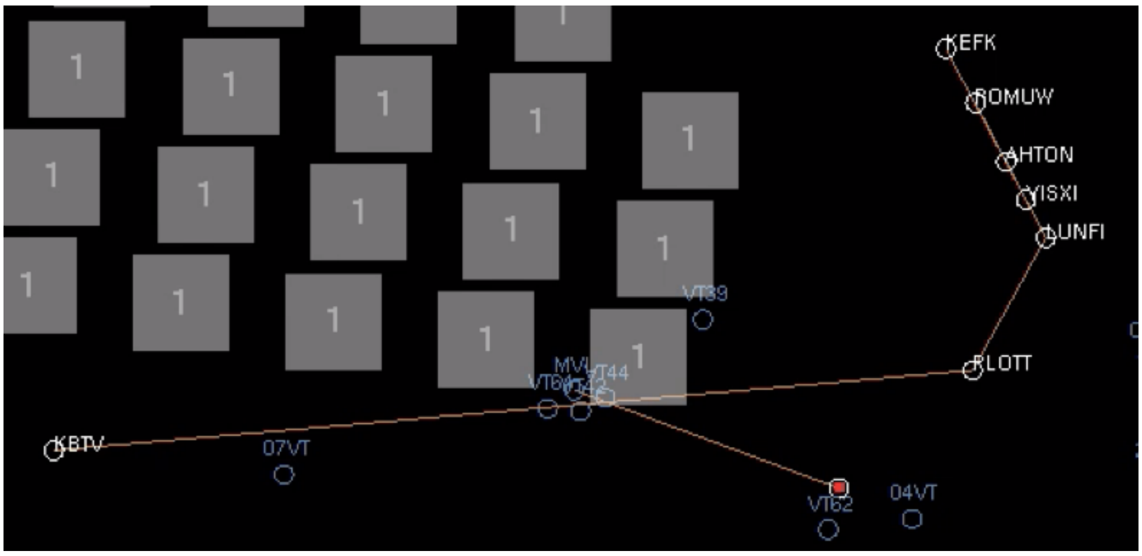


Figure 31: Blob diverting to KMVL

The following two videos show the scenario carried out in the Cardinal. The first video is shot with a GoPro by the safety pilot. The video shows the programs results and compares them to the Garmin 430W results by navigating to the “Nearest Airport” page, which also displays KMVL, with a runway 3700ft long. The second video is a screen recording of the laptop as the program ran during the test.

1. Video 1 - Aircraft video: https://www.youtube.com/watch?v=NQLfZFU_UzM
2. Video 2 - Screen recording: https://www.youtube.com/watch?v=aYq4LB9UMTs

Table 12: Video 1 - Aircraft video pilot action descriptions

Time (seconds)	Action
5	Simulate an engine failure in the python program running in “real flight mode”
14	Show the programs nearest airport selection; KMVL airport with a 3700ft runway
20	Show the programs OpenGL map, reflecting the revised flight plan
31	Compare program results shown at 14s with the Garmin 430W results, which also displays KMVL with a 3700ft runway as the nearest airfield

Table 13: Video 1 - Aircraft video pilot action descriptions

Time (seconds)	Action
4	Simulate an engine failure in the python program running in “real flight mode”
6	Pick a diversion airport and revise the active flight plan
11	Icing severity 4 detected, turn on anti-ice system

5.3.3 Burlington to Newport Flight

The objective of this flight is to demonstrate that the system is capable of sequencing waypoints and properly configuring the systems given icing and flight mode in real time, as the aircraft navigates along its route. It is also intended to validate the data in the SQL databases.

Initially, the Cardinal is positioned at Burlington (KBTV) airport. The OpenGL render displays the following:

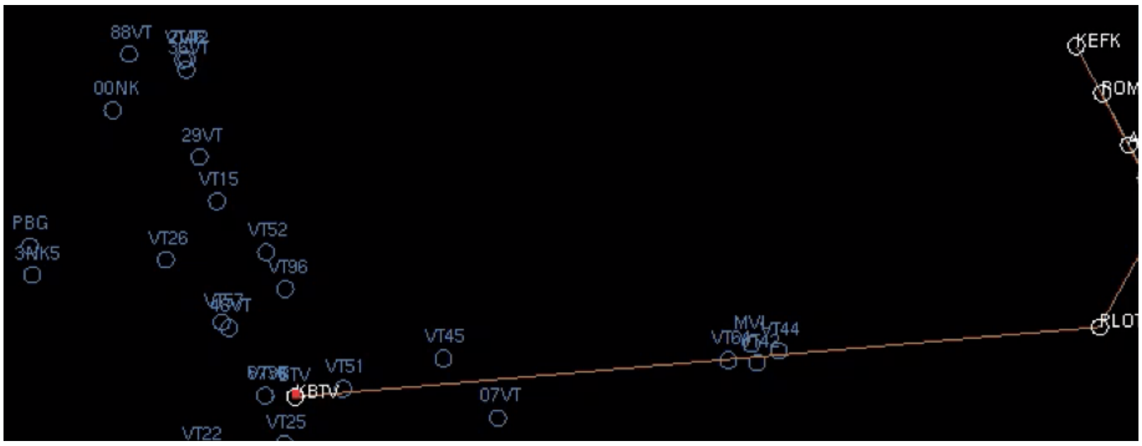


Figure 32: Cardinal positioned in Burlington ready for departure

The terminal displays the following:

```
~~~~~~~~~~~~~~~~~~~~~ Environment Current State ~~~~~~~~~~~~~~~~~~~~~
(initial-fact)
(Blob_systemS (engine1 "run") (engine2 "run") (anti_ice "off") (landing_gear "up"))
(Flight_modE (diversion "FALSE") (phase "CRUISE NORMAL"))
(Nav_approacH (type "") (frequency -999.0) (FAFname "") (FAFLon -999.0) (FAFLat -999.0) (FAFAlt
-999))
(Blob_perF (altitude 1000) (speed 250) (reqdLdgDist 2000))
(EnrouteWX (ice_sev 0) (ice_prob 0.0) (SLD_prob 0.0))
(Nav_waypointS (nextPointName "PLOTT") (nextPointType "Enroute") (nextPointAlt -999) (nextPointSpd
-999) (nextPointLon -72.200731) (nextPointLat 44.554983))
```

For the remainder of the flight, the OpenGL render and terminal outputs are identical to the flight presented in 5.1 and are thus not presented in this section. However, videos of the flight are linked below:

1. Video 1 – Aircraft video: this clip films waypoint transitions on the GPS36 approach into Newport (KEFK). It shows the system sequencing between waypoints, changing flight modes and taking appropriate action as the flight mode changes. Each event is captioned directly in the video.
   Link: https://www.youtube.com/watch?v=BKB3LLcbx-Y
2. Video 2 – Screen recording: this video initially shows the aircraft enroute to waypoint PLOTT, climbing to 7000 feet. As the aircraft climbs, the altitude is updated in the "Blob_perF" fact, and the icing data is updated accordingly. Reaching PLOTT, the flight mode switches to Approach and the system lowers the landing gear. On the approach, the video shows the aircraft descending through the icing layer until there eventually no icing data to display. Each event is captioned directly in the video.
   Link: https://www.youtube.com/watch?v=ErOuB8e_Vp8

To verify the accuracy of the VK-162 GPS chip, the flights ADS-B track is obtained from flightaware.com. Figure 33 shows the Burlington to Newport ADS-B flight track in purple. The re-positioning flight from Newport to Burlington is shown in green, and is not part of the scenario.

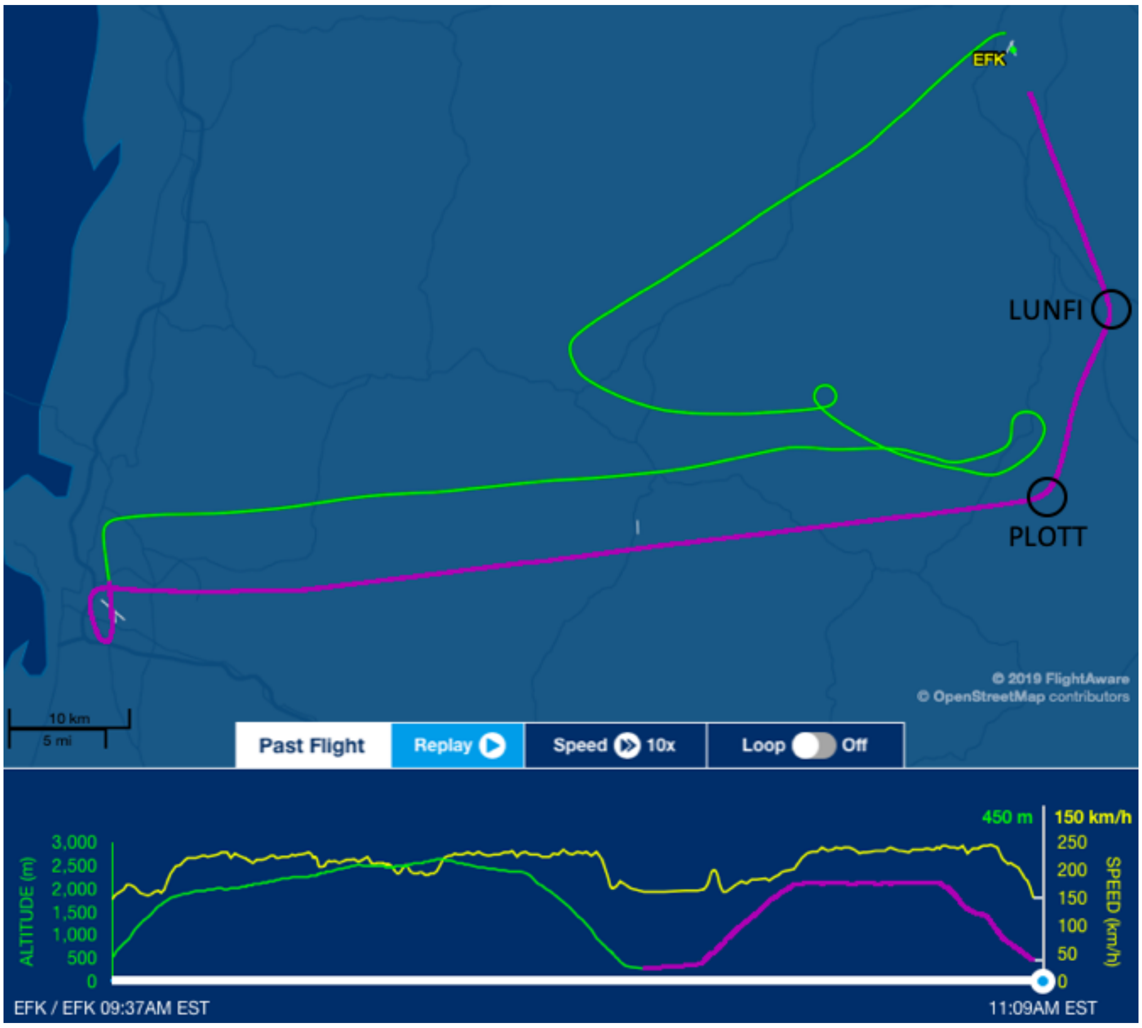


Figure 33: Normal flight (Burlington - Newport [purple trajectory])

The raw GPS data is saved during the flight and is plotted in google earth for comparison to the flightaware ADS-B track. A sectional overlay is loaded so that relevant aeronautical information is displayed such as airport locations. The google earth ".KMZ" file is attached as a downloadable file: https://sigur.ovaltofu.org/paul.public/website/vk162_FlightAware.kmz and can be opened in google earth, a free program downloadable here: https://www.google.com/earth/versions/#earth-pro.

The KMZ loads the flight track as recorded by the Vk-162 GPS chip, the exportable ADS-B track from the flightaware website, and the sectional overlay. Figures 34 and 35 both show that the Vk-162 track for the Burlington to Newport flight is identical to the ADS-B track.

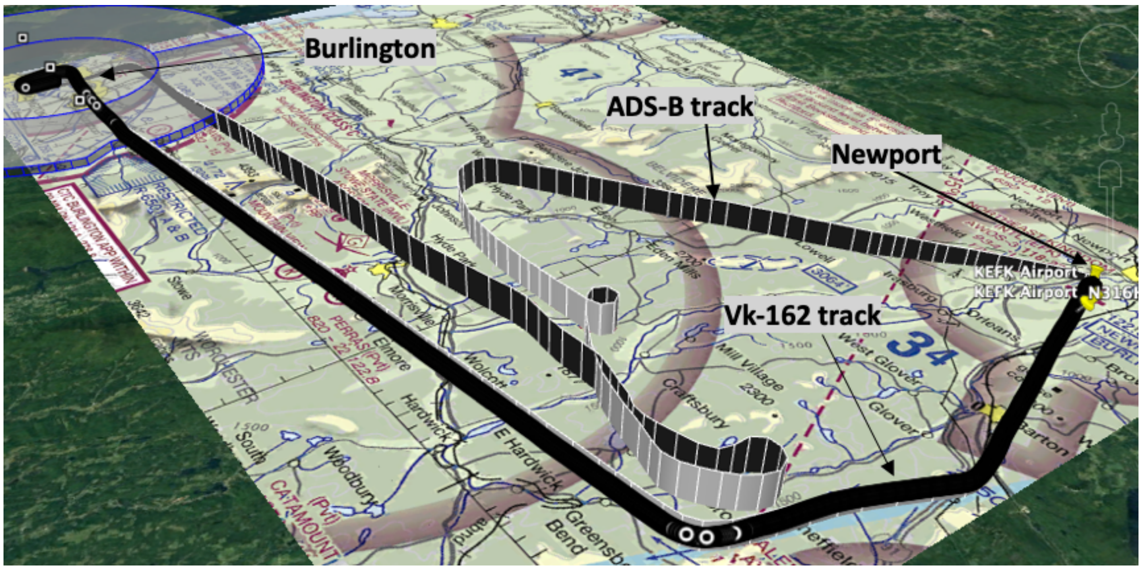


Figure 34: Google Earth GPS & FlightAware overlay

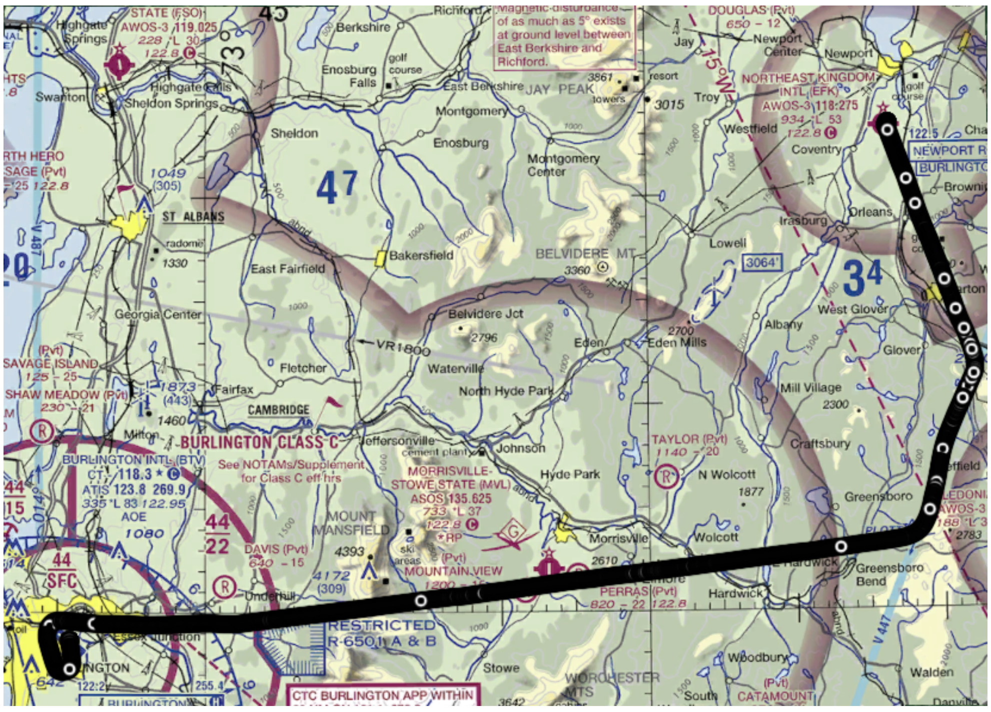


Figure 35: Flight track recorded by Vk-162 GPS in Google Earth

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6 Discussion

These examples serve as a proof of concept to demonstrate the functionality of the program. The behavior coded into the rules is purely arbitrary and was written from a first principles approach based on experience. For instance, if in icing conditions and the anti-icing system fails, the program by default searches for a higher altitude where there is no ice, since the assumption is that icing conditions must be avoided. It does not take into consideration the distance from destination. If the AV is 25 miles from its destination, it may make no sense to climb. A descent or no action at all may be more appropriate, depending on the severity of the ice. Similarly in the engine failure scenario, an immediate diversion may not be appropriate. If the AV can safely continue to operate, the decision to continue on to the final destination may be a good one. All these scenarios are arbitrarily determined. This tool simply provides a platform to the designer to write and test different rules. The advantage of simulation is that many instances of the program can be run continuously to test the programmed behavior. As was then demonstrated in the CE-177-B, the program translates directly to actual flight, since the data represents the real world. Such a tool would have been useful for Fallast and his team [4] in the design and testing of their autonomous landing system. In the article, the authors describe difficulties coordinating the test flights with air traffic control. They discuss hurdles in obtaining the proper authorizations and finally testing the system in a realistic environment unaffected by the limitations imposed by the regulators, one being that they were only permitted to use a specific runway. A second example relates to the recent announcement by Garmin describing their "Safe Return" technology. Garmin describes the system as being capable of directing "the aircraft to a suitable airport nearby for landing based upon a variety of conditions, including but not limited to weather, terrain, approach, runway and aircraft suitability" [49]. This python program has the tools to achieve the same thing. Applications such as "Safe Return" could benefit from such a tool to test and demonstrate their safety in a zero-risk environment. Firstly, developing a set of rules in a simulated environment could save a considerable amount of time and resources. In addition, as the aerospace industry introduces increasingly autonomous decision-making systems, a multitude of scenarios will have to be taken into account and programmed for. This type of platform can be used to cover a wide range of scenarios, some of which could be difficult to test in an actual aircraft.

The need for more pilots may be fulfilled by training, but can also be offset by reducing crew numbers. Expanding single pilot operations to Part 121 carriers is not unfeasible, given technologies like the EFVS. However, to enable SPO, the role of the crew has to be reconsidered. In 1980, when the Presidential Task force on the MD80 studied the reduction of crews from 3 to 2, the subject of pilot incapacitation was discussed and the team concluded it was not a significant factor. Are regulators and the flying public ready to make the same assertion for a transition from 2 to 1? If not, then SPO part 121 aircraft must be treated as fully autonomous. Such aircraft could use an implementation of the method presented in this research to cover the corner case where a pilot may become incapacitated. In this case, SPO actually adds complexity to the problem set given the autonomous decision-making system must also cooperatively involve the single pilot in the operation of the aircraft during normal operations. This also poses other questions about the roles of flight attendants and ATC. If onboard an SPO aircraft the pilot becomes incapacitated, should the flight deck have provisions to enable a well-trained flight attendant to take over and land the aircraft? Or should ATC be able to remotely take control of the aircraft to bring it to a safe landing? And if aircraft are capable of being remote controlled, how can their systems be well protected from hacking and remote hijacking?

This research was done considering the "conventional air environment" used by well-equipped aircraft performing cooperative A to B flights in Instrument Flight Rule (IFR) operations. Aircraft operating IFR communicate with ATC, have flight plans, and by nature of their operations are required to have radios, transponders and now ADS-B. As such, they are cooperative and well integrated in the air environment. Missions such as aerial firefighting, UAM, cropdusting or the VFR aircraft not equipped with a transponder are not considered “cooperative” and/or “conventional” . This approach is taken for several reasons. The first is that the aircraft that use the conventional environment such as airliners are heavily instrumented. They already possess the technologies required for autonomous flight, mainly autopilots and automatic system management. Their flight deck interfaces provide the crew with a plethora of information, which they must analyze to create an accurate mental model of the world around them. So, why not have a system that displays the information and also uses it to suggest navigational decisions? The second reason is that the FAA and NOAA make available large amounts of data describing that environment in the United States at no cost. It is simply up to the user of the data to go searching for it. Applications like ForeFlight and FltPlan Go are widely used by pilots because the service they provide packages the data into a user-friendly format. As it is now, the program cannot be used for “unconventional” applications such as urban air mobility because the data we currently have is not sufficiently granular. For example, locations of power lines, rooftops, TV antennae, tree lines and other features associated with the urban environment are not as rigorously published as airport data for instance, if published at all. The urban space is also not as rigorously regulated as the air environment is, increasing its unpredictability. This is the same problem autonomous cars have to cope with, justifying vision systems. For the urban low-level flying required by missions such as UAM, technologies used in autonomous cars will likely have to be borrowed to detect static obstacles and other traffic that is not ADS-B equipped. This stands in contrast with the data describing the “conventional” air environment, which enables an aircraft to land fully autonomously. From that point of view, the autonomous air taxi mission flying from rooftop to rooftop is more complex than the autonomous A350 mission flying from Los Angeles to Tokyo.

For the conventional air environment in highly instrumented airliners, the hurdles to implementation of autonomous decision making are in technology integration, data management, legal matters, and social perception. Airliners have the capability to follow a flight plan, land themselves and manage their on-board systems. However, taking these technological capabilities in isolation of the other components of the NAS does not provide a complete solution. The roles of ATC, airport personel, flight crew and others will have to be re-considered and likely evolved. Transmission of ADS-B type data will have to become mandatory for all aircraft regardless of where they are operating, and IFR operations will have to become mandatory at altitudes much lower than FL180 (in the USA). This will avoid potential conflicts between ill-equipped VFR flights and IFR traffic. In addition, data and how it is organized will have to regulated. That way, what information is available and how it is presented is uniform across all future suppliers of data and autonomous systems. The AIXM, FIXM, WXXM and NASA ATM ontologies should also be harmonized and kept freely available so that avionics providers can deliver their solutions on the same notion of what exists in the world. This point is based on the understanding that data is at the foundation of what is required for autonomous decision making to be possible, and so the ontologies that organize them should be standardized. In manned aircraft, all pilots are trained to the same standards and follow the same rules. That makes their behavior predictable to other pilots and to ATC, who are then able to anticipate future actions and instructions. This also helps ATC efficiently sequence aircraft. In much the same way, if autonomous systems do not operate on the same understanding of what exists in the world, then the behavior from one system to the next may be inconsistent. To support this harmonization, new certification requirements and processes will have to be written, and made compatible with existing ones. Finally, social perception will have to change. Passengers believe that having someone that wants to safeguard their own life means that their own lives are safer, and that two pilots is better than one. This is particularly true for transportation of passengers, and to some extent still true for cargo, since cargo aircraft also fly over populated areas.

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7 Conclusion

In this research, we have presented a methodology for establishing a data driven interface between the air vehicle and the environment, usable for autonomous decision making in the context of navigation. We discussed the subject of knowledge representation and presented a methodology for capturing relevant information in an ontology. We discussed the implementation of the interface for the "conventional" air environment, fed by publicly available data and used CLIPS to program a decision-making framework. The final solution is implemented in Python, and we presented several scenarios to show how the system works. We concluded the results by discussing the same scenarios in an actual airplane and demonstrated the direct applicability of the system to the real world.

Modern aircraft systems are becoming increasingly complex. Airliners require pilots to process a large amount of information displayed and to act upon it appropriately. The same is true of smaller part 23 general aviation aircraft which are seeing the widespread use of glass panels and autopilots. Unlike their steam gauge counterparts, these systems do more than describe the state of the aircraft. They also describe the environment by displaying weather, maps, air traffic, and more. Though these systems can provide large amounts of information, they do increase the potential for information overload and confusion. The industry is also witnessing a shortage of qualified pilots and increasing interest in un-crewed flight. This combination of elements should prompt the aerospace community to rethink how aircraft are flown and integrated in the national airspace system, and to evaluate the ramification of those changes on the roles of its users.

7.1 Future Work

This research can be used as a starting point to design autonomous decision-making systems. Though an expert system can provide baseline behavior, it is incapable of extrapolating to new situations for which it has not been programmed, and it is widely agreed upon that providing an exhaustive list of all possible scenarios and actions is not a tractable exercise. Python has been very successful in the developer community and there exist many sources that support research in machine learning. Machine learning techniques could be used to evaluate the quality of the rules based on outcome and inform the writing of new or better rules. Modules for reactive actions to cover gaps in the expert system should also be implemented. Because the simulation reflects the real environment, the output can be used to support the development of risk and number-based certification requirements. In addition, the ability to easily test the program in real flight makes this program an ideal sandbox for future experimental development. Finally, human factors research on how to achieve a synergy between the expert system and the pilot in a SPO should be carried out.

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