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AGENT APPROACH TO AIR TRAFFIC CONTROL

AGENTNÍ SYSTÉM ŘÍZENÍ LETOVÉHO PROVOZU

MASTER'S THESIS
DIPLOMOVÁ PRÁCE

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Title:	**Agent Approach to Air Traffic Control**
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Assignment:

1. Research the history of air traffic control simulation.
2. Implement an air traffic simulation framework.
3. Design and implement an agent for air traffic management tasks.
4. Perform testing under various operational conditions and evaluate achieved results.
5. Discuss potential further improvements.

Recommended literature:

- According to supervisor's recommendations.

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Abstract

This thesis is focused on an agent design in the Air Traffic Control environment. The main goal is to create agent systems accounting for pilot and controller agents, that reflect typical situations encountered in the air traffic control environment.

Abstrakt

Tato práce je zaměřena na agentní návrh v prostředí řízení letového provozu. Hlavním cílem je vytvoření agentních systémů pro pilotní a řídící agenty, které odrážejí typické situace v prostředí řízení letového provozu.

Keywords

Air Traffic Control, Agent System, Agent Behavior, Flight Simulation.

Klíčová slova

Řízení letového provozu, agentní systém, agentní chování, letecká simulace.

Reference

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Rozšířený abstrakt

Vzdušný prostor je každým rokem stále více zaplňován. Letový provoz je zvyšován nejen tradičními leteckými společnostmi, ale také velkým množstvím typů bezpilotních dronů a autonomních letounů. Dnešní běžná praxe dispečerů letového provozu se spoléhá plně na lidské pozorování a úsudky. Pravděpodobně tento způsob nebude při řízení všech letadel v okolním vzdušném prostoru v blízké budoucnosti dostačující. Tato práce je zaměřena na agentní návrh prostředí řízení letového provozu. Hlavním cílem je vytvoření agentních systémů pro pilotní a řídící agenty, které reflektují typické situace v prostředí řízení letového provozu.

V úvodní části práce je shrnuta historie řízení letového provozu a jeho simulace. Tato zpětná reflexe zkoumající vznik a směr aktuálních trendů v oblasti simulace řízení letového provozu přechází do další části této práce, která se zabývá návrhem a implementací frameworku pro simulaci letového provozu. V rámci návrhu frameworku jsou zohledněni všichni účastníci letového provozu a jsou zde popsány jejich hlavní činnosti a odpovědnosti. Pozornost je věnována i komunikačním prostředkům a vybavení, pomocí kterého spolu interagují. Taktéž jsou zde popsány jednotlivé třídy letového prostoru a základní pravidla, která v nich platí. Návrh architektury simulačního prostředí zahrnuje dynamiku letu v prostředí, autopilota, vzdušný prostor, letiště, řídící letového provozu a další elementy jako je například počasí.

Nejdůležitější částí, která tvoří simulační prostředí je agentní systém složený z jednotlivých agentů individuálně vnímajících okolní prostředí a komunikujících mezi sebou pro dosažení svých stanovených úkolů. Samotný návrh agentních systémů pro jednotlivé účastníky letového provozu je popsán v kapitole následující za návrhem zmíněného frameworku. Pro tvorbu agentního systému byla zvolena platforma JADE (JAVA Agent DEvelopment Framework), která splňuje standardy pro tvorbu agentních systémů a zároveň nabízí škálovatelné prostředí s interní komunikací mezi implementovanými agenty. Předmětem návrhu agenta pro řízení letového provozu jsou jednotlivé bloky chování, které zajišťují komunikaci s piloty, interpretaci radarových dat, vyhodnocení jednotlivých fází letu, plánování letového provozu a koordinaci jednotlivých pilotů. Samotnému principu plánování příletů a koordinaci pilotů je věnována samostatná sekce, ve které jsou popsány pravidla pro bezpečnou separaci ve vzdušném prostoru.

V praktické implementační části jsou dopodrobna vyobrazeny jednotlivé rozhodovací procesy řídícího agenta. Dále je zde popsána reprezentace letištní oblasti a standardních příletových tratí. V rámci řízení letového provozu je zohledněn i pohyb po pojížděcích trasách na letišti. Po popisu letiště následuje popis komponent chování agenta reprezentujícího pilota při standardních příletech podle pravidel pro let za viditelnosti. Důležitou roli při vyhodnocování aktuální letové fáze je intepretace pozice, která je vždy vztažena k určité oblasti v okolí letiště, jako je například část letového okruhu, nebo příletové tratě z určitého směru. Všechny letové tratě jsou reprezentovány sekvencí traťových bodů, které jsou definovány zeměpisnou šířkou, délkou, letovou hladinou, optimální rychlostí průletu a časovým oknem vymezeným pro daný let. Správné načasování a korektní průlet dané letové trasy zajišťuje řídící letového provozu, který přikazuje pilotům měnit letové parametry a provádět zpožďovací, nebo vyčkávací manévry. Komunikace, která je zasílána mezi piloty a řídícím je založená na standardní letové frazeologii definované Mezinárodní organizací pro civilní letectví.

V závěru kapitoly o implementaci jsou popsány všechny ostatní komponenty potřebné pro realizaci komunikace, přeposílání stavových vektorů jednotlivých letadel, emulace radaru, nebo komponenty pro generování dalšího letového provozu v průběhu času.

V předposlední kapitole je demonstrována funkčnost implementovaných agentů na několika scénářích. Přesnost navigace řídícího je ověřena přiblížením a následným přistáním realizovaným prostřednictvím simulace s vysokou mírou věrnosti, řízenou výhradně autopilotem letícím podle přikázaných traťových parametrů od řídícího. Další fází testování bylo vystavení agentního řídícího letového provozu různým hustotám letového provozu a zaznamenávání vzniklých kolizí.

V rámci této práce byl vytvořen agentní systém, který je dále škálovatelný a rozšiřitelný. Kromě zvyšování počtu účastníků je možné dále optimalizovat plánovač příletů nebo vyvíjet další algoritmy pro efektivnější řízení letového provozu.

Agent Approach to Air Traffic Control

Declaration

I hereby declare that this Master's thesis was prepared as an original work by the author under the supervision of doc. Ing. Peter Chudý Ph.D. MBA. I have listed all the literary sources, publications and other sources, which were used during the preparation of this thesis.

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Jiří Pomikálek
June 17, 2020

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Contents

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List of shortcuts

ACC	Area Control Center
ACL	Agent Communication Language
AFIS	Aerodrome Flight Information Service
ALT	Altitude
APP	Approach Phase
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
ATIS	Automatic Terminal Information Service
ATM	Air Traffic Management
ATZ	Aerodrome Traffic Zone
BADA	Base of Aircraft Data
BDI	Belief Desire Intention
BFF	Body Fixed Frame coordinate system
COMM	Communication Module
CRT	Cathode Ray Tube
CTR	Control Zone
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FCFS	First-Come-First-Served
FIPA	Foundation for Intelligent Physical Agents
FIRST	Flexible Independent Radar Skills Trainer
FL	Flight Level
FSM	Finite State Machine

FTS	Fast-Time Simulation
GCA	Ground Controlled Approach
GMP	Ground Movement Planner
GPS	Global Positioning System
HDG	Heading
IAS	Indicated Airspeed
ICAO	International Civil Aviation Organization
IEEE	Institute of Electrical and Electronics Engineers
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
JADE	Java Agent DEvelopment Framework
LLA	Latitude, Longitude, Altitude
MAS	Multi-Agent System
NASA	National Aeronautics and Space Administration
NED	North East Down coordinate system
NOTAM	Notice To Airmen
PAR	Precision Approach Radar
RNAV	Area Navigation
RTS	Real-Time Simulation
RVSM	Reduced Vertical Separation Minima
TCAS	Traffic Collision Avoidance System
TMA	Terminal Control Area
TMC	Traffic Management Coordinator
UAS	Unmanned Aircraft Systems
UHF	Ultra High Frequency
UTM	Unmanned Traffic Management
VFR	Visual Flight Rules
VHF	Very High Frequency
VOR	VHF Omnidirectional Radio Range

Chapter 1

Introduction

This thesis is focused on an agent design for Air Traffic Control. The main goal is to create an agent system, that reflects typical situations encountered in the Air Traffic Control environment. Simultaneously, the thesis focuses on the design of various behavioral models for pilot agents and a combination of the human pilot with an aircraft, controlled by an agent. The emphasis is on using International Civil Aviation Organization (ICAO) standard phraseology in communication.

The second chapter presents the general history of Air Traffic Control (ATC) development and its simulation. The current trends in Air Traffic Control and its simulation are listed there. At the same time, the thesis deals with innovations in this area and summarizes their possible future variants. In the third chapter a design of an Air Traffic Control simulation framework is introduced. The mathematical-physical description of the spatial motion of the aircraft is also presented. The presented apparatus is the core of flight simulations. The following chapter shows the design of an agent-based Air Traffic Control system and describes the behavior of individual agents and their communication. The fifth chapter contains a description of the implementation of the application and the sixth chapter is devoted to the course of testing and evaluation. The final, seventh chapter summarizes the results of this work and considers the possibilities of further development.

Chapter 2

History of Air Traffic Control simulation

This chapter describes the history and development of air traffic control and the history of the development of technology and principles of air traffic control simulation.

2.1 A brief history of Air Traffic Control

When aerodromes were first put into operation, it was necessary to inform the pilots about the conditions on the aerodrome. Information about the runway, the wind direction, and the presence of other aircraft or vehicles in the area was delivered using signaling flags, flashing lights, or radio communication. This is the service we know today as Aerodrome Flight Information Service (AFIS) [8].

The rapid growth of air traffic together with the bad meteorological conditions in some aerodromes made it necessary for ground operators to provide apart from the state information, also the instructions when and where the pilots have to depart or land, to avoid possible collisions. And that was the moment when the history of Air Traffic Control began [8].

The first actual Air Traffic Control service was provided by aerodrome Croydon in the south of London. After a minor collision between an arriving and a departing aircraft, in 1922, the aerodrome published a Notice To Airmen (NOTAM) in which there was a statement that all pilots had to receive a sequence number for departure and the authorization from the tower for take-off. The authorization was signaled by waving a red flag from the observation tower. Croydon also made a breakthrough in establishing an aeronautical radio-navigation system, ground to air communications, the use of the Q code, and a control zone in which the pilot need to obtain the authorization from the controller before entering the zone. Also, the first standard procedures for departure were developed. They were oriented to satisfy the people who lived near the airports, who complained about the noise rather than focusing on safety reasons. Another service was provided by the control tower. The controller was marking the situation of the aircraft on a map with little flag pointers according to the radio signals the pilots sent. Therefore, the operator was able to send a warning signal to them in case he predicted that the aircraft were about to fly too close to each other [8].

Figure 2.1: Archie League as an airport operator [8].

Figure 2.2: Larry Jewell with an Aldis lamp [8].

Figure 2.3: Controller Bill Darby in radio-equipped airport control tower [21].

2.1.1 Origins of Air Traffic Control

Mr. Archie League was the name that embedded itself in history. He may be considered to be the father of aerodrome control or the pioneer of Air Traffic Control. Archie's career started in St. Louis around 1920. The photograph from 1929 shown in Figure 2.1 shows him at St. Louis dressed for cold weather, where he found employment at the airport as operator to prevent collisions between aircraft. For communication, he used simple tools: a red flag for "hold" and a checkered flag for "go" [8].

The profession pioneered by League soon got more sophisticated. The controllers tracked the position of en-route aircraft by using blackboards, maps, and boat-shaped weights. The en-route controllers had no way to communicate with the pilots but they were communicating with the airport radio operators, airline dispatchers, and airport controllers. Cleveland Municipal Airport established a radio-equipped airport control tower in 1930. During the next five years, about twenty cities followed Cleveland's lead. On Figure 2.3 Controller Bill Darby with the latest equipment is shown in this 1936 view of Newark tower [8].

League joined the Federal service in 1937. He eventually became FAA's (Federal Aviation Administration) Air Traffic Service director and retired as an Assistant Administrator in 1973 [8].

Other important names that created the history are Earl Ward and Glen Gilbert. Name Earl Ward belongs to an airmail pilot who was working for American Airlines in Chicago. He got worried about the unstoppable increase of flights and he assumed that sooner or later an air collision would happen unless the rules were properly set. He then tried to develop a set of rules and figure out how to implement them. The considered maintaining radio contact between all pilots and delivering information to affected aircraft by the presence of the others, crucial. However, this did not guarantee the safety of all flights, unless all other operators followed these rules and used the same approach. Trans World Airlines, United, and Eastern were convinced by Earl Ward to start using his methods and in Chicago, 1935-36, these rules were proven to be very effective in practice [21].

In case of conflict, the solution was meant to be achieved by the pilot actions. Glen Gilbert, Ward's assistant, however, insisted that no solution can be safe unless all pilots comply with clearances provided by the ground personnel, such as altitude adherence and directions flown. Gilbert was given the task to publish these rules. Many of these rules still exist today and they are the basics studied by all Air Traffic Control students. This is the main reason why Glen Gilbert may be credited with the design of the Traffic Separation Rules and Earl Ward with the creation of the first Control Center. These two are considered the fathers of Air Traffic Control in particular because of the substantial difference from the service provided by the Airway Division until then. Since then, elements of active controls were introduced, where the ground operator had to guide the pilots to ensure safe distances between them and not just to inform the pilots of important aerodrome conditions, other traffic in the area or weather. This ground operator of the '20s has evolved in the Air Traffic Controller we know today [21].

Some would give more credit to Gilbert than Ward because he detailed many of the rules that gave birth to Aerodrome, Approach, and Area Control. He used the aerodrome circuit and its legs to sequence traffic for the aerodrome. The circuit was a natural track a pilot would fly to first identify the airfield conditions and then perform the landing. Gilbert established the downwind, the basic and the final legs, the extension of the downwind for sequencing, and the "T" landing indicator. He introduced a spacing of departing traffic by time according to speed and departure tracks and the time separation along a track after reporting on significant visual way-points. As for the Area, he established the vertical separation based on 1000 feet, which later introduced the Flight Level system. This is why Gilbert has left his prints on what is now known as the Air Traffic Rules [21].

2.1.2 Air Traffic Control equipment

In addition to the signal flags mentioned, other visual tools were used, such as the Aldis lamp. On the historical picture shown in Figure 2.2 is Larry Jewell, photographed in 1933 while operating an Aldis lamp and sending the light signals. Radios were known but not all planes were using them. Not even all aerodromes were so equipped. Moreover, radio devices were far from reliable. Essential tools of those days were the Aldis lamp or light gun, which provided better protection than distorted and often unreadable radio signals (Figure 2.2) [21].

In Newark, in 1935, the first Flight Monitoring Center was established and it was housed in the middle of the aerodrome terminal below the tower. There was an area chart, a big clock on the wall, a notepad to write down all flight trajectories and a radio receiver/transmitter. This primitive center was the predecessor of the later ATC centers but in those days they were called the "radio rooms" [21].

Although most of people believe that radar, radio navigation, and ATC were born together, radar was introduced in ATC after World War II and continued a long and fastidious way into getting integrated as ATC's most prominent tool. Radio and Communication systems were and still are by far the major tools of the trade. The war brought along with it some benefits for the ATC that helped the pilot to navigate beyond visual conditions and controllers to detect planes positions on a screen. Although the ATC principles remained the same, these tools have changed the character of the job drastically: it was possible now to control the flights in a more direct way than ever before [21].

The radio goniometers that initially helped E. Ward to plot aircraft positions on a map could help pilots in almost the same way to locate fixed radio beacons on the ground using radio signals only. It was possible now to navigate without having to check for the light beacons [21].

The radar that was used during the Battle of Britain had a major disadvantage: it did not have a rotating antenna and the accuracy of the target direction was poor. In the United States, between 1943-46, they decided to use it only for aircraft on their final landing track - some 10 to 20 miles before the runway, using antennae that would move in small angles covering the cone within the landing route where the aircraft was detected on horizontal plane and vertical. This was the Ground Controlled Approach (GCA) and it was the very first radar used in ATC, even to our days, although its technology has been abandoned. Using the GCA was very flexible: the plane had to be equipped only with radio and the controller was guiding the pilot to stay on its final three-dimensional path on course to the runway by advising him on altitude and direction corrections. Its major disadvantage was that it could only handle one aircraft at a time and the pilot had to use his own eyes to complete the last 2 miles before the runway [21].

The GCA was later named the Precision Approach Radar (PAR). This title was fully in use until about the late 50's when another type of more precise system was developed: the Instrument Landing System (ILS). The ILS, more precise than PAR itself, is still the major radio landing tool for all important aerodromes even today. It provides automatically corrected signals for the accurate positioning of the aircraft relative to the horizontal and vertical path during the final landing and can be linked with the plane's autopilot without any other assistance from the controller. However, it requires more airborne and ground equipment and is more delicate during the installation because of the surrounding obstacles. Its big advantage is that it is usable for more than one landing aircraft at a time and guides closer to the runway than a PAR. The ILS is practically used from about 20 up to 30 miles before the runway and guides the aircraft until a few feet above the runway threshold. It is only due to the extremely heavy fog that some ILS landings cannot be completed [21].

Computers were first introduced experimentally in 1956. Within a few years, the FAA was developing complex systems. From 1965 to 1975, the FAA installed a computerized system that for the first time wedded data from the flight plan with readings from the radar and transponder, producing alphanumeric screen readouts of data on the plane's position, speed, and altitude. Controllers could at last "see" flights in three dimension, and do so continually [21].

2.1.3 Introduction of airways

The Area Controllers who were controlling far larger areas had not yet been equipped with radar and had to wait for many more technical improvements to come, although their traffic increased as well. Around 1950, in the United Kingdom, the first names were officially adopted for some renown airways. The first one ever was the "Green One" (G1), which still exists today, bringing traffic from the United Kingdom, Dover (DVR beacon) to Central Europe via Belgium, Kokseide (KOK beacon), although the official name now is GOLF ONE – the color names have been abandoned [22].

The Atlantic crossings by air were not yet as frequent but were expanding. In 1955, ICAO introduced the 1,000 feet vertical, 120 miles lateral, and 30-minute longitudinal separation between trans-Atlantic aircraft. It is important to know that in those days, international rules have started appearing, affecting all flights over very large regions. The Air Traffic Controller's job became an international profession [22].

2.2 History of Air Traffic Control simulation

The ATC training offers a good example of the appropriate application of high technology simulation. Training can be accomplished without jeopardizing flight operations, an unusual events may be practiced and exposure to learning situations can be controlled. Ideally,

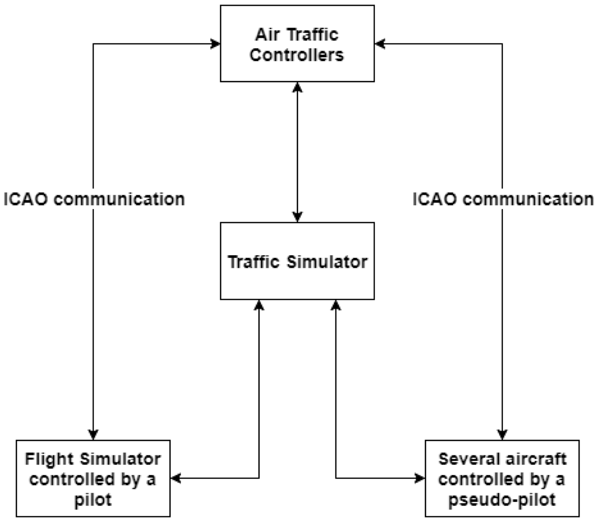


Figure 2.4: ATC simulation architecture [13].

a large portion of ATC training should be accomplished in a simulated training environment. In most cases, the use of simulations can reduce the risk involved in developing a new airport or modifying an existing airport or its operations, at a fraction of the cost of the proposed changes. The use of a real-time human-in-the-loop simulations is extremely useful for evaluating controller workload and identifying factors affecting airport safety and efficiency. Also, operational data such as departure rates and taxi times and pilot-controller communication information, such as transmission rate and duration, can be collected and analyzed.

2.2.1 Simulation architecture

A common architecture of an ATC simulator is shown in Figure 2.4. The controller, pilot, and pseudo-pilot are interacting through a traffic simulator and a simulated radio. The controller is in charge of virtual traffic. Since it is too costly to have a pilot in a simulator for each virtual aircraft, pseudo-pilots are used. A pseudo pilot is a human operator that flies many aircraft simultaneously. The pseudo pilot is in charge of the voice communication of all the aircraft he flies. It is usual, in a research context, to have one aircraft piloted through a flight simulator to increase the realism of the simulation or to test particular scenarios. In this case, the simulation scenario is focused on the aircraft controlled by the pilot. The pilot in the simulator is only in charge of the voice communication of the unique aircraft he flies [13].

2.2.2 First Air Traffic Control simulators

The beginning of Air Traffic Control simulation started even before the days of digital technology. The first multi-target dynamic simulator used 42 pseudo-pilots, each operating a servo-driven optical projector on a large movie screen. This ATC research system served as a modeling tool for airspace and procedures design. It offered the ATC a training capability, but the sheer volume of people required to run a simulation made the training function impractical. The simulator is shown in Figure 2.5 [5].

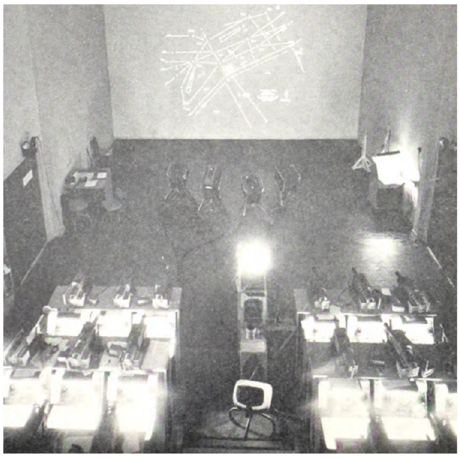


Figure 2.5: Original Air Traffic Control simulators [5].

During the 1950s, aviation simulation research began to investigate the training effects of simulated navigation displays and the use of simulation to train other aviation tasks, such as Air Traffic Control. In 1951 the first Air Traffic Control simulator was developed. It consisted of 16 link trainer "crabs" which traveled over maps on tables in one large room. These were telemetered to Cathode Ray Tube (CRT) displays in the "control tower" next door. This device was the beginning of the Air Traffic Control Simulation Facility which is now located at the FAA Technical Center in Atlantic City, New Jersey [25].

The simulation of the Air Traffic Control was not only used for training purposes. A real-time simulator for studying terminal air sequencing control was developed in 1960. It was based on digital control computer RW-300 and specialized hardware [31]. The simulator was set up in four distinct phases. The first phase used the manual Instrument Flight Rules (IFR) approach control system, with manual radar tracking systems and voice communications. The second phase used semi-automatic tracking but retained voice communications. The third used automatic tracking, but still within the framework of ordinary voice communications. Finally, the last phase used fully automatic tracking and automatic control communications based on some sort of simulated data link. It was concerned with such problems as the amount of latitude which could be granted to the controllers or the pilots in terminal sequencing and effects of various modes of tracking and air to ground communications in terminal maneuvers. This simulation project tried to answer fundamental questions concerning manual, semi-automatic, and fully automatic control of terminal traffic. It showed the implications of these various configurations on the workload of human controllers and pilots. It pointed out specific areas where air traffic could be automated and how much could be automated. However, this study is limited by the technologies that were used at the time. Similar principles for studying and evaluation of human controllers' workload are used today [11].

In 1988 Fred Johnson and Mike Male founded Micro Nav company. Both Air Traffic controllers launched Micro Nav's first-generation Air Traffic Control simulator - Flexible Independent Radar Skills Trainer (FIRST). Mike and Fred pioneered the use of PCs for Air Traffic Control simulation, making it an affordable solution for the first time. In 1991, they developed the FIRST tower simulator and a few years later in 1994, they came up with a full 360° projected FIRST tower simulator. Until today, Mirco Nav is a leading

Figure 2.6: Micro Nav's first generation of Air Traffic Control simulator [17].

specialist developer and a supplier of Air Traffic Control simulators and training systems, with installations across 38 countries [17].

State-of-the-art ATC simulators are commonly used for Air Traffic Management (ATM) research and training. They are capable off simulating new airport operational concepts and procedures and the human factor in the control tower. It allows rapid and flexible scenario generation, efficient training exercises, and faster and more precise validation of new concepts and procedures. All these technologies lead to significant cost savings and the security improvement of all members of air traffic.

2.2.3 Control tower simulation

Considering the latest technological progress of today, a 360° tower is commonly used for Air Traffic Control simulators. They are suitable for training new controllers or developing new technologies and concepts in air traffic management that will not only provide some relief from holiday travel headaches but increase the efficiency, safety, and environmental friendliness of air transportation. One of these is located at National Aeronautics and Space Administration (NASA) Ames Research Center in California's Silicon Valley. It is uniquely equipped to recreate the experience of being in any Air Traffic Control tower, at any airport, with any amount of traffic. Virtually every Air Traffic Control tower in the United States utilizes some form of NASA-developed technology, and any of them can be recreated here. Inside the simulator, everybody believes that they are inside the control tower of their local airport until another location appears outside the windows. The view is recreated on 12 projection screens from high-resolution aerial photography, elevation data, and close-up digital photography. In the simulated world of aviation, planes taxi along the runway, take-off, and land just as they would at a real airport. These simulations are created from a database that includes 3D modeling of more than a hundred aircraft and ground vehicles. For researchers in other fields, this simulation platform can even take them virtually to the surface of Mars [20].

During a simulation, data are recorded containing all elements of the simulated airspace, including voice transmissions between pilots, and summary statistics of aircraft activity, such as taxi times, runway waits and departure rates — allowing NASA researchers to replay an entire simulation run and examine how their tools performed in the hands of real users. Their analyses of these different steps in the process allow them to recommend ways to optimize the routing of planes, the timing of their movements, and the communication among different parties responsible for making a hectic airport move like clockwork [20].

2.2.4 Air traffic operations simulation

Air Traffic Control could be viewed from a higher perspective of global airspace and air traffic flow. For example one of the research projects, the AgentFly ATM Simulation Suite

Figure 2.7: Simulated Air Traffic Control tower at NASA Ames [20].

was developed to be a complex tool for modeling and simulation of air traffic and air traffic management [2].

The simulation consists of flights by Instrument Flight Rules (IFR), or Visual Flight Rules (VFR), and unmanned air traffic and main actors - Air Traffic Controllers, pilots, and airline operation centers. The AgentFly platform is an agent-based simulation framework designed to be used as Fast-Time Simulation (FTS) as well as Real-Time Simulation (RTS). The FTS mode is suitable for what-if studies and analysis, validation of new concepts, or interconnection with other FTS systems. The system allows running various options, settings, and parameters quickly to evaluate changes. The RTS mode is suitable for connection with other real-time systems and can include humans-in-the-loop, e.g., pseudo-pilots or Air Traffic Controllers [2].

Agent-based simulation allows precise control of simulation time, large-scale scenarios with various actors (thousands of Air Traffic Controllers and tens of thousands of aircraft), and controlled uncertainty and randomization. The architecture of the system is highly modular, widely configurable, and flexible, and it allows easy creation of scenarios [2].

One of the major components of the simulation is the model of human cognitive behavior. The model is designed to be generic and it can model various human actors. The AgentFly currently supports executive and planning Air Traffic Controllers in different types of sectors: traffic manager, pilot, a remote pilot for Unmanned Aircraft Systems (UAS), airline operations center operator, and others under development. New actors for future concepts are also supported, e.g., incoming traffic allocator, extended planner, etc. Each actor (air traffic, controller, pilot, etc.) can have a specific configuration or the same configuration can be used for a group of actors [2].

Their cognitive behavior model is based on Multiple Resource Theory using visual, auditory, and psychomotor resources. Human behavior is defined as a set of tasks that represents each actor's interaction with system, environment, and other actors. The AgentFly emulates inputs (e.g., controller's screen), communications (radio, telephone, datalink, etc.), outputs (keyboards, mouse), or environment (view out of windows). The model measures total cognitive workload, execution delays, the composition of tasks, and other metrics related to human behavior [2].

AgentFly use an aircraft simulation model based on Base of Aircraft Data (BADA) performance model family 3 and 4 which allows the precise computation of vertical profile and measures fuel consumption, flown distance, duration of the flight, etc. Other simpler models represent smaller or unmanned aircraft or more detailed models for the specific

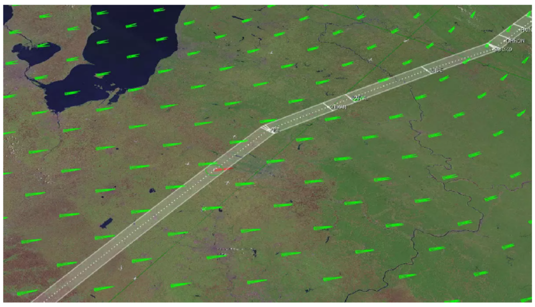


Figure 2.8: Wind Influenced Trajectory in AgentFly [2].

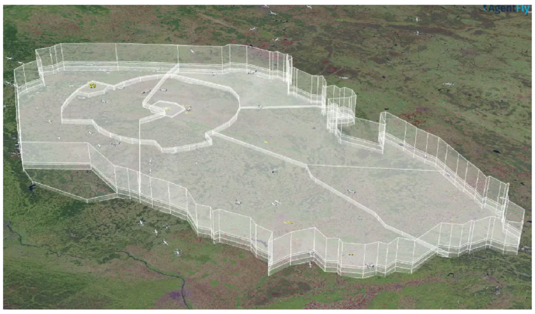


Figure 2.9: Airspace Sectors in AgentFly [2].

aircraft type. The trajectory can be planned using standard “navaids”, allowing partial or complete free-routing or full 4D trajectory. The trajectory can be optimized to achieve increased efficiency of flight [2].

Chapter 3

Implementation of an air traffic simulation framework

The main idea behind designing and implementation of a simulation framework is to perform various simulation tasks under different conditions. The design described in this work is focused on modularity and is multipurpose. Requirements include the ability to simulate different numbers of aircraft with different flight characteristics and different computationally demanding requirements. Furthermore, the design should enable the integration and interconnection of multiple Air Traffic Controllers, to enable the creation of a larger ecosystem. The proposed system should, therefore, be scalable within the available computing power.

For Air Traffic Simulation framework is typical to simulate simultaneously members of Air Traffic Control and members of air traffic. To meet the requirements for the possibility to change the simulation environment and at the same time to simulate more air traffic participants, it is necessary to simulate individual participants separately or externally. With a separated block calculating the spatial movement of aircraft is possible to replace it with higher or lower fidelity simulation. It is possible to use own physical models or use available or commercial resources.

For tasks focused on collision avoidance is preferred usage of high fidelity simulation. On the other hand, observing decision making during non-standard situations requires only low fidelity simulation. There is also a compromise on system scalability. While performing large a long term task are more suitable simulations with lower fidelity. As a result, it is necessary to determine the fidelity of the simulation according to the given task.

The design of the simulation framework includes the possibility of extension for use in several cases. In the following sections are specified individual use cases and their architecture. Within the design of various use cases, the emphasis is placed on the possibility of extending the framework for various human air traffic participants. In the design described in this work, are processed two general use cases. The first use case is focused on the involvement of a human pilot in the simulation framework and the evaluation of his behavior. The evaluation of the human pilot is focused on determining the extent to which the pilot follows the controller's instructions and the extent to which he is flying on the assigned route. The second described use case include human Air Traffic Controller and autonomous pilots. The controller's evaluation is focused on evaluating the effectiveness of aircraft guidance and the number of possible collisions.

All mentioned use cases are described in detail and specified in the following sections. For a better understanding of the issue, the following sections also describe the individual participants in air traffic and its management. Next, their equipment for perception and interaction with other participants is described. There are also listed prescribed rules for specific members of air traffic and their standard behavior. There is also described the environment and its structure, in which are all participants located.

3.1 Framework specifications

This section describes the specifications and components of the proposed simulation framework. The architecture and possible use cases are also described below.

3.1.1 Generic Air Traffic Control framework

The key components and functionalities for the Air Traffic Control simulation framework are as follows:

- Airspace - division and categorization of airspace, where the duties and responsibilities of individual air traffic participants are defined.
- Aerodrome - representation of the airport, runways, taxiways, arrival routes, departure routes, airport circuit, etc.
- Air Traffic Control - includes radar emulation, aircraft scheduling, communication, ground procedures.
- Weather - wind, visibility, other weather conditions.
- Aircraft - flight dynamic model, ground dynamic model, autopilot, communication module, flight rules.

The need to divide airspace is based on different regulations in different flight levels and specific areas. For the proper functioning of Air Traffic Control, it is necessary to be able to define individual classes and areas of airspace within the framework.

In addition to airspace, it is necessary to ensure the representation of airports. Individual airports must contain runways, taxiways, waiting points, and other late parts of the airport. In addition to the ground representation, it is necessary to define the airport circuit and arrival and departure routes.

Emulation of equipment such as radar is necessary to provide Air Traffic Control services. With the help of radar emulation, the perception is limited to seeing the only aircraft around the airport and having realistic information about the environment. One of the main activities of the controller is the planning of arrival, departure, and the creation of time windows for individual flights, for which the aircraft planner is also an important part of the controller. An important part of the operation of Air Traffic Control is the communication module, which allows communicating with aircraft or other controllers.

Another factor that has a significant impact on air traffic is the weather. Important parameters include speed and wind direction, or visibility. It is also necessary to include the time that affects visibility.

In addition to flight dynamics, ground movement must be included for aircraft movement. An autopilot is required to control the aircraft. For planning and operating is a crucial decision-making module. The decision-making module also includes flight rules, which determine the specifications and course of the flight.

3.1.2 Applicable Use Cases

This subsection describes two different use cases of the proposed framework and their specifications.

Use Case 1: Pilot operation in synthetic ATC environment

The first use case assumes the presence of a human pilot, autonomous controllers, and several other autonomous pilots. In this case, the human pilot will follow the instructions of the pilot and fly according to the flight regulations in several scenarios. For simplicity, communication by the pilot is automatically generated based on the position of the aircraft, or as an automatic positive reply to the controller. All instructions are displayed to the human pilot on the pilot task display. The pilot's evaluation is based on measuring the pilot's deviation from the expected flight path and the time deviation from the expected flight time window around specific points. This use case is used primarily for pilot training. Within this use case it is necessary to add the following components:

- Flight controls - user interface for piloting the aircraft.
- Pilot task display - display showing the expected route and instructions from the controller.

Appropriate flight controls are essential for piloting aircraft. The ideal is to use specialized hardware such as a stick, throttle, and pedals. When using other controls, the resulting pilot evaluation will be distorted.

The pilot task display is used to display the communication from the controller. Next, the trajectory that the pilot should follow is drawn. This display is not part of the aircraft equipment, but in the proposed simulation framework it is used to interpret the instruction from the controller and serves as a navigation display.

Use Case 2: Air Traffic Controller operation

In the second use case are all pilots autonomous and the Air Traffic Controller is human. The human controller will have to organize and schedule all aircraft in the area and solve possible aircraft collisions. The controller communication is realized through the communication module and propagated to specific aircraft. The information about the environment and traffic are stored and displayed in the ATC user interface. The controller's evaluation is based on the time when aircraft are in the collision course, on-time delays of aircraft and on-time spend in holding patterns. This use case is used for Air Traffic Controller training. For integrating this use case in the simulation framework are needed the following components:

- ATC user interface,
- ATC Communication module.

A key element for human Air Traffic Control is the user interface. It has several key parts right away. The primary part provides the controller radar information from the airport

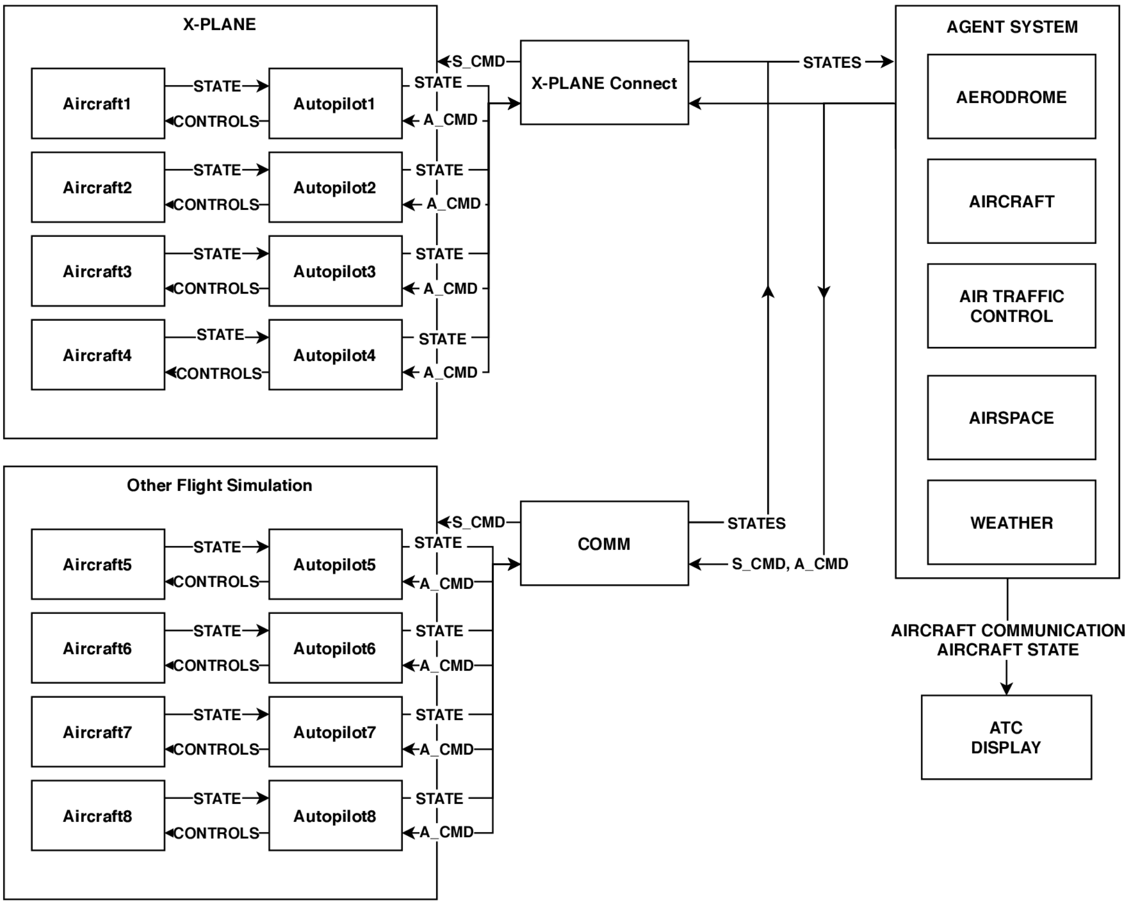


Figure 3.1: Architecture of ATC simulation environment.

area and the flight parameters of individual aircraft. The next part of the interface shows the ground situation at the airport, including the runway in use and all present aircraft. An important component of the interface is the visualization of the flight planner, where time slots for individual aircraft are defined. The interface contains other modules that provide additional information about the current state of the airport or weather.

A communication module is used for communication, which provides an interface for sending messages to individual pilots. This module also generates ICAO communication. An alternative is to use speech and speech recognition technology, but this is a question of future development.

3.2 Simulation framework architecture

This section shows the general architecture of the proposed simulation framework and then describes the modification for the first Use Case.

3.2.1 Generic framework architecture

The designed architecture of the simulation framework for ATC simulation is divided into parts shown in Figure 3.1. The main idea behind the architecture is to create reusable blocks, which could be completely replaced if the same protocols are maintained.

Flight dynamics models that define the aircraft motion are situated in the left blocks. There are running motion simulations, which include flight controls and other conditions and flight parameters. The aircraft are controlled by autopilots.

The X-Plane simulator was selected due to its emphasis on flexibility. It has a fully open structure that allows the user to modify majority of provided components. With thousands of compatible add-ons, it is highly adjustable and it is capable of simulating and displaying a large amount of objects without slowing down [15]. More information about X-Plane introduced in section 3.5.

The connection between motion simulation tools and other parts of the system is provided by the communication modules X-Plane Connect for X-Plane or COMM for other variants of flight simulation. Communication modules deliver commands to autopilots and commands to the flight simulation software (i.e. create new aircraft). On the other hand, the communication module provides the aircraft state vectors. The state vector of an aircraft contains following variables: longitude, latitude, altitude, airspeed, heading, pitch, and roll angles.

An Agent system block, which is described in next chapter, has stored all information about aircraft, environment, airports, events, and other variables. Actual aircraft states are determined, such as specifying the position and it's action i.e. if the aircraft is in Control Zone (CTR) zone if it's on the circuit and is preparing for landing etc. It also contains all decision making processes. More specific details about the Multi-Agent system are described in the next chapter.

All information about aircraft, airport's and communication are visualized in ATC-Display module, which serves for evaluation and testing purposes.

Modifications and additional blocks for specific use cases are described in the following subsections.

3.2.2 Use Case 1: Pilot operation in synthetic ATC environment

Figure 3.2 shows the architecture for Use Case one. The human pilot uses the controls to fly the aircraft in the flight simulation. The state of the aircraft and the environment are visualized to pilot through the visual X-Plane output. Any hardware that is compatible with X-Plane can be used as controls. Conditions permitting, the pilot can perform flight in any advanced flight simulator using X-Plane. The current state of the aircraft, the phase of the flight, and other information are stored and handled by the agent system, where automatic responses to Air Traffic Controller calls are also generated. According to the defined flight plan, the trajectory is displayed on the pilot task display. This trajectory and its parameters are changing after the Air Traffic Controller decisions. For an overview, the display also shows all communication with the controller.

3.3 Air Traffic Control

This section describes all air traffic participants, their equipment, duties, and responsibilities.

3.3.1 Air Traffic Control operations

In the following subsections are listed members of Air Traffic Control and all their operations.

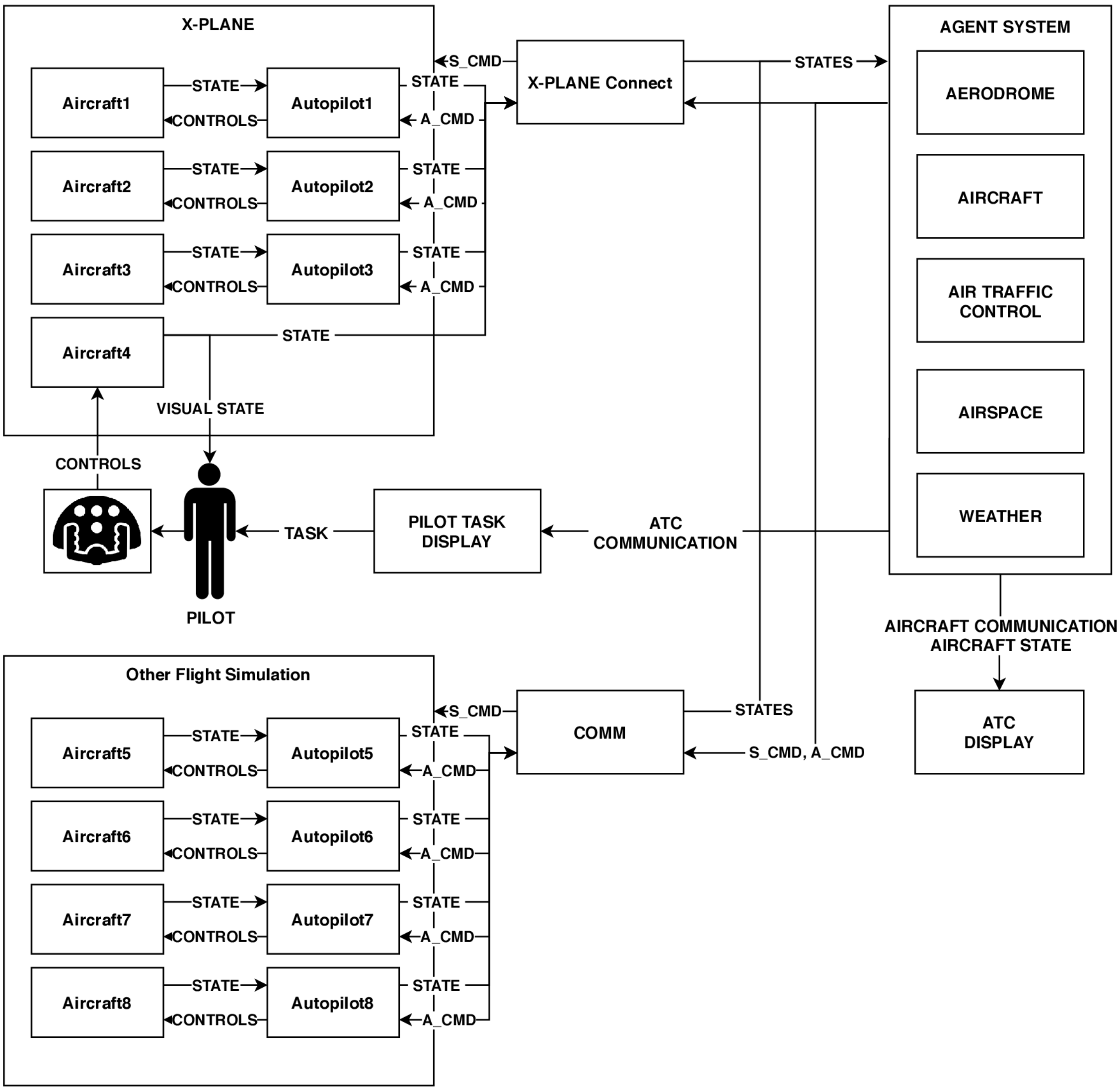


Figure 3.2: ATC simulation environment for Use Case 1: Pilot training.

Air Traffic Control Tower

The tower is a tall, windowed structure located on the airport grounds. Visual observation from the airport control tower servers as a primary method of controlling the immediate airport environment. For the separation and efficient movement of aircraft and vehicles are responsible for Air Traffic Controllers. This includes aircraft and vehicles operating on the taxiways and runways of the airport itself, and aircraft in the air near the airport. Depending on the airport procedures it is generally 9 to 18 kilometers [8].

To assist with controlling air traffic at larger airports are also available surveillance displays. A radar system called secondary surveillance radar may use Controllers for airborne approaching and departing traffic. These displays are included a map of the area, the position of various aircraft, and data tags which include aircraft identification, altitude, speed, and other information described in local procedures. In bad weather conditions, the tower controllers may also use Surface Movement Radar, Surface Movement Guidance, and control systems or advanced Surface Movement Guidance and Control Systems to control traffic on the maneuvering area (runway and taxiways) [8].

For tower controllers, the areas of responsibility fall into three general operational disciplines: ground control, air control, and flight data and clearance delivery [8].

Air Traffic Control Tower equipment

The current equipment of the Air Traffic Controllers is the result of the improvements made in the few previous decades. The computer system controllers use aggregates data from various sources and show them conveniently on the screen. These data include aircraft positions computed from signals from multiple radar stations, flight id, altitude, speed, and flight plan. To be able to display the additional information the secondary radar system must be used. The standard radar emits radio waves and measures the interval between the pulse and when the waves reflected from any solid objects arrive back. This way the position of objects can be determined but the system is prone to interference and reflections from tall buildings, mountains, or even cloud formations. The secondary radar also emits an interrogation signal and aircraft equipped with a transponder will respond according to the interrogation mode. This way the aircraft's flight id and altitude can be shown on the radar screen. The aircraft speed is computed from a few previous positions of the aircraft and its altitude. Another tool used in Air Traffic Control nowadays is Air Traffic Flow Management (ATFM). This system predicts the air traffic density based on the available flight plans and if it reaches the capacity of the destination airport or sector the aircraft is delayed on the ground before it even takes of saving a considerable amount of fuel. The process of computing the airspace capacity utilization is very complex and influenced by many factors most important being the weather and is therefore automated and handled by computers [24].

Ground Control

Ground control is responsible for the airport "movement" areas, as well as areas not released to the airlines or other users. There are generally included all taxiways, inactive runways, holding points, and some transitional aprons or intersections where aircraft arrive, having vacated the runway or departure gate. At each airport in local documents and agreements are clearly defined exact areas and control responsibilities. Any aircraft, vehicle, or person walking or working in these areas is required to have clearance from ground control. This is normally done via VHF/UHF radio, but there may be special cases where are used other procedures. Aircraft or vehicles without radios must be led by vehicles with radios or respond to ATC instructions via aviation light signals. Airport employees who are working on the airport surface usually have a communications link through which they can communicate with ground control, commonly by handheld radio or even cell phone. Ground control is important for the smooth operation of the airport, because this directly impacts the sequencing of departure aircraft, affecting the efficiency and safety of the airport's operation [8].

Air Control

For the active runway, air control is responsible for surfaces, commonly known as "tower control". Air control instructs aircraft for take-off or landing, ensuring that prescribed runway separation will be accomplished at all times. If the air controller detects any unsafe conditions, a landing aircraft may be instructed to "go-around" and be re-sequenced into the landing pattern. This re-sequencing will depend on the type of aircraft and flight and may be handled by the air controller, approach, or terminal area controller [8].

Within the tower, is an absolute necessity a highly disciplined communications process between the air control and ground control. Air control must ensure that ground control is aware of any operations that will impact the taxiways, and work with the approach radar controllers to create secure separation between the arrival traffic to allow departing aircraft to take-off and to allow taxiing traffic to cross runways. On the other hand, ground control needs to keep the air controllers aware of the traffic flow on their runways to maximize runway utilization through effective approach spacing [8].

Clearance delivery and flight data

Clearance delivery is the position that proceeds route clearances to aircraft, typically before they commence taxiing. These clearances contain details of the route that the aircraft is expected to fly after departure. Clearance delivery or, at busy airports, Ground Movement Planner (GMP) or Traffic Management Coordinator (TMC) will, if necessary, coordinate with the flow control unit or relevant radar center to obtain releases for aircraft. When occurs extremely high demand for a certain airport or weather or airspace becomes a factor, there may be re-routes or ground "stops" that may be necessary to ensure the system does not get overloaded. The main responsibility of clearance delivery is to ensure that the aircraft has the correct aerodrome information, such as airport and weather conditions, time restrictions relating to that flight, and the correct route after departure. To ensure that the aircraft reaches the runway in time to meet the time restriction provided by the relevant unit is this information also coordinated with the relevant radar center or flow control unit and ground control. At some airports, clearance delivery also plans engine starts and aircraft push-backs [8].

Flight data is the position that is responsible for ensuring that both controllers and pilots have the most current information: runway closures, airport ground delays/ground stops, outages, pertinent weather changes, etc. Flight data may inform the pilots using a recorded continuous loop on a specific frequency known as the Automatic Terminal Information Service (ATIS) [8].

Approach and terminal control

Many airports have a radar control facility that is associated with the airport. In most countries, this is referred to as terminal control. While every airport is different, terminal controllers usually handle traffic in a 56 to 93 kilometers radius from the airport. If there are many busy airports close together, one consolidated terminal control center may service all the airports. The airspace boundaries and altitudes assigned to a terminal control center, which vary widely from airport to airport, are based on factors such as traffic flows, neighboring airports, and terrain [8].

Terminal controllers are responsible for providing all ATC services within their airspace. Traffic flow is broadly divided into departures, arrivals, and overflights. As aircraft move in and out of the terminal airspace, they are handed off to the next appropriate control facility (a control tower, an en-route control facility, or a bordering terminal or approach control). Terminal control is responsible for ensuring that aircraft are at an appropriate altitude when they are handed off, and that aircraft arrive at a suitable rate for landing [8].

Not all airports have a radar approach or terminal control available. In this case, the en-route center or a neighboring terminal or approach control may co-ordinate directly with the tower on the airport and vector inbound aircraft to a position from where they can land visually [8].

Area control center

ATC provides services to aircraft in flight between airports as well. Pilots fly under one of two sets of rules for separation: Visual Flight Rules (VFR) or Instrument Flight Rules (IFR). Air Traffic Controllers have different responsibilities to aircraft operating under the different sets of rules. While IFR flights are under positive control, in the United States and Canada VFR pilots can request flight following, which provides traffic advisory services on a time-permitting basis and may also provide assistance in avoiding areas of weather and flight restrictions, as well as allowing pilots into the ATC system before the need to a clearance into certain airspace [8].

En-route Air Traffic Controllers issue clearances and instructions for airborne aircraft, and pilots are required to comply with these instructions. En-route controllers also provide Air Traffic Control services to many smaller airports around the country, including clearance off of the ground and clearance for an approach to an airport. Controllers adhere to a set of separation standards that define the minimum distance allowed between aircraft. These distances vary depending on the equipment and procedures used in providing ATC services [8].

3.3.2 Flight operations

This section describes the classification of airspace and services that are provided in the given areas. The individual participants in air traffic and their main procedures, actions, and responsibilities are described below. The individual phases of flight and flight rules for visual flight or flight according to the instrument are also given in the following subsections. Furthermore, the avionics in aircraft for navigation and communication are described here, and the commonly used equipment available to individual Air Traffic Controllers is also listed below.

Flight phases

The job of the Air Traffic Controller is to provide the safe, orderly, and expeditious flow of aircraft through the airspace system. One Air Traffic Controller after another takes responsibility for a specific leg of the trip ensuring that the aircraft is safely separated from other air traffic and vehicles [21].

As a first step, a pilot files a flight plan with the flight service station, or an airline files the plan automatically with the FAA. This plan outlines the route the aircraft will take and alternative plans in the event of an emergency or weather-related problem. Once the flight plan is approved, the pilot is ready to contact the ground controller for taxi instructions [21].

Take-off and departure

The ground controller notifies the pilot when it is safe to push the aircraft out of the gate or enter the controlled movement area at the airport, issues instructions to a runway, and places the aircraft in a departure sequence with other aircraft taxiing about the airport. The local controller in the tower assumes control of the aircraft and integrates its movement into the flow of traffic arriving and departing the runway. The local controller issues a departure clearance and grants permission to enter the runway and depart. After take-off, the local controller will assign the aircraft a frequency change to the departure controller, stationed in a radar room which may be at the airport or several kilometers away. The departure controller assumes responsibility for the plane through its ascent while safely avoiding other arrivals, departure, and transition aircraft [21].

En route

Once the flight departs the airport, controllers in the regional Air Route Traffic Control Center, also called en route centers, take over in sequence. Each center controls all aircraft, military, and civilian, in its defined portion of airspace, called a sector. The en route controllers direct and separate planes flying within their sector. They coordinate with pilots on weather conditions and issue instructions on speed, route, and altitude to ensure positive separation from other aircraft operating under Instrument Flight Rules. When the aircraft moves into a new sector, the next controller takes over [21].

Approach and landing

As the aircraft approaches its destination, the en-route center organizes the traffic into several streams and flows the traffic towards the airport. The center will hand off responsibility for the aircraft to the approach controller located in the same room as the departure controllers and will adjust the aircraft's speed, altitude, and flight path by issuing instructions to the pilot. Once an aircraft has been cleared for the approach, responsibility for the aircraft is transferred to the local controller. The local controller ensures that there is enough spacing between departures and arrivals, both in the air and on the runways, and gives the pilot clearance to land. After landing, the local controller gives responsibility for the flight to the ground controller who ensures safe passage from the runway to the gate [21].

Flight rules

The following subscriptions describe the flight rules and operations associated with them.

Visual Flight Rules

Visual Flight Rules (VFR) shall enable the most flexible operations of aircraft with less demand on certification of aircraft and licensing of pilots, with fewer regulations to be observed and if possible without pre-notification, mainly to enable private flights or other flights requiring a high level of flexibility. Following this, the pilot is highly responsive during the whole flight in all matters [12].

Flights performed under VFR originally used terrestrial navigation combined with dead reckoning navigation along with prominent landmarks. Only basic navigation equipment (magnetic compass, etc.) is required for VFR flights. Traditional VFR navigation is very demanding to the pilot and requires also visual contact to the ground. Today, area navigation methods e.g. Global Positioning System (GPS) are also used for VFR flights [12].

Regarding VFR flights, the surveillance task to locate other traffic is usually performed by the pilot from his aircraft through visual observation and may involve cooperative means such as position reports from other participants. The surveillance task to locate obstacles is in the same way performed by the pilot from his aircraft through visual observation. There is also a minimum safe height prescribed for VFR flights, but not exclusively due to obstacle clearance (e.g. noise abatement). The surveillance task to locate hazardous areas (e.g. weather hazards) during VFR flights rests also with the pilot and is performed through visual observation as well, supported by flight information such as weather forecasts [12].

Because visual observation of the aircraft surroundings plays a very important role for VFR flights, certain visibility minima are prescribed, depending on the airspace class. As clouds are in principle areas of zero visibility, they have to be avoided by all VFR flights [12].

Regarding VFR flights, the tactical ATM decision making task is usually performed by the pilot for his aircraft following standardized rules (e.g. right-of-way), mainly based on visual observation. Traffic information, recommendations, or restrictions may be given by ATC, depending on the airspace class [12].

The VFR flights require the filing of a standardized flight plan just in a few cases. The purpose of this measure is - among others - to enable the provision of alerting service to this particular aircraft, to facilitate the identification of this aircraft especially for cross-border flights and to enable ATC to issue an ATC clearance whenever needed in special cases (e.g. for the transition of airspace class C). However, normally VFR flight plans are not used for pre-tactical or strategic ATM decision making, e.g. VFR flights are not subject to the Air Traffic Flow and Capacity Management (ATFCM), which optimise traffic flows according to air traffic control capacity while enabling airlines to operate safe and efficient flights [12].

Instrument Flight Rules

Instrument Flight Rules (IFR) have been designed to enable reliable all-weather operations including zero visibility flight conditions, mainly to fulfill commercial demands on air transport in terms of reliability. Following this, the basic principle is to fly the aircraft only by making use of cockpit instruments as far as possible and reducing the need for an outside view to a minimum.

Flights performed under IFR normally use radio navigation, area navigation, inertial navigation, and combinations of the three. Therefore suitable navigation equipment such as VHF Omnidirectional Radio Range (VOR) receivers, Area Navigation (RNAV) equipment, etc. is prescribed for IFR flights. Presently there is the intention to move away from prescribing a set of minimum navigation equipment towards prescribing navigation performance standards [12].

Regarding IFR flights, the surveillance task to locate other traffic is usually performed by Air Traffic Control as a third party for all aircraft in a defined area of responsibility. Means to fulfill such responsibilities are a network of ground-based surveillance equipment (e.g.

radar systems) that are supported (or replaced soon) by cooperative onboard equipment such as a transponder or Automatic Dependent Surveillance-Broadcast. Other cooperative procedures to support the surveillance task can be position reports by the pilot. In uncontrolled airspace or airspace without radar coverage, generally speaking, the surveillance task to locate other traffic is performed cooperatively by all pilots involved, again simply using position reports. Provided that visual contact can be established, parts of the surveillance task are delegated to the pilot [12].

The need to locate obstacles is usually excluded as far as possible. This is done on one hand with prescribed minimum vectoring altitudes, minimum sector altitudes, and minimum IFR cruising levels. On the other hand, the dimensions of structures in the vicinity of airports are restricted by law; relevant obstacles are considered during designing the IFR approach and departure procedures. Whenever the instrument navigation precision is insufficient to ensure obstacle clearance (for example short prior touchdown), compensation by visual observation may be necessary, leading to take-off weather minima, approach minima, decision altitudes and minimum descend altitudes [12].

The surveillance task to locate hazardous areas (e.g. weather hazards) during IFR flights normally rests with the pilot. Hazardous areas are reported, predicted wherever possible, and made available for flight planning and decision making, while on-board weather radar or other similar systems enable real-time detection.

The tactical decision about the next maneuver(s) to guarantee a safe distance between two aircraft, between an aircraft and obstacles and between aircraft and hazardous areas. Tactical ATM Decision making is based on surveillance as defined above. Regarding IFR flights, the tactical ATM decision making task is usually performed by Air Traffic Control as a third party for all aircraft in a defined area of responsibility based on standard control procedures and rules such as radar vectoring, level allocation, and separation minima. This requires a reliable communication channel to enable the interaction between the pilot and Air Traffic Control in real-time. Provided that visual contact can be established, parts of the Tactical ATM decision making task can be delegated to the pilot, e.g. for IFR flights in airspace class D or E. In an uncontrolled air traffic environment, this task can also be done cooperatively by all pilots using intention reports [12].

Apart from a few exceptions, flights under IFR require a standardized flight plan, which is to be filed a defined period before the flight. The main purpose of this measure is, on one hand, to inform the responsible stakeholders and service providers about the flight in advance and on the other hand to enable ATM decision making such as Air Traffic Flow and Capacity Management (ATFCM) [12].

For the landing phase while flying by instruments is used Instrument Landing System (ILS). An Instrument Landing System operates as a ground-based instrument approach system that provides precision lateral and vertical guidance to an aircraft approaching and landing on a runway, using a combination of radio signals and, in many cases, high-intensity lighting arrays to enable a safe landing during Instrument Meteorological Conditions (IMC), such as low ceilings or reduced visibility due to fog, rain, or blowing snow [8].

An instrument approach procedure chart is published for each ILS approach to provide the information needed to fly an ILS approach during instrument flight rules (IFR) operations. A chart includes the radio frequencies used by the ILS components and the prescribed minimum visibility requirements [8].

Radio-navigation aids must provide a certain accuracy (set by international standards of ICAO). To ensure this is the case, flight inspection organizations periodically check critical parameters with properly equipped aircraft to calibrate and certify ILS precision [8].

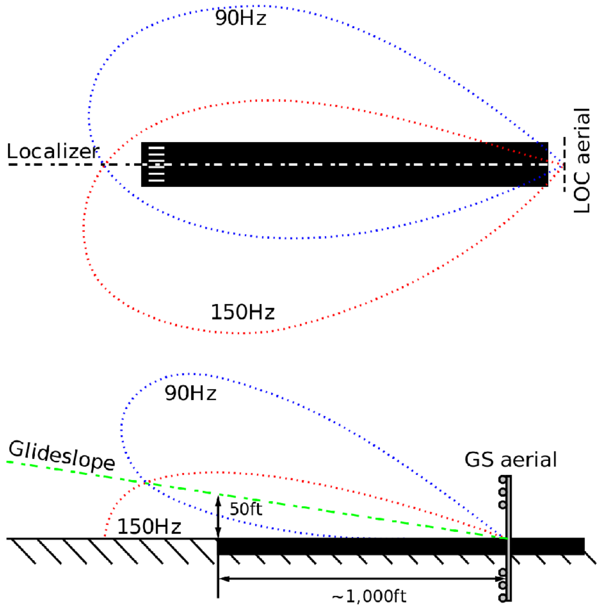


Figure 3.3: Components of Instrument Landing System - localizer and glide slope [10].

An aircraft approaching a runway is guided by the ILS receivers in the aircraft by performing modulation depth comparisons. Many aircraft can route signals into the autopilot to fly the approach automatically. An ILS consists of two independent sub-systems. The localizer provides lateral guidance and the glide slope provides vertical guidance (Figure 3.3) [8].

The localizer station is an antenna array normally located beyond the departure end of the runway and generally consists of several pairs of directional antennas. The localizer will allow the aircraft to turn and match the aircraft with the runway. After that, the pilots will activate Approach Phase (APP) [8].

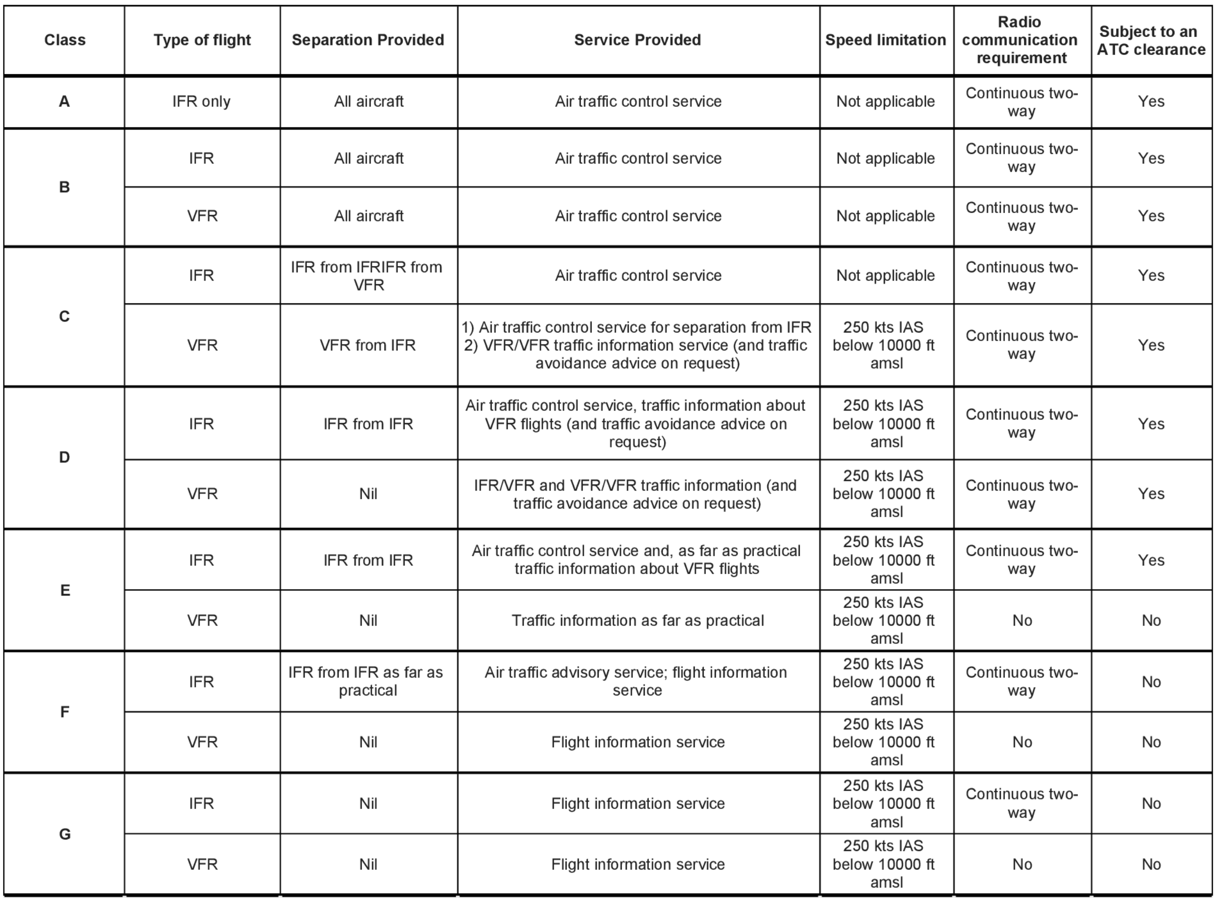
Glideslope station provides vertical guidance for incoming aircraft. The pilot has to correct to the left and a little upwards. The pilot controls the aircraft so that the glide slope indicator remains centered on the display to ensure the aircraft is following the glide path of approximately 3 above horizontal (ground level) to remain above obstructions and reach the runway at the proper touchdown point [8].

Airspace system

Air Traffic Service airspace is classified and designated by the following:

- Class A. IFR flights only are permitted, all flights are provided with Air Traffic Control service and are separated from each other [27].
- Class B. IFR and VFR flights are permitted, all flights are provided with Air Traffic Control service and are separated from each other [27].
- Class C. IFR and VFR flights are permitted, all flights are provided with Air Traffic Control service and IFR flights are separated from other IFR flights and VFR flights. VFR flights are separated from IFR flights and receive traffic information in respect of other VFR flights [27].

Table 3.1: Classification of Airspace [27].



Class	Type of flight	Separation Provided	Service Provided	Speed limitation	Radio communication requirement	Subject to an ATC clearance
A	IFR only	All aircraft	Air traffic control service	Not applicable	Continuous two-way	Yes
B	IFR	All aircraft	Air traffic control service	Not applicable	Continuous two-way	Yes
	VFR	All aircraft	Air traffic control service	Not applicable	Continuous two-way	Yes
C	IFR	IFR from IFRIFR from VFR	Air traffic control service	Not applicable	Continuous two-way	Yes
	VFR	VFR from IFR	1) Air traffic control service for separation from IFR 2) VFR/VFR traffic information service (and traffic avoidance advice on request)	250 kts IAS below 10000 ft amsl	Continuous two-way	Yes
D	IFR	IFR from IFR	Air traffic control service, traffic information about VFR flights (and traffic avoidance advice on request)	250 kts IAS below 10000 ft amsl	Continuous two-way	Yes
	VFR	Nil	IFR/VFR and VFR/VFR traffic information (and traffic avoidance advice on request)	250 kts IAS below 10000 ft amsl	Continuous two-way	Yes
E	IFR	IFR from IFR	Air traffic control service and, as far as practical traffic information about VFR flights	250 kts IAS below 10000 ft amsl	Continuous two-way	Yes
	VFR	Nil	Traffic information as far as practical	250 kts IAS below 10000 ft amsl	No	No
F	IFR	IFR from IFR as far as practical	Air traffic advisory service; flight information service	250 kts IAS below 10000 ft amsl	Continuous two-way	No
	VFR	Nil	Flight information service	250 kts IAS below 10000 ft amsl	No	No
G	IFR	Nil	Flight information service	250 kts IAS below 10000 ft amsl	Continuous two-way	No
	VFR	Nil	Flight information service	250 kts IAS below 10000 ft amsl	No	No

- Class D. IFR and VFR flights are permitted and all flights are provided with Air Traffic Control service, IFR flights are separated from other IFR flights and receive traffic information in respect of VFR flights, VFR flights receive traffic information in respect of all other flights [27].

- Class E. IFR and VFR flights are permitted, IFR flights are provided with Air Traffic Control service and are separated from other IFR flights. All flights receive traffic information as far as it is practical. Class E shall not be used for control zones [27].

- Class F. IFR and VFR flights are permitted, all participating IFR flights receive an air traffic advisory service and all flights receive flight information service if requested [27].

- Class G. IFR and VFR flights are permitted and receive flight information service if requested [27].

Aerodrome traffic zone

The Aerodrome Traffic Zone (ATZ) is established at airports where Air Traffic Control service is not provided. It is bound horizontally by a circle having a radius of 3 NM (5.5

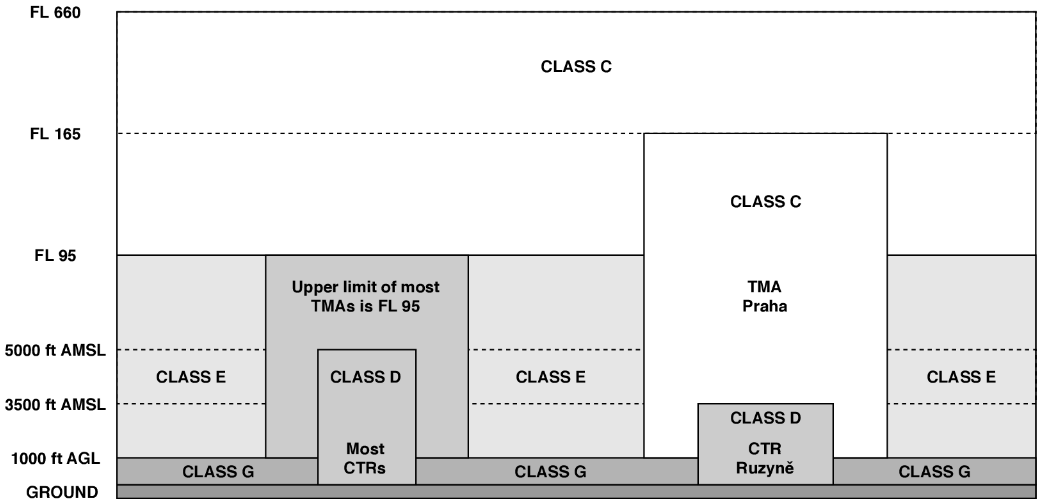


Figure 3.4: Classification of Airspace in The Czech Republic [16].

km) from the aerodrome reference point and vertically by the Earth's surface and an altitude of 4,000 ft (1,200 m). If Class C or D airspace or a restricted area interferes vertically or horizontally with such a defined area, the boundaries of the ATZ shall form the boundaries of these areas. Up to a height of 300 m above ground level, ATZ is class G airspace, above this height it is class E [37].

Control zone

The Control Zone (CTR) is controlled airspace extending from the ground to an altitude of 1,500 m. The CTR provides an Air Traffic Control service and is a Class D airspace. The horizontal boundaries of the CTR are marked on the ICAO aeronautical charts [37].

Terminal control area

A Terminal Control Area (TMA) is a controlled area usually established at locations where air traffic services routes converge near one or more major aerodromes. The lower limit of the TMA is usually from 300 m above the ground, the upper limit is different and extends up to the Flight Level (FL) 165 (4,950 m) and it is a class C or D airspace. The boundaries of the TMA are also marked on the ICAO aerial maps [37].

Aircraft equipment

The modern cockpit of an aircraft is full of avionic equipment, including control, monitoring, communication, navigation, weather, and anti-collision systems. For the line of sight communication such as aircraft-to-aircraft and aircraft-to-ATC is used VHF, HF, or satellite communication. Avionics can use satellite navigation systems (such as GPS), Inertial Navigation System), ground-based radio navigation systems (such as VOR), or any combination thereof. Some navigation systems such as GPS calculate the position automatically and display it to the flight crew on moving map displays. Older ground-based Navigation systems such as VOR require a pilot or navigator to plot the intersection of signals on a paper map to determine an aircraft's location. Modern systems calculate the position automatically and display it to the flight crew on moving map displays. Every aircraft is equipped with a transponder. It is an electronic device that produces a response when it

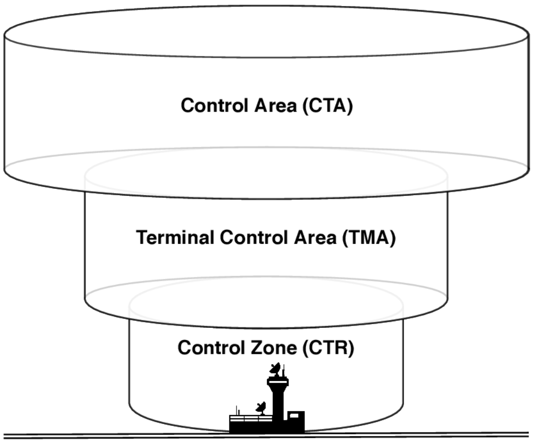


Figure 3.5: Airspace zones near controlled airport [27].

receives a radio-frequency interrogation. Aircraft have transponders to assist in identifying them on Air Traffic Control radar. Collision avoidance systems have been developed to use transponder transmissions as a means of detecting aircraft at risk of colliding with each other.

To supplement Air Traffic Control, most large transport aircraft and many smaller ones use a Traffic Collision Avoidance System (TCAS), which can detect the location of nearby aircraft, and provide instructions for avoiding a midair collision. To help avoid controlled flight into terrain, aircraft use systems such as ground-proximity warning systems, which use radar altimeters as a key element.

3.4 Generic aircraft model

Spatial movement and description of aircraft behavior represent quite complex problems. The purpose of the flight is not only to take the machine into the air but also to keep it in the air, to steer it in the right direction with a variety of weather conditions, lighting conditions, and with an emphasis on ensuring flight safety, including successful landing. All elements of the system from solidity of landing gear elements to trained pilots, they must meet strict international certification standards issued by, Federal Aviation Administration (FAA), European Aviation Safety Agency (EASA), International Civil Aviation Organization (ICAO) [8][7][12].

Flight simulators are used for targeted component testing or comprehensive pilot training. These, in addition to normal air traffic, allow simulation of incidents in flight. All important factors affecting the course of the flight can be summarized into several groups. A generalized summary of key components of the flight is shown in Figure 3.6.

3.4.1 Equations of motion

All equations of motion are non-linear, with 6-DoF (Figure 3.7) oriented in the aircraft coordinate system.

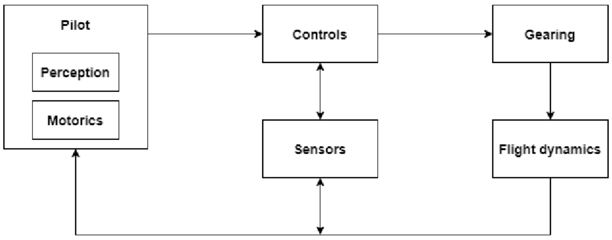


Figure 3.6: Diagram of factors affecting the course of the flight [34].

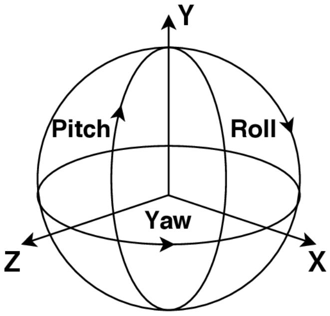


Figure 3.7: Motion in six degrees of freedom [18].

Assumptions

This rigid body model is used to theoretically investigate the purely kinetic effects of forces on a body when its shape and dimensions cannot be ignored, or its rotation must be considered. Let us consider the conditions of windless without mechanical or thermal turbulence. An important prerequisite is the limitation of air properties to incompressible behavior. For simplicity, we will consider the weight of the aircraft constant [26].

Since the center of gravity position is closely related to the aircraft's flight characteristics, we introduce the concept of centering, which determines the positions in which the center of gravity may be located so as not to significantly affect flight stability and maneuverability. If the center of gravity is too close to the rear center of the aircraft, the aircraft may be less manageable. Reduced flight stability can be caused by even the smallest movement of aircraft control. On the other hand, the low sensitivity of the longitudinal control can occur if the center of gravity is too close to the aircraft's front center.

The control surfaces of the aircraft create additional aerodynamic forces, which, by intersecting them at a certain distance from the center of gravity, creates moments to the major axes, causing the aircraft to rotate (maneuvering). This is the principle of aircraft maneuvering. The balanced tipping moment is caused by the movement of the ailerons located symmetrically on both wings of the aircraft. The Yaw movement of aircraft is controlled by a rudder, and the pitch movement is achieved by controlling the elevator. Using the trim system, the pilot can vary the amount of force applied to the steering to achieve easier maneuvering [6].

Differential equations of force

The equation of motion for aircraft is based on Newton's second law for each particle of aircraft mass and its subsequent integration for the entire aircraft, where F denotes the force vector, a acceleration, and m mass [29]:

$$d\vec{F} = \vec{a}.dm \tag{3.1}$$

If we work with the acceleration of each particle, we must include increments of its velocity from linear velocities (u, v, w) in the direction of each coordinate axis, as well as increments due to the angular velocity around each axis (p, q, r). The last components are specific forces (f_x, f_y, f_z). The units of the resulting velocities are $[m.s^{-1}]$ [29].

$$\dot{u} = rv - qw - g\sin\theta + f_x \tag{3.2}$$

$$\dot{v} = pw - ru + g\cos\theta\sin\phi + f_y \tag{3.3}$$

$$\dot{w} = qu - pv + g\cos\theta\cos\phi + f_z \tag{3.4}$$

Momentum differential equations

Momentum differential equations are formulated for rotations around the basic Body Fixed Frame coordinate system (BFF) axes as follows 3.5, 3.6 and 3.7. The time change of angular velocities is expressed as a combination of the sums of moments from aerodynamic and propulsive forces $(\sum L, \sum M, \sum N)$, quadratic moments of inertia around the basic axes in BFF (I_{XX}, I_{YY}, I_{ZZ}), deviation moment I_{XY} and the angular velocities themselves [29].

The physical dimension for angular velocities is $[rad.s^{-1}]$.

$$\dot{p} = \frac{\sum LI_Z + \sum NI_{XZ} + pqI_{XZ}(I_X - I_Y + I_Z) - qr({I_X}^2 - I_Y I_Z + {I_{XZ}}^2)}{I_X I_Z - {I_{XZ}}^2} \tag{3.5}$$

$$\dot{q} = \frac{\sum M - pr(I_X - I_Z) + I_{XZ}(r^2 - p^2)}{I_Y} \tag{3.6}$$

$$\dot{r} = \frac{\sum LI_{XZ} + \sum NI_X + pq({I_{XZ}}^2 - I_X I_Y + {I_X}^2) - qrI_{XZ}(I_X - I_Y + I_Z)}{I_X I_Z - {I_{XZ}}^2} \tag{3.7}$$

Differential equations of attitude

This relationship determines the position angles of the aircraft over time (ϕ, θ, ψ): Relations in equations 3.8, 3.9 a 3.10 defines a differential notation to calculate the time change of Euler angles [29].

$$\dot{\phi} = p + (q\sin\phi + r\cos\phi)\tan\theta \tag{3.8}$$

$$\dot{\theta} = q\cos\phi - r\sin\phi \tag{3.9}$$

$$\dot{\psi} = \frac{q\sin\phi + r\cos\phi}{\cos\theta} \tag{3.10}$$

Differential equation of position

To determine the exact aircraft coordinates (latitude, longitude and altitude) in the global positioning system, LLA coordinates are calculated using the following equations:

$$\begin{bmatrix} \dot{\lambda} \\ \dot{\mu} \\ \dot{h} \end{bmatrix} = \begin{bmatrix} \frac{V_E}{(N_\mu + h)\cos\mu} \\ \frac{V_N}{M_\mu + h} \\ -V_D \end{bmatrix} \tag{3.11}$$

where M_μ and N_μ are defined as:

$$M_\mu = N_\mu \cdot \frac{1 - e^2}{1 - e^2 \sin^2\mu} \tag{3.12}$$

$$N_\mu = \frac{a}{\sqrt{1 - e^2 \sin^2\mu}} \tag{3.13}$$

with the following constants based on the description of the Earth model:

$$a = 6378[km] \tag{3.14}$$

$$f = 0.0034[1] \tag{3.15}$$

$$e = 0.0818[1] \tag{3.16}$$

The transformation of speeds from the BFF coordinate system to speeds in the North East Down (NED) coordinate system is described in the following format:

$$\begin{bmatrix} V_N \\ V_E \\ V_D \end{bmatrix} = M_{ob} \begin{bmatrix} u \\ v \\ w \end{bmatrix} \tag{3.17}$$

where the transformation equation M_{ob} has the shape below:

$$M_{ob} = \begin{bmatrix} \cos\psi\cos\theta & \cos\psi\sin\theta\sin\phi - \sin\psi\cos\phi & \cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi \\ \sin\psi\cos\theta & \sin\psi\sin\theta\sin\phi + \cos\psi\cos\phi & \cos\psi\sin\psi\sin\theta\cos\phi - \cos\psi\sin\phi \\ -\sin\phi & \cos\theta\sin\phi & \cos\theta\cos\phi \end{bmatrix} \tag{3.18}$$

3.5 X-Plane flight simulator

X-Plane is a flight simulation platform developed by Laminar Research. X-Plane is provided with several types of aircraft, as well as global scenery which covers most of the Earth. X-Plane allows to build and customize own aircraft and scenery. X-Plane also has a plugin architecture that allows users to create their components, extending the functionality of the simulation platform. It is designed to be the most flexible flight simulator it has a fully open structure that allows the enthusiast to change every part. With thousands of compatible add-ons there is no kind of flying craft that is not simulated.

The core of the simulation is a virtual wind tunnel that creates realistic flight modeling available on a personal computer. Equally capable of simulating every type of aircraft. The realism of X-Plane is proven by the fact that X-Plane is used as a certified training tool. Each aircraft flies just as it should, from the glider to the Space Shuttle!

X-Plane makes full use of the hardware. Multi-core machines are able to simulate more aircraft and visualize more details but even a moderate machine with X-Plane is capable of displaying a tremendous amount of objects without slowing down [15].

3.5.1 X-Plane Connect

The X-Plane Connect is a research tool used to interact with the flight simulator software X-Plane. The Toolbox itself is open-source and the X-Plane Connect allows users to control aircraft and receive state information from aircraft simulated in X-Plane using functions written in various languages in real-time over the network. The common use of this research tool is for visualization of flight paths, to simulate active airspace or test control algorithms. Possible applications include active control of an X-Plane simulation, flight visualization, recording states during a flight, or interacting with a mission over UDP [15].

The X-Plane Connect Toolbox allows manipulating the internal states of the aircraft and simulation perform by the X-Plane by reading and setting DataRefs. Many functions for effective commands execution are provided. These functions allows to control surfaces and set the position of all aircraft. Also, it provides function to pause and un-pause X-Plane's physics simulation engine [15].

Chapter 4

Design of an agent for Air Traffic Control tasks

Agent Systems theory gives natural solutions to analyze and model the organization of a set of autonomous ATM entities that coordinate and negotiate their actions to achieve their respective goals.

4.1 Agent systems

A agent system or Multi-Agent System (MAS) is a decentralized system composed of multiple interacting intelligent agents. Agents have local perceptions of their environment and require interaction in form of communication to coordinate or cooperate their actions (Figure 4.1). Agent systems are suitable for solving problems that are difficult or impossible for a monolithic system or and individual agent to solve. Intelligence may include algorithmic search, functional, procedural, methodical, approaches, or reinforcement learning [36].

Agent systems consist of agents and their environment. Typically agent systems research refers to software agents. However, the agents in a agent system could equally well be robots, humans, or human teams. A agent system may contain combined human-agent teams. Agents can be divided into types spanning simple to complex. Categories include:

- Passive agents or agents without goals.

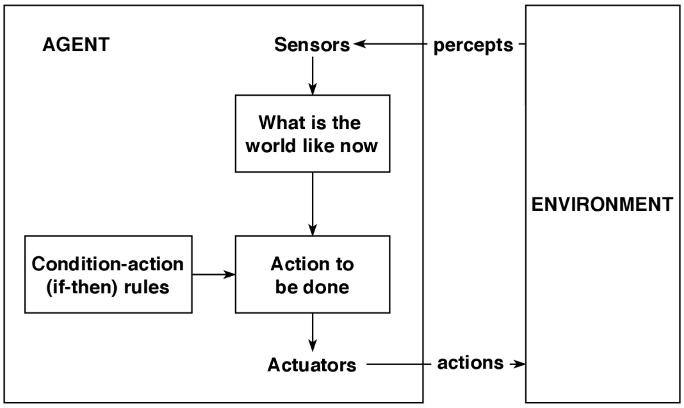


Figure 4.1: Agent and his interaction with the environment [36].

- Active agents with simple goals.
- Cognitive agents.

Agent environments can be divided into:

- Discrete.
- Continuous.

Agent environments can be organized according to variables such as accessibility, determinism ,dynamics, discreteness, episodicity and dimensionality. Agent actions are typically interfaced via an appropriate middle-ware component. This approach offers an abstraction layer for agent systems, providing abstracted interfaces to get resource access and achieve agent coordination [36].

4.2 Agent modeling

This section describes the individual components of behavior according to the method of their planning in the JADE platform.

Simple behaviors can be classified as:

- One-shot behavior, an atomic task to be carried out once, used here for initialization tasks.
- Cyclic behavior, which is iterated while exists, such as messages listening and processing.
- Waker behavior or a one-shot behavior invoked after a certain time.
- Ticker behavior or a cyclic behavior which performs a series of instructions executed keeping a certain fixed time, used in the platform for simulation numeric computation and graphical output.

Composite behaviors are three:

- Finite State Machine Behavior that consists of a class that allow defining a Finite State Machine by means sub-behaviors, where each of them represents a machine state.
- Sequential Behavior that sequentially executes its sub-behaviors.
- Parallel Behavior that executes their sub-behaviors concurrently and ends when a certain condition is satisfied (for one, several or all of them). In this way, agents can concurrently to carry out different tasks and to keep simultaneous conversations.

4.2.1 Belief-Desire-Intention

The Belief-Desire–Intention (BDI) is a software model suitable for development of intelligent agents (Figure 4.2). An agent is characterized by the implementation of an agent's beliefs, desires, and intentions, it uses these concepts to solve a particular problem in agent programming. Practically is provided a mechanism for separating the activity of selecting a plan from the execution of currently active plans. Plans are selected from a plan library or an external planner application. Therefore, BDI agents can balance the time spent on reasoning about plans (choosing what to do) and executing selected plans (doing it). A third activity, creating the plans in the first place (planning), is not within the scope of the model, and is left to the system designer and programmer [35].

Components of a BDI system:

- Beliefs represent the knowledge state of the agent from its perspective, in other words, its beliefs about the world (including itself and other agents). Beliefs can also include inference rules, allowing derivation, which leads to new beliefs. Using the term belief rather than knowledge recognizes that what an agent believes may not necessarily be true (and in fact may change in the future). Beliefs are stored in the database (sometimes called a belief base or a belief set), although that is an implementation decision [35].

- Desires represent the motivational state of the agent. They represent high-level objectives or situations that the agent would like to accomplish or bring about. Examples of desires might be: find the best price, go to the party or become rich. In the context of desires, we introduce a term goal. A goal is a desire that has been adopted for active pursuit by the agent. Usage of the term goals adds the further restriction that the set of active desires must be consistent. For example, one should not have concurrent goals to go to a party and to stay at home – even though they could both be desirable [35].

- Intentions represent the deliberative state of the agent – what the agent has chosen to do. Intentions are desires to which the agent has to some extent committed. In implemented systems, this means the agent has begun executing a plan [35].

- Plans are sequences of actions (recipes or knowledge areas) that an agent can perform to achieve one or more of its intentions. Plans may include other plans: my plan to go for a drive may include a plan to find my car keys. Plans are initially only partially conceived, with details being filled in as they progress [35].

- Events are triggers for reactive activity by the agent. An event may update beliefs, trigger plans, or modify goals. Events may be generated externally and received by sensors or integrated systems. Additionally, events may be generated internally to trigger decoupled updates or plans of activity [35].

Formal definition of BDI agent components:

Agent perception process:

$$\mathrm{see} : \mathrm{S} \rightarrow \mathrm{Per} \tag{4.1}$$

Table 4.1: Definitions and notations of BDI agent [35].

Notation	**Meaning**
Ag	All agent set
S	Environment state set
Per	Perception information set
Bel	Belief set
Des	Desire set
Int	Intention set
Act	Action set

Agent belief revise:

$$\mathrm{brf : B \times Per \rightarrow B} \tag{4.2}$$

Determine the current belief according to perceived external information and agent internal belief. Agent desire determination process:

$$\mathrm{option : B \times I \rightarrow D} \tag{4.3}$$

Agent intention choose:

$$\mathrm{filter : B \times I \times D \rightarrow I} \tag{4.4}$$

Agent execution process:

$$\begin{gathered}\mathrm{execute : I \rightarrow Act} \\ \mathrm{\forall B \in Bel, \forall D \in Des, \forall I \in Int, \forall ACT \in Act}\end{gathered} \tag{4.5}$$

BDI Coordination inference model of Agent ai, ai ∈ Ag:

$$\mathrm{ai \equiv (P, B, D, I, ACT, see, brf, option, filter, execute)} \tag{4.6}$$

Some parts of the agent's belief database store all the information associated with the normal operation of the agent. The other part store external environment and cognition data of other agents, brf: $\mathrm{B \times Per \rightarrow B}$. Desire database stores the knowledge inferred from existing belief according to existing rule in the belief database, option: $\mathrm{B \times I \rightarrow D}$. Intention database store optimum desire from desire database, filter: $\mathrm{B \times I \times D \rightarrow I}$ [35].

4.2.2 Finite State Machine

A Finite State Machine (FSM) is a mathematical model of computation. It is an abstract machine that can be in exactly one of a finite number of states at any given time. The FSM can change from one state to another in response to some inputs. The change from one state to another is called a transition. An FSM is defined by a list of its states, its

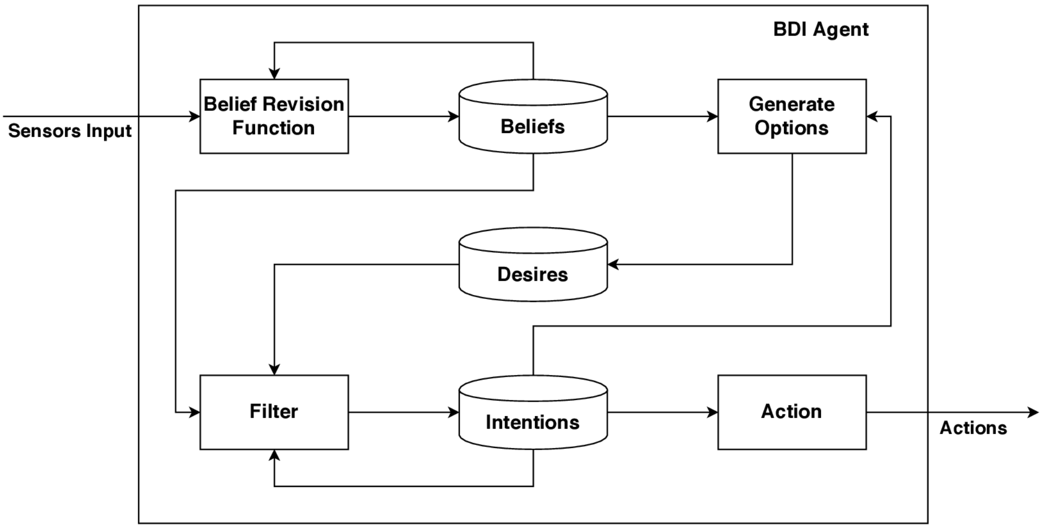


Figure 4.2: The BDI Agent Architecture [35].

initial state, and the inputs that trigger each transition. Finite-state machines are of two types—deterministic finite-state machines and non-deterministic finite-state machines. A deterministic finite-state machine can be constructed equivalent to any non-deterministic one.

The behavior of state machines can be observed in many devices in modern society that perform a predetermined sequence of actions depending on a sequence of events with which they are presented. Simple examples are vending machines, which dispense products when the proper combination of coins is deposited, elevators, whose sequence of stops is determined by the floors requested by riders, traffic lights, which change sequence when cars are waiting, and combination locks, which require the input of a sequence of numbers in the proper order.

The finite-state machine has less computational power than some other models of computation such as the Turing machine. The computational power distinction means there are computational tasks that a Turing machine can do but an FSM cannot. This is because an FSM's memory is limited by the number of states it has. FSMs are studied in the more general field of automata theory.

This kind of behavior allows agents to build much more complex and interesting behaviors in a agent system. Behavior is a finite state machine (FSM) which has registered states and transitions between states.

For design in this thesis is used in this behavior paradigm. The choice for the FSM paradigm was made because this paradigm provides a fair balance between expressiveness, intuitiveness, and usability. Additionally, the representation of FSM closely resembles how humans tend to explain their line of reasoning when they execute a task.

4.3 Agent system architecture

Agent approach of simulating ATC tasks completes previously depicted design (Figure 3.1) in several aspects. The main module handling everything from communication, data storage, interpreting positions, decision making, etc. is disassembled into agents with specific tasks. Motion simulation block remains unchanged, i.e. it calculates flight dynamics, re-

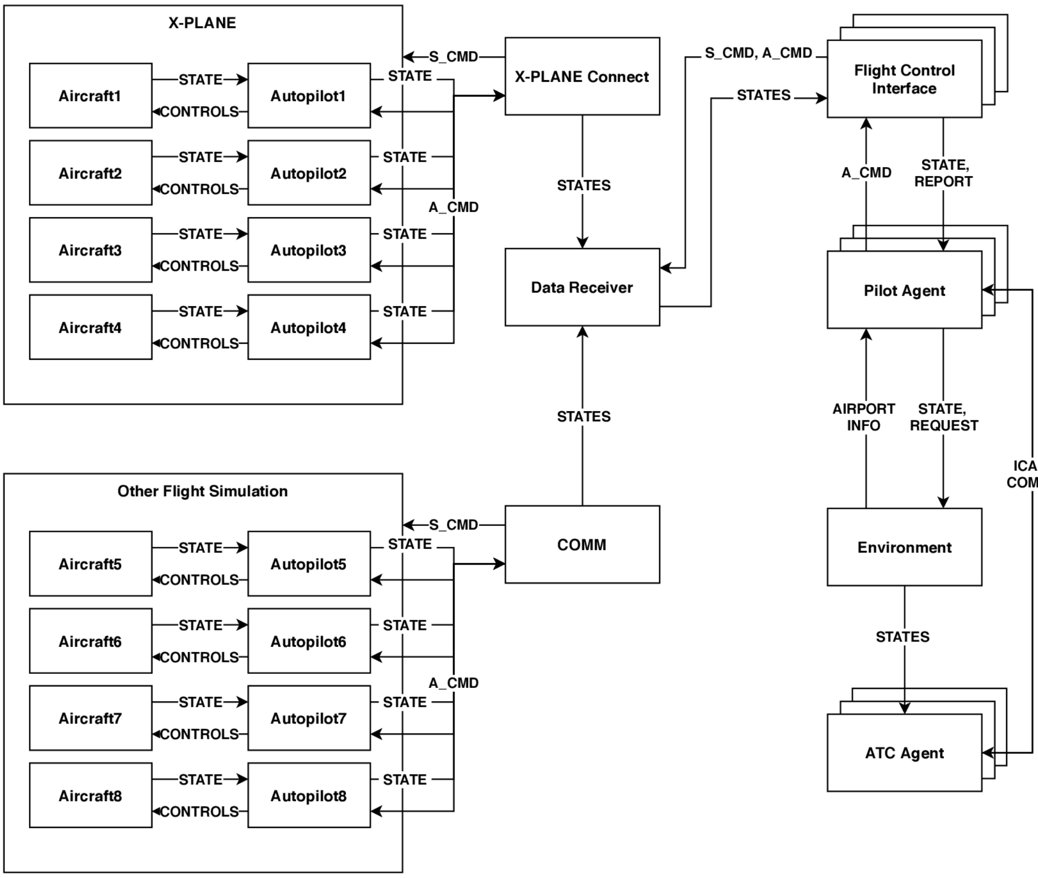


Figure 4.3: Agent for Air Traffic Control System Architecture.

ceiving flight commands for autopilots, and providing state vectors of aircraft. The agent system architecture is visualized on Figure 4.3.

- Environment component creates all other agents, stores and provides additional information about environment variables such as nearest airport, prohibited zones, aircraft on radar, or global time. This design allows for possible future scalability by creating more environment agents with synchronization. Each environment agent would be managing an area with specific ATM agents and have information about surrounding environment agents.
- The ATC agent is divided into three controllers: Radar, Tower, and Ground. The Ground controller is controlling and scheduling taxiing and all movement and clearances for movement at the airport. It communicates with pilot agents through ICAO communication and with internal communication with other controllers at the airport. Tower controller is handling take-off, landing, and approach phases. The important task of the tower agent is also collision avoidance. Tower agent decides the order of incoming aircraft, flight level, and optimal speed and trajectory. It communicates through ICAO commands directly to the pilot agents. Airport state, runway occupation, and take-off clearances are communicated through internal communication with the Ground controller. The radar controller represents radar services outside the controlled zones and provides appropriate guidance information.

All three controllers representing ATM services contain finite state machine behavior models for decision making to ensure the response to a highly dynamic environment is immediate and correct.

- Pilot agents represent the pilot's behavior. It decides when and what report to the ATC and which commands send to the autopilot. Communication interface is for all pilot agents the same, but the behavior could be different. The standard flight is modeled as a finite state machine with exact states and transitions. For non-standard situations is used modified finite state machine or a simple sequence of states. It depends on the modeled scenario and desired behavior of aircraft.
- Flight control interfaces communicate with specific aircraft and navigate aircraft through a specified route defined by waypoints. It receives the navigation commands from an pilot agent and reports evaluated aircraft position and waypoint crossing.
- The DataReceiver is an component, which delegates state vectors from motion simulation to flight control interfaces and serves as an interface to motion simulation. Motion simulation blocks are described above in the chapter design of an air traffic simulation framework.

4.4 Concept of Operations

In this section, the individual concepts of the operation performed by the air traffic controller are presented. The flight path planning, collision avoidance and algorithm for Routing and scheduling are listed below.

4.4.1 Flight path planning

From the pilot's point of view, the approach route is a defined procedure, thanks to which it brings its aircraft close to the destination airport and which determines the runway for landing. From the Air Traffic Controllers' point of view, it is a section of flight with which it can ensure the separation of aircraft arriving from different directions (because there are more arrival routes for one airport) and which can limit aircraft in both speed and altitude for required clearances. In coordination with the Approach Controller (APP), the approach route is assigned to the aircraft by the Area Control Center (ACC), always before reaching the start of the approach route. The aircraft is controlled by the APP service on the arrival route.

VFR routes

For standard VFR flights, flight routes are recommended for entry and movement in the controlled airport area. The entry route always leads through one of the CTR entry points. Next, the route leads to a specific control point, which also defines a standard holding pattern. At the call of the controller, the rest of the route is planned for the airport circuit entry and landing.

On Figure 4.4 is a visualized CTR of Brno/Turany airport. The aircraft could enter CTR through $NOVEMBER$, $ECHO$, $WHISKEY$, $ZULU$, or $SIERRA$. Then head to the control points $ALPHA$ or $BRAVO$, where is also drawn holding pattern.

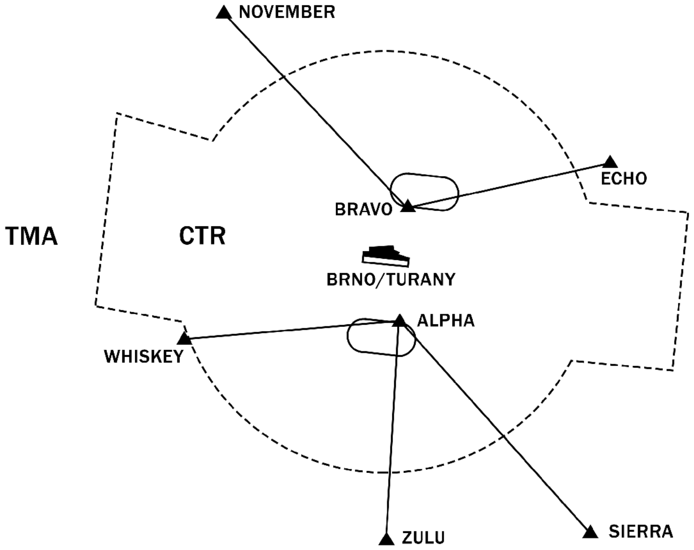


Figure 4.4: CTR Brno Turany and marked VFR traffic routes for landing [3].

4.4.2 Collision avoidance

Along with transferring control over aircraft from one sector to another and applying standard operating procedures for take-off or landing is keeping air traffic separated one of the main duties of Air Traffic Controllers. Proper separation ensures safety and eliminates the risk of collision. The rules Air Traffic Controllers use to keep aircraft separated are called separation minima. Separation can be achieved in two basic ways: vertical and horizontal. Their description follows [8].

Vertical separation

The common separation procedure is vertical separation. For the vertical separation, the ATC controller assigns to aircraft different cruising levels. Below the flight level 290 were set the standard vertical separation minima to 1000 ft, while to 2000 ft above the flight level 290 were established 2000 ft minimal separation. This was because altimeter precision decreases with increasing altitude. Over time were developed more precise altimeters and other equipment to measure aircraft altitude. It allowed to reduce the 2000 ft separation minima and establish the Reduced Vertical Separation Minima (RVSM) system. In the airspace with RVSM, the separation minima up to flight level 410 is 1000 ft and 2000 ft above this flight level. If the maintained altitude of two aircraft is equal or greater as the separation minima, the aircraft are considered as separated [8].

Horizontal separation

The horizontal separation must be applied, when two aircraft fly at the same flight level. There are two types of horizontal separation, lateral or longitudinal. The controller can navigate individual aircraft to perform the separation with or without radar equipment. To guide the aircraft, the controller needs to know its position. He either gets it directly from the radar screen, or he has to rely on reporting the position through the radio communication.

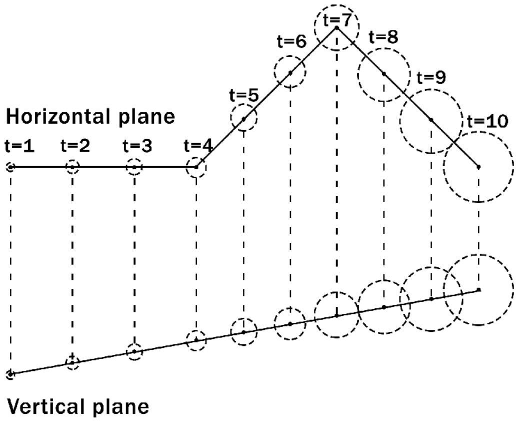


Figure 4.5: Modeling of aircraft position over time.

Standard lateral separation assumes an airways width of 8 nautical miles. In rare cases where the airways are crossed or aircraft cross a control point in different directions, the separation may be less than 8 nautical miles. Lateral separation conditions are met even if the aircraft flies in the holding patterns whose airspace does not overlap [8].

The longitudinal separation must be used, when converging routes of two aircraft are not vertically separated or aircraft are flying in same airway. Aircraft are considered longitudinal separated if they are flying at the same speed or the lead aircraft flying at higher speed than the following aircraft. The longitudinal separation is defined ad the minimal distance between two aircraft in nautical miles or as a time delay between crossing specific position or flying over the control point [8].

Potential collisions and disturbances of the ordered separation can be detected according to the planned trajectory and the probable occurrence of the aircraft in the future. Collisions may occur if aircraft are at any given time in their probable areas of occurrence in both the vertical and horizontal planes. The area of probable occurrence of the aircraft increases over time and degrades the prediction of a collision. An illustration of the area of possible occurrence in the horizontal and vertical planes is shown in the Figure 4.5.

Wake turbulence separation

Behind every aircraft a wake turbulence in form of air vortex is formed as it moves through the air. The size and strength of turbulence depends on the size, mass and speed and other parameters of the aircraft.The danger occurs when the aircraft is followed by a smaller and lighter aircraft. The turbulence is not visible and can significantly disrupt the flight of the aircraft. It is necessary to pay increased attention when flying in low wind conditions, because the turbulence does not just disappear and may continue to propagate to a parallel path or descend to a lower altitude into the path of another aircraft. [8].

Time separation at runway threshold

On the final approach trajectory, the minimal distance separations are based on aircraft weight class and landing order as determined by the FAA's wake vortex safety rules. The Table 4.2 gives examples of aircraft models falling in the different weight categories. The distance separations in table 4.2 are transformed to equivalent time separations for the

Table 4.2: Minimum distance separations between two aircraft at a runway threshold [19].

		Trailing aircraft categories [nm]				
		Super	Heavy	B757	Large	Small
Leader aircraft categories [nm]	Super	2.5	6	7	7	8
	Heavy	2.5	4	5	5	6
	B757	2.5	4	4	4	5
	Large	2.5	2.5	2.5	2.5	4
	Small	2.5	2.5	2.5	2.5	2.5

Table 4.3: Minimum time separations with true air speed 130 knots [19].

		Trailing aircraft categories [s]				
		Super	Heavy	B757	Large	Small
Leader aircraft categories [s]	Super	69	166	194	194	222
	Heavy	69	111	138	138	166
	B757	69	111	111	111	138
	Large	69	69	69	69	111
	Small	69	69	69	69	69

further use by the scheduler. The conversion process is complex. It requires modeling the airspeed profile of each type of aircraft and the wind speed on the final approach and then integrating the equations of motion along the final approach route. The result of this process is the time separation matrix given in table 4.3 during the zero wind conditions.

The numerical values given in these tables should be interpreted as representative examples for this paper. They may be revised when new operational experience determines that vortex separation rules need to be modified to improve safety [19].

4.4.3 Routing and scheduling

For the scheduler design, the arrival airspace is divided into TMA and CTR regions described previously. CTR region is a roughly circular area about 20 nautical miles in radius around an airport and is surrounded by the TMA airspace. Certain waypoints located on the boundary between the two regions are referred to as entry points. During moderate and heavy traffic conditions when delays are expected, traffic is funneled through these gates as a means of controlling or metering the flow rate into the terminal area. In most terminal areas, arrival routes are merged at gates corresponding to the primary arrival directions.

From each gate, routes that lead to all possible landing runways for each independent stream are defined in the CTR airspace. For the design of the scheduler, the exact horizontal paths of the routes provide a structure from which the trajectory estimation can produce nominal flying times from each gate to all landing runways. These flying times must be provided as input.

The basic objective of the scheduler in air-traffic-control automation is to match traffic demand and airport capacity while minimizing delays. This objective gives rise to a surprisingly complex algorithmic design problem when all necessary operational constraints are considered. This section presents an outline of the solution to this problem.

The dynamic nature of air traffic flow requires that the scheduler be designed to operate as a realtime process, which is defined in the following way. The scheduler must generate an

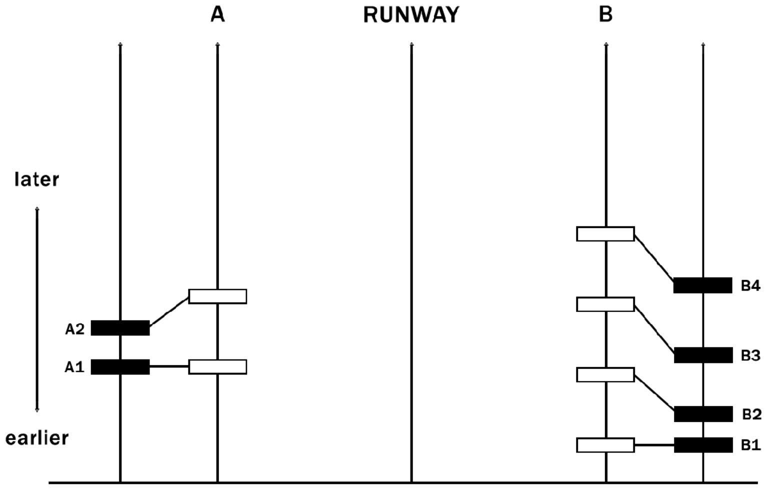


Figure 4.6: Adding in-trail constraints at the entry points [23].

updated schedule for the set of aircraft to be scheduled both periodically and in response to non-periodic events. The objective of minimizing delays would require mathematical optimization to be performed by the scheduler in real-time.

Schedule-optimization problems are closely related to the well-known traveling salesman problem. Both types of problems give rise to search procedures that exhibit polynomial growth rates in computing time as the number of schedulable aircraft increases. Such procedures become computationally impractical to implement in real-time applications for all but a small number of schedulable aircraft.

First-Come-First-Served Arrival Sequence Orders

The basic input to the scheduler is the set of estimated times of arrival of all schedulable aircraft, computed to the appropriate entry points. This set is provided by the trajectory estimation. In the first step are applied in-trail separation constraints at entry points. This step is illustrated in Figure 4.6.

The second step (Figure 4.7) determines the runway threshold landing order. As previously stated, the overall objective is to generate an First-Come-First-Served (FCFS) landing order at the runway. However, when in-trail constraints are present at the entry points, such as those visualized on Figure 4.4, the definition of FCFS at the runway becomes ambiguous because arrivals enter the terminal airspace via multiple entry points. The ambiguity is removed by choosing the aircraft by entering the CTR order when establishing the FCFS order at the runway. Simulation and analysis have shown this choice produces both a fairer schedule overall as well as one that is slightly more efficient [23].

In the third step are computed scheduled times of arrival at the runway threshold. The time separations between the unconstrained runway times are stretched, when necessary, to conform to the minimum time-separation matrix given in table 4.3. This stretching yields the scheduled times of arrival at the runway threshold. The process involves inserting the appropriately chosen minimum time separation from table 4.3 between pairs of aircraft in sequence starting with the first aircraft in the known landing order and terminating with the last. The processes described in this step are illustrated by the example in Figure 4.8. A blocked time interval has been included as a constraint.

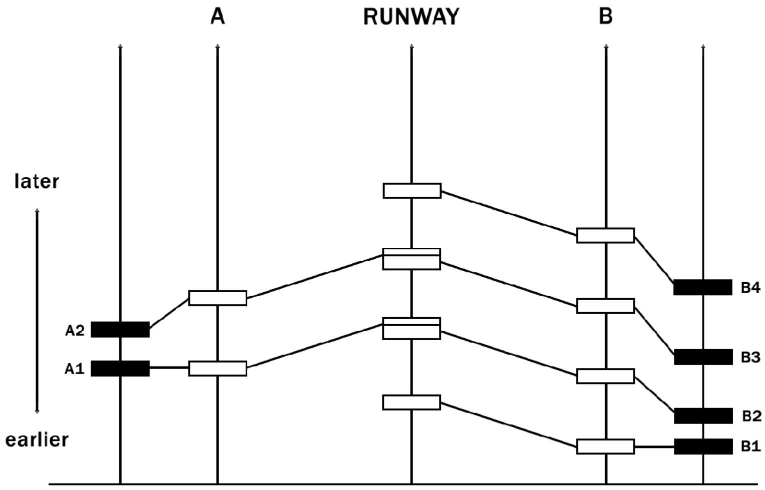


Figure 4.7: Determining landing order [23].

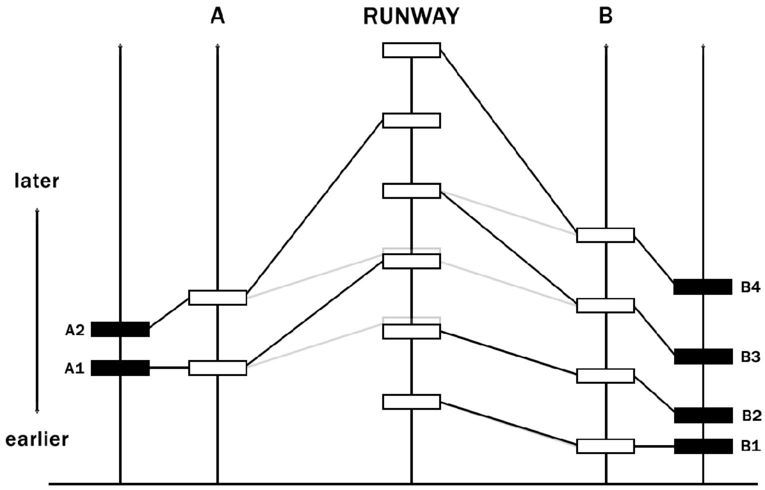


Figure 4.8: Adding landing related time constraints [23].

Chapter 5

Implementation

This chapter describes the environment in which the implementation is realized. The structure and behavior of individual agents are depicted and described here. Furthermore, the implemented types of communication and their protocols are described here. At the end of the chapter, the visualization and outputs are described and illustrated.

5.1 JAVA Agent Development Framework

Java Agent DEvelopment Framework (JADE) is a framework implemented in Java language. It provides the tools for the implementation of agent systems through a interface that complies with the Foundation for Intelligent Physical Agents(FIPA) specifications and through a set of tools that allows the debugging and maintaining code. The agent platform can be distributed among computers and the configuration can be controlled through a remote graphical user interface. The configuration can even be changed at runtime by creating new agents and moving agents from one computer to another, as needed.

Agents are basically implemented as a single thread per agent, but agents often need to perform parallel tasks. In addition to the multi-threaded solution offered directly by JAVA, JADE also supports cooperative behavior planning, where JADE schedules these tasks in an easy and efficient way. The runtime also includes some behaviors ready to use for the most common agent programming tasks, such as FIPA interaction protocols, waking under certain conditions, and structuring complex tasks as aggregation of simpler ones.

The communication architecture offers flexible and efficient messaging, where JADE creates and manages a queue of incoming Agent Communication Language (ACL) messages, private to each agent. Agents can access their queue via a combination of several modes: blocking, polling, timeout, and pattern matching based. The complete FIPA communication model was implemented and its components were fully integrated: interaction protocols, envelope, ACL, content languages, coding schemes, ontologies, and finally transport protocols. Most FIPA-defined interaction protocols are already available [14].

5.1.1 Foundation for Intelligent Physical Agents

Foundation for Intelligent Physical Agents (FIPA) is an Institute of Electrical and Electronics Engineers (IEEE) Computer Society standards organization that promotes agent-based technology and the interoperability of its standards with other technologies.

FIPA, the standards organization for agents and agent systems was officially accepted by the IEEE as its eleventh standards committee on 8 June 2005. FIPA specifications represent

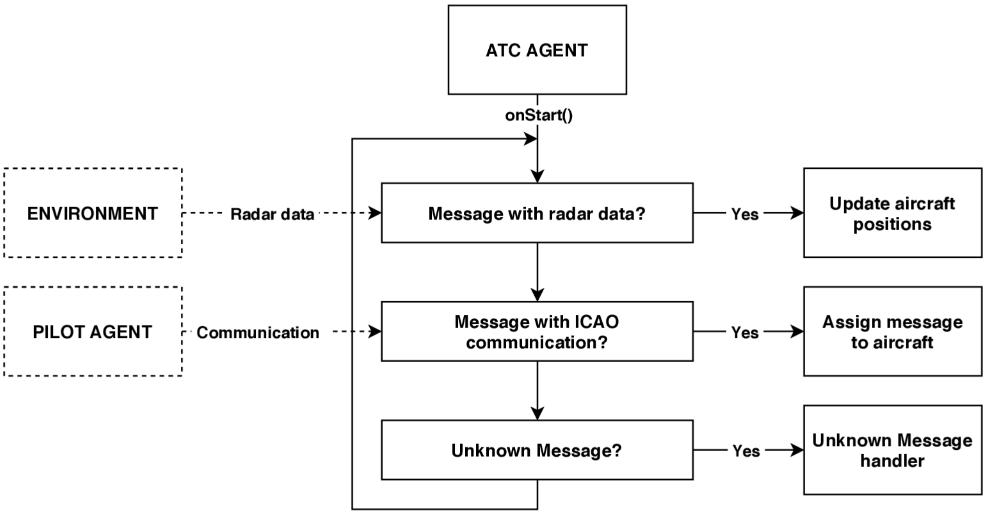


Figure 5.1: Air Traffic Control agent MessageReceiver cyclic behavior.

a collection of standards that are intended to promote the interoperation of heterogeneous agents and the services that they can represent.

The life cycle of specifications details what stages a specification can attain while it is part of the FIPA standards process. Each specification is assigned a specification identifier as it enters the FIPA specification life cycle.

5.2 Air Traffic Control agent

Air Traffic Control agent represents the Air Traffic Controller, his behavior and actions and airport state. The agent is fully autonomous and is linked with one particular airport. The following subsections describe individual parts of this agent and his behavior.

5.2.1 ATC agent behavior components

The behavior of an Air Traffic Control agent is divided into multiple modules. The MessageReceiver module shown in Figure 5.1 is used to receive all messages. The AircraftHandler module from Figure 5.2 is used to evaluate the current states of all aircraft in the vicinity of the airport. The interpretation of the current position of the aircraft is provided by the PositionChecker shown in Figure 5.4 and the planning of arrival and departure is handled by the AircraftScheduler (Figure 5.5).

The MessageReceiver behavior block is cyclically evaluated in the shortest interval possible. Its task is to continuously capture incoming messages. The most common incoming messages are radar data, which contain all information about the aircraft shown on the airport radar. Messages with radar data are sent by the Environment Agent. After receiving the message with radar data, all information about individual aircraft are updated, new ones are added, or those that are no longer valid are deleted. Another type of expected message is the ICAO communication, which is sent by an individual aircraft. Each message received is assigned to a specific aircraft, which will be processed later. If any unknown message arrives on the right, it is recognized and logged for possible detection of invalid behavior.

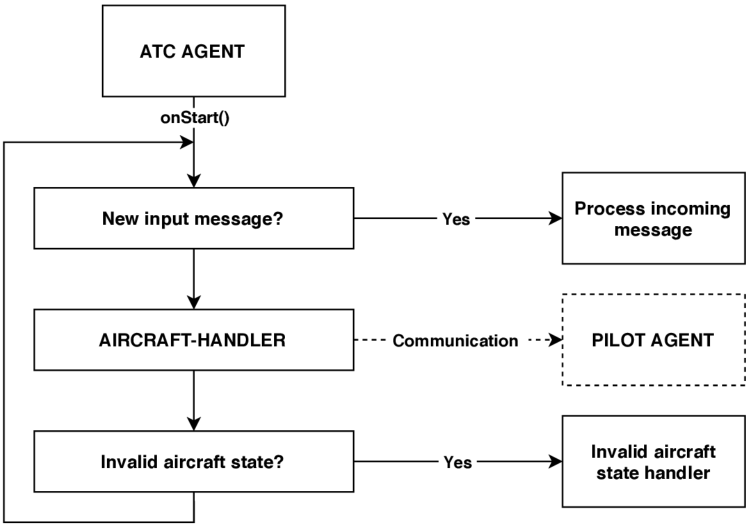


Figure 5.2: Air Traffic Control agent AircraftHandler cyclic behavior.

The most important behavior block is the AircraftHandler behavior from the Figure 5.2. It is again a cyclical block, which controls the aircraft states in the smallest intervals as possible. The state and flight phase for each aircraft visible on the radar is evaluated in the main part of the AircraftHandler behavior block. First, the handler tries to find out if the aircraft sent any communication, if so, the incoming message is processed. Then it evaluates the current state of the aircraft based on its flight phase, current position, and incoming communications. If the aircraft reaches a certain position or state, appropriate communication is generated and sent to the aircraft with additional instructions for standard arrival or departure. After evaluating the state, the evaluated state is validated, if the state of the aircraft conflicts with the expected position, a correction instruction is generated and sent to the aircraft. If the aircraft repeatedly fails to comply with the instructions and is outside the expected area, its state will change into a not-responding state and all other aircraft will be routed away from the not-responding aircraft.

As mentioned in the previous paragraph, the main part of the AircraftHandler behavior block is the Aircraft-Handler itself. This module evaluates the current state for each aircraft on the radar. First, the aircraft status is validated, which requires information about the flight phase, flight parameters such as latitude, longitude, altitude and airspeed, and finally the incoming communication. For each flight phase, areas and flight levels with a given speed are defined, in which the aircraft can be located. If the aircraft is not in a given phase of flight in a given area or is moving at different flight level, an invalid condition is detected. In the event of an invalid condition, the flight phase of the aircraft is considered invalid if its parameters show values incompatible with the flight, such as low altitude or speed, or, vice versa, too high altitude or speed. If the flight parameters are OK but the aircraft is not communicating, it is marked as “Not responding”. In the case of a valid status, the incoming communication is first analyzed and if there is some independent message on the flight phase, such as information on requests for surrounding traffic or the status of the airport. Independent communication also includes all emergency messages and responses to required maneuvers for correction. After independent communication is analyzed, the flight phase is processed. According to the current flight phase, the status of the flight phase is gradually evaluated. Evaluating the state of the flight phase requires additional

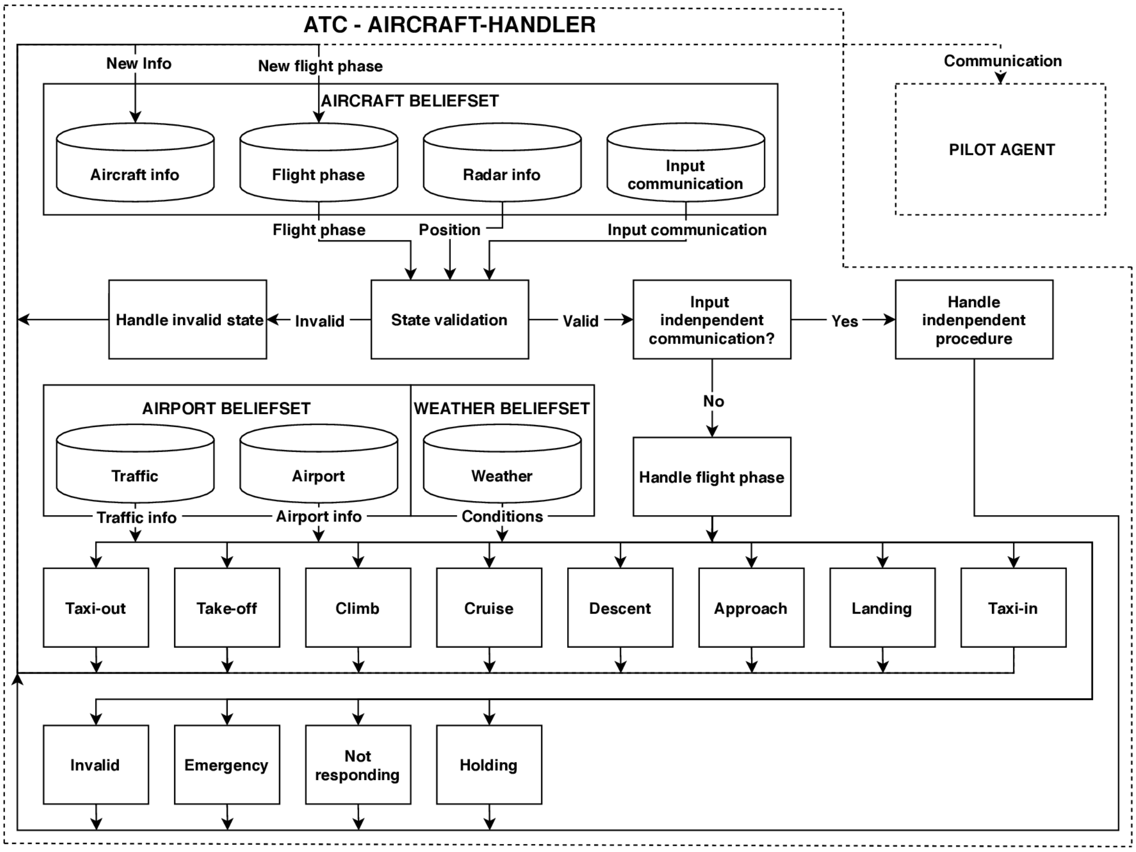


Figure 5.3: Air Traffic Control agent Aircraft-Handler diagram.

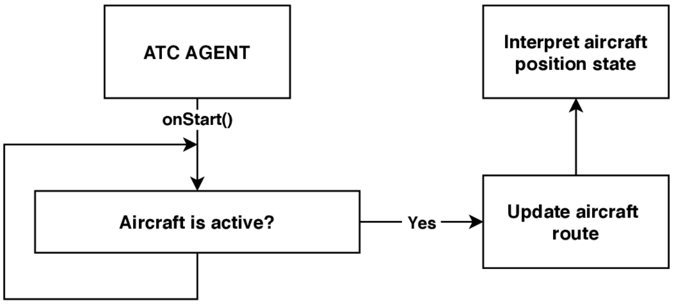


Figure 5.4: Air Traffic Control agent PositionChecker cyclic behavior.

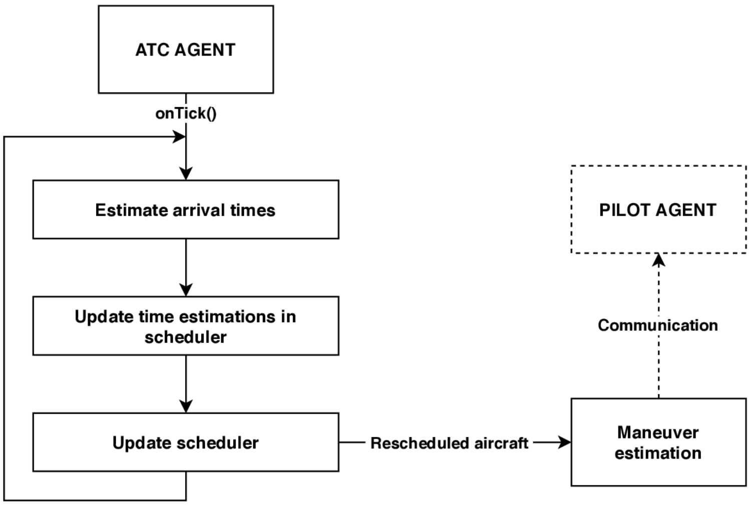


Figure 5.5: Air Traffic Control agent AircraftScheduler ticker behavior.

information such as surrounding traffic, wind direction, and speed, visibility, runway in use, optimal approach routes based on the position of the aircraft, etc. The evaluation of the status of a specific flight phase includes sequences of communication, control of the reaching of specific waypoints, or flight parameters, and conditional transitions to other flight phases. Standard flight phases are Taxi-out, Take-off, Climb, Cruise, Descent, Approach, Landing, and Taxi-in. In addition to the standard flight phases, the aircraft can be in non-standard phases, namely in the Invalid, Emergency, Not-responding, or holding phases. The aircraft can enter non-standard phases from any standard phase and, conversely, from non-standard phases it can return to the standard flight phase under certain conditions. The output of the processing of the flight phase status is the updated flight phase of the aircraft, updated additional information about the aircraft, and possibly generated communication to the Pilot agent.

Next behavior block is also cyclic. It is shown in Figure 5.4 and it is called PositionChecker. This module is used to interpret the current position according to the latitude, longitude, and altitude. Its output is information about whether the aircraft is on the arrival route, on the airport circuit, or the runway, etc. The interpreted information is processed in the previous block called AircraftHandler (Figure 5.2).

The last behavior block of the Air Traffic Controller agent is AircraftScheduler behavior (Figure 5.5). It is a ticker behavior and is evaluated at regular time intervals. The main task of this block is to manage the occupancy of the airport and to evenly plan and direct individual flights. In the first phase, aircraft arrivals to en-route points along their expected trajectory are estimated. Subsequently, the arrival times in the flight planning and the order of check-in of individual aircraft are updated. After that, collision detection will take place on scheduled flights. If a conflict arises, it is resolved in the next phase either by rescheduling and changing the arrival time, or if possible, the aircraft route or its parameters are modified. When modifying the route, the most suitable maneuver for correction is selected and is sent to the specific aircraft with information about the required maneuver.

5.2.2 Airport representation

To serve the changing needs of airlines and Air Traffic Control, the airspace and route structure surrounding a large airport have evolved into increasingly complex forms. For simplification are included only those features that relate directly to the design of the real-time scheduler. The features are described for simple airspace, but the concepts and algorithms apply to the general case.

Airports are represented by an object that contains the location in the geographic coordinate system, altitude, size of CTR, set of runways, set of entry and control points, set of taxiways, and set of aprons. The implemented representation is shown in Figure 5.6.

Entry points

Entry points to CTR are defined by their name, location, and constraints. The constraints include flight level and speed. Every entry point has a unique name and assigned following the control point. The control point is defined by the same parameters as the entry point. In general, these parameters serve to create waypoints for navigation. The creation of an entry route is based on aircraft position determined the closest entry point. The entry route consists of the specified entry point and the following control point. Similarly on departure route is assigned the closest entry point, in this case, it is the exit point and is determined by the closest distance to the destination.

Runways

Runways are defined by location, dimensions, and magnetic direction for correct using the runway. From the runway dimensions and location are also derived circuit patterns. By the hand, the rule is determined left and right circuit pattern in the direction of using the runway. The circuit patterns are visualized on Figure 5.11. The pattern is defined by corner points which determines the transitions between circuit legs. For entering on downwind is added an extra point in the middle of the downwind leg. Altitude and speed constraints for every circuit leg are defined in order to perform proper flight on airport circuit.

Taxiways

Taxiways are defined by exit points on runways. Where applicable, the taxiways are generated perpendicular to runway. Figure 5.6 shows an example of an airport scheme generated by defining runway location, six exit points location, and APRON point location. Taxiing speed constraints are added, to achieve realistic movement along the taxiways.

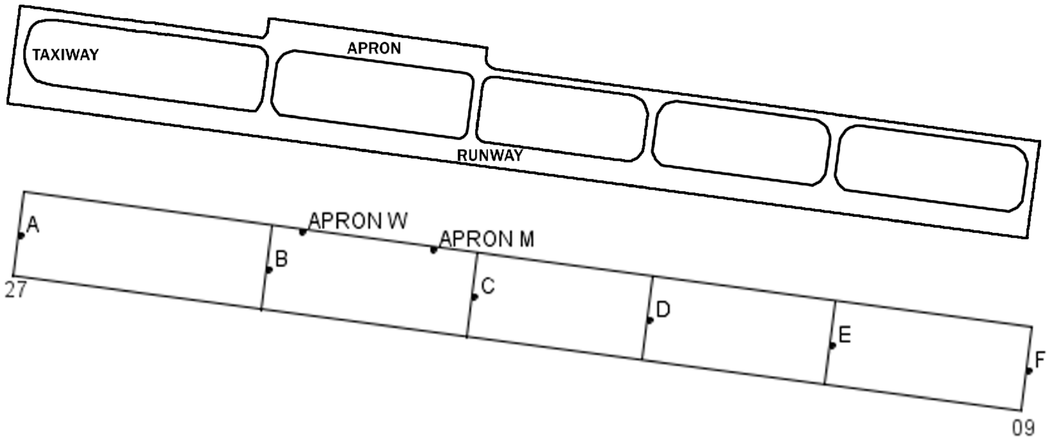


Figure 5.6: Runway and taxiways description and implemented representation.

5.3 Pilot agent

A Pilot agent represents the aircraft, its state, and behavior. It was designed to be fully autonomous, but when used with a human pilot, it can interpret human actions and generate communication. So it works the same, with the difference that it does not take any decisions. Which are decided by the human pilot. The following subsections describe individual parts and behavior.

5.3.1 Pilot agent behavior components

The internal logic of an Pilot agent consists of two main behavior modules. The first is called MessageReceiver and is used to receive all types of messages and subsequent processing of received messages. This behavior is cyclical and is therefore started over and over again at the shortest possible intervals to promptly capture the input message.

The behavioral block diagram is shown in the Figure 5.7. The basic functionality is to control the receiving of any message. After receiving any message, the message is decoded and specific actions are performed depending on the message type. If the message contains information about the environment, such as the nearest airport or destination airport, the information is stored in the knowledge base. Information messages are usually sent only by the Environment component on request. Another possible incoming message is the termination of the agent. Here is performed only the cleanup and the agent is subsequently terminated by the Environment component.

The most common type of incoming messages is ICAO communication, which is sent by Air Traffic Controllers. Upon receiving the ICAO message, it is detected whether it is an independent command of a specific maneuver to adjust the flight and comply with the scheduled time window, or whether it is a standard communication within the approach and landing or departure. In this case, the condition of the aircraft is then evaluated based on the current position, flight phase, and incoming message. The evaluation of the flight phase may then generate ICAO communication back to the controller, or a new assignment for the autopilot, or a request to obtain aerodrome data, or a request to terminate the agent after the end of the flight.

Another possible message is a message from an autopilot, announcing reaching of a certain waypoint. Then the phase of flight is evaluated again, which is described in the

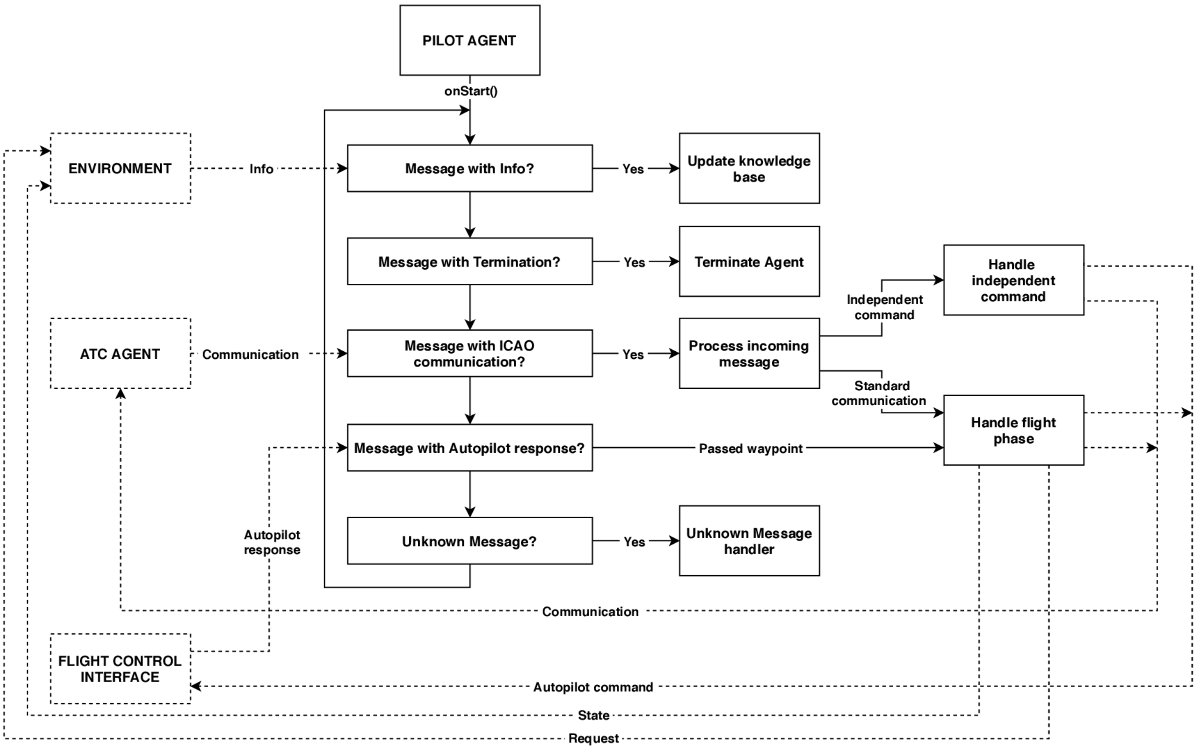


Figure 5.7: Pilot agent MessageReceiver cyclic behavior.

previous paragraph. If any unknown message arrives on the right, it is recognized and logged for possible detection of invalid behavior.

The second module behavior of the Pilot agent (Figure 5.8) is used to evaluate the current phase of the flight. This behavior is triggered at regular intervals. It practically evaluates the situation in the same way as the previous module, but with the only difference. The difference from the previous module is that the evaluation is not conditioned by the received message. This block is evaluated regardless of the incoming message.

5.3.2 Flight to/from non-controlled airport

The basic difference between operating at a tower-controlled airport and one without an operating control tower is the difference between instructions and advisories. Tower controllers issue taxi, departure, and arrival instructions for pilots to follow on specific ATC frequencies. At non-controlled airports, you will hear advisories on a RADIO service, but the responsibility for collision avoidance, sequencing, and knowing the local procedures lies solely with the pilot.

On non-controlled airports is not control tower or ground control. Instead of CTR (controlled traffic region), the airport is surrounded by the ATZ (Aerodrome Traffic Zone). It serves to protect airport air traffic. It extends vertically from the Earth's surface to a height of 4000 feet. The horizontal border is formed by a circle with a radius of 3 miles (5.5 km) centered on the reference point of the airport.

The ATZ traffic is not controlled. Only the Aerodrome Flight Information Service (AFIS) or RADIO and emergency services are provided in ATZ. In practice, this means that the AFIS dispatcher cannot give the pilot a permit to fly, but only provides him with

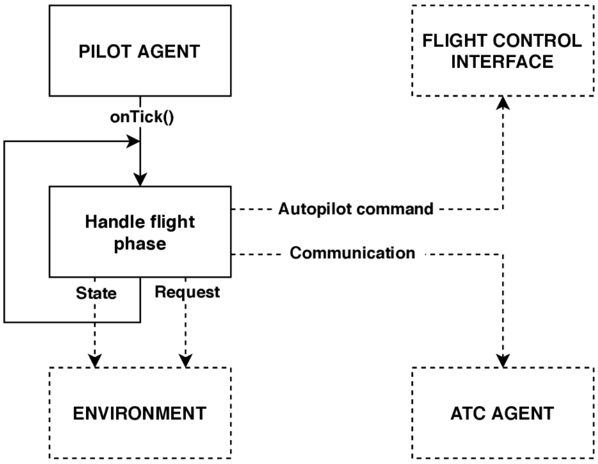


Figure 5.8: Pilot agent Evaluate ticker behavior.

useful information (airport traffic, meteorological information) and, in extreme cases, can issue an order or prohibition. However, the pilot decides on his own and all responsibility lies with him. Aircraft entering ATZ should establish contact with AFIS/RADIO. It should avoid or join an airport circuit [12].

Based on the type of planned flight it is possible to divide flight states to the two sets. The first set of flight states visualized on Figure 5.9 is used when aircraft are entering ATZ from outside and passing through the ATZ or planning to land at the local airport. The second set of states in Figure 5.10 describes all flights during aircraft take-off from the local airport.

Flight into Aerodrome Traffic Zone

As soon as the aircraft enters the ATZ on an non-controlled airport, it initializes contact with local RADIO service and announces the plans of flight. If the RADIO service is not responding, the aircraft is still announcing its actions and intentions (Figure 5.9).

If the aircraft is flying through the ATZ it takes recommendations from RADIO service and information about traffic. Aircraft should avoid the area of local traffic circuit around the airport. When the aircraft is leaving the ATZ, it ends the communication by announcing about leaving ATZ to RADIO service.

An aircraft hat planning to land at a local airport enters the recommended traffic circuit and performs preparation for landing. Next aircraft perform approach and landing. If any problems occur, the aircraft returns to the circuit and makes an additional loop on the circuit. After successful landing aircraft moves to the apron, gas station, or the hangar and announce the end of the communication.

Take-off from aerodrome traffic zone

When aircraft are planning to take-off, it contacts local RADIO service and announces the plans of flight. Then aircraft moves to the holding point. If there is no oncoming traffic, aircraft taxi on a specific runway and take-off. If any problem during departure occurs, aircraft moves back to the holding point.

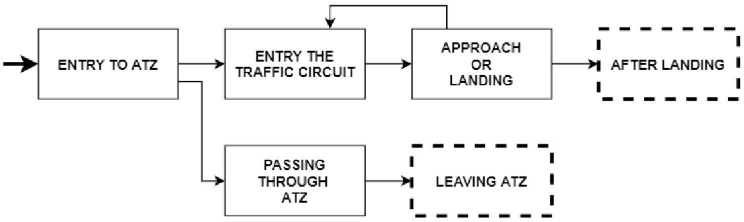


Figure 5.9: Aircraft flight states when entering ATZ.

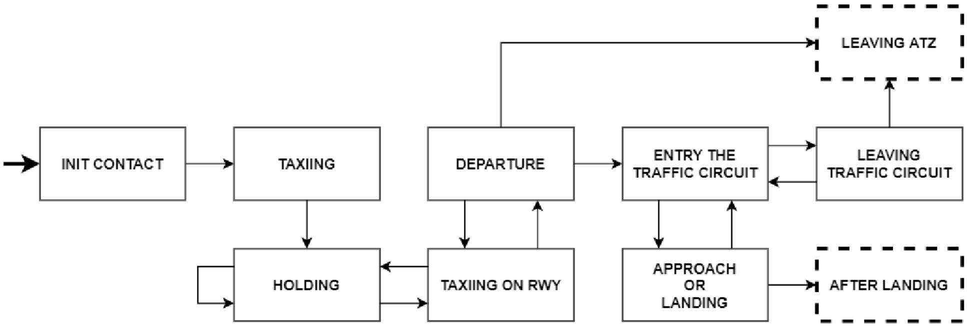


Figure 5.10: Aircraft flight states during take-off from non-controlled airport.

After take-off aircraft enter the traffic circuit or fly straight to the target destination. Aircraft announces leaving the circuit or leaving ATZ. Approach and landing are the same as described above in the previous subsection.

5.3.3 Interpretation of aircraft position states

Along with the longitude and latitude the position state is specified by the location of aircraft in the traffic pattern around the airport. The position state is determined by aircraft longitude, latitude, altitude, behavior, and local airport variables.

On Figure 5.11 are visualized traffic patterns on non-controlled airport. Left and right-hand traffic patterns as depicted in the Pilot's Handbook of Aeronautical Knowledge issued by the Federal Aviation Administration [8]. Because the active runway is chosen to meet the wind at the nearest angle (with take-offs and landings upwind), the pattern orientation also depends on wind direction. Patterns are typically rectangular in basic shape and include the runway along one long side of the rectangle. Each leg of the pattern has a particular name:

- Upwind leg - A flight path parallel to and in the direction of the landing runway. It is offset from the runway and opposite the downwind leg.
- Crosswind leg - A short climbing flight path at right angles to the departure end of the runway.
- Downwind leg - A long level flight path parallel to but in the opposite direction of the landing runway.
- Base leg - A short descending flight path at right angles to the approach end extended center-line of the landing runway.

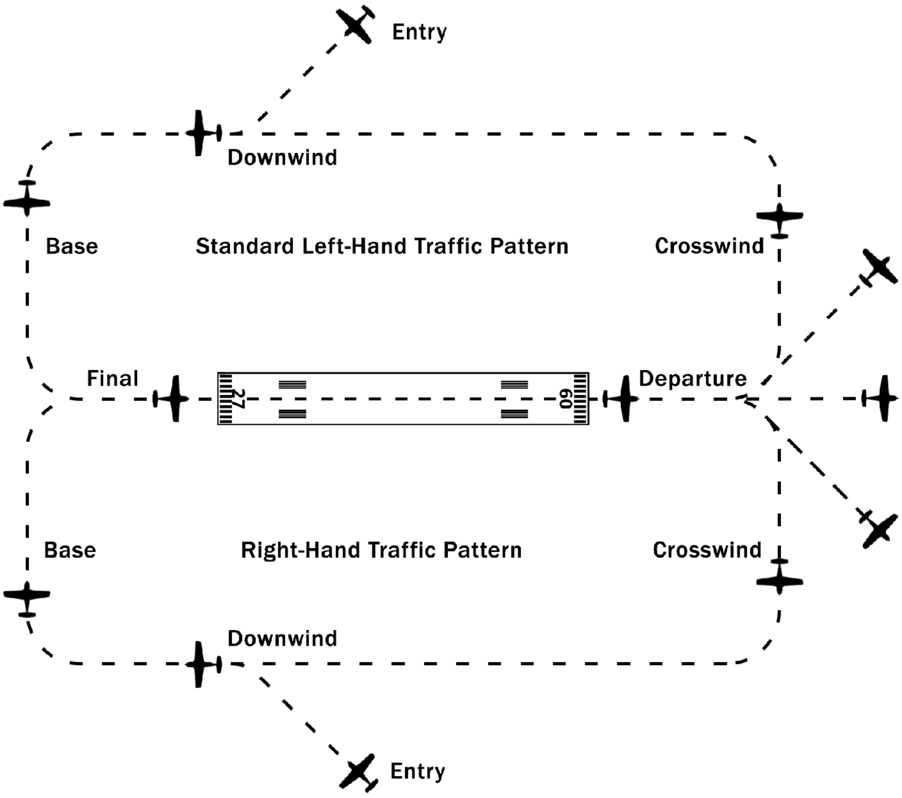


Figure 5.11: Traffic patterns on non-controlled airport [9].

- Final approach - A descending flight path in the direction of landing along the extended runway center-line from the base leg to the runway. The last section of the final approach is sometimes referred to the as short final.
- Departure leg - The climbing flight path along the extended runway center-line which begins at take-off and continues to at least 1/2 mile beyond the runway's departure end and not less than 300 feet below the traffic pattern altitude [8].

The analogy to that is the representation of the various pattern locations along with possible transitions between them (Figure 5.12). There are highlighted left and right-hand traffic circuits, with extended routes. An important position state is GO around, used during a fly over the runway.

To determine the correct position, it is necessary to calculate the distances based on longitude and latitude, magnetic bearing to get correct orientation and determine the new point based on magnetic bearing and distance from another point. With the help of Haversine Formula [33], it is possible to compute the great-circle distance (the shortest distance between two points on the surface of a Sphere), which represents the geographic distance on the Earth. Formula to calculate the distance between two geographical points is as follows:

$$d = 2R\arcsin(\sqrt{\sin^2(\frac{\varphi_2 - \varphi_1}{2}) + \cos(\varphi_1)\cos(\varphi_2)\sin^2(\frac{\lambda_2 - \lambda_1}{2})}) \tag{5.1}$$

where d is result distance in km, $R = 6378$ km is radius of the Earth. φ_1, φ_2 are latitudes of two points and λ_1, λ_2 are longitude of two points [33].

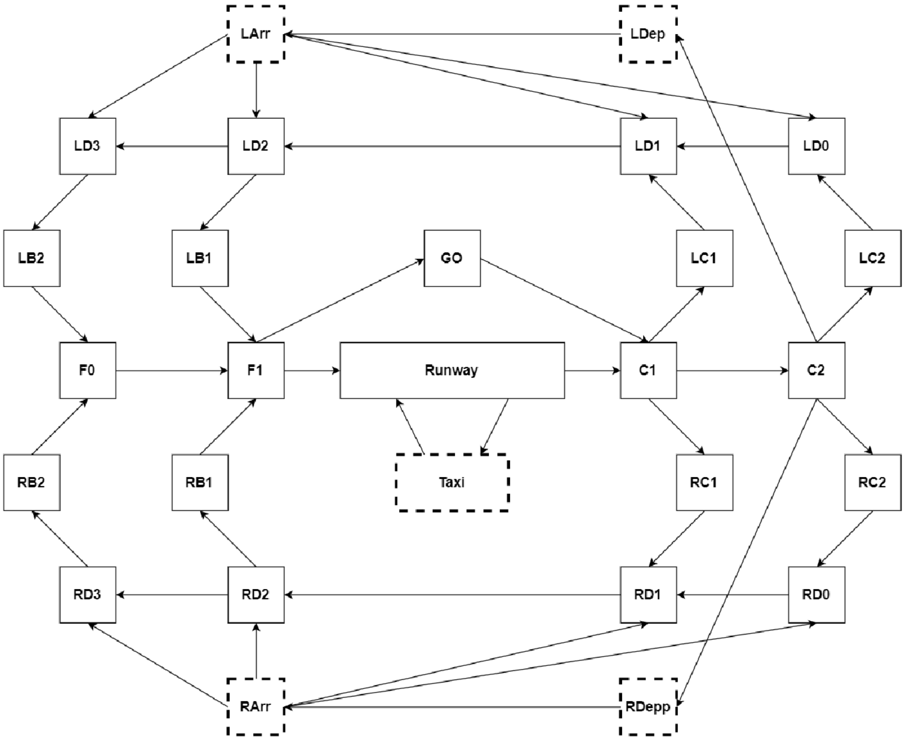


Figure 5.12: Interpretation of position states around non-controlled airport [4].

The calculation for the magnetic bearing between two points was used to calculate the course. Magnetic bearing from point A to B, can be calculated as follows:

$$\beta = atan2(\cos(\varphi_2)\sin(\lambda_2 - \lambda_1), \cos(\varphi_1)\sin(\varphi_2) - \sin(\varphi_1)\cos(\varphi_2)\cos(\lambda_2 - \lambda_1)) \tag{5.2}$$

where β is the result magnetic bearing, φ_1, λ_1 defines point A and λ_1, φ_2 defines point B [33].

Here is the formula to find the second point, when first point, magnetic bearing and distance is known:

$$\varphi_2 = \arcsin(\sin(\varphi_1)\cos(d/R) + \cos(\varphi_1)\sin(d/R)\cos(\alpha)) \tag{5.3}$$

$$\lambda_2 = \lambda_1 + atan2(\sin(\alpha)\sin(d/R)\cos(\varphi_1), \cos(d/R) - \sin(\varphi_1)\sin(\varphi_2)) \tag{5.4}$$

where φ_2, λ_2 defines the second point and α is magnetic bearing, d is distance in km from first point defined by φ_1, λ_1 and $R = 6378$ km is radius of the Earth [33].

5.3.4 Aircraft timing procedures

For the basic timing, changes of airspeed are used if the conditions and aircraft state allows it. Speed is calculated by ATC to arrive at a specific location at a specified time. If the condition or aircraft cannot perform a change of desired speed, or if the change is significant, the trajectory has to be changed. For basic trajectory change is used horizontal diversion maneuver.

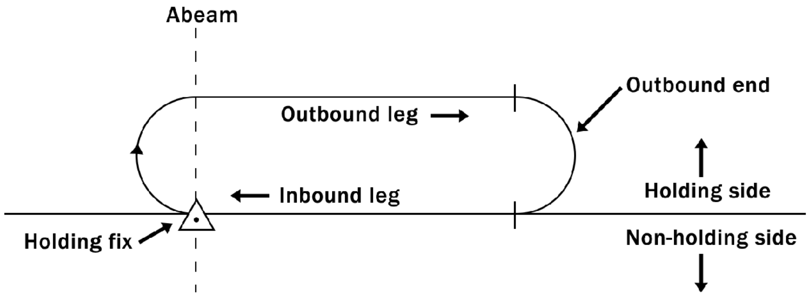


Figure 5.13: Holding pattern.

The horizontal diversion maneuver can be used either to keep a separation between aircraft in collision avoidance or to extend the aircraft flight plan to postpone its arrival to given location (typically airport). The maneuver is defined by the diversion angle, length of the diversion, and return point. The ATC orders the pilot to divert to a given magnetic heading and await further instruction. The pilot turns as soon as possible abandoning the current flight plan. When the aircraft reaches the desired position, ATC orders the pilot to change direction back to a return point and resume flight on the original flight plan from the return point on.

Orbit

If the horizontal diversion maneuver is not enough to delay the aircraft or are active restrictions of changing altitude, there is a possibility to perform orbit maneuver. The ATC determines speed, turn rate for the orbit, and direction to turn and then instructs the pilot. The pilot starts performing the desired turn until the aircraft reaches the same magnetic heading before performing the orbit maneuver.

Holding pattern

Holding procedure is a predefined maneuver that keeps the aircraft in predetermined airspace while waiting for clearance. The procedure is the same for VFR and IFR flights. Holding fix is a geographical location that serves as a reference point for holding procedures. The pattern itself is defined by the holding fix, heading of the inbound leg, and length of the pattern. The pattern and some terms used for its description are shown in Figure 5.13.

Reasons for holding can be traffic congestion, delays at the destination airport, or aircraft problems. The holding procedure is usually published beforehand but ATC can specify the details of a holding pattern if the situation calls for it. The turn direction is usually right, but left-hand turn holding patterns can be used if needed. Several aircraft can hold over the same holding fix, these aircrafts must be separated vertically. Normally the aircraft to arrive first holds on the lowest level with the following aircraft using successively higher levels. Jet aircraft can hold at higher levels to save fuel, but the order must be retained. Maximum holding speeds are established by ICAO to keep the aircraft within the protected holding space. Aircraft can also have specific holding speed prescribed by the manufacturer. This speed is lower than typical cruising speed and is used to conserve fuel. There are three different entry procedures for the holding pattern depending on in which direction the aircraft arrives at the holding fix. Direct entry is straight forward, the aircraft flies directly to the holding fix and turns outbound as soon as the holding fix is reached.

In offset, entry aircraft flies over the holding fix into the protected area and through the area and then turns back at the outbound end and continues the holding from there. In the parallel entry, the aircraft flies over the holding fix and continues parallel to the inbound leg on the non-holding side. At the outbound end, the aircraft turns and continues back to the holding fix a holds from there [12].

5.4 Components

This section lists the other components that the implemented agent system contains.

5.4.1 Communication component

A fundamental characteristic of agent systems is that individual agents communicate and interact. All types of messages are realized by the internal agent communication, which include various data transfers, ICAO communication, various requests and reports and terminate requests. Description and types of communication are listed in following subsections.

Internal agent communication

This is accomplished through the exchange of messages and, to understand each other, agents must agree on the format and semantics of these messages. Jade follows FIPA standards so that ideally Jade agents could interact with agents written in other languages and running on other platforms. There are many auxiliary parts to a message in addition to the content, for example, the intended recipients, the sender, and the message type. The message as a whole needs to respect a common format. In JADE, messages adhere strictly to the ACL standard which allows several possibilities for the encoding of the actual content [14].

To receive messages, each agent has implemented a cyclic behavior, in which all incoming messages are processed according to their content. Messages with ICAO communication are transmitted as plain text. Other messages for data transmission or various requests are transmitted in serialized objects, the class defines the type of message and the individual transmitted variables represents the content of the message.

ICAO communication

The communication between pilot and controller is based on voice communications that are affected by various factors. Communication between controllers and pilots can be improved by the mutual understanding's operating environment. The pilot-controller communication loop is visualized in Figure 5.14. It supports the safety and redundancy of pilot-controller communications. The pilot-controller communication loop constitutes a confirmation and correction process that ensures the integrity of communications. Whenever adverse factors are likely to affect communications, strict adherence to this closed-loop constitutes a line of defense against communications errors.

The communication is mostly initiated by the pilot requesting specific action permission, asking for guidance, reporting state, or asking for another information. Every initiation of communication starts with the identification of the recipient and follows the identification of the sender. For identification are used callsigns which are used for the entire flight and during all following conversations to exactly recognize specific aircraft. After the callsign

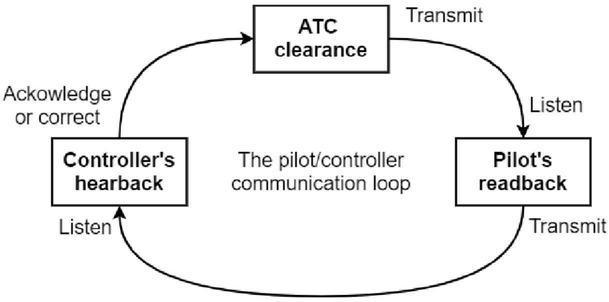


Figure 5.14: The Pilot-Controller Communication Loop [30].

follows the body of the message. In the message-body are specified requests, or other information. After the body could be added additional information and parameters of the body.

After the request from the pilot to ATC, the ATC response contains all requested information, clearance or restriction, and aircraft callsign. Then the pilot performs the readback and repeat all important parts of the message and adds aircraft callsign as identification. If everything is correct, ATC confirms the readback or repeat the information if readback is incorrect.

5.4.2 Environment component

The Environment component is the main component to create, maintain and terminate all other agents. This component is fully autonomous. It defines and creates an environment in which individual agents interact with each other. Its main task is to determine how individual agents perceive their environment. Most agents creating a simulation environment are configured statically before the simulation begins. During the simulation, agents representing aircraft can be created dynamically - Pilot agents and Flight control interfaces. The following subsections describe individual parts and behavior.

Environment modules

The operation of the Environment component is divided into two modules. The first module is called AircraftUpdate (Figure 5.15) and is used to receive all types of messages and at the same time to update the status of individual aircraft and respond to their requests for information about the environment. At the same time, this component is used to terminate individual agents. The second component is called RadarUpdate (5.16) and is used to update radar information for each controller.

The behavior block diagram of AircraftUpdate component is shown in Figure 5.15. It is a cyclical type of behavior and collects all types of messages. If it receives a message containing an aircraft state vector, it saves it and later uses it to interpret radar data. Another type of message is an information request or an agent-termination request. During information requests, the Pilot agent will normally request for information about the nearest or target airport. This information interprets knowledge that the pilot usually knows, or the information is in the flight manual or is transmitted through the Automatic terminal information service. This approach does not require all information about airports to be included in each Pilot agent, only information about a specific airport will be sent on request.

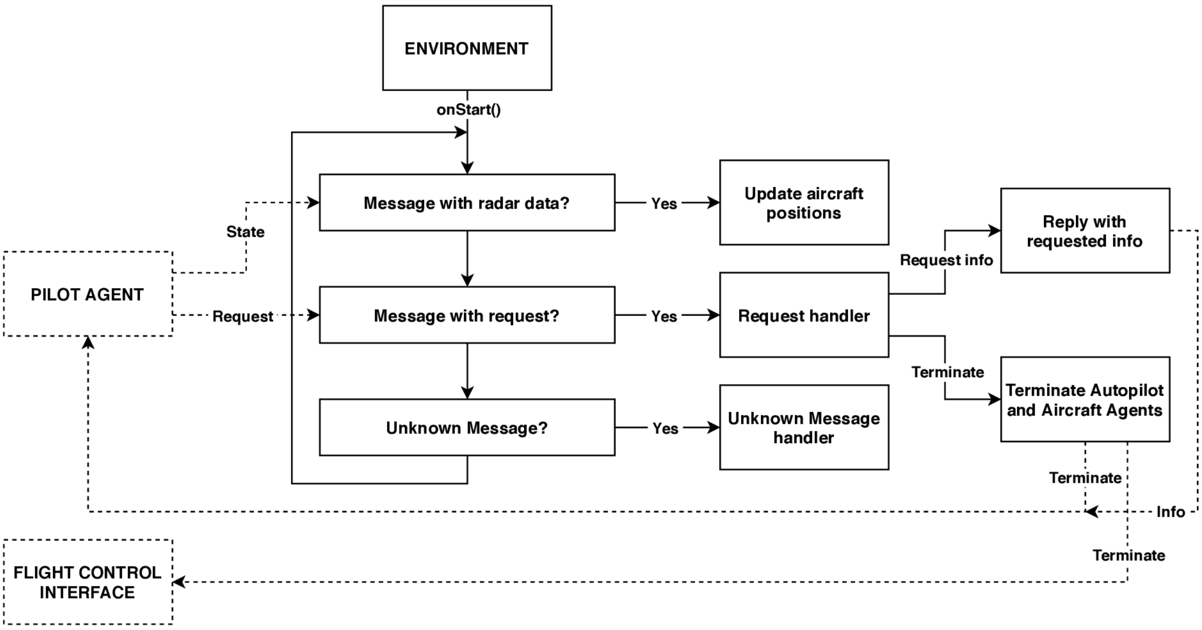


Figure 5.15: Environment component AircraftUpdate cyclic module.

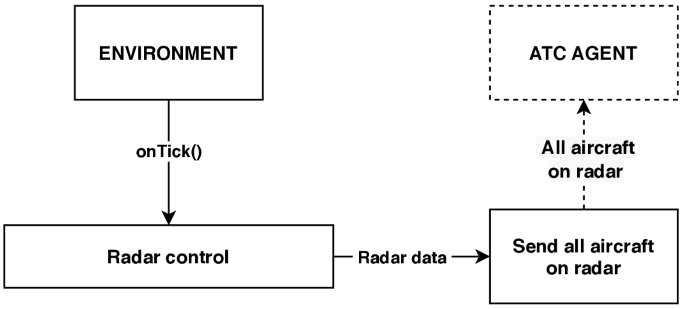


Figure 5.16: Environment component RadarUpdate ticker module.

If a request is made to terminate the Pilot agent, the Pilot agent and also the Flight control interface are terminated. The last step of this component is to check for invalid messages that detect invalid behavior.

The second component, called RadarUpdate (Figure 5.16), runs at regular intervals corresponding to the size of the radar frequency. Radar data are interpreted for all Air Traffic Controller agents, which includes all aircraft in the area in charge of the controller. So each controller only has information about the surrounding aircraft as if he saw them on the radar.

5.4.3 Flight control interface

Flight control interface represents the autopilot of aircraft and handling flight controls. It is fully autonomous and controls the aircraft through the given set of the waypoints defined by latitude, longitude, altitude, and speed, or maintain the flight parameters such as heading, speed, and altitude. It receives the commands by the Pilot agent and sends back the information about reaching certain waypoints. The following subsections describe individual parts and behavior.

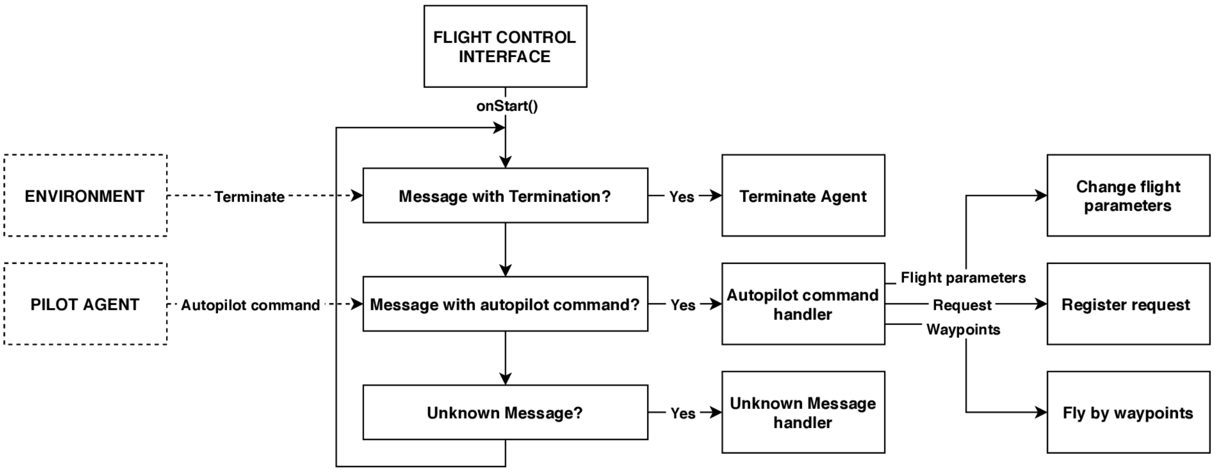


Figure 5.17: Flight control interface MessageReceiver cyclic module.

Flight control interface modules

The behavior of the autopilot is controlled by two modules. The first is MessageReceiver (Figure 5.17), which is used to receive messages and update the required flight configuration. The second block is called Evaluate (Figure 5.18) and is used to set the correct configuration of control and flight control along the required route.

MessageReceiver (Figure 5.17) is cyclical behavior and tries to capture incoming messages at the shortest possible intervals. Upon receiving the message, it triggers an action based on the type of message.

If it arrives from the Environment component with a command to terminate, all actions and behavior stops and the agent will terminate. The terminate message is sent to the Flight control interface and Pilot agent at the same time by default.

The usual message for an Flight control interface is a command from an Pilot agent. This command contains either the parameters of the required flight configuration, a set of waypoints, or a request to report the reaching of a particular waypoint. If the command contains a flight configuration, the flight via waypoints is canceled and a flight with the given configuration is established.

If a set of waypoints arrives, the flight is established according to the specified trajectory. A message with a set of waypoints can contain a parameter for overwriting the entire planned route with a new one, or a parameter for adding waypoints to an existing planned route. Another possible variant is to change the route parameter to adjust the flight level or speed for all established waypoints. This is used mainly during performing time correction maneuvers. The last-mentioned variant of the message type is the request to report the reaching of a given waypoint. This information activates the reporting state for a specific point. The actual control of reaching a given point is performed in the next block called Evaluate (Figure 5.18). Finally, an invalid message is being checked for a communication or synchronization error. This is mainly for future development and testing purposes.

The second behavior block of Flight control interface is Evaluate behavior (Figure 5.18). This behavior is a so-called ticker behavior, which is triggered at regular intervals with a specified frequency. In the first phase, a control is made to see if a waypoint has been reached. For robustness, each waypoint has a defined tolerance, which indicates the distance from which the waypoint can be marked as reached. The tolerances at the approach route

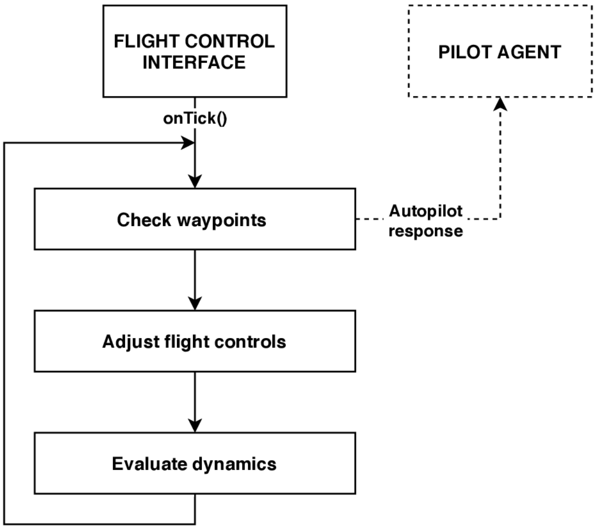


Figure 5.18: Flight control interface Evaluate ticker module.

are higher than at waypoints on the airport circuit or directly on the runway. If a waypoint is reached and has an active request to report the reaching of this point, the report message to the Pilot agent is sent.

In the second phase, the degree of deviation from the required course, altitude, and speed is determined and according to the difference, flight controls are adjusted. In use case with X-Plane is sent a message to the X-Plane autopilot with navigation command. For higher smoothness of movement and less frequency of navigation instructions, the values of the already instructed directions are preserved, and therefore if the autopilot has already been instructed to turn to a specific course, the message is not sent again with the same course in the next iteration.

In the last phase, the dynamics of the flight are evaluated using an X-Plane or another motion model. The state vector of the aircraft is further distributed to all agents who operate with it.

5.4.4 Visualization component

For testing and evaluation were implemented visualization screens. One for airport radar and one for the ground situation at the airport.

Airport radar screen

In the center of the radar screen is located airport and visualized runway with labels indication direction. The circles serve for distance estimation. Around the airport are marked control points and entry points labeled with corresponding names. All aircraft located on the radar are marked with the aircraft symbol and the line directing the aircraft heading. Next to the aircraft symbol is visualized aircraft callsign and aircraft current altitude. Behind the aircraft is a marked flown trajectory.

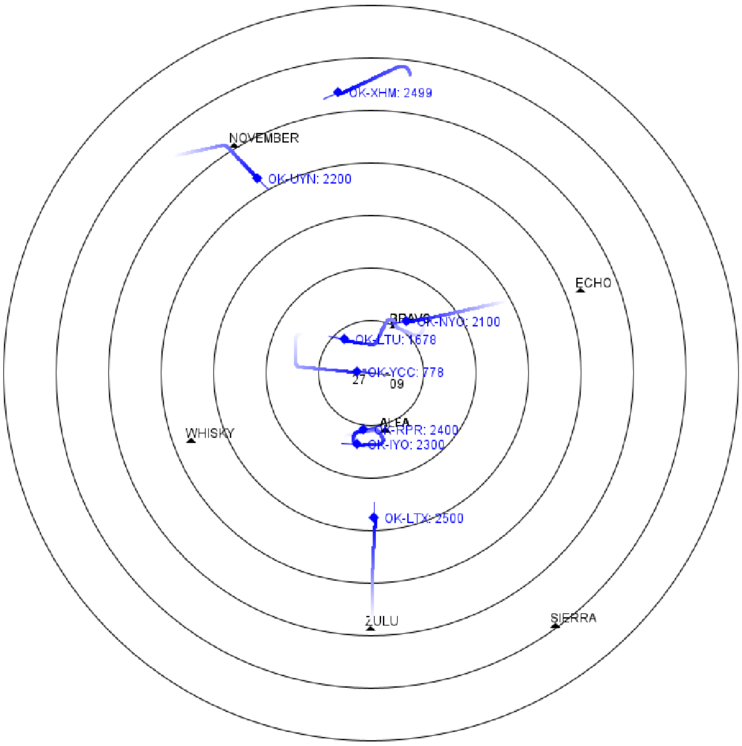


Figure 5.19: Airport radar screen visualization.

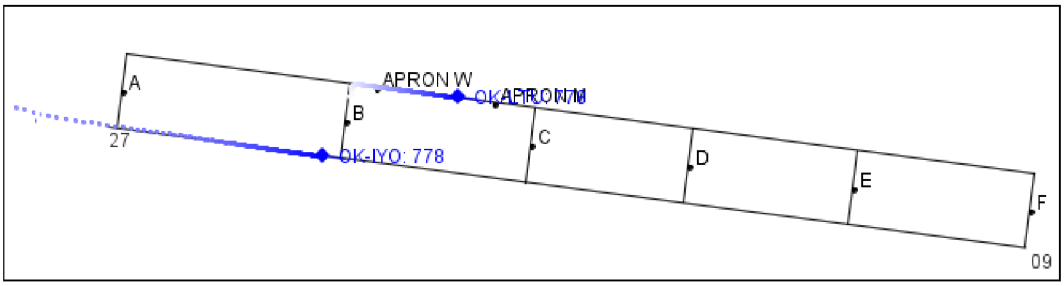


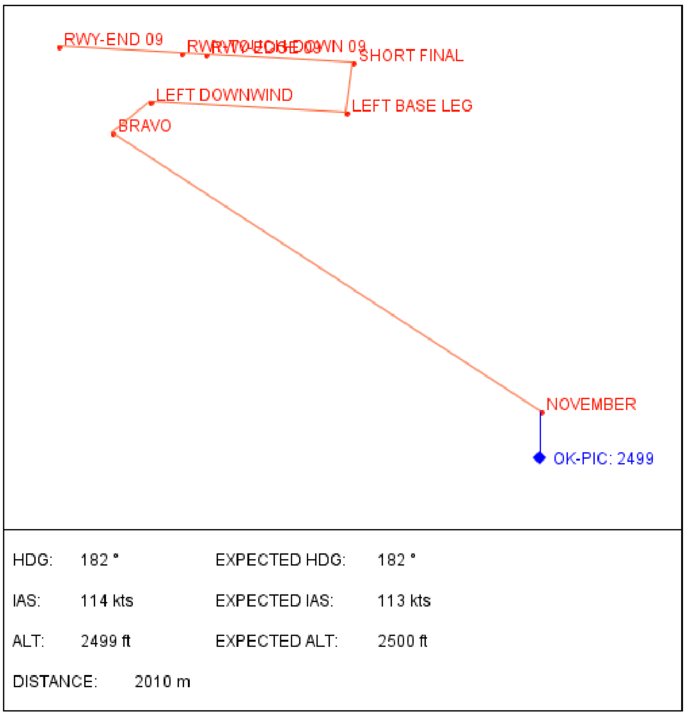
Figure 5.20: Airport ground scene visualization.

Airport ground situation screen

On the ground screen is visualized all taxiways from the runway into APRONS. The taxiways are labeled by a symbol, which also represents the holding point. All aircraft located on the airport are marked with the aircraft symbol and the line directing the aircraft heading. Next to the aircraft symbol is visualized aircraft callsign.

Pilot task screen

The pilot task screen (Figure 5.21) shows the current flight parameters and the planned route. The orientation of the display is according to the current course of the aircraft. At the bottom left, the current main flight parameters are displayed, such as the current course Heading (HDG), which is given in degrees, and the Indicated Airspeed (IAS) in knots and Altitude (ALT) in feet. In addition to the current flight parameters, the expected values



HDG: 182 ° EXPECTED HDG: 182 °
IAS: 114 kts EXPECTED IAS: 113 kts
ALT: 2499 ft EXPECTED ALT: 2500 ft
DISTANCE: 2010 m

Figure 5.21: Screen for visualization of pilot's tasks and planned trajectory.

of the flight parameters for navigation to the nearest waypoint are also given here, and the optimal speed depends on the expected arrival time at the given waypoint. The distance in meters to the nearest waypoint is also given here. The individually planned waypoints are also named according to the defined names at the specific airport. The route between the individual route points is marked. The route from the previous waypoint is distinguished by the blue color to visualize the degree of deviation from the assumed route.

Chapter 6

Testing and Evaluation

This chapter describes the test scenarios for verifying the functions of the implemented Air Traffic Control agent and the Pilot agent. Also described below are The metrics and methods of evaluation of implemented Use Case for a Pilot operation in synthetic ATC environment.

6.1 Testing scenarios

The functional verification of the implemented agent system was performed using a range of tests. The navigation and the correct decision-making for a secure approach and landing were tested using the Air Traffic Control precision test, which demonstrates the accuracy of navigation on high fidelity flight simulation with an autopilot. Determining the performance and limitations of autonomous air traffic control proposed in this work was evaluated using performance tests with different air traffic densities while recording potential collisions between individual aircraft. The following subsections describe and visualize individual test scenarios.

6.1.1 Air Traffic Control precision test

The test of navigation precision consists of flying an airport circuit, performing a correct approach, and a safe landing. All of this is demonstrated in a high fidelity flight simulation with an autopilot, which is given the parameters of the flight course, target altitude, and speed. The X-Plane flight simulation with an autopilot developed by the AeroWorks team at the Brno University of Technology [1] was used in the course of the flight simulation. The flight scenario itself consisted of an aircraft approaching from the northeast inbound LKTB airport, Brno Turany, and landing under visual flight rules conditions and an advisory of implemented autonomous Air Traffic Controller.

The following figures show the environment and the progress of the accuracy test. Figure 6.1 shows the approach of the aircraft with the callsign $OK - ONP$ on the radar screen of the Air Traffic Controller. Figure 6.2 shows the expected route starting with the entry point $ECHO$ and joining the airport circuit via control point $BRAVO$. The current status and specific flight parameters for navigation to the next waypoint are displayed at the bottom left of the Figure 6.2.

Figure 6.3 shows the current flight situation in the X-Plane simulation environment and displays the geographic position of the aircraft during the approach on a flight map.

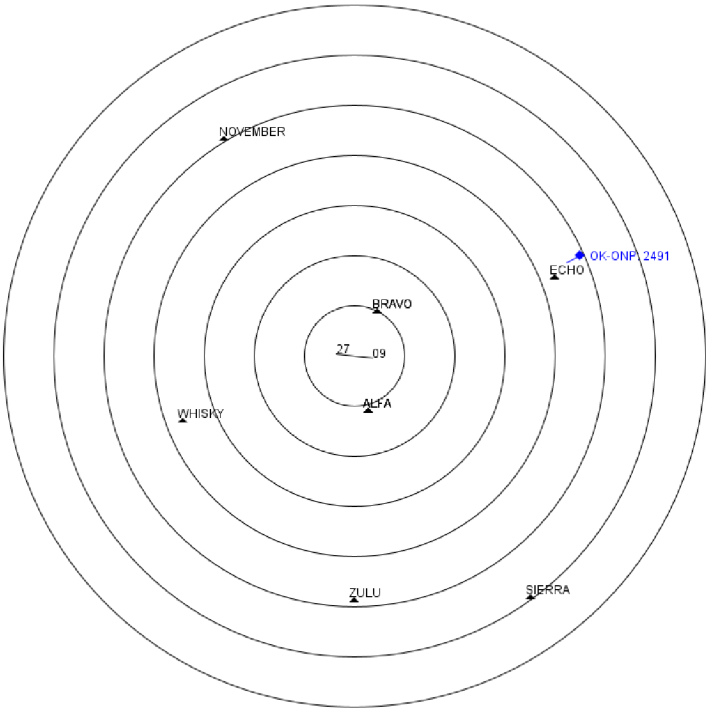
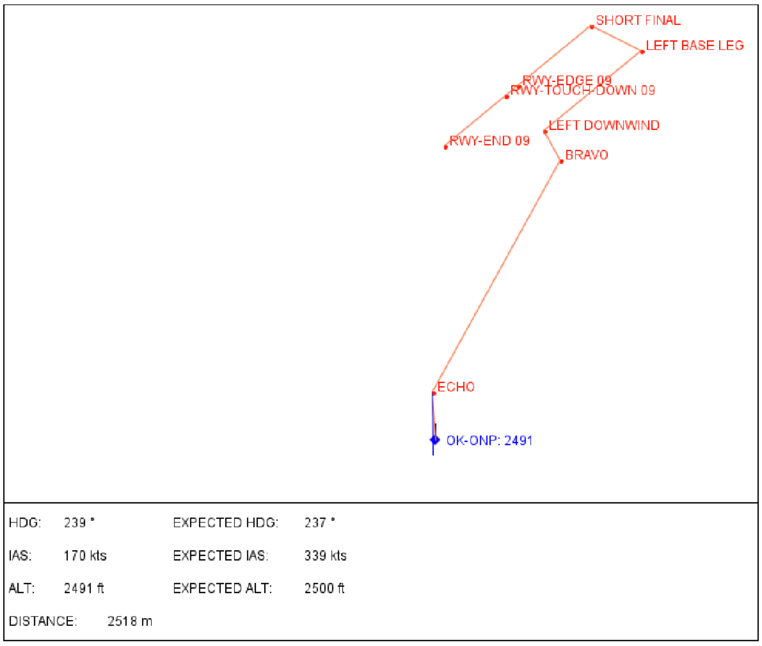


Figure 6.1: ATC radar screen during precision landing scenario.



HDG: 239 ° EXPECTED HDG: 237 °
IAS: 170 kts EXPECTED IAS: 339 kts
ALT: 2491 ft EXPECTED ALT: 2500 ft
DISTANCE: 2518 m

Figure 6.2: Pilot task screen during precision landing scenario.

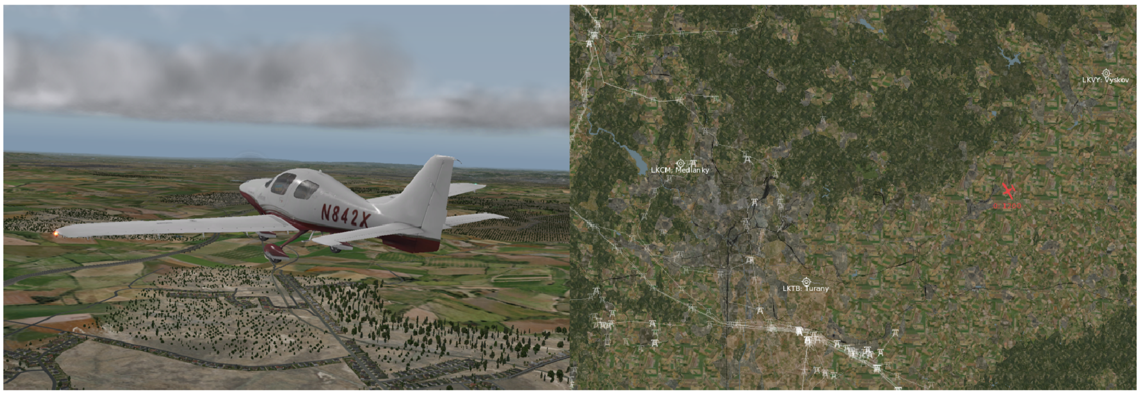


Figure 6.3: X-Plane simulation and map overview during the precision landing scenario.

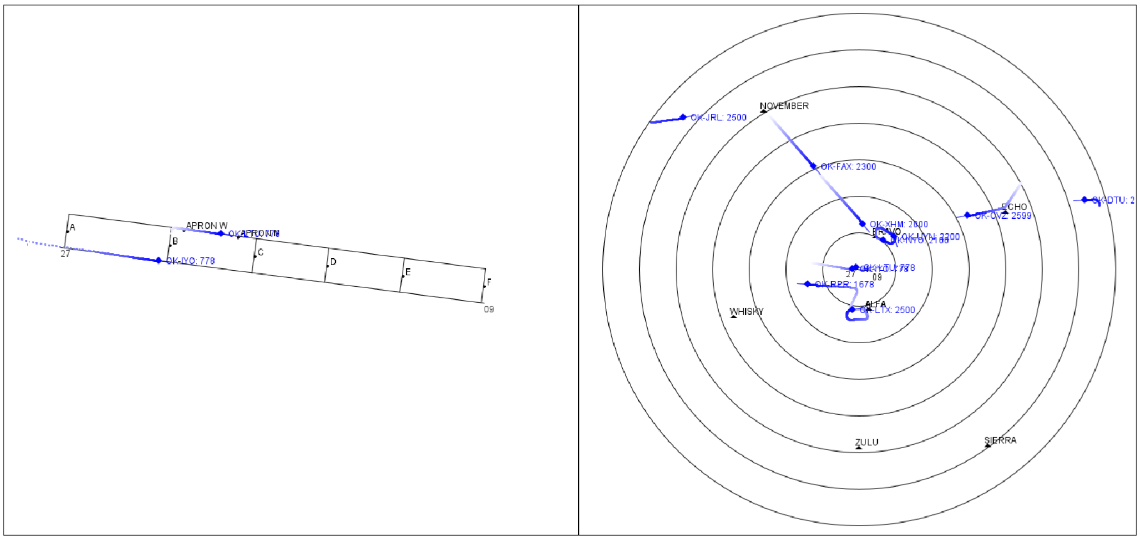


Figure 6.4: ATC radar screen and ground scene during performance tests.

During the precision landing test, the aircraft remained on the specified route with the given flight parameters and remained within performance boundaries on the specified trajectory. The aircraft landed safely, thus confirming the accuracy of the implemented system. This test was repeated several times and performed using different intercept directions and runways.

6.1.2 Air Traffic Control performance test

A performance test is designed to evaluate the function of the arrival scheduler, which will demonstrate the ability to effectively plan arrivals and at the same time meet the safety criteria of separation. As part of this testing, the air traffic control agent is exposed to various air traffic densities.

To simulate air traffic, an air traffic generator was implemented, which generates individual aircraft in the vicinity of the airport CTR according to specified parameters. The input parameters for the generator are the time interval and the probability with which the generator will generate a new aircraft at a given time slot. The position of the aircraft is random up to a certain distance from the CTR. Even though the time interval is regular,

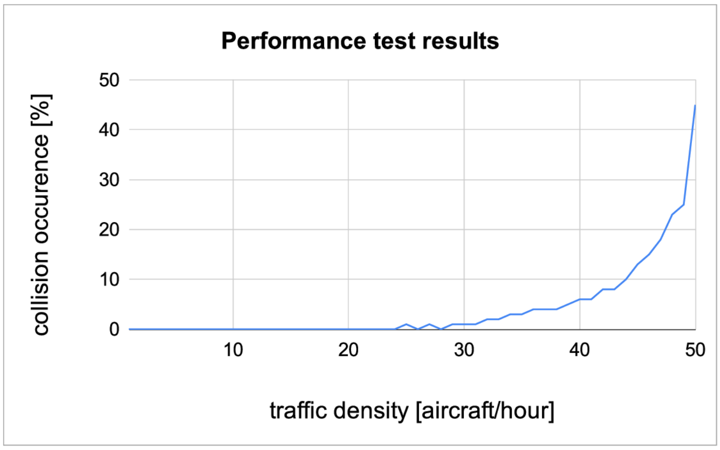


Figure 6.5: Performance test results of ATC handling different aircraft flows.

various distances from the airport will ensure uneven air traffic and at the same time accomplish the set number of aircraft per unit of time. For the sake of performance testing the probability of aircraft generation at a given time was set to the maximum applicable value.

The performance test was performed gradually for different traffic densities. Each test ran in fast time mode for the equivalent of half an hour of real-time. Possible collisions were recorded during each test. All situations, where two or more aircraft were at the same flight level and did not observe the distance for the safe separation were evaluated as potential collisions. Figure 6.4 shows the actual situation on the air traffic control radar screen and on the runway and airfields during the performance test.

The result in Figure 6.5 shows that the optimal number of aircraft that the autonomous controller can safely navigate is approximately 20 per hour. During the flight of more than 25 aircraft per hour, the number of encountered collisions grows.

6.2 Pilot evaluation metrics in Use Case 1

This section describes metrics and scenarios for evaluating the implemented Use Case 1 for the Pilot operation in a synthetic ATC environment.

The basic evaluation criteria for pilot evaluation when interacting with the driver are knowledge of flight rules, compliance with the controller's instructions, knowledge of the environment, and proper communication. In this case, communication is generated automatically, so it will not be the subject of evaluation. Other criteria can be expressed by the flight path and time estimations in which the aircraft should fly the route. These criteria are known as 4D trajectory and are the subject of research toward a new generation of automated Air Traffic Control [28].

The time difference is determined by the current delay of the aircraft compared to the expected arrival to the specific waypoint. The deviation from the expected trajectory is determined by the distance from the planned flight path. With increasing distance from the expected route, areas that represent the deviations from planned trajectory are defined. The individual deviation levels from the planned route are shown in Figure 6.6.

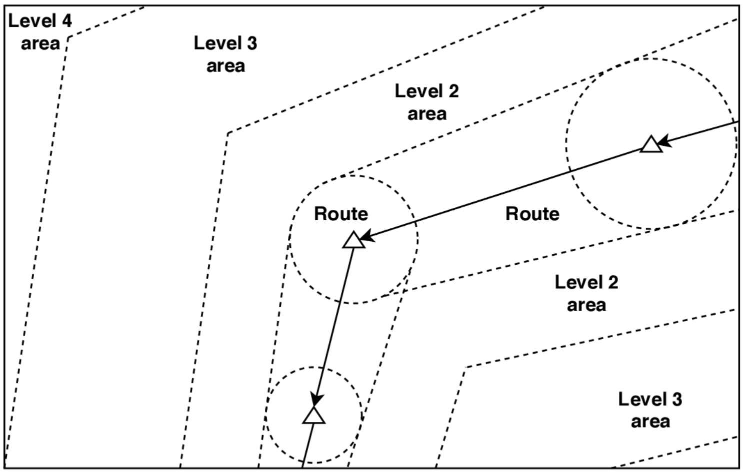


Figure 6.6: Areas leading along the flight path for pilot evaluation.

The resulting values for evaluating the success and experience of a given pilot are the total time intervals during which the aircraft was in the given deviation area during the flight. The recorded time intervals can be used as metrics for evaluating the pilot's experience. However, based on this one metric alone, the exact level of experience of the evaluated pilot cannot be determined and is not the subject of this work.

6.2.1 Traffic scenarios in Use Case 1

Possible scenarios for the pilot evaluation contain the application of the described metrics during different flight conditions. The basic possible scenario is a standard arrival during low traffic. In this scenario, the pilot has to fly the route, which remains constant during the flight, as it is not affected by other air traffic participants.

Another possible scenario is flight during increased air traffic. During the standard density of air traffic, the pilot is exposed not only to the standard instructions of the air traffic controller but also to the instructions for changing the flight parameters, such as changing to another flight level or adjusting the air speed. In rare cases, the pilot is also instructed to establish a holding pattern at a fixed waypoint.

In a high-traffic scenario, the pilot is instructed to make evasive maneuvers to deconflict between aircraft to maintain safe separation. Due to the high occupancy of the airport, the pilot will have a scheduled landing interval, which he must comply with.

In addition to increasing air traffic, a non-standard situation is also possible when the non-compliant aircraft or an aircraft with the maximum priority operates in the CTR of a given airport. In this case, all operations are suspended and the pilot is instructed to establish a holding pattern in the place where he is currently located and to wait until the non-standard situation passes.

Chapter 7

Conclusion

This work was aimed at a design of an agent system for an Air Traffic Control environment and design and implement agents for the pilot and controller, respectively the setup was constructed as to reflect the typical situations occurring in an Air Traffic Control environment. The prerequisite task of this work was to research the history of Air Traffic Control simulation and implement an Air Traffic simulation framework. Based on the knowledge gained from the research chapter on the history of Air Traffic Control simulation an Air Traffic simulation framework was designed and implemented. Furthermore, an agent system for Air Traffic Control with an aircraft scheduler was designed and subsequently implemented and integrated into the designed Air Traffic simulation framework. The implemented Air Traffic Control agent system was subjected to a series of tests, examining the navigation precision of individual air participants. An associated task was to evaluate the performance at different air traffic densities. In addition to the control agent itself, a Use Case for the Pilot operation in a synthetic Air Traffic Control environment was designed, which can be used as one of the metrics for pilot evaluation.

7.1 Potential further improvements

The implemented agent system can be further expanded for other possible applications such as training and evaluation of Air Traffic Controller. Thanks to its agent structure, the system can be expanded with additional air traffic participants, or the entire system can be scaled to cover more airport areas. The implemented flight scheduler can be further optimized or extended with algorithms based on reinforcement learning. For further possible analysis or learning, the possibility to speed up the simulation time the agent system can also be used for generating a datasets of air traffic. Another direction of development is the Unmanned Traffic Management (UTM), which is a concept of fully automated Air Traffic Control and with the growth of air transport and unmanned vehicles some sort of automation will be necessary [32].

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Appendix A

Additional documentation for precision landing test

Communication between ATC and approaching pilot during precision landing test:

A: TURANY APPROACH, OK-ONP

ATC: OK-ONP, TURANY APPROACH GO AHEAD

A: OK-ONP, CESSNA 172 VFR FROM KYJOV, 2499 FEET, 5 MILES TO CONTROL ZONE BOUNDARY, FOR LANDING AT TURANY INFORMATION ECHO

ATC: OK-ONP, TURANY APPROACH, ENTER TURANY CONTROL ZONE VIA ECHO, QNH 1029

A: ENTER VIA ECHO QNH 1029 OK-ONP

ATC: OK-ONP, CONTACT TURANY TOWER 119.605

A: TURANY TOWER 119.605, OK-ONP

A: TURANY TOWER, OK-ONP

ATC: OK-ONP, TURANY TOWER GO AHEAD

A: OK-ONP, CESSNA 172 VFR FROM KYJOV, 2499 FEET, AT ECHO, FOR LANDING AT TURANY

ATC: OK-ONP, TURANY TOWER, AFTER PASSING ECHO AT ALTITUDE 2500 PROCEED VIA BRAVO TO JOIN LEFT DOWNWIND RUNWAY 09 QNH 1029

A: PROCEED VIA BRAVO, ALTITUDE 2500, JOIN LEFT DOWNWIND RUNWAY 09 QNH 1029, OK-ONP

ATC: OK-ONP, TURANY TOWER, REPORT LEFT DOWNWIND RUNWAY 09

A: REPORT LEFT DOWNWIND RUNWAY 09, OK-ONP

ATC: OK-ONP, DESCENT TO FLIGHT LEVEL 20

A: DESCENT TO FLIGHT LEVEL 20, OK-ONP

A: OK-ONP, LEFT DOWNWIND

ATC: OK-ONP, TURANY TOWER, REPORT SHORT FINAL

A: REPORT SHORT FINAL, OK-ONP

A: OK-ONP, SHORT FINAL

ATC: OK-ONP, TURANY TOWER, RUNWAY 09 CLEARED TO LAND, WIND 78 DEGREES 15 KNOTS

A: RUNWAY 09 CLEARED TO LAND, OK-ONP

ATC: OK-ONP, VACATE RUNWAY VIA TAXIWAY B, TAXI TO APRON M

A: VACATE RUNWAY VIA TAXIWAY B, TAXI TO APRON M, OK-ONP

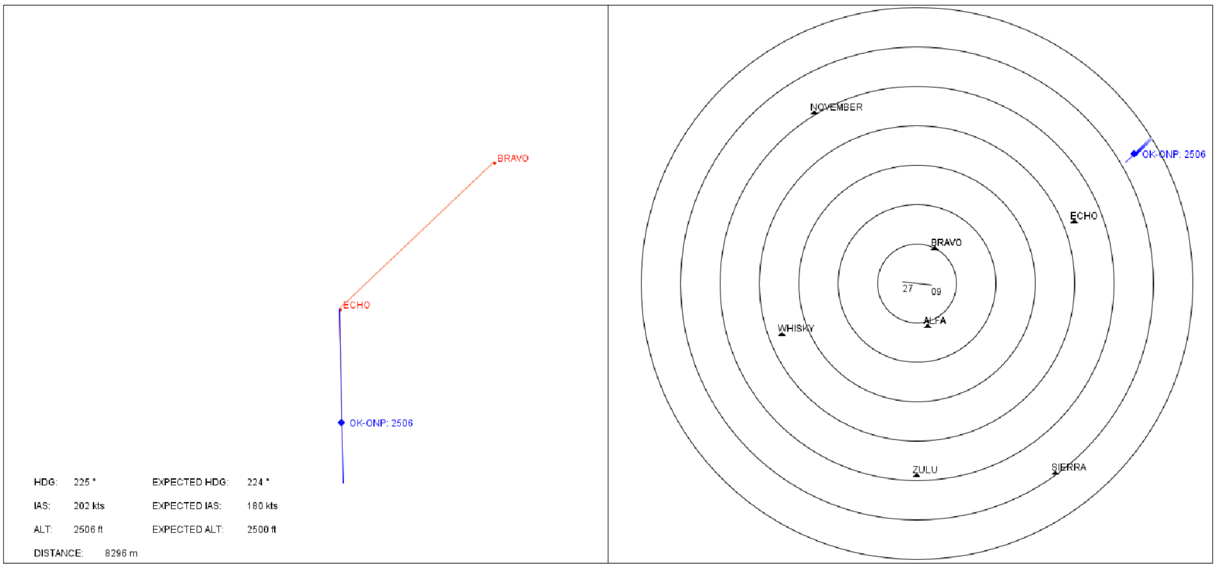
ATC: OK-ONP, REPORT APRON M

A: REPORT APRON M, OK-ONP

A: OK-ONP, APRON M

ATC: OK-ONP, GOODBYE

A: GOODBYE, OK-ONP



HDG: 225 ° EXPECTED HDG: 224 °
IAS: 202 kts EXPECTED IAS: 180 kts
ALT: 2506 ft EXPECTED ALT: 2500 ft
DISTANCE: 8296 m

Figure A.1: Approach flight phase of precision landing test.

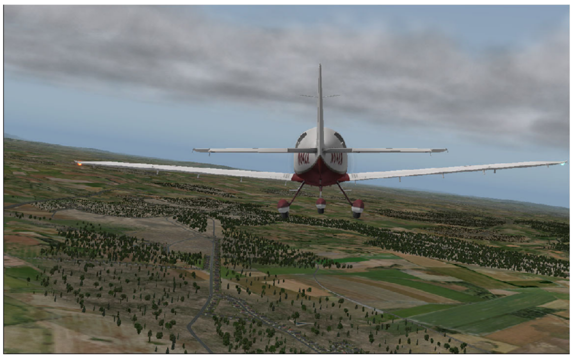


Figure A.2: Approach in X-Plane.

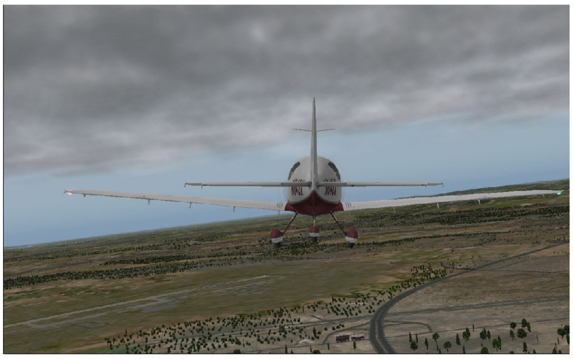
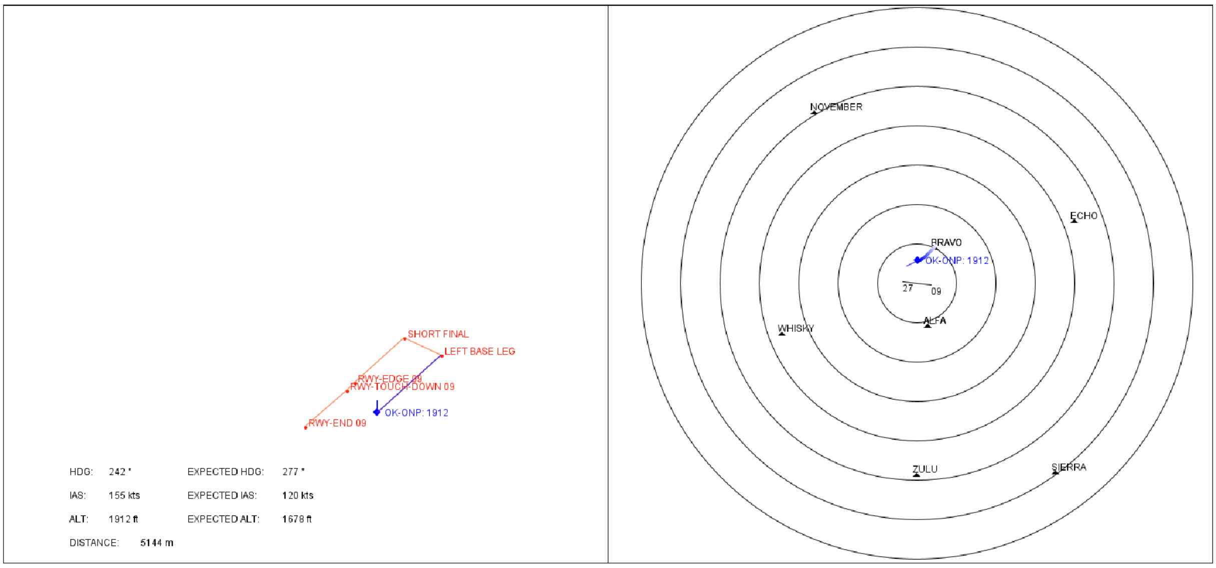
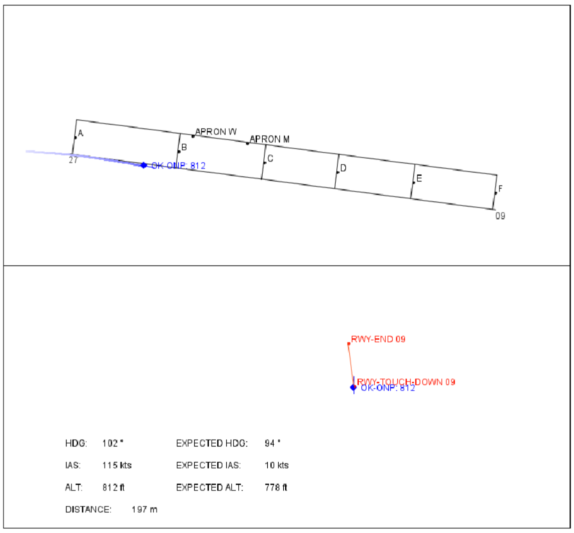


Figure A.3: Circuit entry in X-Plane.



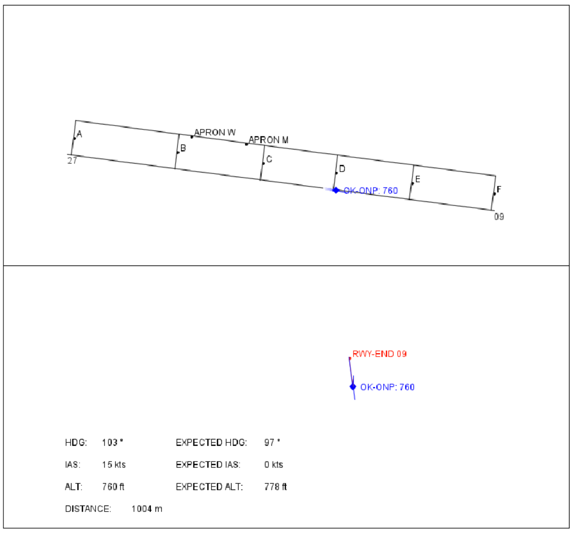
HDG: 242 ° EXPECTED HDG: 277 °
IAS: 155 kts EXPECTED IAS: 120 kts
ALT: 1912 ft EXPECTED ALT: 1678 ft
DISTANCE: 5144 m

Figure A.4: Entering the circuit phase of precision landing test.



HDG: 102 °
EXPECTED HDG: 94 °
IAS: 115 kts
EXPECTED IAS: 10 kts
ALT: 812 ft
EXPECTED ALT: 778 ft
DISTANCE: 197 m

Figure A.5: Short final phase.

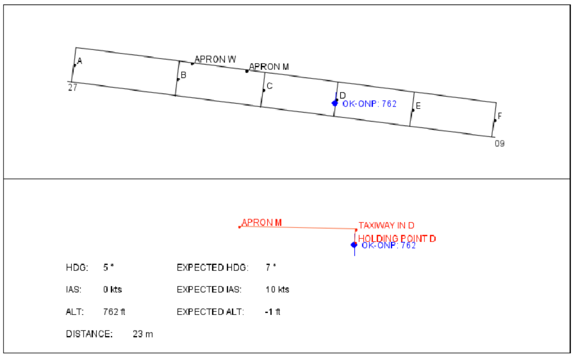


HDG: 103 °
EXPECTED HDG: 97 °
IAS: 15 kts
EXPECTED IAS: 0 kts
ALT: 760 ft
EXPECTED ALT: 778 ft
DISTANCE: 1004 m

Figure A.6: Landing phase.

Figure A.7: Short final in X-Plane.

Figure A.8: Landing in X-Plane.



HDG: 5 °
EXPECTED HDG: 7 °
IAS: 0 kts
EXPECTED IAS: 10 kts
ALT: 762 ft
EXPECTED ALT: -1 ft
DISTANCE: 23 m

Figure A.9: Taxi-in phase.

Figure A.10: Taxiing in X-Plane.

Appendix B

Content of the enclosed CD

- bin: binary files
- doc: documentation source codes
- src: application source codes
- dp.pdf
- license
- README