Czech Technical University in Prague
Faculty of Electrical Engineering

Department of Cybernetics

DIPLOMA THESIS ASSIGNMENT

Student: Bc. Lukáš Koranda

Study programme: Open Informatics

Specialisation: Artificial Intelligence

Title of Diploma Thesis: Conflict Resolution Model of Human Radar Controller in Air-Traffic Management

Guidelines:

1. Study approaches of air-traffic controllers used for removal of identified collision on flight trajectories within en-route sectors.
2. Get familiar with the architecture of the multi-agent system AgentFly and its internal model of the behavior of human air-traffic controller.
3. Design architecture of the module for the selection of suitable resolution maneuver removing conflict on flight trajectories. The proposed architecture has to be based on the search over multiple alternative maneuvers generated using different approaches (vertical, lateral and speed changes) considering evaluation function. Coefficients from this evaluation function have to be configured from the configuration files.
4. Implement designed architecture in the system AgentFly as the new module for the model of air-traffic controller.
5. Test the implemented conflict resolution module within simulation and compare its output characteristics with the existing approach in the system. Analyze influence of all coefficients from the evaluation function to the selection of conflict resolution strategy.

Bibliography/Sources:

[1] Michael S. Nolan: Fundamentals of Air-Traffic Control, Thomson, 2004.
[2] Federal Aviation Administration: Air-traffic procedures
[3] Šišlák, D.; Volf, P.; Pěchouček, M.; Cannon, C.T.; Nguyen, D.N.; Regli, W.C.: Multi-Agent Simulation of En-Route Human Air-Traffic Controller. In Proceedings of the 24th IAAI Conference. Toronto, AAAI Presss, 2012.
[4] Šišlák, D.; Pěchouček, M.; Volf, P.; Pavlíček, D.; Samek, J.; Mařík, V.; Losiewicz, P.: Agentfly: Towards Multi-Agent Technology in Free Flight Air Traffic Control. Defence Industry Applications of Autonomous Agents and Multi-Agent Systems. Birkhauser Verlag, 2008.

Diploma Thesis Supervisor: Ing. David Šišlák, Ph.D.

Valid until: the end of the summer semester of academic year 2013/2014

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Prague, January 10, 2013

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ZADÁNÍ DIPLOMOVÉ PRÁCE

Student: Bc. Lukáš K o r a n d a

Studijní program: Otevřená informatika (magisterský)

Obor: Umělá inteligence

Název tématu: Model chování leteckého dispečera při výběru řídícího zásahu odstraňující budoucí kolizi na letové trase

Pokyny pro vypracování:

1. Seznamte se s postupy letového dispečera pro odstranění identifikovaných kolizí na letových trasách ve střední fázi letu (tzv. en-route).
2. Prostudujte architekturu multi-agentního systému AgentFly a jeho modelu chování letového dispečera obsluhujícího pracoviště oblastního řízení.
3. Navrhněte architekturu pro modul zajišťující výběr vhodného zásahu odstraňující kolizi na letových trasách. Založte tento model na prohledávání stavového prostoru vygenerovaného za pomocí různých přístupů k řešení (vertikální, horizontální a rychlostní změny) s pomocí ohodnocovací funkce, kde půjdou volit koeficienty jednotlivých komponent.
4. Navrženou architekturu modulu implementujte v simulačním systému AgentFly jako další modul modelu letového dispečera.
5. Implementovaný modul v rámci simulace otestujte a porovnejte jeho výstupní charakteristiky proti stávajícímu přístupu k řešení kolizí. Proveďte analýzu vlivu jednotlivých koeficientů navržené ohodnocovací funkce na volbu rezoluční strategie.

Seznam odborné literatury:

[1] Michael S. Nolan: Fundamentals of Air-Traffic Control, Thomson, 2004.
[2] Federal Aviation Administration: Air-traffic procedures
[3] Šišlák, D.; Volf, P.; Pěchouček, M.; Cannon, C.T.; Nguyen, D.N.; Regli, W.C.: Multi-Agent Simulation of En-Route Human Air-Traffic Controller. In Proceedings of the 24th IAAI Conference. Toronto, AAAI Presss, 2012.
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Master's Thesis

Conflict Resolution Model of Human Radar Controller in Air-Traffic Management

Bc. Lukáš Koranda

Supervisor: Ing. David Šišlák, PhD.

Study Programme: Open Informatics

Field of Study: Artificial Intelligence

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Finally, I am thankful to my family and friends for unconditional support and facing difficulties on making my education foremost priority.

Prohlášení

Prohlašuji, že jsem předloženou práci vypracoval samostatně a že jsem uvedl veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací.

V Praze 10. 5. 2013 Lukáš Kamarda

Abstract

The aim of this thesis is a design of a module of the multi-agent simulation AgentFly for a simulation of air traffic controllers of flight trajectories within en-route sectors. The goal of designed module is to model behaviour of the air traffic controller during selection of a suitable solution manoeuvre for a collision removal. The suitable solution is chosen by evaluation of a fully configurable penalty function. The output of this thesis is an implementation of a collision resolution module, which is able to model different behaviour of the air traffic controller in the en-route sectors.

Abstrakt

Tato práce se zabývá návrhem modulu pro multi-agentní simulaci AgentFly, jejíž cílem je simulace letových dispečerů na letových trasách ve střední fázi letu (tzv. en-route). Úkolem navrženého modulu je modelovat chování dispečera při výběru vhodného zásahu odstraňujícího kolize na letových trasách v en-route. Vhodný zásah je volen pomocí hodnotící funkce, která je plně konfigurovatelná. Výsledkem této práce je implementovaný modul řešení kolizí, který je možné použít k modelování rozličného chování letových dispečerů nejen v en-route.

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Chapter 1

Introduction

The fastest way of transportation on long distances is air transport. Nothing else commercially used could be faster. Although air traffic grows with raising accessibility of air transport for people and companies, it cannot grow forever. There are limits which are influenced by security restrictions, airport capacities and possibilities of aircraft as well.

When it is needed to utilize air space more, something has to be changed. Aircraft manufacturers are trying to build bigger aircraft that could transfer more cargo at once, but changing the size of aircraft is not the only way. International Civil Aviation Organization (ICAO) in cooperation with Federal Aviation Administration (FAA) of the United States are working on flight rules improvement in harmony with requirements on air transportation.

1.1 Why is Simulation of Air Traffic needed?

It has been almost 110 years since the Wright brothers made the first powered flight ever. After some attempts they travelled 852 feet in 59 seconds in one go, it was a low flight above the earth, then everything started.

Aircraft industry has gone through a long journey since then, aircraft are faster and they are equipped with board instruments that allow to fly in low visibility, even the whole flight can be made by autopilot today. The dependence on computers could be dangerous. Something bad could happen and then the human pilot is needed to save the situation. The same problem appears in the air traffic control. Fully automatic systems can be developed but when everything fails, controllers have to supervise air traffic like in the early days of air traffic control only with a few pieces of paper, pencil, map and radio.

The important role of the air traffic simulation is to test and evaluate changes in flight rules and controllers' operations to find out if they don't exceed abilities of pilots or controllers. It would be difficult and dangerous to experiment with flight rule changes in real life traffic.

Looking at this problem from another point of view, it can be said that complete computer air traffic simulation could reduce costs of new flight rules preparation because every change in flight rules has to be tested on real equipment with real people. These simulations are called human in the loop and they are supposed to test applicability of new flight rules or changes in air space segmentation. They are simulated in computer simulation which uses retired controllers or controllers off duty to control traffic. When some pre-tests are introduced then it is possible to decide whether the new update of flight rules is applicable or not before these depended tests are executed. This approach could save money and time of many people and it could lead to faster advancement of air traffic control. The ideal state is to develop a high accurate system which can simulate real conditions and completely replace the Human in the loop simulations (HITL).

1.2 AgentFly System

AgentFly[10] system is aimed at distributed simulation of civilian air traffic over the National Air Space (NAS) of the United States. It also serves as a tool for validation of algorithms proposed for the NextGen concept. Current development is focused on simulation of air traffic controller (ATC), simulation of its tasks and workload during air traffic control in en route sectors of NAS.

The ATC tasks include aircraft separation, handoff aircraft between sectors, control of flow of air traffic and navigation of aircraft to its destination. The main task is to keep aircraft separated from each other which means that ATC should detect and resolve potential conflicts (collisions) between aircraft. An ATC's prediction of future paths of aircraft called SgPlan is used for this purpose.

1.3 Thesis Goals

The goal of this thesis is to implement an intelligent collision resolution (ICR) module. The ICR module is a high fidelity collision resolution module which simulates the sector air traffic controller's way of finding solution of conflicts. The solution of the conflicts is the best according to safety of aircraft flight, minimizing probability of future collision, minimizing number of air traffic controller's interventions in aircraft trajectory and other solution requirements like flight time delay and density of other traffic in the sector.

The Sub-goal of implementation of the ICR module is to implement a plan change evaluator. The plan change evaluator purpose is to be able to compare two predicted flight path plans of aircraft and provide a value which will enumerate the difference between these plans. It is used for deciding which solution of conflict is the best regarding mentioned conditions above. The conditions are specified through a detailed configuration which could be defined separately for each ATC. The main goal of implementation of the plan change evaluator is that it allows to model different ways of ATC collision resolution reasoning.

The second part of thesis explains the implementation of miles in trails (MIT). The MIT is a way how to spatial separate aircraft that are heading for the same airport during the flight so they do not have to wait for a free runway when they arrive to the terminal manoeuvring area (TMA) of the airport. The details about MIT will be described at the end of following chapter. The MIT will be implemented as sub-module of the ICR module.

The final part of the thesis describes testing of the new implemented methods and discusses possibilities of the intelligent collision resolution module configuration.

Chapter 2

Introduction to Air Traffic Management

This chapter will shortly introduce the domain of air traffic control, ways of solving conflicts and affecting flow of air traffic. Theoretical procedures usable for conflict resolution will be introduced and explained.

Air traffic management is a term which encompasses several areas of air transportation such as air traffic control, air traffic flow management, air navigation systems, air space management and aeronautical meteorology. This thesis aims at air traffic control and air traffic flow management. The air traffic flow management will be represented with miles in trails (MIT) in this thesis.

2.1 Brief History

Aviation history[6] is written from the beginning of the twentieth century. The need for air traffic control was firstly registered in late 1930's when air traffic on airfields near larger cities started to grow up more rapidly than earlier. Up to that time everything was in hands of pilots. First air traffic controllers' function was to control use of runways. Air traffic controller (ATC) had to instruct aircraft visually by red and green flag whether they can land or take off. Everything else was under control of visual flight rules which specified how pilots have to act during a flight without any flight supporting instruments. It was not possible to fly in low visibility weather conditions.

A radio equipped control tower that allowed more efficient communication between the pilot and the controller was the first bigger step in air traffic control. Nevertheless, flying at night was still too risky because bonfires were used for navigation between airports. The pilot flew from one bonfire to another but spotting another aircraft was almost impossible. Over time the bonfires were replaced by radio navigation aids.

When first transportation companies were established, the need to fly in low visibility conditions and in the night increased. Thanks to progress in development of onboard instruments it was possible to fly in the night in a specific direction and use the radio navigation aids for navigation. But it was still too risky because there was possibility of collision with another aircraft.

First attempts to en-route air traffic control were made in the middle of 1940's when airway traffic control units (ATCUs) were established. ATCU works with the radio and an airway map which was used for separating aircraft. Air traffic controllers on ATCU had the flight Id, destination and flight plan of aircraft on a card which was attached to a brass holder that was called shrimp boat because of its resemblance to a small fishing ship. Pilots reported their positions to controllers and they moved the shrimp boards along the airway map. But this method started to be demanding when the air traffic more increased.

In late 1950's new supporting systems for aircraft navigation were developed. Concretely it was VHF omnidirectional range (VOR) and distance measuring equipment (DME). VOR is used for determining aircraft radial from navigation beacon and DME is used for measuring distance from navigation beacon.

A radar was developed before and during World War II. Its first successful use was by defending coast of Great Britain during WWII. The first intentions to use radar for separation civilian aircraft in air traffic came after WWII. But the separation task was completely different from first purpose of radar which was to detect incoming enemy aircraft. It took some years of development and in 1956 the first air route surveillance radar was purchased for use in the air traffic control centres. A research and development began on a secondary radar system that would use transponder in each aircraft to display aircraft's id and altitude on the radar screen. This system is known as air traffic control radar beacon system (ATCRBS).

The current ATC equipment is based on evolved and improved systems which have been known for over 50 years. They are combined with computers and help ATC navigate more safely and separate aircraft on airways than ever before. These systems are still developing and improving.

2.2 Today's ATC Equipment

The current ATC's computer is primarily used for displaying information from radar data processing systems (RDP). RDP is a system which aggregates signals from several radar stations, calculates aircraft positions and process data for separate ATCs' computers where the ATC has the controlled sector on the radar screen that means that every ATC has view of his sector which is represented by sector borders, important navigation points and combined aircraft position and direction representation from several radar stations which covers his sector.

This modern system allows ATC to look conveniently at information about displayed flights like flight id, current flight speed and altitude, so he could easily access flight plan of aircraft too.

2.2.1 Air Route Surveillance Radar

As I mentioned in the history chapter the air route surveillance radar[6] was firstly deployed in 1956. The radar system as a whole unit has made a big progress since that time but the main physical principles and limitations are still the same. This thesis does not intend to describe precisely function of the radar but basic principles are needed to understand why the AgentFly simulation system uses some of its concepts.

The basic principle of a radar is grounded on the fact that every solid object reflects and blocks radio waves. The radar has the transmitter which transmits a signal in some known exact direction. An object located in the direction of the transmitted signal reflects that signal and radar receives the reflected signal. The first practical use was made by two researchers, A. Hoyt Taylor and Leo C. Young, in 1922.

The first primitive radar was used on board of the U.S. Navy vessels to detect enemy vessels. The radar used two directional antennas, one for a transmitter and the second for a receiver of radio signals. Both antennas could be manually rotated 360° in azimuth. The transmitter operated continuously and the radar operator was equipped with a radar display similar to an oscilloscope. When the operator rotated the antennas he could see strength of a reflected signal which was received by the receiver antenna. He rotated antennas until he found the strongest reflected signal direction. The radar of this kind could easily determine direction to an enemy vessel. When two vessels found their direction to enemy vessel then they could use triangulation to determine enemy vessel's exact position. This radar is called continuous wave radar. This solution was not effective enough.

Later in 1920s, Gregory Briet and Merle A. Tuve of the Carnegie Institute of Washington finished a radar system that used short radar pulses, that radar system was used for distance measuring. The researchers measured time elapsed between the pulse transmission and the reception. They easily got the distance from the radar to the reflected object because radio signals travel at the speed of light, so 1 nautical mile is travelled in 6.18 microseconds, so when we measure time to an object 1 nautical mile far then the radar pulse has to travel 1 nautical mile and its reflection has to travel 1 nautical mile back to the radar. It means that the time needed to travel 1 nautical mile is equal to 12.36 microseconds. The function of the pulse radar is depicted on Fig. 2.1.

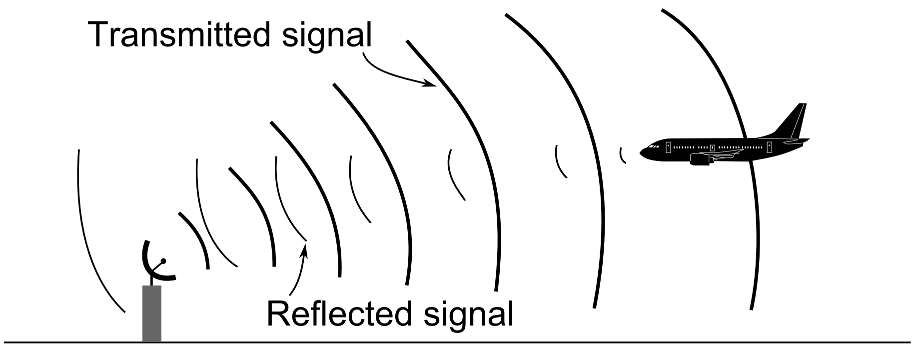


Figure 2.1: Pulse radar function

Before and during World War II researchers built a radar which is known as a pulse-type radar and it has been used with some improvements till today. This radar uses one directional antenna for both the transmitter and the receiver. The radar uses a duplexer which ensures that the receiver is disconnected from the antenna when the transmitter transmits the radar pulse and vice versa. The radar transmits the pulse in tightly focused beam only 1° or 2° width and approximately 40° height. The radar pulse lasts for 1 microsecond and for the next 999 microseconds is the transmitter switched off and the receiver is switched in the circuit instead of the transmitter. The time between the transmission of the pulse and the reception of its echo is measured and the distance of the reflected object is calculated. This process is repeated during the rotation of the antenna. The typical speed of the antenna is from 5 to 15 revolutions per minute.

When the radar receives the echo of an aircraft then a dot is displayed on the radar screen in the place that corresponds to aircraft's magnetic direction and the distance from the radar. Because almost everything reflects radio waves, the radar screen displays echoes of tall buildings, mountains, broadcast towers that interfere in the area covered by the radar. The detection of moving targets helps the radar to filter these junk echoes.

Nowadays air traffic controllers have modern computerized radar systems. The each air traffic control centre has main computer which processes data from several radars that cover the area controlled by the centre. Every air traffic controller of the centre gets on his screen visualisation of the sector which he has under control, the information about aircraft position could be composed of data from one or more radars, it's said that a radar system creates a radar mosaic. The ATC computer could display a sector map on the radar screen, navigation aids positions, significant navigation points like highest mountains, broadcast towers or skyscrapers.

2.2.2 Air Traffic Control Radar Beacon System

Because an identification of targets on the radar screen based only on communication with aircraft is very difficult and demanding in traffic peak hours, a secondary radar system was introduced in 1956. The secondary system is called Air traffic control radar beacon radar system[6]. The radar is equipped with secondary antenna which sends an interrogating signal. The aircraft is equipped with a transponder which responds on the interrogating signal and sends back to the radar reply. Several modes of the interrogating signal and replies are specified. The reply signal contains aircraft identification in all modes. The mode "C" is interesting because it contains aircraft current altitude in reply. Other modes differ in their usage, some of them are designated for military use.

When the radar receives a reply from an aircraft which is equipped with a transponder, the moving dot on the radar screen is marked with a slash symbol and the aircraft identification, and if the radar and the transponder in the aircraft are capable of mode "C" then the aircraft altitude is displayed on radar screen too. The radar displays a few slashes behind the main aircraft position, the extra slashes represents earlier position of the aircraft and helps ATC to determine the current aircraft direction. The ATC computer displays the current ground speed of the aircraft too. The speed of the aircraft is computed from the current and older positions of aircraft and the information about its altitude.

2.3 Units Used in Air Traffic

Distances are measured in nautical miles (NM). 1 nautical mile is exactly 1,852 meters.

Speed is measured in knots. 1 knot is equal to 1 nautical mile per hour. There are three different types of speed measured in the air traffic control. The types of speed are a true airspeed, a calibrated airspeed and a true ground speed. The true airspeed is a speed of an aircraft relative to the atmosphere. The calibrated airspeed is a speed of aircraft corrected for instrument errors and position errors. The ground speed is a speed of an aircraft relative to ground.

Altitude is measured in feet (ft) and in flight levels (FL)[2](G-7, 4-5). The flight level is specific barometric pressure that is expressed in hundreds of feet. The pressure is computed assuming the constant International standard sea-level pressure. The altitude measured in the flight levels is not exactly same as the altitude measured from the sea-level. The aircraft flying on FL 330 is not exactly flying on the altitude 33,000 feet above sea but it is safely separated by 1,000 feet from an aircraft that is flying on FL 320. Other altitude types like altitude above mean sea level (AMSL) in feet and true altitude above ground level (AGL) in feet are measured in the air traffic but they are not currently used in the AgentFly system and neither in this thesis.

Direction of flight is expressed in magnetic heading in degrees. Where 0° stands for the north direction and degrees are imputed from 0° to 359° clock wise so 360° is equal to 0° and zero is used instead. 180° stands for the south direction.

2.4 Flight Rules

Flight rules are specified by national aviation authority in cooperation with International Civil Aviation Organisation (ICAO) in every country. The largest national aviation authority is the United States Federal Aviation Administration (FAA) which is equal partner of ICAO. It is very important that the rules are unified the worldwide. It allows that aircraft equipped with the same instruments could fly in America and in Europe. The unified flight rules provide some kind of security because pilots do behave the same in all situations the worldwide.

National aviation authority maintains and updates aeronautical information publication (AIP)[12][3]. This publication specifies standard operation procedures, information about national air space, it contains specification of routes, information about navigation aids and air maps.

2.5 Air Space Classification

Air space is partitioned in several classes[1](Chapter 3). The classes differ from each other in type of control, type of allowed aircraft, assigned altitudes and some other criteria. AgentFly project currently aims at high en-route sectors which are classified as air space class "A". Class "A" states for airspace which is fully controlled by ATCs and does not allow visual flight separation. So class "A" sectors could be used by aircraft which are fully capable of instrument flight and they have to be equipped with the transponder.

The size and shape of sectors depend on traffic amount in peak hours. Sectors near busy airports are smaller than sectors in which controllers just separate traffic on long distance routes.

2.6 Flight Plan

Every flight has its flight plan[1](Chapter 5)[6](Chapter 10). The flight is led along the flight plan from a departure airport to a destination airport. The flight plan is forwarded from the departure area control centre to all control centres which cover aircraft's route from the departing airport to the destination airport.

The flight plan is composed of a sequence of fixes or routes and aircraft identification, aircraft type, departure airport, departure time, destination airport, aircraft colour, requested airspeed and altitude of flight and few other attributes. That guarantees minimal interference of ATCs during the flight if it is not necessary.

2.6.1 Fix

Fix could be the navigation beacon or virtual point which is triangulated by navigation beacons. Nowadays global navigation satellite system (GNSS) is used for aircraft navigation, so the fixes could be specified as GPS positions. The fix represents important navigation point on the route which should be flown over by the aircraft. Fly-over means that the fix should be missed maximally by few nautical miles.

Aircraft are equipped with navigation computers in which its crew fill in the flight plan. The computer automatically supervises on the route fixes and designates an aircraft course.

2.6.2 Route

A Route is a sequence of fixes and is listed and managed by national aviation authority. Restrictions like minimal and maximal altitude, allowed direction of flight, type of allowed aircraft (propeller or jet), size of allowed aircraft and etc. could be specified for route.

2.7 ATC Duties

ATC has to supervise traffic in his sector[11](Chap. 2.). ATC's main duties are to secure and separate aircraft which are flying in his sector. All aircraft in the sector must be separated by safe minimal distances known as separation limits.

Other important duties are handoffs and application of standard operation procedures (SOP). Handoff is transfer of radio and radar control to a controller of the bordering sector in which aircraft is going to enter. SOPs specify for example how ATC should treat aircraft that is heading for landing on airport or how to treat aircraft which is climbing to the en route sector.

Non-radar separation procedures will be not mentioned because this thesis models behaviour of the radar controller. The non-radar separation procedures are still important and needed in areas which could not be well covered by radar for example on transoceanic routes. A Radar equipped control centre could use the non-radar separation procedures in some cases when it is easier to apply or as the backup.

The separation of aircraft is specified by separation limits and could be done with two basic types of manoeuvres. The separation could be done with vertical or horizontal manoeuvre.

2.7.1 Separation Limits

The biggest advantage of the radar is that the horizontal separation limits used by the radar separation are smaller than the separation limits of the non-radar separation.

Vertical separation[1](Chap. 4, Sec. 4) is the easiest to hold. When the radar is equipped with secondary radar system, then the ATC can easily read conflicting aircraft altitudes and decide whether a climbing or a descending with one or another aircraft will be favourable and how much should new altitude differ from the previous. The minimal vertical separation limit is 1,000 feet. Since the aircraft altimeter could be affected by air temperature and other factors, how I mentioned earlier, two aircraft separated by 1,000 feet are considered to be separated vertically. There are some other restrictions which say that aircraft operating above flight level 270 must be separated by minimum of 2,000 feet but there are some exceptions[1](Chap. 4, Sec. 6) which allow separation by minimum of 1,000 feet.

Horizontal separation[1](Chap. 4, Sec. 4) is divided to longitudinal and lateral separation. For both are valid the same separation limits. "Because the width of a radar pulse increases as the pulse travels away from the antenna, distant targets appear much larger on a radar display than those located closer to the radar antenna. For this reason, the FAA has provided increased separation criteria for aircraft located more than 40 nautical miles from the radar antenna."[6](Chap. 9, p. 363-367) When aircraft are closer than 40 nautical miles to the radar antenna, they should be separated by 3 nautical miles. If aircraft are further than 40 nautical miles from the radar antenna, they should be separated by 5 nautical miles.

When the controller is using a radar system that creates a radar mosaic[6](Chap. 9, p. 363-367), he does not know whether the aircraft is further or closer than 40 nautical miles from the radar antenna. In this case ATC must always aircraft horizontally separate by 5 nautical miles.

2.8 Holding Pattern

A holding pattern[2](10-10 Holding Procedures) is a circuit defined in air maps or a standard specification of the holding pattern for en-route sector. The specifications of the holding patterns are published in the AIP. This circuit has a specified altitude, an allowed maximal airspeed and a direction. The holding pattern is typically connected with a VOR navigation beacon and specifies a flight in direction and a returning direction both in absolute magnetic heading.

The holding pattern is used for delay an aircraft in small area of the airspace when a landing runway is not available for use or is used by other aircraft.

2.9 Radar-Assisted Navigation

The radar ATC could issue verbal heading instructions known as vectors which navigate a pilot through the airspace. The radar vectoring could be used for collision resolution and delaying of aircraft. "When vectoring an aircraft, the controller must instruct the pilot to turn to a specific magnetic heading, to turn right specific number of degrees, or simply to fly a particular heading."[6](Chapter 9, p. 370) The specific magnetic heading is typically whole number divisible by 5 because it facilitates the communication. If the ATC wants to use the radar vectoring, he must exactly know and must be sure about the current aircraft heading. If he is not sure about aircraft heading he could use an instruction "fly" which says that pilot should turn to desired heading with shortest turn, otherwise he could use an instruction "long way around" if he wants the pilot to make longest turn.

When the ATC thinks that the reasons for radar vectoring have passed away then he could easily say to the pilot that he has to return to the normal navigation.

When the ATC wants to apply radar vectoring on an aircraft, then the aircraft position and altitude must fulfil minimum vectoring altitudes which in general says that the aircraft could be vectored if the aircraft will remain at least 3 nautical miles laterally from or at least 1,000 feet above any obstruction.

2.10 Miles in Trails

Miles in trails (MIT)[7] is an approach that should affect inbound flow of traffic to the airport so that the TMA controllers do not have to let the aircraft hold in a holding pattern.

For example, we have an airport that can handle 60 aircraft operations in one hour. If the airport runway is used for both arrivals and departures balanced, we can say that an aircraft could land at the airport every 2 minutes.

If two aircraft arrive in a TMA sector of the airport simultaneously, one of them has to wait in the holding pattern until the first one lands and leaves the runway. When this situation happens with more than two aircraft, it becomes more difficult to delay aircraft in limited airspace of the TMA.

The Solution for this problem could be the miles in trails. The aircraft heading for the same airport are grouped in one MIT group. The aircraft are then separated in the MIT group. The time separation is measured to the sector border. The required time separation is converted to a distance between aircraft because it is easier to separate aircraft on some distance using the radar and the separation can be done everywhere during the aircraft flight in the sector. It then becomes each ATC's responsibility to ensure that aircraft exit the sector separated from each other with the required spacing.

The MIT separation is longer than minimal separation limits because it is intend to create spaces between aircraft that allows direct landing of "train" of aircraft on one runway. That means that the leading aircraft lands and leaves the runway before the second aircraft reach the airport. These spaces are required to be larger and larger with growing distance from the airport that allows easily connecting two flows of aircraft from two different directions. A term spacing separation or MIT separation will be used with connection with MIT aircraft spacing in this thesis that will prevent confusion between MIT separation and minimal separation limits which specifies a minimal safe distance between aircraft in the instrument flight.

Chapter 3

AgentFly System

The AgentFly[10][9] is aimed at creation of multi-agent simulation of sector air traffic controller (ATC). The AgentFly simulation is event based and time stepped. Each pilot and air traffic controller is modelled as an independent agent. The agents communicate to one another using a sector radio. The sector radio is half duplex - everyone hears everything but only one agent can speak at the same time.

3.1 AgentFly Goal

The main goal of the AgentFly is to authentically model the sector ATC's workload considering operations needed to control traffic in sector. This is very important for testing changes in air traffic control procedures and changes in air space.

3.2 AgentFly Air Traffic Model

Air traffic is modelled by flights. Every flight has specified flight plan, aircraft type, simulation start time, start position, destination and several further parameters. Every aircraft is modelled using the Base of Aircraft Data (BADA). BADA is a database of high-fidelity performance models of aircraft. The aircraft are flown by pilots whose are modelled as the agents.

There are four types of agents in the AgentFly system: ATC, pilots, aircraft and the radar display. The ATC and pilot agents communicate with each other over the radio and the ATC agent is using radar display to monitor behaviour of the pilots. The pilots directly control aircraft.

3.3 Coordinate Systems used in AgentFly

The AgentFly system uses two coordinate systems: GPS coordinate system and stereographic coordinate system.

The GPS coordinate system is used to represent positions of aircraft, their flight waypoints a fixes. The sectors are also represented in GPS coordinate system. The stereographic coordinate system is created by projection of spherical GPS positions on a plane. Each sector in the AgentFly has its own stereographic projection of the world. The stereographic coordinate system and the GPS coordinate system have one common point called projection point. This projection point could be understood as position of sector radar in AgentFly system. The stereographic projection displays sphere on the plane with several compromises. E.g., when an aircraft is flying far away from the projection point, it is seemed as turning even if flying straight or it is seemed to fly slower than it actually is.

3.4 Pilot Model

The pilot is modelled as an event-based agent. The pilot is reacting to orders from ATC that are represented as events. The pilot models its task duration as a timestamp associated with the event. When the pilot receives an order, he needs some time to process it. After the order has been processed, he has to reply to ATC. The duration of order processing is done by an event, which is fired after the time needed to process order expires.

3.4.1 Pilot's Flight Plan Model

Every pilot in the AgentFly system follows the flight plan (see 2.6) which he has represented as GPS flight plan represented in the GPS coordinates. The GPS flight plan represents waypoints or fixes of a flight path filled in the flight plan. The GPS flight plan is accurate representation of a future flight path of aircraft because it reflects pilot's actions and intentions. If the pilot does not have any other instructions from the ATC then he follows the GPS flight plan.

3.5 Air Traffic Controller Model

The ATC model is divided into two types of modules: RSide[1] and ATA[2]. The RSide modules model the ATC's actions and reactions on the events from the radio and the radar display. The ATA modules models processes of ATC connected with ATM computer, such as typing on keyboard, watching radar screen and high complexity computing operations (e.g. collision resolution). The new ICR module will be implemented as ATA module.

3.5.1 Air Traffic Controller's Workload Model

The ATC's workload is modelled with respect to the Multiple Resource Theory (Wickens 1984) and the Visual, Cognitive, Auditory and Psychomotoric workload model (McCracken and Aldrich 1984). That means that the ATC has several pools of resources which can be used to perform its operations. When there are several operations which need the same resources, they have to be performed sequentially, e.g. the ATC cannot solve collision between aircraft and made handoff of other aircraft at the same time.

[1] RSide is naming convention in the AgentFly system

[2] ATA is naming convention in the AgentFly system

3.5.2 Air Traffic Controller's Flight Plan Model

The ATC also needs to have its own representation of aircraft flying in his sector. The ATC gets all information about aircraft from the radar screen. It is needed to model ATC's thoughts or information set about what he sees. Firstly, the ATC needs to remember which aircraft is already controlled and in the sector, with which aircraft he only communicates over the radio and which aircraft is flying outside the controlled sector. Secondly, the ATC needs to be able to predict future movement of aircraft displayed on the radar screen. That cannot be done using a GPS flight plan, as the ATC sees the aircraft as points on the radar screen, which only reflects GPS positions of the aircraft. The ATC also does not know anything about pilots' actions and intentions and he could only expect pilot's reactions on his commands. The ATC knows the aircraft flight plan (see 2.6) and so he predicts future position of the aircraft. The prediction is more inaccurate as it is looked more in the future. SgPlan was created for this purpose.

3.6 Predicted Flight Path – SgPlan

The ATC model should consider that the human ATC predicts himself future path (i.e. trajectory) of aircraft based on knowledge of the current direction, the flight speed and the flight plan of aircraft. The human ATC predicts future conflicts from this predicted future path. The SgPlan allows to model this ability in the ATC model. The "Sg" in name means stereographic projection.

The SgPlan is divided into two parts: a horizontal plan and a vertical plan. The horizontal plan represents virtual ATC's prediction of flight path between flight plan fixes, i.e. the horizontal plan represents predicted horizontal aircraft position in the airspace. The horizontal plan also reflects all inaccuracies caused by communication delays, e.g. time which pilots need to process ATC's commands. The horizontal plan is comprised of segments connecting the fixes. The vertical plan maps climb, descend and speed change manoeuvres on the horizontal plan. The speed change manoeuvres are modelled by the vertical plan because the climb and descend manoeuvres affect the airspeed too. The vertical plan is comprised of climb, descend or cruise segments.

The SgPlan is represented as a polyline in 3-dimensional space. The polyline combined with the minimal separation limits (described in section 2.7.1) turns in blocks stacked behind each other. The width and the height of the blocks are equal to the horizontal respectively vertical separation limits, while the length is defined by the length of the polyline segment which represents path between two way-points or fixes.

SgPlan furthermore contains a complete set of information about the aircraft in addition to the horizontal and vertical plan. The information set contains the filled airspeed, filled altitude and other information from the flight plan.

3.6.1 Aircraft Position in SgPlan

A current position of an aircraft is updated every time the aircraft is swept by the radar beam. In the AgentFly system this period is set as 12 seconds. The current position is represented as a distance to the next fix in the aircraft horizontal part of flight plan and it can be converted to a 2-dimensional point. The horizontal plan also holds history of aircraft positions. A future position could be calculated as a point which differs by some distance from the current position, or from an end of any segment in the horizontal plan. The future position can be converted to a 2-dimensional point as well, however it is only an estimate since the future position is predicted and it is not accurate due to inaccuracies described earlier.

3.6.2 Radar Display Model

A Radar display is modelled using current positions and positions history taken from the horizontal plan of the displayed aircraft SgPlans. Visualisation of the radar display is depicted on Fig. 3.1.

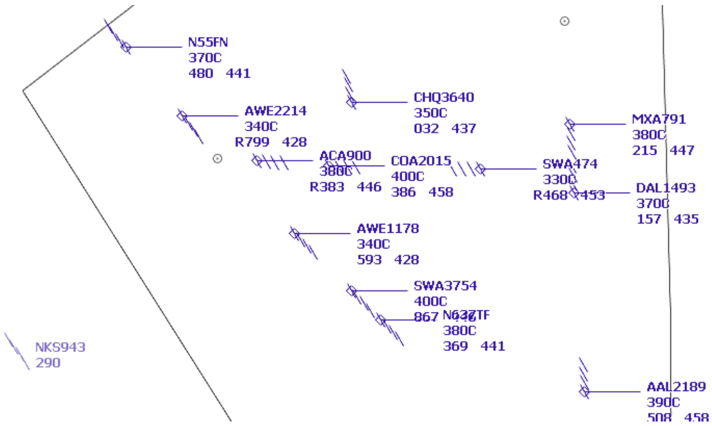


Figure 3.1: Partial cutout of radar screen display
Figure has inverted colours.

3.6.3 Collision detection in the SgPlan

Collision detection can be done as search for intersection of the two aircraft SgPlans blocks in time. The aircraft are not on a collision course when there is found no intersection of blocks representing their paths. That means the aircraft are separated because the blocks reflect the separation limits.

Chapter 4

Collision Detection and Resolution

The collision detection and resolution main concepts in AgentFly system will be described in this chapter. At first will be described a existing collision resolution module. Description of a new intelligent collision resolution module and its concepts will follow.

A general collision resolution module consists from two sub-modules: collision detection module and a collision resolution module. The intelligent collision resolution module mainly differs from the existing module in collision resolution module.

4.1 Separation limits in AgentFly

The separation limits mentioned in theory chapter are the uttermost limits. These limits should not be crossed anyway. The AgentFly system has its own separation limits because the ATC model works with SgPlan which counts with horizontal imprecision of the flight plan prediction.

The AgentFly vertical separation limit stays same as the minimal vertical separation limit, thus 1,000 feet, because the altitude is measured by aircraft altimeters and it is precise. The AgentFly horizontal separation limit is longer that the minimal horizontal separation limit and it is 8 nautical miles. The AgentFly horizontal limit is longer because it has to count with imprecision mentioned earlier. There is another horizontal separation limit in case that the collisions are resolved horizontally. This limit is 8.5 nautical miles and it is used for checking that generated flight plan is collision free.

4.2 Collision Detection in AgentFly

The collision detection is performed for each aircraft in regular time intervals. The collision detection is performed in two extra cases in addition to the regular checks. The cases are when the aircraft is entering sector and before the handoff to neighbour sector is done. The first case is made because every new aircraft in sector can cause new conflicts with aircraft which already are in sector. The second case is made because it is important to have checked flight path till sector border because the ATC loses radio control over aircraft immediately after handoff but the aircraft receiving sector cannot control the aircraft until it is behind the sector border.

The collisions are detected between tested aircraft and the other aircraft in the sector. The collisions are detected for every aircraft from its current position only next few minutes of flight because ATC's flight plan prediction (SgPlan) is not so precise that it makes sense to look further in the future. The checked length of flight path in minutes is longer than the length of time interval between regular check. There has to be some reserve of checked flight path in time of regular check because the ATC needs some time to resolve detected conflicts and pilot needs some time to execute ATC's commands.

The detection is done in two steps. The first step detects the collisions only roughly. The MIT separation collisions are detected in the first step even if the aircraft are in same MIT group. The standard collisions are detected when the aircraft separation is smaller than 24 nautical miles. The second step detects the collisions exactly. The MIT separation collisions are detected if the aircraft separation is smaller than minimal spacing separation. The standard collisions are detected if the aircraft separation is smaller than 8 nautical miles (AgentFly minimal separation limit). The main reason for this two step collision detection is that it models the human looking on the radar screen. When the human sees aircraft with possibility of collision on the radar screen then he focuses on these aircraft and checks them on collisions precisely.

If some collisions are found then they are passed to collision resolution. There are several exceptions that are not passed to collision resolution. The exceptions are collision close to sector border. These collisions are not solvable because ATC model in AgentFly does not allow communication between ATCs which is needed for resolving this kind of collisions. The limit specifying collisions close to the sector border is by default set to 120 seconds of flight.

4.3 Collision resolution in AgentFly

The task of collision resolution is to resolve detected collision of two aircraft i.e. found conflict solving solution for one of the pair of the colliding aircraft. The solution is intended to be as easiest to apply as it is possible. The ATC uses its flight path prediction (SgPlan) for finding the collision solution. The details of collisions resolution vary by method.

For each generated manoeuvre is created a new SgPlan which is valid from the current aircraft position until the aircraft destination. The newly generated SgPlans are solutions of the solved collision if they fulfil the suitable collision solution requirements which vary by method.

4.4 Existing Collision Resolution Method

The existing collision resolution module is aimed to find the first suitable collision solution. Solution solving conflict in existing collision resolution module is solution that will not have collision with some aircraft in next 8 minutes of flight.

The main advantage of existing collision resolution method is its straightforward implementation which is easy to understand and configure. The other advantage is computational efficiency of this algorithm. The main disadvantage is that the existing method could omit a better collision solution e.g. which minimizes delay caused by a horizontal diversion from an original flight path. The other disadvantage is that the existing method cannot simulate different ATCs with different preferences for manoeuvre type usage. These preferences could not be divided only between manoeuvre types but the ATC could prefer one manoeuvre type under certain conditions.

All the values used for description of this algorithm in this section can be changed through configuration XML file like many other not mentioned parameters.

4.4.1 Collision Detection

Collision detection is done for each aircraft once per 8 minutes of flight. Until there is nothing requiring earlier check then next collision detection will be scheduled 4 minutes before end of checked section of flight.

4.4.2 Collision resolution

There are strictly given priorities of collision resolution manoeuvres in the existing collision resolution method. The priorities are in this order: vertical manoeuvre, horizontal manoeuvre and speed change manoeuvre. The existing collision resolution generate first possible manoeuvre solving conflict in that specified order.

A vertical manoeuvre generation method generates updated flight plan that will use the first free flight level above or under of a flight level of the colliding aircraft until the new flight level is not lower or higher by more than 5,000 feet or is out of bounds of the sector.

A horizontal manoeuvre generation method generates horizontal diversion from original flight plan using ten degree steps on each side from current heading. It skips future path fixes until they are in ATCs controlled sector or to the first fix behind border of ATCs controlled sector.

A speed change manoeuvre generation method generates speed changes to miss the collision with delaying or accelerating the aircraft. It is done by speeding up or slowing down by 5 knots from airspeed.

4.5 Intelligent Collision Resolution Method

The intelligent collision resolution (ICR) module is based on state space search algorithm. The states are represented as the all possible conflict solving manoeuvres for conflicting pair of aircraft under control of the sector. At first the solution space is generated and each solution is evaluated. Finally, the best solution is used to resolve collision.

ICR adds the new functionality in collision resolution. The new functionality is MIT. ICR is responsible not only for collision resolution but is also responsible for separation of aircraft heading for same destination. There are several new features which improves quality of simulation of ATC's resolution process.

ICR consists of two modules: collision detection and resolution module and miles in trail module. The collision detection and resolution module could work alone. The MIT module adds its functionality in the collision resolution module. Both of them are in detail configured through configuration XML files. The configuration of these modules will be described later in this chapter.

4.5.1 Main Requirements on ICR

The main requirements on ICR are to safely resolve collisions with adjustable priority of solution selection that will reflect solution properties too. In borderline cases the solutions with future conflicts can be generated that could help solve some currently unsolvable types of collisions. The handling of collisions close to the sector border has to be improved.

ATC model is highly configurable and thanks that the ATC model using ICR is able to properly model different behaviour of different ATC's approaches and preferences to collision resolution.

4.5.2 Collisions Close to Sector Border

A collision is too close to sector border when there is no time to solve collision before or after the border is crossed. In many cases is this caused when the aircraft are flying from one sector to another and they are in collision behind the border. The time limit for collisions close to the sector border is 120 seconds of flight from border. One of the colliding aircraft is currently removed from simulation because 120 seconds is too short time to apply some manoeuvre which solves the collision.

One sub-case is when one aircraft is inside and under control of the sector and other aircraft is still outside of this sector that it cannot be controlled – the other aircraft is only on radio. The ICR is intended to handle this situation with applying some collision solving manoeuvre at the aircraft which is inside the sector.

4.5.3 Collision Types in ICR

The ICR distinguishes three types of collisions:

- standard collisions
- MIT collisions
- combination of both collisions

The standard collisions are collisions where the separation is smaller than 8 nautical miles horizontally and 1,000 feet vertically. The MIT collisions are collisions where the MIT separation is horizontally smaller than specified spacing limit. The combined collision type is special case when the aircraft is in standard collision with an aircraft from which it should be spaced in MIT.

4.5.4 Allowed Future Conflicts

Requirement on allowing future conflicts means that the controller is able to generate conflict solution which will have future conflict that will happen later than solved conflict. The conflict could be with the same aircraft as before or could be with another aircraft. The future conflict with the same aircraft can be useful when the airspace is too crowded to resolve the collision in time of collision detection and there is time to postpone the collision resolution.

The collision solution with future conflict could be generated under certain conditions. The conditions vary by collision type. The solution of standard type collision allows future collision when the future collision is happened later than the time to solved collision with addition of limit of minimal time between solved and new collision. The limit of minimal time between solved and new collision is 120 seconds. The solution of miles in trail collision allows future collisions when the future collision is happened later than a minimum application time. The minimum application time is AgentFly system constant which specifies minimal uttermost time needed by pilot to apply ATC's commands. The minimum application time is 240 seconds in typical configuration.

4.5.5 Collision Detection

Collision detection includes same collision detection as in existing collision resolution (see 4.2) and violation of miles in trail separation detection in the ICR.

The ICR sorts the detected collisions by their priorities. These priorities are following. The standard collisions have highest priority. The standard collisions are sorted by distance from aircraft to the first detected colliding position in the predicted path. The MIT collisions have lowest priority. The MIT collisions are sorted by how much the required spacing separation is violated. The MIT separation violation detection will be described later in ICR MIT section.

The ICR collision detection is scheduled for each aircraft in regular intervals. Sometimes, the ICR collision detection has to be performed earlier than it is planned because the collision solution could be generated with future conflicts. There is another case which allows postponed collision detection. This case happened when the collision cannot be solved by ATC model right now but there is distance between current position end first collision occurrence that is enough long that it allows resolving the collision later.

4.5.6 Collision Resolution and Solution Selection

At first the ICR has to select which manoeuvres should be generated. That is specified by collision type. If standard type collision is solved then are generated only horizontal, vertical and speed change collision resolution manoeuvres. If MIT type collision is solved then are generated only spacing horizontal and spacing speed change manoeuvres. In case that the combined collision type is solved then are generated manoeuvres for both types of collisions because the standard collision in that case could be solved by spacing manoeuvre.

For each generated manoeuvre is created a new SgPlan from the current aircraft position until the aircraft destination. The newly generated SgPlans are solutions of the solved collision if they fulfil the suitable collision solution conditions. The conditions are: every manoeuvre will be finished before the handoff of the aircraft to the neighbour sector and that the solution will not have future collisions that will happen earlier than solved collision.

Then the ICR generates possible solution state space as all collision solving SgPlans for colliding aircraft. The generated solutions are evaluated by a plan evaluator which will be described later. The plan evaluator assigns to penalty value to the plans. Solution with best penalty value will be picked as the conflict solving solution.

The speed change generation method solving standard type of collision is as same as in the existing conflict resolution method. Other methods are new in AgentFly system. Standard type of collision is solved by new horizontal manoeuvre generation method and by new vertical manoeuvre generation method and by speed change generation method. The miles in trail type of collision is solved by horizontal spacing manoeuvre generation method and speed change spacing generation method. The approaches of these methods will be described in independent sections later.

When the collision resolution selects solution which counts with future conflict then the collision resolution schedules earlier irregular collision detection for an aircraft modified by this solution. When the collision cannot be resolved now and if there is enough time before collision, that allows safe collision resolving later, then the collision resolution schedules earlier irregular collision detection too. The reason why is not scheduled the collision resolution directly is that it is useful to have updated information about collisions.

4.5.7 New Horizontal Manoeuvre Generation

The analytical manoeuvre generation uses horizontal part of ATC's prediction of future flight paths of colliding aircraft. The analytical manoeuvre generation applies vector mathematics on these horizontal 2-dimensional representations of flight paths. At first general method will be described. Method for calculation diversion of chosen direction will be described after. The description of AgentFly horizontal manoeuvre geometry is in appendix D.

This manoeuvre generation uses spatial domain method described in papers Automated Conflict Resolution for Air Traffic Control (Heinz Erzberger)[5] and An Algorithm for Level-Aircraft Conflict Resolution (Ralph Bach, Chris Farrell and Heinz Erzberger)[4]. This method is not directly applicable on collision resolution in the AgentFly. The modifications of this method will be described after.

4.5.7.1 Collision Resolution Algorithm in Spatial Domain[5][4]

The Goal of this method is to calculate minimal parameters of a horizontal diversion which led to solution of collision between two aircraft. It is needed to find two parameters. The parameters are a diversion angle and a turn back point. The diversion angle specifies turn to a straight diversion segment. The turn back point specifies position of a return turn to original flight path on the diversion segment. The return turn is heading to some of the following fixes of flight plan which are behind the collision. Several fixes of flight path could be skipped when the horizontal diversion manoeuvre is applied.

Consider the situation on Fig. 4.1. Let colliding aircraft are A and B. v_A and v_B are their velocity vectors. The calculations are made in the relative coordinate system with the x-axis pointing East and the y-axis pointing North. All angles are measured positive clockwise from the North direction. A separation circle is around the aircraft B. The radius $R_m s$ of the separation circle represents minimal aircraft separation, in our case it is 8.5 nautical miles. Tangents of separation circle of aircraft B are constructed from position of aircraft A.

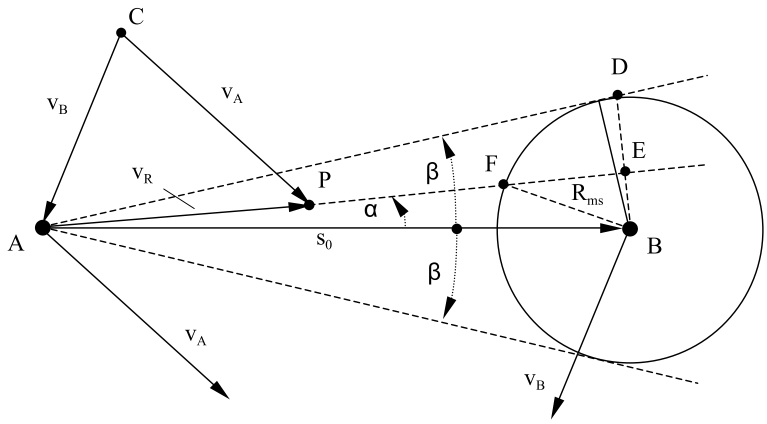


Figure 4.1: Graphical solution of collision in spatial domain[4]

For aircraft A is calculated relative velocity vector v_R, relative distance S_0 between the aircraft and a the heading angle ψ_0 between the aircraft. Relative vectors are related to aircraft B.

$$\mathbf{v_R} = \mathbf{v_A} - \mathbf{v_B},\ S_0 = \sqrt{(x_B - x_A)^2 + (y_B - y_A)^2},\ \psi_0 = \arctan\frac{y_B - y_A}{x_B - x_A}$$

The vector $\mathbf{s_0}$ is called as a line of sight vector and it is used with the separation circle tangents to determine a minimal conflict diversion angle β from the line of sight. The tangents of separation circle represent directions of relative velocity vector $\mathbf{v_R}$ which are minimal solutions of collision. The angle β is used to determine angle μ which is used to rotate relative velocity vector $\mathbf{v_R}$. The rotation of vector $\mathbf{v_R}$ is done by rotating velocity vector $\mathbf{v_A}$ of aircraft A.

$$\mu = \beta - \alpha$$

The solution is different for two cases at this point because the solution is found like intersection between circle made by rotation of velocity vector $\mathbf{v_A}$ and the tangents of separation circle. If aircraft A is faster than aircraft B then there are only two intersections, one with upper tangent and second with lower tangent. The situation is depicted on Fig. 4.2. The resolved headings for aircraft A are then obtained from equation (4.1).

$$\psi_A^* = \psi_R^* + \arcsin(\sigma \sin(\psi_B - \psi_R^*)),\ \sigma = \frac{V_B}{V_A} \tag{4.1}$$

The ψ_R^* is a heading of rotated relative velocity vector $\mathbf{v_R}$. The ψ_B is heading of aircraft's B velocity vector $\mathbf{v_B}$. The ψ_A is a heading of aircraft's A velocity vector $\mathbf{v_A}$. The ψ_A^* is

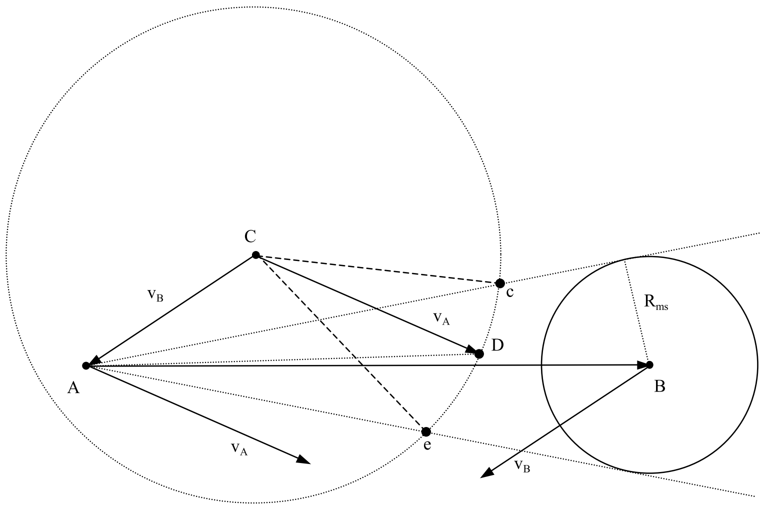


Figure 4.2: Graphical solution for faster aircraft[4]

a new heading of aircraft A that causes rotation of the relative velocity vector $\mathbf{v_R}$ into the heading ψ_R^*. The heading ψ_A^* is the collision resolving heading for the aircraft A.

In case that the aircraft A is slower than the aircraft B then it is possible to find 4 new directions for the aircraft A because there could be 4 intersections of the rotated velocity vector $\mathbf{v_A}$ and the tangents of separation circle. The situation is depicted on Fig. 4.3. The resolved headings for the aircraft A are obtained from the equation (4.1) and (4.2).

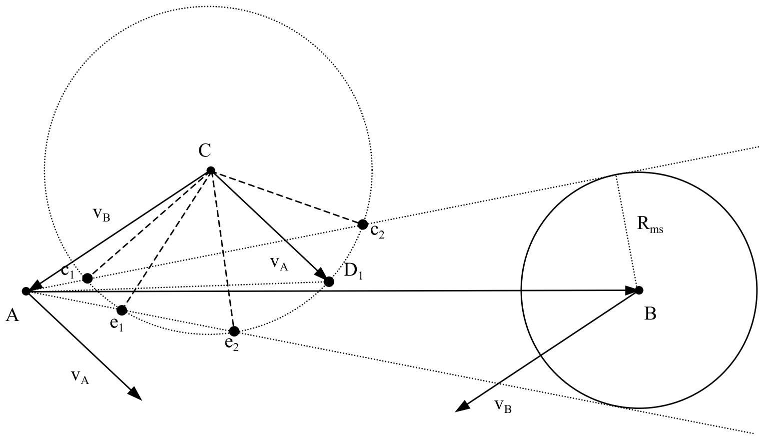


Figure 4.3: Graphical solution for slower aircraft[4]

$$\psi_A^* = \psi_R^* - \arcsin(\sigma \sin(\psi_B - \psi_R^*)) + \pi,\ \sigma = \frac{V_B}{V_A} \tag{4.2}$$

The obtained headings are used to determine a turn back point position. The turn back point is depicted on Fig. 4.1 as point D. A turn of no more than -2μ will avoid re-entering the separation circle of aircraft B. The distance between the position of the aircraft A and the turn back point D is given by

$$d_{tb} = S_0(\cos\beta + \sin\beta\tan\mu) \tag{4.3}$$

Then time for reach the turn back with speed of the rotated relative vector V_R^* is

$$t_{tb} = \frac{d_{tb}}{V_R^*} \tag{4.4}$$

Actual distance for the aircraft A needed to reach turn back point is

$$d2tb = V_A t_{tb} \tag{4.5}$$

4.5.7.2 Diversion Calculation for Chosen Diversion Turn

The obtained headings from last section can be used to determine a several larger headings that are avoiding the collision. The turn back point position is recalculated using following procedure for each chosen heading[4].

At first the aircraft's A heading is ψ_A^*.

$$\psi_A^* = \psi_A + \Delta\psi$$

The heading and the speed of relative velocity vector (ψ_R^*, V_R) are obtained. and the following attributes are calculated.

$$\beta = \psi_R^* - \psi_0,\ \mu = \beta - \alpha$$

The distance to the turn back point is obtained from equation (4.5) using equations (4.3) and (4.4).

4.5.7.3 Modifications for AgentFly

The method needs to be modified for use in the AgentFly system because this method considers that the both aircraft A and B are already on straight segment heading to collision and that cannot be always satisfied in the AgentFly system. The second problem is that the turn back point is specified indirectly through a return angle in the AgentFly not directly like in spatial domain method. The needed modifications are depicted on Fig. 4.4.

The starting positions, directions and speeds are needed to be recalculated for use in the AgentFly system. The aircraft A holds its starting position but the direction and speed are changed. The aircraft A direction is changed to a direction heading directly to next fix after collision. The aircraft A current speed is calculated as average speed needed to reach the conflict. The aircraft B is virtually moved to the same distance as it is from collision in the direction which aircraft B has in the moment of collision. The aircraft B speed is recalculated the same way like aircraft A speed. That allows finding as narrowest solution

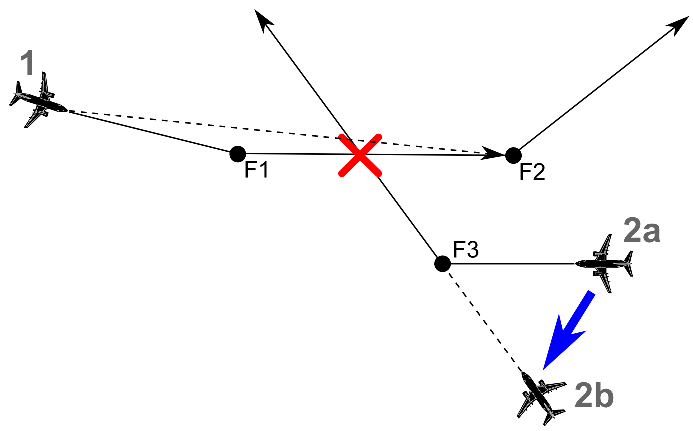


Figure 4.4: Modifications of spatial domain method
Points F1, F2 and F3 are flight route fixes. The collision avoiding trajectories of the aircraft 1 are calculated, the aircraft is heading to F2 - the first fix after collision. The aircraft 2 is moved from the position 2a to the position 2b.

as it is possible. The recalculated aircraft attributes are used in the described analytical method finding the minimal diversion parameters in the spatial domain.

The return angle is obtained as angle between a line connecting the starting position of aircraft A and the target fix of diversion (following fix after collision or later) and a line connecting the calculated turn back point and the target fix of diversion.

4.5.7.4 Generation of Several Different Trajectories

From nature of the ICR it is needed to generate several different trajectories. At first the minimal diversion angle is determined for each side of current heading. From these minimal diversion angles are generated by adding 5 degrees new diversion headings. For each generated heading is calculated a minimal return angle and further return angles are generated by adding 5 degrees.

The horizontal manoeuvre is limited by a horizontal size of the sector. The AgentFly system currently limits control of an aircraft to airspace of the controlled sector. It means that the controller has to order pilot to return his own navigation before the handoff is made. When it is detected that the turn back point is behind the handoff point then the method increases the diversion angle until it finds a solution or reaches a maximal diversion angle limit. This approach was chosen because the diversion is typically narrow and near the sector border and then the turn back point is typically behind the handoff. Diversion widening could cause that the diversion can be done whole inside the sector. The diversion widening is done by adding 5 degrees to the diversion angle. These additions do not count to the maximal limit of generated diversion angles.

Consider that configuration specifies that 5 diversion angles are generated and for each diversion angle is generated 5 return angles. That gives 25 different trajectories for one aircraft with one target fix. The method is applied on both colliding aircraft so in final method gives 50 different trajectories solving the conflict.

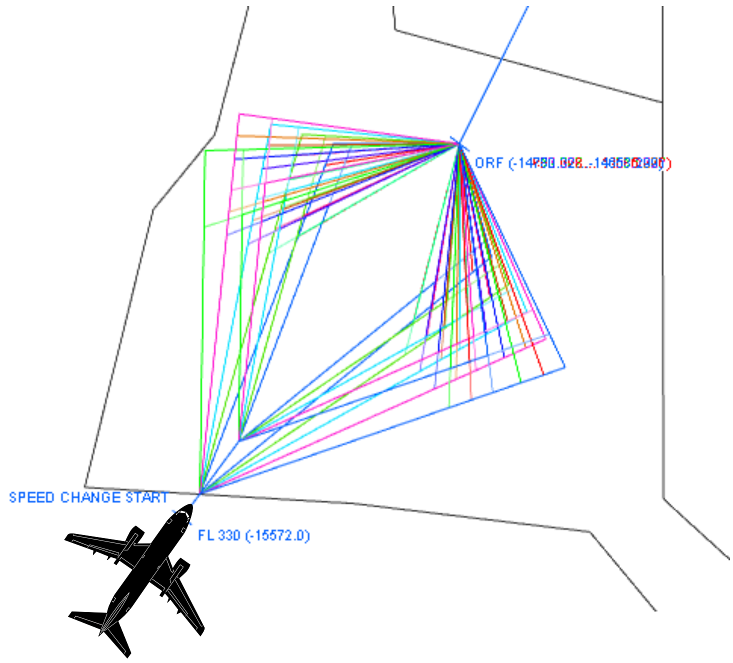


Figure 4.5: Trajectories generated by the new horizontal manoeuvre generation, visualized using their SgPlans

The result of manoeuvre generation method is presented on Fig. 4.5.

4.5.8 New Vertical Manoeuvre Generation

Vertical manoeuvres are generated by search for a free flight level under or above the colliding aircraft flight level. The free flight levels are generated by adding or by subtraction of 1,000 feet from flight level of colliding aircraft because 1,000 feet is the vertical separation limit.

A temporary flight on different flight level is specified by excluded flight levels in the AgentFly. The excluded flight levels are represented as a block of airspace in which is aircraft not allowed flying. This block is specified by lowest and highest covered altitudes and by its start and end positions in aircraft horizontal flight plan. When the aircraft is needed to flight by 1,000 feet lower than its current altitude then the excluded flight levels block lowest altitude is equal to the aircraft altitude lower by 1,000 feet and highest altitude is equal to infinity.

The main benefit of newly implemented method is that it counts with other aircraft in the sector.Firstly the starting and ending position of detected collision are used to determine excluded flight levels block width for first lower or higher altitude. The newly generated excluded flight levels block is used to generate new aircraft SgPlan and it is tested on collisions. If new SgPlan is without collisions then it is added between suitable solutions. If there are new collisions with other aircraft then the excluded flight levels block is horizontally expanded that it covers the new collisions too. If the expanded excluded flight levels block

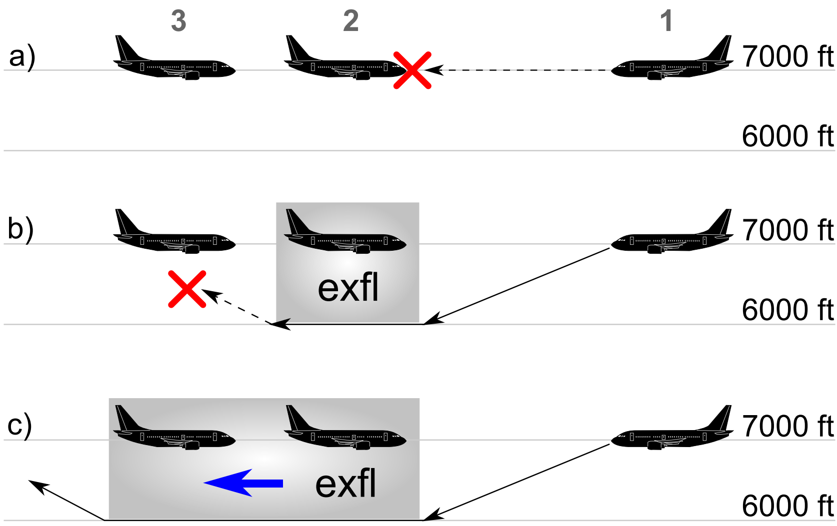


Figure 4.6: Vertical manouvre generation
The excluded flight levels block is represented by "exfl" rectangle, which vertical goes to infinity.

is collision free then it is added between suitable solutions. This procedure is repeated for each generated flight level. The steps of the method are depicted on the Fig. 4.6.

4.5.9 ICR Miles in Trails

ICR Miles in trails (MIT) is implemented as separated module which adds miles in trails functionality to ICR module. Miles in trails module provides methods for detection of miles in trails separation violation and methods for separating aircraft from each other.

4.5.9.1 Detection of Spacing Separation Violation and Sorting of Aircraft

The separation should be measured on a sectors exit border but that brings some problems. The typical problems are that the sector border is not always straight and the aircraft in same MIT group are not exiting sector in an exact same place. The problems were solved in following way which is intend to approximate measuring of distance between aircraft on the radar screen.

Aircraft needs to be sorted in the MIT group at first. The aircraft are sorted only when they are entering the sector. The sorting criteria are absolute sector exit time and an actual separation distance of original not delayed SgPlan. The ATC model holds their original absolute sector exit time, an original sector exit position and direction for sorting aircraft in MIT. The informations about the aircraft original sector exits ensures that the MIT group aircraft are leaving the sector in exactly same order as the MIT module is not active.

A following method is used for determining MIT spacing separation between aircraft. When the method is used for sorting aircraft in the MIT group then it is used with the

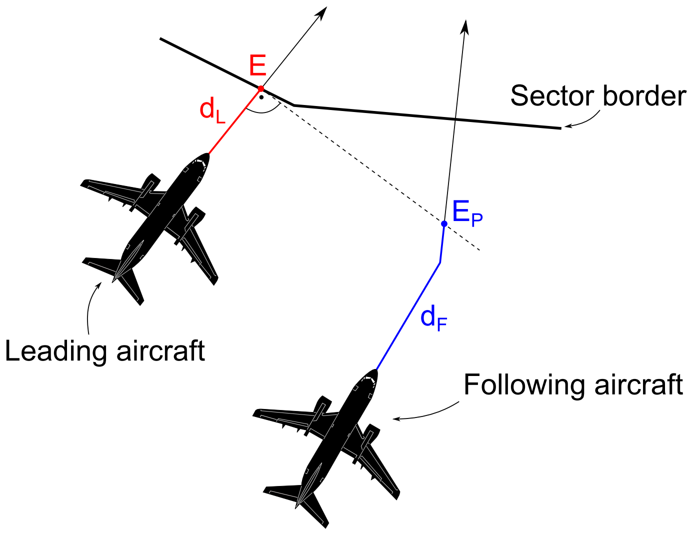


Figure 4.7: Detection of Spacing Separation Violation and Sorting of Aircraft
The E is the sector exit position of the leading aircraft. The E_p is the leading aircraft's sector exit position projected on the flight trajectory of the following aircraft. The d_L is distance between the current position and the sector exit position of the leading aircraft. The d_F is distance between the current position of the following aircraft and the projected sector exit position of the leading aircraft.

original sector exits for both aircraft. When the method is used for detection of spacing separation violation then it is used with actual sector exits for both aircraft.

The sector exit position of leading aircraft is projected on the flight path of following aircraft. A spacing separation distance in meters is then equal to distance between the following aircraft current position and the projected leading aircraft exit position. The method is visualized on Fig. 4.7. The spacing separation limit is then converted to nautical miles and compared with a sector MIT configuration.

The sector MIT configuration specifies two values – optimal MIT separation and minimal MIT separation both in nautical miles. Until the current separation of the aircraft in the MIT group is more than the minimal separation then no action is taken. When the current separation of the aircraft in the MIT group is less than the minimal separation then the aircraft are separated on distance at least longer than the minimal separation or as much as possible nearest to the optimal separation.

4.5.9.2 Separation Methods

Methods used for separation of aircraft are following – horizontal spacing manoeuvre generation and speed change spacing generation. The methods are described in individual following sections of this thesis.

4.5.10 Horizontal Spacing Manoeuvre Generation

A horizontal spacing manoeuvre generation method is used to spacing of aircraft in the MIT groups. The main principle of method, which description will follow, was described in a paper Automated Conflict Resolution for Air Traffic Control (Heinz Erzberger)[5]. The main difference between new horizontal manoeuvre generation method and horizontal spacing manoeuvre generation is that the new horizontal manoeuvre generation method is avoiding the collision with turn but the spacing method delays one of the aircraft in time. The spacing method is used to delay an aircraft with horizontal diversion manoeuvre and it is based on fundamental geometric properties of an ellipse. It is needed again to calculate the return angle for a selected diversion angle because the delay is made by the same horizontal manoeuvre like the horizontal collision solution. The description of AgentFly horizontal manoeuvre geometry is in appendix D.

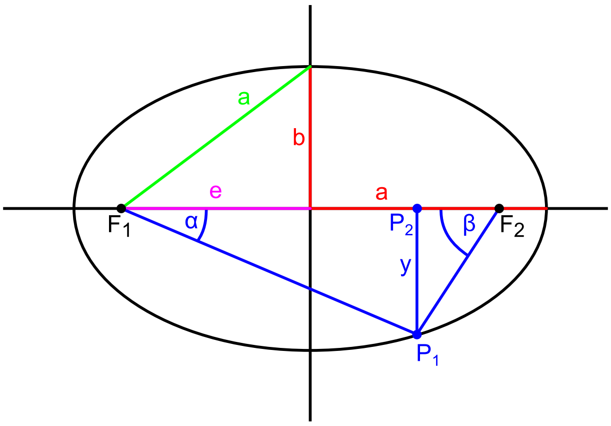


Figure 4.8: Ellipse parameters

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \tag{4.6}$$

The method principally uses a fact that between a, b and focus distance e holds the Pythagorean theorem and that summation of lengths of lines F_1P_1 and F_2P_1 is exactly same for each point P_1.

$$e = \sqrt{a^2 - b^2} \tag{4.7}$$

Consider that the F_1 is the current position of aircraft and the F_2 is the target fix of horizontal diversion manoeuvre. The α is the required diversion angle. The l is the distance between the current aircraft's position and the target fix. The $l + \delta$ is the delayed distance. It holds that

$$e = \frac{l}{2},\ a = \frac{l+\delta}{2},\ |F_1P_2| = x + e,\ b = \sqrt{a^2 - e^2} \tag{4.8}$$

$$y = \tan\alpha(x + e) \tag{4.9}$$

The return angle β can be easily obtained from these facts and from the ellipse equation (4.6):

$$x^2b^2 + a^2y^2 - a^2b^2 = 0 \tag{4.10}$$

The y is substituted with (4.9) in (4.10).

$$\begin{aligned} x^2b^2 + a^2(x+e)^2 \tan^2\alpha - a^2b^2 = 0 \\ x^2b^2 + a^2(x^2 + 2ex + e^2)^2 \tan^2\alpha - a^2b^2 = 0 \\ x^2(b^2 + a^2\tan^2\alpha) + x(2a^2e\tan^2\alpha) - a^2b^2 + a^2e^2\tan^2\alpha = 0 \end{aligned}$$

$$H = (b^2 + a^2\tan^2\alpha),\ P = 2a^2e\tan^2\alpha,\ Q = -a^2b^2 + a^2e^2\tan^2\alpha$$

$$x^2H + xP + Q = 0$$

$$x = \frac{-P + \sqrt{P^2 - 4QH}}{2H}$$

$$\beta = \alpha + \arctan\frac{(x+e)\tan\alpha}{e-x} \tag{4.11}$$

The equation (4.11) is used to determine the return angle β for the selected turn angle α. The basic turn angle α_0 is selected so it makes trajectory looks like an isosceles triangle.

$$\alpha_0 = \arccos\frac{b}{a} \tag{4.12}$$

4.5.10.1 Generation of Several Different Trajectories

It is needed to generate not only several different trajectories with same length but trajectories with different length too because the method is limited by a horizontal size of the sector like the analytical horizontal manoeuvre generation method.

Two smaller diversion angles and two larger diversion angles are generated for the basic diversion angle, all of them stepped by 5 degrees. The return angle is calculated for each generated diversion angle. The diversion angle and the return angle create trajectories with the same length. The trajectories with different length are made by adding or subtracting 5 degrees from the calculated return angle. If the generation method detects that the turn back point is behind the handoff point then it makes the diversion wider like the analytical horizontal manoeuvre generation method.

The result of manoeuvre generation method is presented on Fig. 4.9.

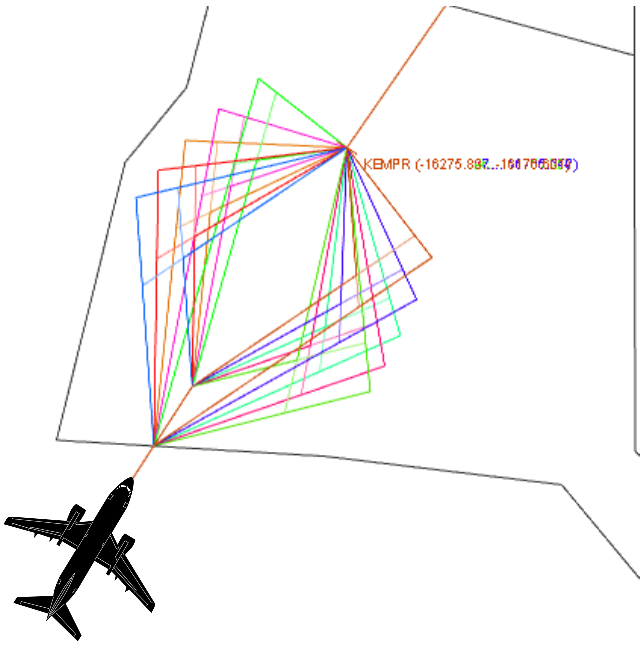


Figure 4.9: Trajectories generated by the spacing horizontal manoeuvre generation, visualized using their SgPlans

4.5.11 Speed Change Spacing Generation

A speed change spacing generation method generates spacing solutions by slowing down the aircraft. The aircraft is minimally slowed down so that it is delayed by exact pre-calculated time. That is very easy because the spacing separation violation value is known and it is used for determining a minimal slowdown of the aircraft.

$$v_{new} = \frac{d_e - d_{sv}}{d_e / v_{avg}} \tag{4.13}$$

The slower airspeed is calculated from a current distance to the sector exit d_e, a current average speed v_{avg} and the spacing separation violation value d_{sv}. The aircraft has to virtually fly longer distance (the current distance to the sector exit + the spacing separation violation value) in the same time. The maximal speed slowing down the aircraft enough is calculated using equation (4.13).

4.5.12 Configuration of Manoeuvre Generation

Configuration of manoeuvre generation is very important. The state search space is large in this domain and could contain solutions which could be rejected without evaluation in advance. That is done with well defined generation limits.

- **Configuration Parameters of Horizontal Manoeuvre Generation**

Parameters for generation of horizontal manoeuvres are the same for the new horizontal manoeuvre generation and for the horizontal spacing manoeuvre generation. The parameters are described in table 4.1.

Parameter	Description	Default value
use horizontal CR/MIT	determines if the ATC is using horizontal manoeuvres to collision/separation resolution	true/true
turn up to	maximal relative turn angle counted from the generated minimal collision resolution turn angle	20°
turn step	step used to generate turn headings	5°
max turn angle	maximal turn angle that will be generated	90°
return up to	maximal relative return angle counted from the minimal generated return angle	10°
return step	step used to generate return angles	5°
max return angle	maximal return angle that will be generated	90°
return skip fix	the horizontal manoeuvre will be generated for next fix if the return angle generated for current target fix will be larger than this parameter	20°
max skip fix count	maximal count of fixes which will be skipped	4
minimal distance between fixes	minimal distance between skipped fixes	20NM

Table 4.1: Parameters of Horizontal Manoeuvre Generation

- **Configuration Parameters of Vertical Manoeuvre Generation**

  Parameters for generation of vertical manoeuvres are described in table 4.2.

- **Configuration Parameters of Speed Change Generation**

  Parameters for the generation of speed changes are the same for the speed change manoeuvre generation and for the speed change spacing generation. The parameters are described in table 4.3.

4.5.13 Plan Change Evaluation

When the new plans solving a future collision have been generated then there are several solutions solving the conflict and it is needed to choose the optimal one. That is why a plan change evaluator is needed. The plan change evaluator can measure quality of found solutions. Then the best plan can be picked as the plan with the lowest penalty value. The plan evaluator is implementation of a penalty function which reflects differences between an original flight plan and the new one.

Parameter	Description	Default value
use vertical CR	determines if the ATC is using vertical manoeuvres to collision resolution	true
climb to	maximal difference between current flight level and the new generated one while climbing	5,000ft
climb step	step used to generate flight levels	1,000ft
descend to	maximal difference between current flight level and the new generated one while descending	5,000ft
descend step	step used to generate flight levels	1,000ft
horizontal extension seconds	the time before and after excluded flight levels of flight on the generated altitude	20s
horizontal extension NM	the distance before and after excluded flight levels of flight on the generated altitude	1NM
max recalculations of length	the length of excluded flight levels will be recalculated n-times after that the generation algorithm continues with next altitude	2

Table 4.2: Parameters of Vertical Manoeuvre Generation

4.5.13.1 Penalty value of the SgPlan

A total penalty value is summation of differences between original SgPlan and the new one penalty values of various criteria which will be described in the next section. The total penalty value is obtained as

$$P = \sum_i p_{new_i} - p_{orig_i}, i \in I$$

4.5.13.2 Penalty Function

The plan evaluator uses two types of penalty functions: linear penalty function and a polyline penalty function. The polyline penalty function is also used in its inverse variant.

The polyline penalty function is penalty function with 2 segments (standard and considerable), each is specified by different penalty coefficients. The polyline penalty function is depicted on figure 4.10.a. The segments are a standard segment p_s and a considerable segment p_c. The standard segment is segment where the penalty is usually small because when the solution is in standard segment then the solution is acceptable. The considerable segment is segment where the penalty is usually large because when the solution is in considerable segment then the solution is too demanding on ATC's time, length of flight path, needed space and etc. A value where standard segment passes into considerable segment is specified as a considerable point c_p.

Parameter	Description	Default value
use speed change CR/MIT	determines if the ATC is using speed change manoeuvres to collision/separation resolution	true/true
speed up to	maximal relative speed-up generated from current airspeed	50kn
speed up step	step used to generate faster speeds	5kn
slow down to	maximal relative slowdown generated from current airspeed	50kn
slow down step	step used to generate slower speeds	5kn

Table 4.3: Parameters of Speed Change Generation

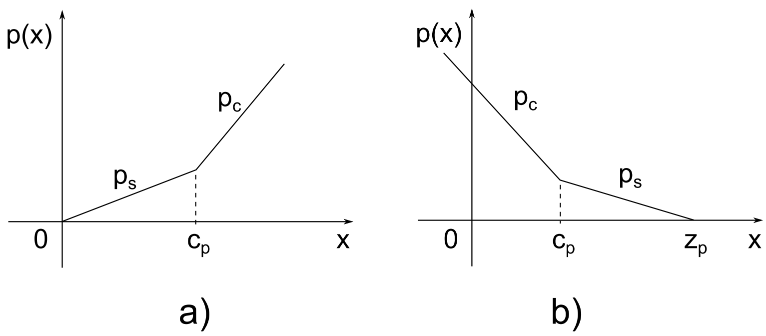


Figure 4.10: Penalty function
a) polyline penalty function, b) inverse polyline penalty function

The inverse polyline penalty function has the zero value point z_p which specify point where the value of penalty is equal to zero. The inverse polyline penalty function is shown on Fig. 4.10.b.

4.5.14 Plan Evaluation Criteria

Every kind of manoeuvre has its own set of penalties which evaluates manoeuvre quality. Some penalties evaluate the SgPlan only in the controlled sector and other penalties evaluate the whole SgPlan. There also are criteria which are not connected with the generated manoeuvres. The chapter about testing of this thesis will discuss the concrete penalty values configuration.

- **Number of Applications Penalty**

  Each manoeuvre costs the ATC some actions – orders to aircraft. These actions costs ATC his time and increases the ATC's workload. For example when the vertical manoeuvre solving collision as a temporary flight on lower altitude then the ATC has to do 2 actions extra – ATC orders a pilot to descend on temporary altitude and orders a pilot to climb on original altitude. But if there were planed some SOP vertical manoeuvre which will order the pilot to descend on specified altitude and the vertical manoeuvre solving the collisions only ensure that the aircraft descend on altitude specified in the SOP earlier then there is not needed an extra action. The number of applications penalty uses only linear penalty function.

- **Trajectory Length Penalty**

  A trajectory length penalty penalizes the lengthening of the aircraft flight path. The lengthening is measured in nautical miles. This penalty is applied on the whole SgPlan.

- **Future Collisions Penalty** A future collisions penalty penalizes count of future collisions.

- **Time to Future Collisions Penalty**

  When the generation of solution with future collision is allowed then has to be preferred solution with farther future collisions.

  A time to future collision penalty uses inverted poly line penalty function. A zero penalty value is defined in some time in the future and the penalty is larger the closer the future collision is. The considerable point is specified between current time and the zero penalty value time. The total time to future collisions penalty is obtained as summation of time to future collision penalty values of each future collision.

- **Future MIT Collisions Penalty**

  A future MIT collisions penalty penalizes number of future collisions with aircraft which are in MIT.

- **Climb Penalty and Descend Penalty**

  A climb penalty and a descend penalty penalize every climbed or descended foot. The climb and descend penalty distinguish between immediate and postponed climb manoeuvre. The immediate vertical manoeuvre has to be done immediately after planning, but the postponed vertical manoeuvre is planed manoeuvre in the future. If the vertical manoeuvre can be planned in the future then it is needed to penalize need to remember position where the pilot has to be ordered.

- **Flight Level Evaluation**

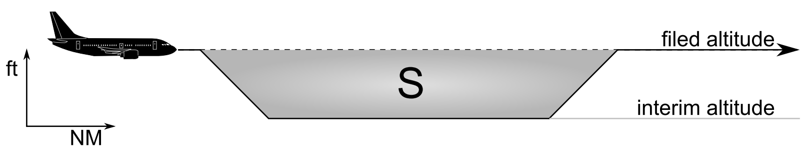


Figure 4.11: Flight level evaluation
S is the penalized surface.

The aircraft is supposed to fly on its filed altitude (requested cruise altitude in the flight plan). The filled altitude is usually the altitude where the operation of the aircraft is the most economic. It is needed to penalize situation when the aircraft is not flying on its filed altitude. A flight level evaluation penalizes every nautical mile flown on different altitude than is the filled altitude. This penalty value is represented as a surface between flight path flown on temporary altitude and the original flight path flown on filed altitude. The penalty is depicted on Fig. 4.11

- **Horizontal Turn Penalty**

  A horizontal turn penalty penalizes size of turn into diversion segment. The horizontal turn penalty also distinguishes between an immediate and a postponed turn like the climb and descend penalty. The description of horizontal manoeuvre geometry is in appendix D.

- **Horizontal Return Penalty**

  A horizontal return penalty penalizes size of return turn from diversion segment to heading to the next fix in the flight path.

- **Horizontal Join Penalty**

  A horizontal join penalty penalizes size of a join turn. The join turn represents turn needed to achieve heading to the next fix after target fix of horizontal diversion.

- **Off Track Penalty**

  An off track penalty is a constant penalty which penalizes horizontal manoeuvre which causes diversion from the flight plan.

- **Off Track Length Penalty**

  An off track length penalty penalizes length of the aircraft flight path which was not flown along the flight plan.

- **Skipped Fixes Evaluation**

  The plan evaluator also evaluates how many fixes has been skipped in the flight plan. The penalty is applied on count of skipped fixes and there could be also specified constant penalty which is applied when some fix is skipped.

- **Speed change Evaluation**

  A speed change evaluation is divided into speed up and slow down penalty. The speed change penalties are evaluated as calibrated airspeed in knots. The speed change evaluation also distinguished between immediate and postponed speed change.

- **MIT Separation Penalty**

  A MIT separation penalty penalizes every nautical mile by which the spacing separation is lost. This penalty is applied only on separation between tested aircraft and aircraft which are in the same MIT group and are flying in front of the tested aircraft.

- **MIT Successor Separation Penalty**

  A MIT successor separation penalty penalizes every nautical mile which all the successors of tested aircraft in its MIT group loose by tested aircraft manoeuvre.

- **MIT Direction Change Penalty**

  When the aircraft in the same MIT group are spaced using a horizontal manoeuvre then it is desired that all the aircraft of MIT group turn into the same space of the sector. It usually means that they turn in the same side of their path. A MIT direction change penalty penalizes situation that a leading aircraft turned into right and a following aircraft turned into left and vice versa.

4.5.15 Calculation of ICR Process Duration

The ICR module models process of solving collisions between aircraft in controlled sector. The AgentFly simulation needs to have a model of time needed to resolve collision. It is very hard to determine how long the collision resolution process lasts.

The ICR time duration has defined an upper and a lower bound. The lower bound b_L represents time needed to resolve collision that is easy to solve. The lower bound is 1 second $\pm$ standard deviation with upper bound 0.25 second. The upper bound b_U represents time needed to resolve collision that is hard to solve. The upper bound is 10 seconds $\pm$ standard deviation with upper bound 2 seconds.

The ICR time duration model is based on rating of a complexity of the resolution process. The complexity of the resolution process c is determined as ratio of the number of applicable solutions s_A to the number of usable generated solutions s_A.

$$c = \frac{s_A}{g_U}$$

The applicable solutions s_A are all solutions that are evaluated by the plan change evaluator. The solutions evaluated by the plan change evaluator are all solutions that do not have the disallowed earlier future collisions. The usable generated solutions are all generated solutions that were not rejected because their manoeuvres exceed the borders of the controlled sector. The usable generated solutions count g_U could be obtained as

$$g_U = g_{Tot} - g_R$$

The g_{Tot} is total count of generated solutions and is calculated from the generation limits. The g_R is total count of solutions that were rejected because their manoeuvres exceed the borders of the controlled sector. The usable generated solutions count contains solutions that are applicable or has disallowed future collision.

The total time t_{Tot} needed to resolve collision is obtained as

$$t_{Tot} = b_L + c(b_U - b_L)$$

This total time t_{Tot} is individually evaluated according to the selected solution. If the selected solution is made by vertical manoeuvre then the total time is shortened by 10 percent because it is easier to resolve collision vertically than horizontally. If the selected solution is made by horizontal or speed change manoeuvre then the total time is extended by 10 percent because it is harder to use these manoeuvre than the vertical manoeuvre to resolve collision.

Chapter 5

Implementation

The whole AgentFly system is implemented in the Java programming language. It uses high fidelity AGLOBE platform. "AGLOBE is an agent platform designed for testing experimental scenarios featuring agents' position and communication inaccessibility, but it can be also used without these extended functions. The platform provides functions for the residing agents, such as communication infrastructure, store, directory services, migration function, deploy service, etc. Communication in A-globe is very fast and the platform is relatively lightweight. AGLOBE is suitable for real-world simulations including both static (e.g. towns, ports, etc.) and mobile units (e.g. vehicles). In such case the platform can be started in extended version with Geographical Information System (GIS) services and Environment Simulator (ES) agent."[8]

The part of AgentFly aiming on simulation of the ATCs is developed as NextGen AgentFly project. The whole implementation of the ICR is done in one package. Several modifications have been done in NextGen AgentFly project before the implementation of the ICR was possible because the main implementation requirement on ICR was that the existing CR module and the ICR will be interchangeable.

5.1 Preparation for Implementation of ICR

The collision resolution module is divided between **EomRSideCDR** and **EomAtaCd**[1], **EomAtaCr** modules. The existing CR module and the ICR module modify only ATA modules because the RSide module is a time based simulation model of ATC's behaviour and remains unchanged. The RSide module is slightly modified and new abstract classes describing interface and providing some base methods of ATA CD and CR modules are implemented. The existing modules are changed to extend these abstract classes and new ICR modules are based on the abstract classes of CD and CR modules as well. This modification causes some further minor changes in several other modules.

The next modified module is **EomAtaRSideEntryCheck** module. This entry check module performs entry check which approves or disapproves the handoff of an aircraft from a neighbour sector. The entry check checks the aircraft on the collisions close to the sector

[1] This is an original name of the existing module, further it is used as a name of an abstract class used in implementation of the ATA modules

border. The modification causes that when the entry check detects one of the cases described in 4.5.2, the entry check displays warning on standard error output and approves the handoff. The warning is displayed because it is possible that the ATC of a receiving sector is still not able to resolve this kind of a collision close to the sector border without manoeuvring with the aircraft outside the sector. Manoeuvring with the aircraft outside the sector is currently not supported by the AgentFly system because it requires simulation of inter sector communication.

5.2 Implementation of ICR

The implementation of ICR ATA modules are in the package of ATA modules[2]. The whole implementation of ICR collision resolution methods, plan evaluator and further supporting classes is in the separate package[3].

5.2.1 ICR ATA CD Module

An ICR ATA CD module is implemented in class **EomAtaCdSearchSpace**. The ICR CD module implements the collision detection using the class **CollisionDetector** which was modified for the needs of ICR CD and CR modules. The ICR CD module checks presence of an ICR In-trail module. If the ICR In-trail module is present, a detection of spacing separation violation is performed in ICR In-trail module.

The first rough step of collision detection is done in method **computeVCheck**. The second precise step of collision detection is done in method **computeHCheck**. Both processes are described in detail in section 4.5.5 and in section 4.2.

The ICR CD module creates a list of detected collisions. This list is sorted according to the priorities of detected collisions as described in 4.5.5. The collisions are represented by classes corresponding to the types of collisions (**IcrStandardCollisionProblem**, **IcrMitSeparationProblem**, **IcrMitCollisionProblem**). All the classes are extended from abstract class **IcrProblem**. The **IcrProblem** class provides basic functionality. The **IcrProblem** specify flight IDs of colliding aircraft and a time to collision. The **IcrProblem** is compared by the time to collision. MIT problem description classes add information about current separation distance between specified aircraft. The **IcrMitSeparationProblem** is sorted by separation distance according to priorities described in 4.5.5.

5.2.2 ICR ATA CR Module

The ICR ATA CR Module is implemented in class **EomAtaCrSearchSpace**. The ICR CR module implements collision resolution using the manoeuvre generation methods described in ICR chapter of this thesis.

All of the manoeuvre generation methods are implemented by an interface **IcrProblemSolver<IcrProblem>**. The interface has only one method which should calculate collision solution and return abstract class **IcrProblemSolution**. All solution returning

[2] atc.faa.atm.enroute.ata
[3] atc.faa.atm.enroute.icr.*

types described below are extended from this abstract class. The **IcrProblemSolution** class contains information about flight ID, newly generated SgPlan, penalty value of the solution, detailed record about partial penalties and an information whether an earlier collision detection on the new SgPlan is needed. The implementation of concreted collision resolution methods is described in table 5.1.

Type	Generation class and its solution	Solution contains description of
Horizontal	**IcrHorizontalDeconflictionAnalytical** **IcrProblemHorizontalSolution**	horizontal diversion manoeuvre
Vertical	**IcrVerticalDeconfliction** **IcrProblemVerticalSolution**	excluded flight levels block
Speed ch.	**IcrSpeedChangeDeconfliction** **IcrProblemSpeedChangeSolution**	speed change

Table 5.1: Implementation of standard collision resolution manoeuvre generation methods

The ICR CR module checks the presence of an ICR MIT module in the same way as the ICR CD module. If the ICR MIT module is present, a collision resolution of separation problems is done in ICR In-trail module.

5.2.3 ICR Plan Change Evaluation

The ICR plan change evaluation is implemented in separate class **IcrPlanEvaluator**. The **IcrPlanEvaluator** class is created for both of the colliding aircraft in the beginning of the collision resolution. The **IcrPlanEvaluator** is initialised with original plan of the aircraft. The new generated solution plans for the aircraft are evaluated using the **IcrPlanEvaluator**. The evaluation of individual penalty criteria is done in method **getPlanPenalties** which inputs are the new collision solving plan, solution type and the plans of other aircraft which are in the controlled sector. The method **getPlanPenalties** returns list of penalty values which are used in solution evaluation method **evaluateSolution**. The method **evaluateSolution** returns the total penalty value for the new generated plan.

5.2.4 ICR In-trail Module

The ICR in-trail module is an implementation of MIT sub-module of the ICR. The ICR in-trail module is implemented in class **EomAtaIntrailSpaceSearch**. The ICR in-trail module implements method **getCurrentSeparationNM** for detection of separation violation and method **calculateThisBarierPosition** which projects sector exit position of one aircraft flight plan on other aircraft flight plan. Both of these methods are used for sorting aircraft in MIT group. The sorting in MIT group is event based action which is executed when the aircraft is entering the sector as a part of the entry check.

All of the separation manoeuvre generation methods are implemented by interface **IcrIntrailProblemSolver<IcrMitCollisionProblem>**. The interface has only one method which should calculate collision solution and return abstract class **IcrProblemSeparationSolution**. All solution returning types described below are extended from this abstract class. The **IcrProblemSeparationSolution** class is extended from **IcrProblemSolution** and additionally contains flight ID of aircraft from which the solved aircraft is separated. The implementation of concreted MIT separation problem resolution methods is described in table 5.2.

Type	Generation class and its solution	Solution contains description of
Horizontal	**IcrIntrailHorizontalSeparation** **IcrProblemHorizontalSeparationSolution**	horizontal diversion manoeuvre, turn direction (right/left)
Speed ch.	**IcrIntrailSpeedChangeSeparation** **IcrProblemSpeedChangeSeparationSolution**	speed change

Table 5.2: Implementation of MIT manoeuvre generation methods

5.2.5 Implementation of Calculation of ICR Process Duration

Calculation of ICR process duration is done in separate class **IcrDurationCalculation**. This class is initialized with the generation limits. It has only one method **getTimeNeededToResolveCollisionMs**. The inputs of this method are the selected solution type, count of evaluated solutions and count of rejected solutions for all the types of generation methods. The result is duration of collision resolution process in milliseconds.

5.2.6 Configuration of ICR

All the values used in this thesis to describe algorithms, behaviour and many other properties are in detail configurable via XML configuration files. The ICR configuration is different by each sector. Each sector is configured in a sector configuration file. The ICR configuration file contains specification of generation limits and penalty functions attributes for each criterion. The default configuration of penalty coefficients is described in appendix C.

Chapter 6

Testing

The testing of ICR implementation is very important part of this thesis because it is needed to prove that the algorithms are behaving like it was intended. The testing chapter is divided into three parts. The first part is aimed on testing of setting of priorities of the solution selection. The second part of this chapter is aimed on evaluation of ICR behaviour during controlling of large traffic. The new ICR module will be also compared to the existing CR module in the second part. The third part aims on separate testing of MIT sub-module and its integration with the ICR module.

The tests in this chapter are done through scenarios. The scenario is aggregation of several simulation settings. The simulation settings are configuration of sectors (shape, assigned flight levels, etc.), configuration of sectors ATC (used modules of ATC, time model of ATC, ICR configuration, MIT spacing limits) and air traffic. The air traffic is defined as individual flights which have their own flight plan and time of its appearance in simulation.

All scenarios used for testing have time model called "zero-times" because main goal of testing is to test behaviour of ICR module in collision resolution not the workload of the ATC during collision resolution. The "zero-times" time model is time model in which every action of ATCs and pilots takes constant time, 3 milliseconds. That ensures that the results are not distorted by ATC's overload when the traffic is too large.

The default penalization configuration described in appendix C was used as basis for the all tests scenarios. Modifications of the default configuration are described in each test.

This chapter is extended in appendix B describing videos attached on this thesis on enclosed CD. The videos show outputs of visualisations of AgentFly system. The videos better show that the implemented ICR module is fully functional.

6.1 Testing of Priority Settings

Tests of the priority setting are made on a small scenario with only two aircraft. The main reason is that the changes of ATC's priorities are easily visible on two aircraft. The situation in the scenario is shown on Fig. 6.1. The aircraft AAL1049 is colliding with COM749 in the middle of the sector ZDC34. The priorities will be changed to prefer each of the standard collision resolution methods during the test.

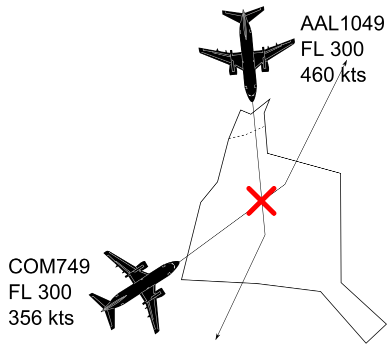
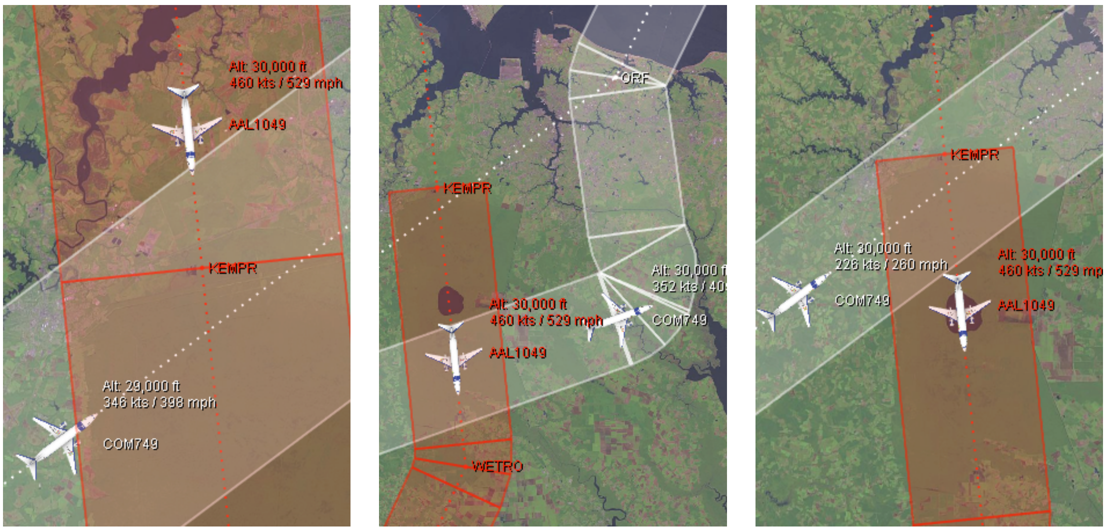


Figure 6.1: Scenario for testing priority settings in sector ZDC34

The default configuration prefers the use of the collision solution that uses vertical manoeuvres. The result of collision resolution with start configuration is depicted on Fig. 6.2a that depicts the vertical manoeuvre of the aircraft COM749.



(a) Vertical (b) Horizontal (c) Speed change

Figure 6.2: Manoeuvres preferred by aircraft COM749

29 horizontal manoeuvres, 10 vertical manoeuvres and 4 speed change manoeuvres were generated during the first run of the test. These counts do not change in following tests because the generation limits will not change for following tests.

Now the default configuration is changed so that the penalties for the horizontal manoeuvre are set to some minimal value. The minimal value can be 1, 0.001, or some other value which is small raising in penalty context. The minimal value should not be zero because the zero value say that we do not care about quality of preferred solution. The settings for this test are stated in table 6.1.

horizontal turn, return and join	standard immediate and postponed penalty	1.0
	considerable immediate and postponed penalty	2.0
off track length	standard penalty	1.0
	considerable penalty	2.0

Table 6.1: Changed penalization parameters to prefer horizontal manoeuvres

The result of collision resolution with modified configuration that prefers the horizontal manoeuvre is shown on Fig. 6.2b.

The last test is made with default configuration modified to prefer speed change manoeuvres. The modifications are stated in table 6.2.

speed up and slow down	standard immediate and postponed penalty	1.0
	considerable immediate and postponed penalty	2.0

Table 6.2: Changed penalization parameters to prefer speed change manoeuvres

The result of collision resolution with modified configuration that prefers the speed change manoeuvre is depicted on Fig. 6.2c.

The first part of testing chapter proved that setting of priorities of selected collision solving manoeuvre are fully functional.

6.2 Testing of Behaviour of ICR in Large Traffic

The second part of testing is aimed to evaluate and analyze the ICR module behaviour in the large traffic scenario. For this purpose is used generic scenario which traffic configuration provided by the FAA. The generic scenario was used as the HITL simulation. The scenario contains 273 aircraft which fly through the sector during 3 hours.

Two tests are made in this part of testing chapter. Both of them examine an effect of indirect penalization criteria on the type of selected conflict solving manoeuvre. The first test modifies the off track length penalty and observes the usage of the manoeuvre types. The second test modifies the flight level evaluation penalty and observes the usage of the manoeuvre types. The assumption is that both penalties should change ratio of manoeuvre usage between horizontal and vertical manoeuvre. Several runs of scenario with different settings of mentioned penalties were made to test this assumption. Only one run was made for each penalty value because the "zero-times" time model is used. The "zero-times" time model with constant time durations of actions ensures that the behaviour of the ICR model is deterministic during the test. Both penalties for this test are set to linear, so the standard and the considerable part of the penalties is the same.

The horizontal manoeuvre turns' penalties were modified according to table 6.3.

horizontal turn	standard immediate and postponed penalty	2.5
	considerable immediate and postponed penalty	5.0
horizontal return and join	standard immediate and postponed penalty	2.5
	considerable immediate and postponed penalty	4.5

Table 6.3: Changed penalization parameters for test scenario

	Count of applied manoeuvres		
Penalty / NM	**Horizontal**	**Vertical**	**Speed change**
0.000	14	24	3
1.000	16	28	2
2.000	12	37	2
2.250	11	39	2
2.375	5	46	2
2.500	4	47	2
3.000	3	49	2
5.000	3	49	2

Table 6.4: Results of measurement of dependence between Off track length penalty and count of applied manoeuvres

6.2.1 Effect of Off Track Length Penalty on Manoeuvre Usage

An assumed effect of changing the off track length penalty is that the probability of using the horizontal manoeuvre to resolve collision will decrease with increasing off track length penalty.

The table 6.4 shows the measured results and Fig. 6.3 shows a graph that visualises the measured results.

The results prove the assumption of this test. The use of the horizontal manoeuvre is decreasing with increasing the off track length penalty. The minimal use of the horizontal manoeuvre in this test is exactly 3 times because these collisions solved horizontally cannot be safely solved with other manoeuvre.

Two side effects are seen in results. The first side effect is that the total count of applied manoeuvres is changing with changes of the off track length penalty during the test. This is happened from two reasons. The first reason is that the applied horizontal manoeuvres are shorter with increasing of the off track length penalty. The second reason is that several horizontal manoeuvres are replaced by vertical manoeuvres. Both reasons lead to same conclusion that the aircraft are flying different paths and that causes different collisions than with other off track length penalty setting. The second side effect is that a count of applied speed change manoeuvres differs by the test runs. That is caused by same reasons like the first side effect.

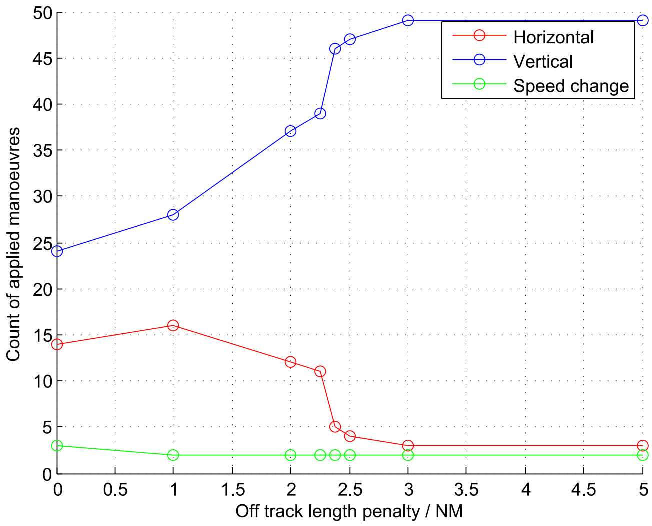


Figure 6.3: Visualisation of measured dependence between Off track length penalty and count of applied manoeuvres

6.2.2 Effect of Flight Level Evaluation on Manoeuvre Usage

An assumed effect of changing the flight level evaluation penalty is that the probability of using the vertical manoeuvre to resolve collision will decrease with increasing flight level evaluation penalty.

	Count of applied manoeuvres		
Penalty / (ft*NM)	**Horizontal**	**Vertical**	**Speed change**
0.0000	14	29	2
0.0010	16	28	2
0.0020	16	28	2
0.0025	16	22	3
0.0030	16	22	3
0.0040	16	21	3
0.0050	17	20	3
0.0060	19	20	3
0.0075	20	20	3
0.0100	20	20	3

Table 6.5: Results of measurement of dependence between Flight level evaluation and count of applied manoeuvres

The table 6.5 shows the measured results and Fig. 6.4 shows a graph that visualises the measured results.

The results prove the assumption of this test. The use of the vertical manoeuvre is decreasing with increasing flight level evaluation penalty. The minimal use of the vertical

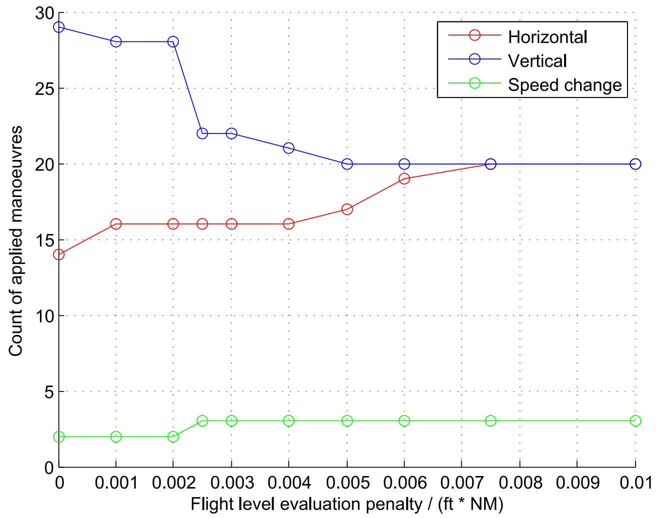


Figure 6.4: Visualisation of measured dependence between Flight level evaluation penalty and count of applied manoeuvres

manoeuvre in this test is exactly 20 times because these collisions solved vertically cannot be safely solved with other manoeuvre. The same side effects like in first test but for vertical manoeuvre are seen in the second test.

6.2.3 Comparison with the Existing CR Module

The existing CR module has constant preferences of the manoeuvre types. The first used manoeuvre type is vertical, second horizontal and last is speed change manoeuvre. The tests made in this section prove that the ICR preferences of manoeuvre selection are continuously adjustable and one of the goals of this thesis was successfully achieved.

6.3 Testing of ICR MIT sub-module

Tests of ICR MIT sub-module are aimed to prove functionality of implemented solution. All the tests were made on one scenario depicted on Fig. 6.5.

The scenario models MIT applied on aircraft heading to John Fitzgerald Kennedy Airport (JFK) in New York. The testing scenario contains only 7 aircraft heading for JFK. All aircraft are separated vertically or horizontally regarding to minimal separation limits but aircraft are not spaced properly. The ATC of JFK TMA will have problems to land all aircraft without use of holding patterns. The tests goal is to prove that the ICR MIT module of sector ZDC54 properly separates aircraft heading to JFK on required spaces by ATC of JFK TMA. 4 aircraft fly through the sector ZDC34 before they enter the sector ZDC54.

The basic visual test of functionality was done at first. The figures are displaying situation after last aircraft in JFK MIT group leaves the sector ZDC54. The Fig. 6.6a displays

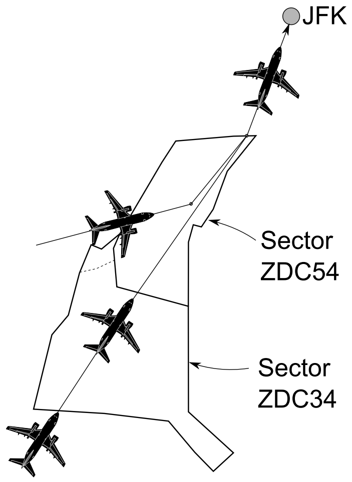


Figure 6.5: Scenario for testing ICR MIT sub-module

how the aircraft leave the sector ZDC54 when the ICR MIT is not activated. The Fig. 6.6b displays how the aircraft leave the sector ZDC54 when the ICR MIT is activated.

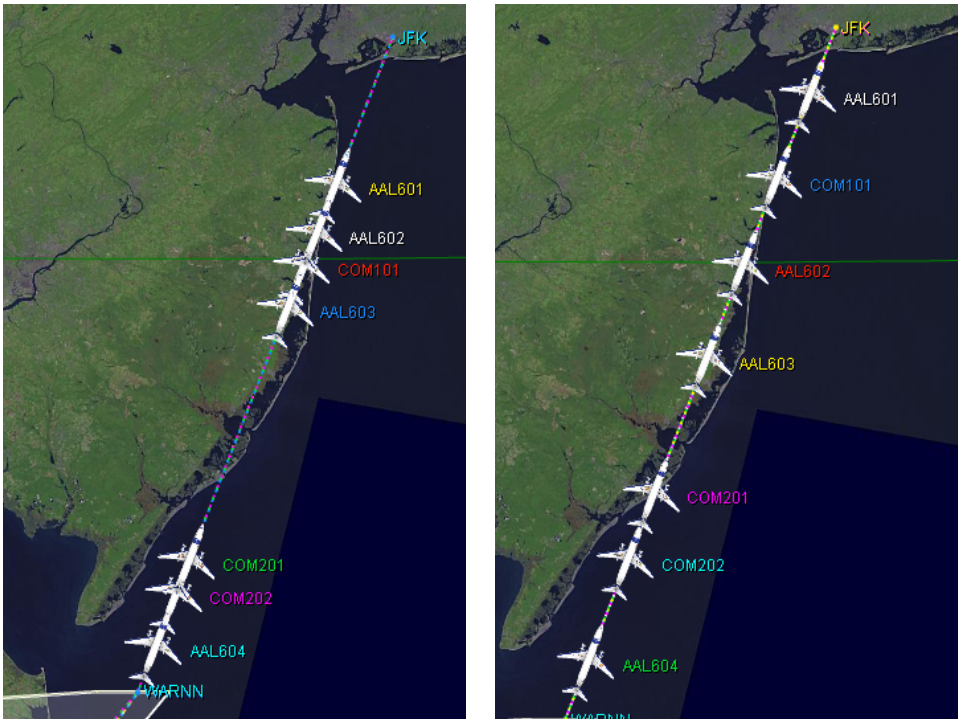
Test	1.	2.	3.	4.
Minimal separation [NM]	12	13	14	15
Optimal separation [NM]	14	15	16	17

Table 6.6: Tests of ICR MIT sub-module

The tests spacing separation limits are stated in table 6.6. The second test results are in table 6.8. The rest results can be found in appendix A. Not all of the aircraft are separated with optimal separation distance because the sector ZDC54 does not provide enough space for horizontal and speed manoeuvring which is able to separate all aircraft properly.

Criteria	**Result**
Separation of aircraft at the sector entry > the optimal separation	46%
Separation of aircraft at the sector exit > the optimal separation	46%
Separation of aircraft at the sector exit > the minimal separation	83%
Separation of aircraft at the sector exit > the minimal separation - 1NM	96%

Table 6.7: ICR MIT tests result summarizing table



(a) MIT not activated (b) MIT activated

Figure 6.6: JFK approach

Flight	Predec.	d_S	d_E	d_Δ	$d_S > s_O$	$d_E > s_O$	$d_E > s_M$	$d_E > s_M - 1$
COM101	AAL601	14.63	14.63	0.00	yes	no	yes	yes
AAL602	COM101	3.17	14.26	11.09	no	no	yes	yes
AAL603	AAL602	15.07	15.5	0.43	yes	yes	yes	yes
COM201	AAL603	22.98	24.01	1.03	yes	yes	yes	yes
COM202	AAL201	6.41	12,18	5.77	no	no	no	yes
AAL604	COM202	9.62	17.37	7.75	no	yes	yes	yes

Table 6.8: ICR MIT test results for minimal separation 13NM and optimal separation 15NM The all values are measured in nautical miles (NM). The d_S is separation distance between flight and predecessor at the moment of the flight's sector entry. The d_E is separation distance between flight and predecessor at the moment of the predecessor's sector exit. The d_Δ is difference between d_S and d_E. The s_M is the minimal separation distance. The s_O is the optimal separation distance.

The table 6.7 summarizes the results from all the tests as percentages of successful completion of several requirements. The results from summarizing table can be interpreted as success. It is needed to consider that the spacing manoeuvres needs that the sector is in case of horizontal manoeuvre enough wide and in case of speed change manoeuvre enough long. The size of sectors is specially very limiting when larger spacing separation distances are required to fulfil.

6.3.1 Testing Integration of MIT to ICR

As the testing scenario is used the same scenario like for general testing but as traffic is used record of real traffic which was provided to AgentFly team by FAA. The ATCs of sectors ZDC34 and ZDC54 have to separate aircraft regarding to minimal separation limits. Moreover they have to ensure that the aircraft heading to JFK are separated regarding to spacing separation limits required by ATC of JFK TMA. The spacing separation limits for sectors are stated in table 6.9.

Sector	ZDC34	ZDC54.
Minimal separation [NM]	13	13
Optimal separation [NM]	15	15

Table 6.9: Separation limits for sectors ZDC34 and ZDC54

The test consists from comparison of counts of applied manoeuvres types when the MIT module is active and when the MIT module is not active. A Table 6.10 provides this comparison for the sector ZDC34.

MIT	Off	On.
Horizontal manoeuvres count	2	2
Vertical manoeuvres count	5	4
Speed change manoeuvres count	1	1
Spacing horizontal manoeuvres count	0	5
Spacing speed change manoeuvres count	0	1

Table 6.10: Count of applied manoeuvres in the sector ZDC34 with/without MIT activated

The JFK approach MIT group spacing separation distances on the sector ZDC34 were measured and the results are filled in the table 6.11. Fig. 6.7 shows aircraft which were additionally separated regarding the requirements of ATC of JFK TMA. The aircraft on Fig. 6.7 are on their path between the sector ZDC54 and the JFK.

The tables 6.10, 6.11 and the Fig. 6.7 are prove that the ICR module with its MIT sub-module are able to separate aircraft regarding to minimal separation limits and that they are able to apply the MIT separation limits.

Flight	Predec.	d_S	d_E	d_Δ	$d_S > s_O$	$d_E > s_O$	$d_E > s_M$	$d_E > s_M - 1$
COM749	AAL400	-4.80	16.96	21.76	no	yes	yes	yes
COM624	COM749	60.51	60.48	-0.03	yes	yes	yes	yes
EGF4404	COM624	27.38	27.34	-0.04	yes	yes	yes	yes
AAL696	EGF4404	59.47	59.46	-0.01	yes	yes	yes	yes
COA5569	AAL696	51.73	52.36	0.63	yes	yes	yes	yes
UAL53	COA5569	0.01	18.65	18.64	no	yes	yes	yes
DAL28	UAL53	0.01	17.44	17.43	no	yes	yes	yes

Table 6.11: ICR MIT test results for minimal separation 13NM and optimal separation 15NM, in the sector ZDC34 with other traffic
The all values are measured in nautical miles (NM). The d_S is separation distance between flight and predecessor at the moment of the flight's sector entry. The d_E is separation distance between flight and predecessor at the moment of the predecessor's sector exit. The d_Δ is difference between d_S and d_E. The s_M is the minimal separation distance. The s_O is the optimal separation distance.

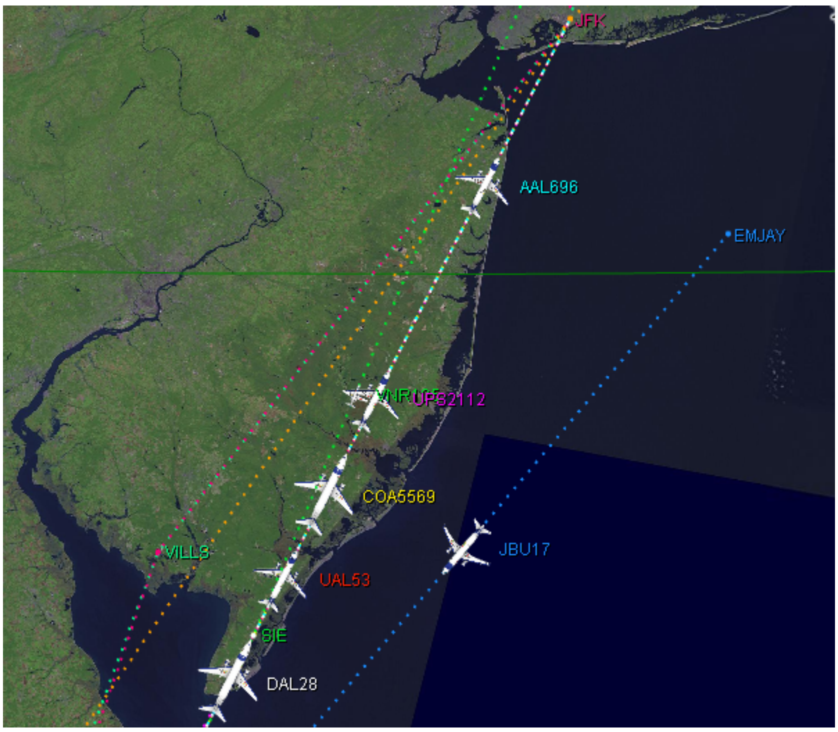


Figure 6.7: Aircraft from the JFK approach on their path from the sector ZDC54 to the JFK

Chapter 7

Conclusion

In a scope of this thesis, I have studied approaches of air-traffic controllers used within en-route sectors and I have got familiar with the architecture of the multi-agent system AgentFly and its model of ATC. I have used this newly acquired knowledge to design and implement new ICR module for AgentFly according to all requirements on this module. The new ICR module brings a completely new way of modelling the ATC's behaviour into the AgentFly system.

In the first part of this thesis I have provided a short introduction into the area of air traffic control and into the AgentFly system. In second part of thesis I have presented design of the new ICR module and its collision resolution methods. The methods of ICR module use several different approaches (vertical, horizontal and speed change) to generate alternative manoeuvres that resolve identified collisions in on flight trajectories within en-route sectors. I have also presented design of the MIT sub-module of ICR which allows simulating of airport approaches handling in the en-route sectors. I have implemented these new ICR and new MIT modules.

Ability of the new ICR module to model ATC with different priorities of manoeuvres used for removal of identified collisions was tested. All tests of influence of all coefficients in the evaluation function are beyond the scope of this thesis, however tests which present capabilities of the new ICR module the best were performed. Finally, the integration of MIT module in the new ICR module was validated as a good way to realize this feature in the AgentFly system. The robustness of the new ICR module has been proved by an extensive experimental validation with hundreds of simulated flight hours. Several serious bugs were revealed and fixed.

I could not provide detailed comparison of output characteristics with existing CR module in system due to a serious error in the existing module, which makes the existing CR module unable to finish the simulation scenario used for testing the new ICR. However the presented tests represent possibilities of smooth modification of the ATC's behaviour that could not be done with existing CR module.

The implementation of the ICR module described in this thesis is currently used in a version of the AgentFly system designated for validation by FAA.

7.1 Future Work

In the new ICR module, there are several areas which could be improved in the future. A weakness in the ATC's prediction of future trajectory of the aircraft was found. The weakness causes two problems which are important to resolve. First problem is that it is does not allow to do a turn when two aircraft are flying to close behind each other on same path. The position of the second aircraft is then virtually moved to front where collides with the first aircraft. This is done because the inaccurate position of aircraft in turn is modelled as tetragon. That causes a "distortion" in aircraft position which causes conflicts that actually do not exist. The second problem is that the imprecision caused by ATC's prediction of turns makes the calculation of total length of flight path inaccurate in way that is could be shorter than original path which is straight. I suggest that an improvement of behaviour of the ATC's prediction of aircraft future trajectory is necessary.

The ICR needs further improvements in resolution of collisions of two aircraft when one of them is climbing or descending and their trajectories are overlapping. This situation needs better handling which could be done as a combination of horizontal manoeuvre and temporary vertical manoeuvre. The second solution could be completely new horizontal manoeuvre in case that the aircraft have the same horizontal trajectory. Then, the new horizontal manoeuvre will allow to fly along current trajectory in some constant distance.

The second ICR improvement could be done in evaluation of the following aircraft separation violation that is caused by manoeuvres applied on the leading aircraft. The system is currently not perfect in this area. A task of the following aircraft separation violation penalty is to better spread MIT group separation between all aircraft in this group. Tests showed that the current implementation evaluation of the following aircraft separation violation is too aggressive and the results are not as good as it was expected. It can be seen on the results in section 6.3 that a large gaps stay in the MIT "train" while some aircraft need to be better separated.

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Appendix A

Testing of ICR MIT - Measured Data

Description of data tables

- The d_S is separation distance between flight and predecessor at the moment of the flight's sector entry.
- The d_E is separation distance between flight and predecessor at the moment of the predecessor's sector exit.
- The d_Δ is difference between d_S and d_E.
- The s_M is the minimal separation distance.
- The s_O is the optimal separation distance.

Flight	Predec.	d_S	d_E	d_Δ	$d_S > s_O$	$d_E > s_O$	$d_E > s_M$	$d_E > s_M - 1$
COM101	AAL601	14.63	14.63	0.00	yes	yes	yes	yes
AAL602	COM101	2.27	13.45	11.18	no	no	yes	yes
AAL603	AAL602	13.78	14.39	0.61	yes	yes	yes	yes
COM201	AAL603	25.02	25.63	0.61	yes	yes	yes	yes
COM202	AAL201	6.41	12.98	6.57	no	no	yes	yes
AAL604	COM202	9.62	12.69	3.07	no	no	yes	yes

Table A.1: ICR MIT test results for minimal separation 12NM and optimal separation 14NM
The all values are measured in nautical miles(NM).

Flight	Predec.	d_S	d_E	d_Δ	$d_S > s_O$	$d_E > s_O$	$d_E > s_M$	$d_E > s_M - 1$
COM101	AAL601	14.63	14.63	0.00	yes	no	yes	yes
AAL602	COM101	3.17	14.26	11.09	no	no	yes	yes
AAL603	AAL602	15.07	15.5	0.43	yes	yes	yes	yes
COM201	AAL603	22.98	24.01	1.03	yes	yes	yes	yes
COM202	AAL201	6.41	12,18	5.77	no	no	no	yes
AAL604	COM202	9.62	17.37	7.75	no	yes	yes	yes

Table A.2: ICR MIT test results for minimal separation 13NM and optimal separation 15NM
The all values are measured in nautical miles(NM).

Flight	Predec.	d_S	d_E	d_Δ	$d_S > s_O$	$d_E > s_O$	$d_E > s_M$	$d_E > s_M - 1$
COM101	AAL601	14.63	14.63	0.00	yes	no	yes	yes
AAL602	COM101	4.15	15.53	11.38	no	no	yes	yes
AAL603	AAL602	16.48	15.43	-1.05	yes	no	yes	yes
COM201	AAL603	21.02	22.11	1.09	yes	yes	yes	yes
COM202	AAL201	6.41	13.61	7.2	no	no	no	yes
AAL604	COM202	9.62	18.72	9.1	no	yes	yes	yes

Table A.3: ICR MIT test results for minimal separation 14NM and optimal separation 16NM
The all values are measured in nautical miles(NM).

Flight	Predec.	d_S	d_E	d_Δ	$d_S > s_O$	$d_E > s_O$	$d_E > s_M$	$d_E > s_M - 1$
COM101	AAL601	14.63	14.28	-0.35	no	no	no	yes
AAL602	COM101	2.24	15.32	13.08	no	no	yes	yes
AAL603	AAL602	18.37	20.39	2.02	yes	yes	yes	yes
COM201	AAL603	22.88	18.79	-4.09	yes	yes	yes	yes
COM202	AAL201	6.41	8.94	2.53	no	no	no	no
AAL604	COM202	9.62	19.27	9.65	no	yes	yes	yes

Table A.4: ICR MIT test results for minimal separation 15NM and optimal separation 17NM
The all values are measured in nautical miles (NM).

Appendix B

Videos

This chapter describes enclosed videos. All the enclosed videos are records of the visualisation output of the AgentFly system.

B.1 Testing of Priority Settings

The videos stated in table B.1 were made to demonstrate abilities of ICR module to set priority of chosen collision resolving manoeuvre. All the videos of this section are enclosed on CD in file `videos/test1`.

Priority	File	Description
Horizontal	`horizontal.avi`	Video shows horizontal manoeuvre applied on COM749 to avoid collision with AAL1049.
Vertical	`vertical.avi`	Video shows vertical manoeuvre applied on COM749 to avoid collision with AAL1049.
	`vertical3rdPerson.avi`	Video shows vertical manoeuvre applied on COM749 to avoid collision with AAL1049 from 3rd person view.
	`verticalRadar.avi`	Video shows the radar screen visualisation during the the scenario from videos showing vertical manoeuvre application. In front are windows which represent sector radio (OUT - ATC's commands, IN - Pilot's replies), keyboard input (ATC's work with ATM computer) and simulation actions log. This video should provide better overview what is happening in simulation during the manoeuvre application.
Speed change	`speedChange.avi`	Video shows speed change manoeuvre applied on COM749 to avoid collision with AAL1049.

Table B.1: Testing of Priority Settings - videos description

B.2 Testing of Behaviour of ICR in Traffic

The video `videos/test2/behaivourTraffic.avi` was made to demonstrate ability of ICR module to select different collision resolving manoeuvre types which are appropriate to resolve concrete conflicts.

B.3 Testing of ICR MIT sub-module

The videos stated in table B.2 were made to demonstrate difference between JFK approach scenario with MIT sub-module activated and without MIT sub-module. All the videos of this section are enclosed on CD in file `videos/test3`.

MIT	File	Description
Off	`withoutMIT.avi`	Video shows scenario of JFK approach without MIT sub-module activated on testing set up of sectors ZDC34 and ZDC54. It is shown that the aircraft are creating clusters. These clusters are very hard to handle in TMA of destination airport.
On	`withMIT.avi`	Video shows scenario of JFK approach with MIT sub-module activated on testing set up of sectors ZDC34 and ZDC54. It is shown that the aircraft are better spaced. The aircraft are almost separated by the same distances. The optimal spacing separation is 15NM and the minimal spacing separation is 13NM in this video.

Table B.2: Testing of ICR MIT sub-module - videos description

Appendix C

Default ICR Configuration

Default ICR penalty function coefficients configuration is described in this appendix. See section 4.5.12 for default ICR generation parameters.

C.1 Horizontal penalties

turn, return and join	standard immediate and postponed penalty	3.0
	considerable immediate and postponed penalty	6.0
	considerable point	20°
off track length	standard penalty	1.5
	considerable penalty	4.0
	considerable point	50NM
total track length	standard penalty	2.5
skip fix	is skip fix	3.0
	skip fix count standard penalty	3.0

Default horizontal penalty values

Example: Consider new generated SgPlan using horizontal manoeuvre with following parameters: Turn angle: 20°, return angle: 38°, join angle: 10°, off track length: 50NM, total lengthening of trajectory by 5NM and two skipped fixes. The penalty difference from original plan is:

$$p_{Tot} = 20 * 3 + (20 * 3 + 18 * 6) + 10 * 3 + 50 * 1.5 + 5 * 2.5 + 3.0 + 2 * 3.0 = 354.5$$

C.2 Vertical penalties

climb and descend	standard immediate and postponed penalty	0.2
	considerable immediate and postponed penalty	2.0
	considerable point	3,000ft
flight level evaluation	standard penalty	0.0002
	considerable penalty	0.002
	considerable point	50,000 ft*NM

Default vertical penalty values

Example: Consider new generated SgPlan using vertical manoeuvre with following parameters: Aircraft filled and current altitude are FL 300. The aircraft will fly 20 NM on interim altitude FL280. The altitude difference is 2,000ft. We neglect the climb and descend. The penalty difference from original plan is:

$$p_{Tot} = 2,000 * 0.2 + (2,000 * 20) * 0.0002 = 408$$

C.3 Speed change penalties

speed up and slow down	standard immediate and postponed penalty	15.0
	considerable immediate and postponed penalty	50.0
	considerable point	20kn

Default speed change penalty values

Example: Consider new generated SgPlan using speed change manoeuvre with following parameters: Aircraft original speed is 280kn. The aircraft will slow down on interim speed 254kn and after a while the aircraft will return to the original speed. The penalty difference from original plan is:

$$p_{Tot} = (20 * 15 + 6 * 50) + (20 * 15 + 6 * 50) = 1200$$

C.4 MIT separation violation penalties

Separation from leading aircraft	standard penalty	30.0
	considerable penalty	70.0
Following aircraft lost separation	standard penalty	10.0
	considerable penalty	25.0
MIT direction change	penalty	200.0

Default MIT separation violation penalty values

The MIT separation penalties are using the inverse polyline penalty function (see figure 4.10.b). The zero-value point z_p is defined as optimal spacing separation limit of the sector and the considerable point c_p is defined as minimal spacing separation limit of the sector.

Example 1: Consider that aircraft is separated from leading aircraft 12 NM. The minimal spacing separation is 10 NM and the optimal spacing separation is 15NM. The aircraft is in bound of the minimal spacing separation so no further action will be taken. The penalty of current plan is:

$$p_{Tot} = (15 - 12) * 30 = 90$$

Example 2: Consider new generated SgPlan using speed change manoeuvre will cause that the following aircraft in MIT group will lost its spacing separation. The following aircraft separation will be 8.5 NM after applying the speed change manoeuvre. The minimal spacing separation is 10 NM and the optimal spacing separation is 15NM. The penalty difference from original plan is:

$$p_{Tot} = (15 - 10) * 10 + (10 - 8.5) * 25 = 87.5$$

C.5 General penalties

Future standard collisions count	for each	100.0
Time to future standard collision	standard penalty	0.5
	considerable penalty	10.0
	zero-value point	1440s
	considerable point	540s
Future MIT collisions count	for each	3.0

Default general penalty values

Appendix D

Geometry of Horizontal Manoeuvre in AgentFly

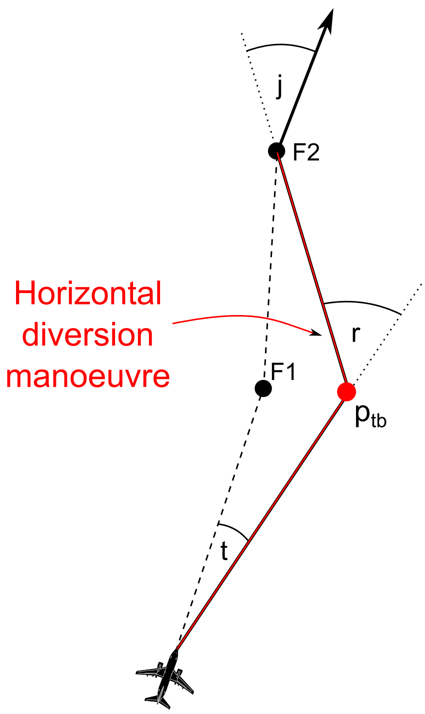

Figure D.1: Geometry of Horizontal Manouvre in AgentFly
Red segment is the horizontal diversion manoeuvre and the length of the red segment is penalized as off track length penalty. F1 and F2 are fixes of original trajectory which is depicted with dashed line. F1 is skipped fix. **Generation geometry:** t is turn angle, r is return angle, and turn back point p_{tb} - the turn back point is created as intersection of line from aircraft position in heading of turn angle and line from fix F2 in heading of return angle. **ICR evaluation geometry:** t is turn angle, r is return angle and j is join angle.

Appendix E

List of Abbreviations

AGL Above Ground Level

AIP Aeronautical Information Publication

AMSL Above Mean Sea Level

ATC Air Traffic Controller

ATCRBS Air Traffic Control Radar Beacon System

ATCU Airway Traffic Control Unit

ATM Air Traffic Management

BADA Base of Aircraft Data

CD Collision Detection

CR Collision Resolution

DME Distance Measuring Equipment

ES Environment Simulator

FAA Federal Aviation Administration

GIS Geographical Information System

GNSS Global Navigation Satelite System

GPS Global Positioning System

HITL Human in the Loop

ICAO International Civil Aviation Organisation

ICR Intelligent Collision Resolution

ID Identifier

JFK John Fitzgerald Kennedy Airport - ICAO code

MIT Miles in Trails

NAS National Air Space

RDP Radar Data Processing

SG Stereographic

SOP Standard Operation Procedure

TMA Terminal Manoeuvring Area

VHF Very High Frequency

VOR VHF omnidirectional range

WWII World War II

XML Extensible Markup Language

ZDC Washington Air Route Traffic Control Center - ICAO code

ICAO codes of airlines

These codes are used in flight IDs of several aircraft in chapter 6.

AAL American Airlines

COA Continental Airlines

COM Comair

DAL Delta Air Lines

EGF American Eagle Airlines

JBU JetBlue Airways

UAL United Airlines

UPS UPS Airlines

VNR Avantair

Appendix F

Contents of Enclosed CD

```
|-- sources                   - source codes of implemented module
|                               (plain Java)
|-- videos                     - videos described in appendix A
|   |-- test1                 - videos for section:
|   |                           Testing of Priority Settings
|   |-- test2                 - videos for section:
|   |                           Testing of Behaviour of ICR
|   |                           in Large Traffic
|   \-- test3                 - videos for section:
|                               Testing of ICR MIT sub-module
|-- text                      - this thesis in PDF format
\-- tex                       - this thesis text source code in LaTeX
                                with images in SVG, PNG formats
```