Bachelor's Thesis

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in Prague

F3

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Department of Cybernetics

Conflict Detection and Resolution Among UAS and Manned Aircraft

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II. Bachelor’s thesis details

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Řešení problematiky kolizních situací mezi UAS a pilotovanými letouny

Guidelines:

1. Study the problem of unmanned aerial systems (UAS) integration into shared airspace.
2. Survey existing sensors for detection of surrounding air traffic.
3. Design encounter models for UAS and VFR flights.
4. Implement these encounter models within existing AgentFly simulation framework.
5. Experimentally determine remain-well-clear (RWC) volumes for safe aircraft operation based on sensor suite used.

Bibliography / sources:

[1] Seung Man Lee.: Evaluating Alerting and Guidance Performance of a UAS Detect-and-avoid System. Moffett Field, CA: National Aeronautics and Space Administration, Ames Research Center, 2016.
[2] Seung Man Lee, Chunki Park, Marcus A. Johnson, and Eric R. Mueller: Investigating Effects of Well Clear Definitions on UAS Sense-And-Avoid Operations in Enroute and Transition Airspace, Aviation Technology, Integration, and Operations Conference. Los Angeles, CA, 2013.
[3] Cesar Munoz, Anthony Narkawicz, James Chamberlain, Maria C. Consiglio, and Jason M. Upchurch.: A Family of Well-Clear Boundary Models for the Integration of UAS in the NAS. 14th AIAA Aviation Technology, Integration, and Operations Conference. Atlanta, GA, 2014.

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Ing. Milan Rollo, Ph.D. Supervisor’s signature	doc. Ing. Tomáš Svoboda, Ph.D. Head of department’s signature	prof. Ing. Pavel Ripka, CSc. Dean’s signature

III. Assignment receipt

The student acknowledges that the bachelor’s thesis is an individual work. The student must produce her thesis without the assistance of others, with the exception of provided consultations. Within the bachelor’s thesis, the author must state the names of consultants and include a list of references.

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Date of assignment receipt Student’s signature

Acknowledgement / Declaration

I would like to show my greatest appreciation to Ing. Milan Rollo, Ph.D. Without his assistance and dedicated involvement in every step throughout the process, this bachelor's thesis would have never been accomplished.

I declare that the presented work was developed independently and that I have listed all sources of information used within it in accordance with the methodical instructions for observing the ethical principles in the preparation of university theses.

Prague, date 22. 5. 2018

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Abstrakt / Abstract

Tato práce stručně shrnuje problematiku detekce a řešení konfliktů mezi UAS a pilotovanými letouny. Vzhledem k tomu, že potenciální využití UAS v různých oblastech se rozšiřuje, potřeba řešení tohoto problému roste. V první části se práce zabývá teoretickým zázemím a podmínkami, které v současné době platí pro pilotované letouny. Existuje předpoklad, že obdobné pravidla budou v budoucnu platit i pro UAS. Následně přináší možné návrhy, jak řešit problematiku detekce pilotovaných letounu pomocí kamery . Tyto návrhy jsou později testovány v různém prostředí a za různých podmínek prostřednictvím systému AGENTFLY. Systém AGENTFLY navržený na ČVUT řeší otázku integrace UAS do sdíleného vzdušného prostoru. Výsledky jednotlivých testu jsou shrnuty a vyhodnoceny na konci této práce.

Klíčová slova: UAS, detekovat a vyhnout se, odstranění kolize, předpověď dráhy, systém předcházení kolizím.

This thesis briefly summarizes problematics of conflict detection and resolution among UAS and manned aircraft. As potential usage of UAS in different areas is expanding, the need for solving this issue is growing. Firstly the thesis describes theoretical background and conditions which exist nowadays for manned aircraft and UAS will have to also fulfil them in the future. Later thesis brings possible suggestions, which are solving the issue of detection of manned aircraft with a camera. These designs are later tested on various scenarios using an AGENTFLY system, which is developed ar CTU for solving the question of integration of UAS into shared airspace. The results of tested scenarios are summarized and discussed at the end of this thesis.

Keywords: UAS, detect and avoid, conflict resolution, path prediction, collision avoidance system.

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Chapter 1
Introduction

Over the last few years, the number of discussions about unmanned aircraft vehicle (UAV) was increasing. UAVs are part of unmanned aircraft system (UAS), which can be either controlled by a human from the ground or by onboard computers or by a combination of human and computer, depending on the level of UAS automation piloted flights. UAVs were mainly used in military applications, in operations which were too risky for human-based operation. However, their potential is much bigger than just a military area. In future, they could be spread out in different applications as scientific research, commercial spheres, or rescue operations which are too dangerous to be made by a human. The reason why they are not already used in these areas is that they have to operate in civil airspace. In current time, UAS is not able to fulfill conditions under which it is allowed to operate in civil airspace together with other traffic. The biggest challenge is collision avoidance ability. UAVs have to be able to detect other aircraft and obstacles, and safely avoid them following the same rules which human-pilot aircraft do. Since society is aware of economic and technological growth which usage of UAVs in commercial sphere would bring, currently UAVs and their detect and avoid system (DAA) is often a topic of research.

This topic is also interesting for many research groups. In [2] Eurocae describes in details safety rules, which UAV's DAA has to follow and requirements which DAA has to fulfil to be comparable with systems which are nowadays used to avoid collision between manned aircraft. In [3] NASA is discussing the effect of alerting criteria and pilot response delay on safety and performance of UAS's DAA. Also, there have been published a lot of research which is focusing only on the very specific problem as in [4] where authors are comparing performance and robustness to sensor noise between two collision avoidance algorithms. Even though a lot of research has been carried out in the area of UAS DAA, there are still a lot of problems which need to be solved.

This thesis is also focusing on UAS's detect and avoid the problem. We discussed and simulated the interaction between aircraft since it has some special characteristics compared to aircraft-obstacle interaction. Our goal is to find out a minimum separation distance between aircraft in conflict when escape maneuver has to be started, so the collision can be avoided within safety envelope distance. Safety envelope of aircraft is 3D space around aircraft in which no other objects should enter. The concept of finding separation needed to determine what action is necessary to remain an appropriate distance from other aircraft is called remain-well-clear (RWC). Specifically, in this thesis, we will focus on finding RWC distance of same type aircraft through visual flight rules (VFR). The structure of this thesis is following: chapter 2 is focusing on different categories of UAS, and on rules which need to be followed while operating in civil airspace. Chapter 3 describes in details structure of DAA and its specifications. In chapter 4 we introduce the architecture of AGENTFLY system, which is a system developed at the department of computer science, FEE, CTU in Prague. We will use this system for simulations of various conflict situations. Chapter 5 describes DAA implementation in AGENTFLY. Chapter 6 is the most important and main part of this thesis. This chapter is dedicated to simulations of different encounter situations. These situations vary in aircraft's closing speeds and angles under which the conflict situations occur. The results of these tests are separation standards of RWC in such a way, that conflict situations can be resolved safely. At the end of chapter 6 a short discussion about parameters of sensors which are used to sense surrounding environment (in our case camera) is made.

Chapter 2
Unmanned aircraft system

Every aircraft, manned or unmanned, needs to follow rules while operating in civil airspace. The idea behind bringing UAVs into current air traffic is that the rules which are followed by pilots in case of manned aircraft, have to be followed by used technology in case of UAV. Therefore before the discussion about problems and solutions for UAV's DAA can be started, it is important to mention regulations and divisions which are already established in civil airspace operation.

One of the most important definition is a division of airspace zones around each aircraft. In [5], the approach of defining two spheres around aircraft is presented. This concept with the addition of warning zone is shown in figure 2.1. The sphere of conflict resolution is defined by separation minima. Separation minima are defined by the distance from aircraft outside which, escape maneuver can be made in non-aggressive way and the original flight plan will change only slightly. While avoiding collision inside of conflict resolution sphere, usually requires aggressive maneuvers which are trying to avoid collision and do not take into consideration anything else. Avoidance of collision inside of conflict resolution sphere is the responsibility of collision avoidance system (CAS). CAS is a sub-system of DAA designed to reduce the severity of an accident. At the edge of conflict resolution sphere and collision avoidance sphere is zero seconds time-to escape point. Once this point is reached, aircraft will be inside of collision avoidance zone and beyond this point, collision cannot be avoided anymore. Around the two zones which were described in [5], the third zone can be added. When aircraft will appear in the warning zone, it will receive an alert about the collision. This brings more time to calculate the best escape maneuver and avoid collision more safely.

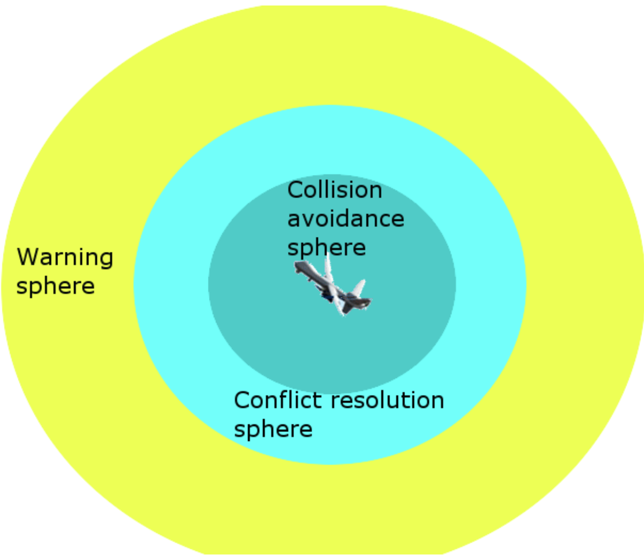

Figure 2.1. Collision and conflict zones around aircraft

2.1 Division of airspace

Airspace is divided into two main types: controlled and uncontrolled space. The main difference between controlled and uncontrolled airspace is that in controlled airspace, the aircraft is directed by air traffic controller (ATC) and for entering to the controlled airspace a permission is needed. On the other hand in uncontrolled airspace, everyone can fly without any permission and pilots are responsible for collision avoidance through following general rules. Airspace is divided into five categories [10]. Representation of this division into airspace classes is shown in figure 2.2. Classes A - E are covering controlled airspace. The only class which is under uncontrolled airspace is class G. This means that anyone can enter to class G and pilots are only operating under either instrument flight rules (IFR) or under visual flight rules (VFR) since they are often not visible to ATC. Special cases are restricted areas and no flight zones. For flying in restricted areas certain typed permission is needed. Restricted areas are usually established above big public events, military areas or around air show operation. No flight zones are usually established about areas in which military operations are happening. Division into individual classes varies little bit from country to country but generally speaking following categories can be defined:

Class A – is airspace defined in the altitude from around 5500 m to 18000 m. All airplanes in this class are under operating IFR and are directed by ATC. To enter this zone ATC clearance is required and all aircraft are separated by ATC. UAVs are prohibited in this class unless operating under special permission.

Class B and C – surround busy airports. Airplanes in both classes have to operate either under IFR or VFR. In class B all airplanes are directed by ATC, while in class C airplanes operating under IFR are separated by ATC but airplanes operating under VFR are not. Airplanes in class C which are flying under VFR are also receiving information about traffic flying under IFR.

Class D – surrounds all local aviation airports. Airplanes operating under IFR are separated by ATC. All airplanes are getting information about positions of airplanes flying under IFR as well as about those flying under VFR.

Class E – rest of the controlled space which was not included in previous classes. Airplanes flying under IFR are separated by ATC but flights under VFR are not under ATC clearance. This class is also extended to the ground level around local airports without a control tower, to reach the better level a safety, especially for landing and departing traffic.

Class G – the only class of uncontrolled space. Anyone can enter this class airspace without any permission but flights are still operating either under IFR or VFR. Even though this space is uncontrolled, the pilot has to follow VFR rules if the flight is not operating under IFR. Because of this and because UAV is missing a pilot on board, UAVs are currently only allowed to fly in such a distance, in which a pilot is able to see airspace around UAV from a “ground position” and safely avoid a collision.

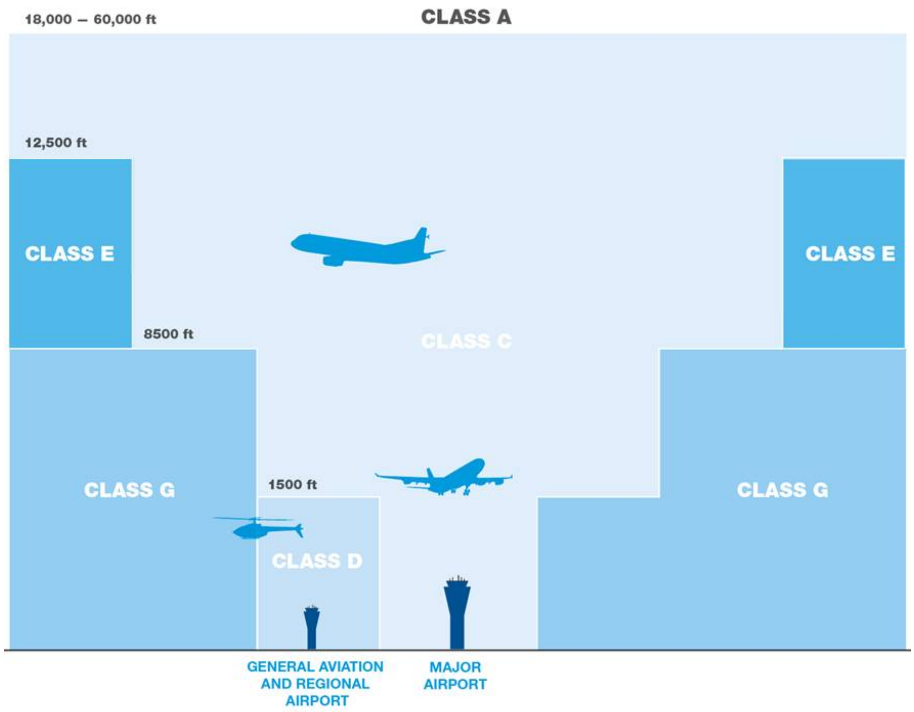

Figure 2.2. Division of airspace into classes [9]

2.2 Classification of UAV

Nowadays UAVs are used in different areas, therefore they differ in a lot of technical parameters e.g. type of aircraft (fixed wing or rotorcraft), flight altitude, weight, speed, size, etc. Because of these variations, there is no commonly accepted classification of UAVs. But generally speaking, larger UAVs are flying at higher altitude and using larger engines. This brings them longer endurance and more payload capacity compared to smaller UAVs. Even though the classification may vary from organization to organization the typical weight limits for different classes such as 25 kg, 150 kg, and 600 kg are widely accepted. The purpose of this thesis is to add another technical equipment on UAVs to avoid conflict, so the most meaningful division for us is the classification according to weight limits. Table 2.1 is representing UAS weight classification according to US Department of Defense [10].

Uas Category	Max Takeoff Weight (kg)	Normal Operating Altitude (ft)
Group 1	<10	<1200 above ground level
Group 2	10 - 25	<3500 above ground level
Group 3	25 - 600	<18000 mean sea level
Group 4	>600	<1800 mean sea level
Group 5	>600	>18000 mean sea level

Table 2.1. Classsification of UAS [10]

In 2016 the Federal Aviation Administration [11] introduced regulations for small UAVs which weight less than 25kg. The regulations include maximum ground speed of 87 knots and maximum altitude up to 400 ft above ground level. Also, visual-line-of sight is obligatory to keep. By this rule, flight time got limited to civil twilight (from 30 minutes before sunrise to 30 minutes after sunset). It is expected that soon will come regulations also for bigger UAVs which puts even bigger pressure on solving DAA for all the types of UAVs.

2.3 Visual Flight Rules

Visual flight rules (VFR) is set of regulations for flying under visual meteorological conditions (VMC). The pilot flying under VFR is fully responsible for conflict avoidance with other traffic, so the clear view in front of and around airplane is critical. Constant view of the ground, ability to visually detect and avoid other obstacles and aircraft is necessary. If current weather conditions are under a minimum of VMC, flying under VFR is not possible anymore and pilots have to switch to IFR.

The pilot has to be able to see to the certain distance, so VMC are generally defined as following [13]: no clouds within a distance of 1500 m horizontally and 1000 m vertically. Also pilot has to be able to see to the distance of 8 km in the airspace above 10000 ft MSL. In case the aircraft is flying below 10000 ft MSL, distance to which pilot has to see is reduced to 5 km. This reduction is a consequence of airplanes naturally flying slower at lower heights, so distance which is needed for safe conflict avoidance maneuver is shorter.

When there is a possibility of collision of two aircraft, certain maneuvers have to be made to avoid the collision. For this kind of situations, right–of–way rules were established. When these rules give a right–of–way to another aircraft, the pilot has to give way to that aircraft and may not pass over, under, or ahead of it unless well clear. Well, clear is state of maintaining a safe distance from other aircraft that would not normally cause the initiation of a collision avoidance maneuver by either aircraft [6]. Always the aircraft which has the right–of–way must maintain its direction and speed. The right–of–way is given to aircraft under following conditions [13]:

- In distress – aircraft which is in an emergency has always right–of–way.
- Different type aircraft converging – when aircraft which are in the potential collision, are not the same type, the right–of–way is given depending on their method of thrust. Powered aircraft have to give right-of-way to everything, airships are giving right–of–way to balloons and gliders, gliders to balloons and the balloons have right over all other aircraft. In case aircraft is towing or refueling other aircraft, then it has the right–of–way.
- Same type aircraft converging – when aircraft flying at approximately same altitude are converging, aircraft with the other aircraft on its right–hand side has to give right–of–way.
- Approaching head on – when two aircraft are approaching head on, both of them have to shift course to the right.
- Overtaking – when two aircraft are flying at the same altitude, path and at different speeds, the overtaken plane has the right–of–way, while the faster–moving aircraft should pass on the right side of slower aircraft.
- Landing – aircraft on the final approach to land or during landing has the right–of–way. In case that there are two aircraft approaching to the airport for the landing, the one which is at lower altitude has the right–of–way.

Except the rules mentioned above, it is necessary to take into consideration also an effect of wake vortex turbulence of aircraft with right–of–way. Wake vortex turbulence (WT) is turbulence which is produced by the passage of an aircraft in flight. The lift of aircraft is generated by the creation of differential pressure over the wing surface. This differential pressure meets at the wingtip which is causing counter-rotating vortex behind each wingtip. Strength of the vortices is mostly determined by weight, speed and wing's shape of the aircraft. These vortices spread vertically from aircraft as far as 760 m, with vertical drop up to approximately 150 to 270 m, in the possible distance up to 15 km behind the aircraft or in time it corresponding to 3 minutes [14]. This three-dimensional space is called WT envelope.

When another aircraft experiences WT turbulence, WT encounter occurs. In this case, aircraft has to deal with flight altitude disturbance, a loss of height or climb rate and structural stress. Because the strength of WT turbulence and effect of it on the following aircraft depends mostly on the weight of the leading and following aircraft, there has been established separation minima for different categories. The separation minima for the case when two aircraft are in trail or closely spaced are displayed in table 2.2:

Leader/Follower	Upper Heavy	Lower Heavy	Upper Medium	Lower Medium	Light
Super Heavy	7.4 km	9.3 km	9.3 km	11 km	14.8 km
Upper heavy	5.5 km	7.4 km	7.4 km	9.3 km	13 km
Lower heavy		5.5 km	5.5 km	7.4 km	11.1 km
Upper Medium					9.3 km
Lower Medium					7.4 km
Light					5.5 km

Table 2.2. Seperation wake vortex minima between aircrafts [14]

Under light category are falling aircraft of maximum takeoff weight less than 17000 kg (so all UAV used in this thesis) and as it was mentioned previously, in the most of situation light category has right–of–way in front of other categories. Because of these facts, for us is important only the last column of table, especially the fact that light weight category aircraft can be affected by aircraft in front, from 5.5 km up to 14.8 km depending on category of aircraft in front.

Different rules apply in case of landing or departure where separation minima are not measured in distance but in time. Also, the issue of landing/departing position needs to be taken into consideration. However, this problematics is behind the scope of this thesis.

Chapter 3
Collision avoidance system

The purpose of detect and avoid system (DAA) is to detect and avoid future conflict situation between aircraft in shared airspace soon enough to perform an avoidance maneuver. The conflict between two aircraft is detected when the euclidian distance separating two objects is less than required minimum. Depending on UAV's level of autonomy, purpose of DAA might range from just simple collision detection and warning, up to providing full autonomous detection and avoidance maneuver. The structure of fully autonomous DAA is divided into three main phases, which are sensing technology, conflict detection, and conflict avoidance [6]. The architecture of DAA is displayed in block diagram in figure 3.1.

The main purpose of sensing part is to monitor surrounding environment and collect all valuable information about intruders. To be able to detect different variables of an object in the surrounding environment (e.g. velocities, heading of other aircraft), we have to use communication systems and sensors like radars or cameras. The purpose of conflict detection part is to evaluate the possibility of conflict risk based on data which were obtained by sensing part. If actual conflict will occur in near future, position of this conflict point needs to be determined. The low probability of false collision alert is important from the economic point of view and probability of false not collision alert is crucial because of safety. Because of this, cost of not detecting a potential collision is really high. In case an actual collision should occur, the avoidance maneuver has to be performed. The conflict avoidance part is divided into three sub-parts: maneuver selection, maneuver realization and return to a course. So far in research, mostly selection of right maneuver is based on VFR described previously in chapter 2. The maneuver can be provided by changing speed or altering path either vertically or horizontally. After the realization of avoidance maneuver, aircraft is returning back to the course which was following before avoidance maneuver started.

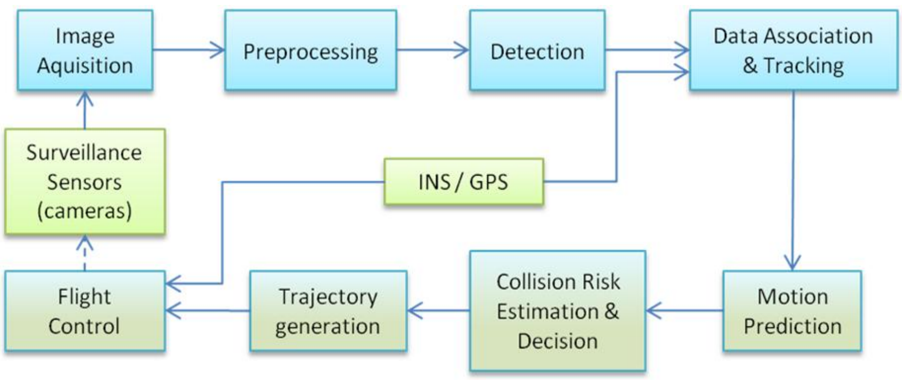

Figure 3.1. Collision avoidance system diagram [15].

3.1 Sensing technology

Monitoring surrounding environment can be accomplished by different sensors like EO/IR cameras or radars. Basic parameters which every sensor is collecting are range, azimuth, and elevation of all targets of interest as can be seen in figure 3.2. The standards limits require aircraft to see within ±15°of elevation and ±110° of azimuth [6]. The range of the sensing technology has to be sufficient enough to be able to detect and avoid a collision within separation minima.

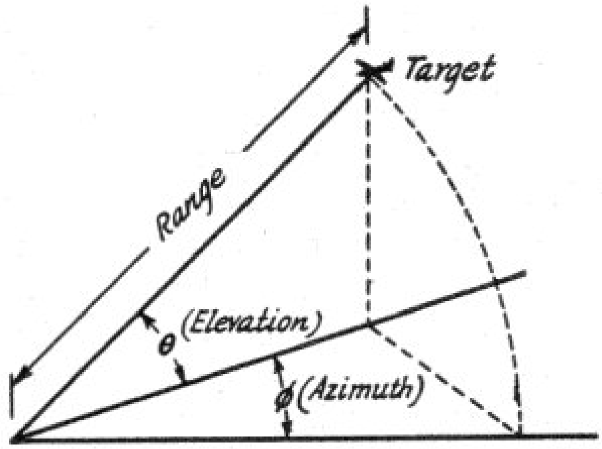

Figure 3.2. Spherical coordinate system

Sensors can be divided into two basic groups: cooperative and non-cooperative sensors. Non-cooperative sensors can be further divided into active and passive sensors.

3.1.1 Cooperative sensors

Nowadays, the most frequent collision cooperative avoidance system is traffic alert and collision avoidance system (TCAS). Through TCAS, the detection of an object is possible up to 160 km. This kind of communication is used in control airspace where all airplanes carry are equipped with secondary surveillance radar. First, airplane sends a request for information to nearby airplanes. Righ after nearby airplanes receive this request, they sent back information through secondary surveillance radar about their height, course, airspeed and vertical speed. The distance between aircraft is determined through time intervals between request and received an answer. Once the collision is recognized within 45 s, pilots are warned. If a collision is happening in following 30 s, TCAS provides a suggestion for escape maneuver. Aircraft using TCAS are only able to communicate and see aircraft which are equipped with TCAS as well.

Automatic Dependent Surveillance-Broadcast (ADS-B) is a cooperative system which is broadcasting information, from which pilots and ground-based stations are able to obtain information about aircraft distanced in about 240 km radius. ADS-B system provides two types of service ADS-B Out and ADS-B In. ADS-B periodically broadcast real-time information about each aircraft, through an onboard transmitter. This information includes not just aircraft's position but also altitude, speed, flight number, type of aircraft and relative change of altitude, or possible turning. ADS-B In is receiving not only ADS-B but also data from other services. These data include information about weather conditions or real-time position of nearby aircraft ADS-B has many advantages such a provision of accurate information, reliability, easy implementation and compatibility of future techniques. The main disadvantage is a disability to detect stationary objects and objects which are not compatible with ADS-B.

Generally speaking, cooperative systems have been used for many years in manned aircraft. During this time they proved their reliability, but they have many disadvantages connected to usage in UAVs. The cost, weight, and power consumption are inappropriate for smaller UAVs.

3.1.2 Non-cooperative sensors

Non-cooperative sensors do not depend on communication with similarly equipped aircraft. Another big advantage of this type of sensors is that they have also the ability to detect non-moving objects. These technologies include radar, LIDAR, electro-optical (EO), infrared (IR) and acoustic sensors. Based on the way by which objects are detected, they are divided into two categories: passive and active. Active sensors broadcast signal to determine if there is an obstacle in the path, while passive sensors rely on recognition of emitted signals by obstacles. Generally, active sensors are able to detect an object in the further distance but are more expensive, need more energy and power, which increase their size and weight. Due to big size and weight active sensors can be used only for bigger UAVs. On the contrary, passive sensors are much smaller, lightweight, affordable and more suitable for small UAVs.

Radar is a typical example of an active sensor, which transmits periodically electromagnetic waves and is detecting their reflections. Based on the time of reflections, shifts of frequencies and angle of reflection it is able to calculate distance, speed of an object in the path and its relative position to the radar. The biggest advantage of radar is that it is possible to use it also in very bad weather conditions. It is able to detect airplanes, guided missiles, terrains and even weather formations (rain, snow etc.). On the other hand, radar systems are usually bigger, more expensive and are not able to produce such degree of real-time imagery as EO systems are.

Another active sensors technology is LIDAR. LIDAR beams number of infrared, ultraviolet or visible light pulses in certain time intervals towards a target and detects their reflections. Based on measured time interval of reflections and shifts of reflected wavelength, distance and speed of the object are determined. The advantage is exact measuring of range from 200 m to 3 km and possibility of usage in different weather conditions. But the main benefit of LIDAR is the ability to detect also non-perpendicular surface in high resolution from 5 mm in diameter. Unfortunately, LIDAR is ineffective during heavy rain or low hanging cloud.

Electro-Optical (EO) cameras are considered as passive technology. They work on the base of detecting natural light or reflections of light from the object. Dominant features of EO cameras are detailed information about azimuth and elevation angles of object's position, along with good mass-power ratio and relatively low price. Unfortunately, since EO cameras work on detection of light reflections, this type of sensors are not precise in non-ideal weather conditions and are not suitable for detecting during the night. Additionally, to cover a wide field of view, the combination of several EO cameras is needed.

Another passive technology which can be used for UAVs DAA is infrared (IR) cameras. IR cameras detect objects based on absorption of object's heat. Because IR cameras do not use visible light to detect objects, the main benefit of this technology is recognition of objects also during night-time. However, disadvantages are the ability to detect object only on shorter distance than by EO cameras, fact that range is not recognized and fulfillment of VMC is needed.

A lot of problems which are caused by not having enough wide horizontal or vertical FOV can be solved by a different combination of sensors either of the same type or different types. We will be simulating implementation of the camera while conflict situations in different configurations occur between two aircraft of same weight group.

3.1.3 Choice of camera

While selecting a suitable camera for DAA of UAV, some important parameters to consider are resolution, FOV, refresh rate, weight and inclusion of global shutter. Global shutter works on the principle that the whole picture is captured at one moment while rolling shutter works on scanning line by line from top left corner to bottom right corner. Capturing pictures with rolling shutter containing moving objects can bring some problems with displaying lines as slanted where they should be straight. For example, a rectangular city bus will look more like a parallelogram and since recognition of the correct shape of objects in the airspace is important for us and objects are moving relatively fast, the distortion could be too big using roller shutter. Therefore the inclusion of global shutter is crucial. For simulation in this thesis, we are going to use parameters of the DI-SC120R camera invented by HITACHI company, which is lightweight enough to be carried by small UAV. The parameters of DI-SC120R are following:

- resolution - 1280 (H) 720 (V)
- FOV - $\pm 31.2°$ in azimuth, $\pm 25°$ in elevation
- refresh rate - 30 Hz
- global shutter included
- weight - 260 g
- diagonal size - 6mm with format 1/3" which refer to size: 4.8mm by 3.6mm
- ability to detect object when the object covers 43 pixels [7]
- range of 321 m for detection of Cessna type airplane [8]

3.1.4 Data processing and association

After receiving data from sensing technology, it is necessary to break them down into understanding form. Data are usually received in different forms, depending on the sensing technology used to obtain data. In case of a camera, we will receive information in pixel form. If radar would be used, information would come in radio waves form. Processing of data is done by algorithm, which is able from obtained data determine the position of aircraft or obstacles.

Next step after detecting an object is data association. In this process decision about if points captured at different time frames are corresponding to the same object or not is made. Data association is usually made through two approaches. The first approach is the nearest neighbor method and the second is probabilistic data association. A comparison of those two methods can be found in [16]. There can be more than one measurement of a single target at any time frame since false measurements can come from other sources than the target. The nearest neighbor method is based on computing a distance of all these measurements to the predicted point. Measurement with the closest distance is then chosen as next position of the tracked target. Disadvantage of this method is that there is always some probability that chosen point is not the correct one and with this incorrect point, the track updates. Including this point as most recent, prediction of position in next time frame is made. Therefore this method can lead, in the worst case to lost of the real track. The probabilistic data association is based on Bayesian approach. It takes into consideration all the valid measurements plus the possibility of no observation match and calculates their weights according to proximity. Advantage of this method is that correct measurement is highly unlikely to be excluded but there is also a high probability that incorrect measurements will have some undesired influence.

Trying to detect more targets at the same time brings another difficulty to data association because we have to recognize not only if measurements correspond to the target of interest but also to which concrete target it belongs to. Except this, multitarget tracker has to count with the possibility of new aircrafts' appearances and disappearance of old ones. Currently, three most popular multitracker algorithms are joint probabilistic data association (JPDA), multiple hypothesis tracking (MHT) and random finite set (RFS) [17]. JPDA comes from probabilistic data association which is used for single target tracking. It extends this algorithm in such a way, that probability of next update is calculated as a combination of targets' next positions and not independently for each target. MHT is recently the most often used method for multiple tracker data association. It looks at data association's problem form another side of view. Instead of calculating expected next position of the target and finding the best fit to it, MHT looks into past points of the target. MHT is dealing with data association by enumerating all possible associations over time. MHT put track hypothesis into multiple track trees, in which every layer is a representation of one time–frame. From all of the tracks, the best set of non-conflict tracks is chosen. The last method which is usually used for multiple tracking is RFS. This method works with a set of random variables of random size instead of data associations. Each variable models state prediction of one target and random size parameters models uncertainty by which concrete target will be present. Choice of concrete solution can be either done by Bayes recursion function or by PHD filter. More information about concrete implementations can be found in [17].

3.2 Conflict detection

Before DAA is able to decide if conflict is occurring in the future, the future trajectories of aircraft have to be predicted first. The prediction of future positions is made from detected points in the past, followed by calculation if the conflict is occurring or not. In case that conflict is happening, positions of this conflict in future needs to be determined.

3.2.1 State dimensions

Depending on sensing technology used, information about traffic and objects of nearby airspace are obtained either in 2D or 3D. In case of 2D, information covers either horizontal plane, vertical plane or both. The only model of sensing technology covering only vertical plane is ground proximity warning system (GPSW) which is controlling collision with the ground. The rest of the sensing technologies brings data usually in 3D or in 2D horizontal plane. Ability to collect a lot of information by indirect methods brings us advantage of working in dimension from which we do not have a complete description. For example, TCAS is resolving conflicts in a horizontal plane, even though in reality it measures only range.

3.2.2 Path predicition

One of the major features of DAA is the ability to predict future state and path of detected objects from the current and past states. There are three elementary prediction methods: nominal, worst case and probabilistic. Since path projection differs in reliability and directly influence collision detection, detect and avoid system can be only as reliable as used state projection is alone. For estimating trajectory, there can be used different mathematical approaches as linear approach and neural networks in [18], Taylor series in [19] and Kalman filters in [20].

In the nominal method, the current position is projected into the future along a single straight trajectory, only based on velocity vector. Because this method is very simple and does not take into consideration any maneuver by aircraft, this method is only suitable for short-time future prediction.

On the contrary, the worst case method looks at a whole range of possible maneuvers. If only one of the possible maneuvers could cause a conflict, the situation is evaluated as conflict situation. Even though this method detects conflict in the worst case, this method is highly inefficient and leads to many false alerts. Therefore the worst case method is currently limited only to certain look-ahead time projection to avoid often false alerts which could lead to reducing traffic in the airspace.

The probabilistic method includes uncertainties which model possible variation in predicted future trajectories. This is usually done in two ways. The first option is to add certain error to a nominal trajectory, follow by calculation of conflict probability. The second option is to take a whole range of possible maneuvers, each weighted by the probability of occurrence and calculating the conflict probability by density function. For both approaches, in the case when conflict probability is above a certain value, conflict alert is activated. Probability function includes in itself nominal and worst case methods. This fact brings along advantages as causing less of false alarms compared to worst case method and less missed alarms compared to the nominal method. However, the biggest disadvantages of the probabilistic method are complex processing and difficulties in finding the probabilities for trajectories.

3.2.3 Conflict Matrix

Through conflict matrices, DAA is obtaining alerting decisions. These conflict matrices are acquired through combinations of current position and predicted future positions. Most of techniques in conflict detection systems today focus on physical matrices method such as separation distance, time of the closest approach or time to impact. The main characteristics of these physical metrics are that data needed to create them can be easily collected directly from sensors, through additional filtering or estimation, and achievement of goals as a false alarm, safety, or success probabilities. However current progress in techniques brings us the opportunity of deriving more precise complex matrices. Using more complex matrices, alerting decision are derived directly from computed values of performance matrices. One of performance matrix can be false alarm probability as discuss in [22].

By comparison of conflict matrix and threshold matrix, the decision about whether a conflict occurs and whether avoidance maneuver is needed is made. Threshold values are usually obtained through a combination of analysis and user expertise and afterward adjust by using test scenarios in simulations. Ideally, threshold values should dynamically change based on the situation (e.g different separation minima is needed when aircraft in conflict is coming from forward than when it is approaching from backward). It is important to notice that not every time when conflict occurs also avoidance maneuver is made. For example, if the alert is far in the future, it is not appropriate to react to collision alarm right away, since the trajectories might change in future and then the performance of maneuver would be unnecessary and costly.

3.3 Conflict Avoidance

After alerting alarm by collision part of DAA, avoidance maneuver procedure has to start soon enough to fulfil RWC conditions, therefore within minimum safe time. The minimum safe time before the impact is the minimum time during which collision is still avoidable by escape maneuver. The choice of maneuver should take into consideration time to the impact since some maneuvers are faster to provide than others. On the other hand, they are also usually more economically costly, so we are trying to minimize their occurrence. After escape maneuver is finished and conflict situation solved, the airplane will return to its original path.

3.3.1 Conflict Resolution

Conflict resolution determines which approach of escape trajectory should be used to avoid a conflict. There are three main categories: prescribed, optimized and force field. Depending on the level of aircraft autonomy, manual resolution can be another option.

Prescribed trajectory escape maneuver is based on fixed predefined rules. These rules are clear and easily followed which helps to minimize the time needed to respond. This type of escape maneuver is used e.g in GPSW the climbing maneuver is performed in case of conflict with the ground. However, prescribed maneuvers are usually less optimal and less effective then maneuvers which are computed in real time. Also the lack of possibility to modify escape trajectory, limits reactions to unexpected events. When the climbing maneuver is made without taking into consideration that there might be another aircraft, which is separated by some vertical distance and this distance will narrow by climbing maneuver, the result might be another conflict situation.

The optimized maneuver is choosing the escape maneuver with the lowest cost from the set of escape trajectories calculated in a geometrical way. The cost of trajectory includes parameters like flight time, needed amount of energy and deflection from the original path. For example, TCAS escape maneuvers are based on a climb or descend maneuver and optimized approach is choosing the least aggressive maneuver, so the cost function is minimized. The logic behind the optimized algorithm is based on game theory, genetic algorithm, or fuzzy control. In game theory, the cost function is the distance between two agents, where the evader tries to maximize it [23]. A genetic algorithm is motivated by the principles of evolution by natural selection and can be used for searching effectively for optimal structures from a number of candidate patterns [24]. Fuzzy control logic [25] is an approach based on the fact that truth values can have any value between zero and one, so the result can be also partially true or partially false. Even thought optimized algorithm seems to be a great solution since the cost is minimized, the complexity of computation is high and difficult to understand.

The force field as discuss in [26] is an artificial method which is based on coulomb forces mapping the volume between two airplanes. Each airplane is treated as a charged particle and repulsive forces are used to generate escape maneuvers. The advantage is that even though this method used simple electrostatic equations, yet it is still able to calculate the continuously collision-free path. Unfortunately, to reach free collision path-goal, a force field often requires sharp discontinuous maneuvers or wide variation of speed for a longer time. These sharp variation maneuvers are highly inefficient and sometimes even not possible.

3.3.2 Maneuver Selection

Avoidance maneuver is provided trough set of actions by either one or all aircraft included in the collision, depending on how coorperative avoidance system are those aircraft using. In case of UAV's current trend, DAA is usually uncooperative, so the maneuver will be provided by one airplane. Decision about which airplane will make the maneuver is based on VFR which were mentioned in chapter 2. Choice of maneuver is made in such a way that updated trajectory does not vary from the original path a lot and includes returning to the original path.

The basic maneuvers can be realized in three dimensions: horizontal dimension, turning left or right; vertical dimension, climb or descend; and speed change, speeding up or slowing down. The final set of maneuvers can contain either only single maneuver or combination of more maneuvers. In case of a combination, maneuvers can be performed either simultaneously or in sequence.

Chapter 4
AGENTFLY

For the performance of simulation, we will use AGENTFLY environment. Agentfly is multi-agent system for free-flight simulation and flexible collision avoidance[27]. Free flight uses no centralized air traffic controllers. Instead, trajectories of airplanes are arranged without taking into consideration other traffic. Free flight concept brings the advantage of flying on the most optimal and shortest trajectories. Because of not present air traffic controllers, the conflicts detection have to be detect and solved by each aircraft individually.

AGENTFLY is build on top of the A-globe multi-agent platform. A-globe has been developed in the Gerstner Laboratory, Czech Technical University. It is fast and lightweight agent platform designed for fast prototyping and application development of multi-agent systems[28]. One of the biggest advantages of the A-globe is that compared to other agent platforms, A-globe is extended by Geographical Information System and Environment Simulator agent, thus it is possible to use it for real-world simulations.

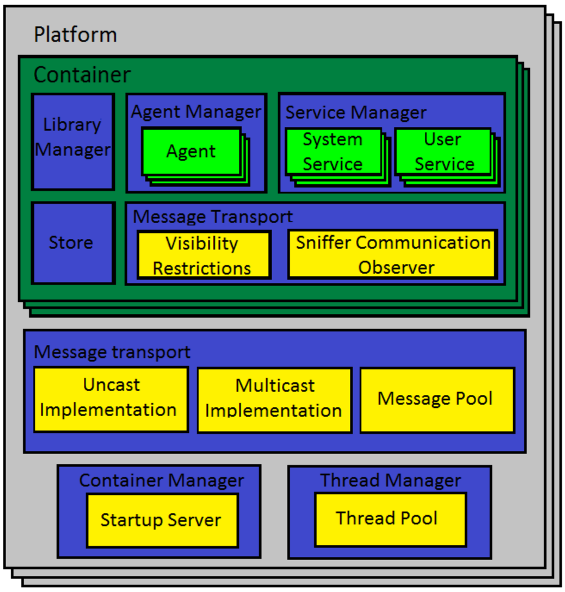

Figure 4.1. A-globe architecture.

As it can be seen in Fig. 4.1, A-globe architecture contains few following core components:

- Agent Platform serves basic functionality required to run agent containers, the container manager, and the library manager.
- Agent Container provides elementary functions such as communication, storage, and management of agents.
- Services ensure shared functions for all agents into one container.
- Environment Simulator Agents simulates real-world environment and visibility among agent containers.

- Other types of agents responsible for processes like user interface, hardware components or computational processes. They also provide basic functional entities in specific simulation scenarios.

  For more information about A-globe functionality and architecture see [28].

4.1 AGENTFLY architecture

For more information about A-globe functionality and architecture see [28]. Each aerial asset is represented as asset container which host combination of intelligent software agents and every flight operation is the responsibility of the corresponding container. The movement of each vehicle is determined by a time-arranged group of unspecified amount of geographical waypoints. Because AGENTFLY works on free flight concept, these waypoints are distinguished before take-off, without taking into consideration another object which might occur in the airspace. The conflicts situations are recognized during flight by implemented systems. Subsequently they are solved by peer-to-peer negotiation and change of flight operation.

AGENTFLY is fully written in JAVA, therefore it provides the possibility to be run on assets with different operating systems. AGENTFLY structure contains few basic components[27], which can be seen in fig 4.2.

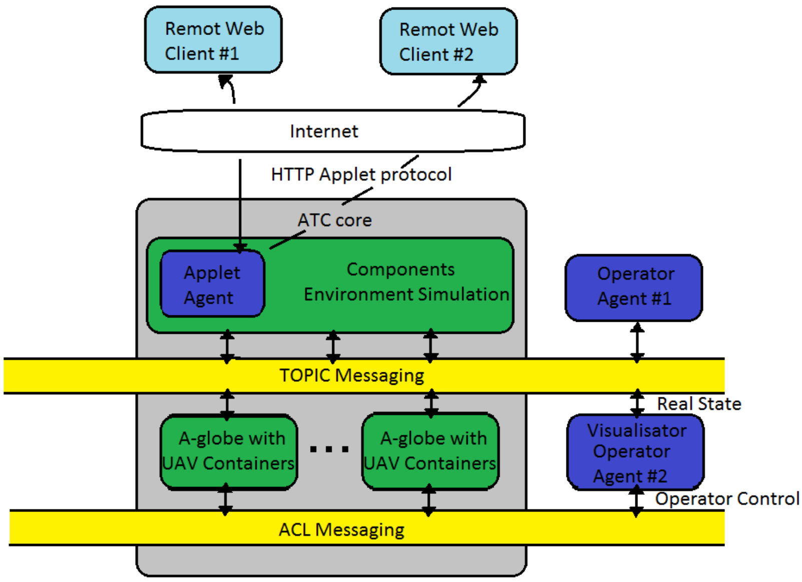

Figure 4.2. AGENTFLY system structure

4.1.1 Server Component

The server component, see Fig.4.3 of the core system is a sole central element of the system[29]. It is responsible for simulations of the environment, airplanes hardware, weather conditions, length in which the airplanes are able to communicate with each other, manipulation with aircraft, etc. When the system will be implemented into real aircraft, these components will be replaced by data observes from UAA hardware and control of aircraft's path will be replaced by its engines.

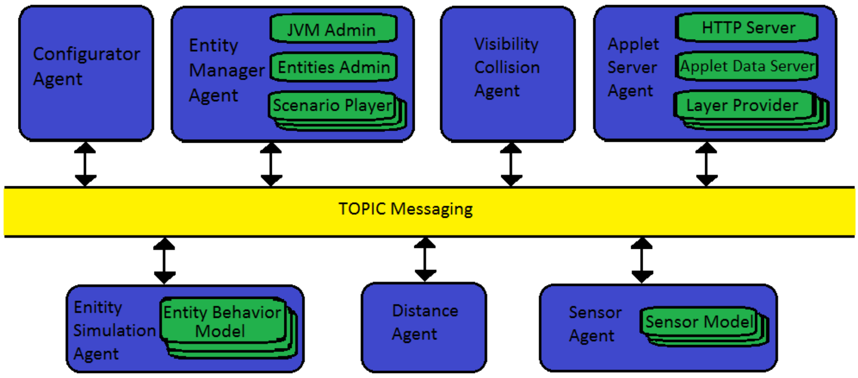

Figure 4.3. Agents of server component.

Configurator agent arranges fundamental configurations according to specification files and delivers them to other agents. Purpose of entity manager agent is the management of connected platforms and aircraft containers, which means that it is responsible for starting new planes with the proper initial condition and removing of existing planes. Function of entity simulation agent is to figure out current position of aircraft. Distance agents determines Euclidian distance between pars of airplanes. Visibility collision agent controls aircraft communication restrictions and recognizes their physical collisions. When this kind of collision is recognize, the aircraft start uncontrollably falling down. Sensors agent administrates sensor on aircraft's board. Applet server agent supports communication interface between Agentfly and remote web client. More information about individual agents can be found in [29].

4.1.2 UAA Container

Every UAA container represents exactly one airplane. In one platform can start many UAA containers but also none. UAA container consists of two agents – plane and pilot agent, see Fig.4.4. Pilot agents are a main control unit of UAA. It contains components as flight planning and replanning, no–flight zones manager, which specify where the plane can fly or not and entity controls. Entity controls consist of collision avoidance and operator module. Collision avoidance module is responsible for arrangement of CAS as it was described in chapter 3. Therefore it contains all the key elements as data processing, detection of other objects, prediction of future trajectories, position and time of conflict detection and conflict resolution by finding replace flight plan. Operator module brings the possibility of changing no-flight zones, redefinition of plans by a human.

Plane agent simulates real airplane's conditions through following components: configuration, radar, time, UAV control, operator bridge. Configuration describes all aircraft's parameters such as maximal velocity, acceleration, and deceleration, minimal turn radius, weight, etc. Radar provides all the information obtained from sensors which are on board. Time keep time synchronization. UAA control takes care of changes in the flight plan and gives information about the current position and operator bridge manages communication between operator agents in pilot module and user interface.

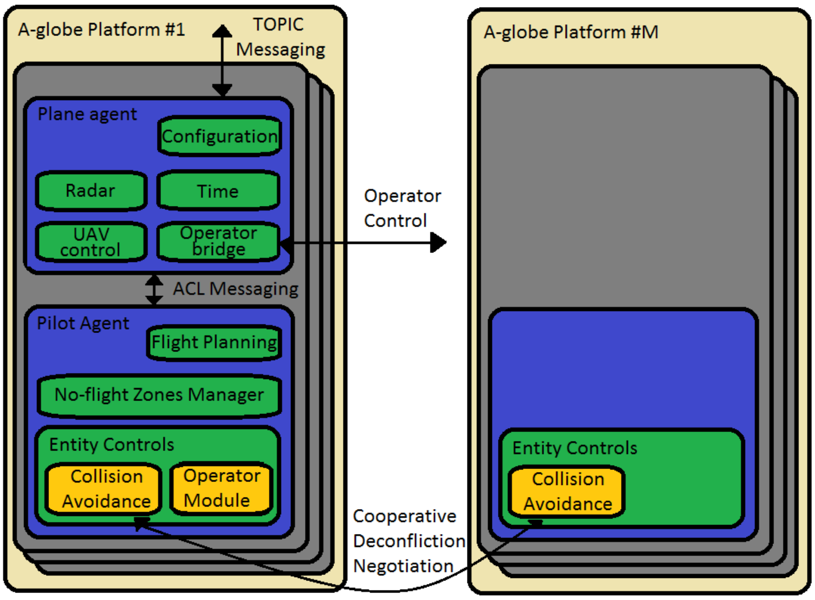

Figure 4.4. Stucture of UAA Container.

4.2 Agent–Based Collision Avoidance Methods

AGENTFLY includes a set of collision avoidance methods – both cooperative and non-cooperative. The difference between them is that while in cooperative methods all participating aircraft in collision provide information to each other and are trying to work together, in noncooperative collision avoidance methods the aircraft is solving a collision as an individual asset with other objects which do not interact with to–be–avoided asset. Agentfly features three types of cooperative methods – Rules based collision avoidance, Iterative peer–to–peer collision avoidance and Multi–party collision avoidance.

4.2.1 Rules Based Collision Avoidance (RBCA)

RBCA is passive cooperative algorithm based on VFR which were explained in chapter 2. According to these rules, each airplane performs appropriate maneuver based on what kind of collision situation from its point of view is occurring according to following procedures. First, type of collision has to be determined. This is done through an angle which is between direction vectors of the concerned aircraft projected to the ground plane. The visualization of different conflict situations which can happen is displayed in 5.3. Based on the type of situation and VOF which applied to each airplane's view of situation, each airplane performs separately an avoidance maneuver. The maneuvers are characterized by angle between airplanes and by information about future collision position. However, the main inefficiency of the RBCA algorithms is that they provide avoidance maneuvers without change of airplane's altitude.

4.2.2 Iterative Peer–to-Peer Collision Avoidance (IPPCA)

IPPCA is active cooperative collision avoidance algorithm, where the solution is provided for a pair of airplanes, see Fig.4.5. The algorithm is trying to find the most optimal solution, therefore airplanes are trying to find flight plan which would result in collision-free paths but at the same time maximize the sum of their utilities.

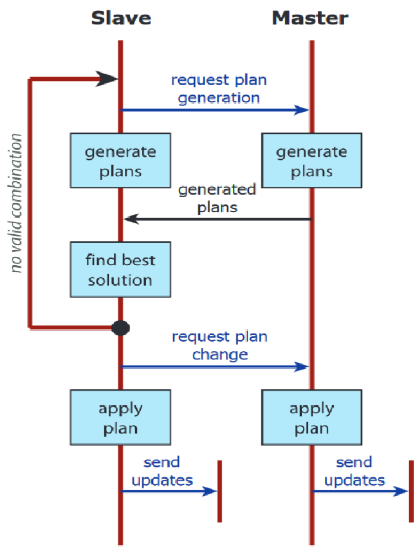

Figure 4.5. Negotiation process during IPPCA4.2.

As the first allocation of master and slave role to airplanes participating in a collision is made. Usually, an airplane which detected collision first has master role. The decisions which airplane is taking which role does not affect the quality of avoidance algorithm since IPPCA is a cooperative algorithm and therefore they optimize algorithm together. Both participants generate set of new plans based on predefined rules. Slave set is then sent to master. Every flight modification includes also information about its utility which is calculated by following formula:

$$u = \frac{\sum_i \alpha_i u_i}{\alpha_i}$$

where α_i is the weight of i component of the utility function. The master chooses from the set the pair of flight plans which has the highest utility sum. In case that two or more pairs have the same utility value, the final pair of flight plans which will be used is chosen randomly from those pairs.

4.2.3 Multi–party Collision Avoidance (MPCA)

MPCA is algorithm similar to IPPCA approach solving multi–party collision - a situation when more than two mutual aircrafts' collisions are predicted. The multiparty coordinator is presented. Its purpose is to find the optimal set of collision-free flight plans for a group of conflict UAVs. Multiparty coordinator is processing all the information about the group and ensures the communication with planes about collision-free trajectories which were found by itself. Because MPCA is operating while planes are in movement, the time for finding a solution is limited.

4.2.4 Noncooperative

The noncooperative method is base on using path planning algorithm for replanning trajectories, once an aircraft will be in collision with a flying object. When collision point is detected, the point is enclosed by dynamic no-flight zone. No-flight zone is placed on the position of collision point, not on the position of observed object. Size of dynamic no-flight zone depends on speeds of aircraft, distance between collision point. Current positions of aircraft and shape are derived from all possible future trajectories, the shape of no-flight zone for immediate collision can be seen in 4.6. The noncooperative algorithm is executed for every object in radar scan and for every radar scan.

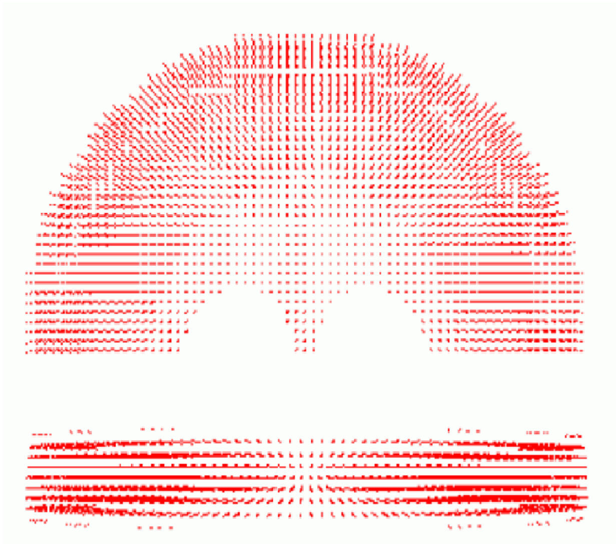

Figure 4.6. Shape of dynamic no-flight zone for immediate collisions4.2.

Chapter 5
Implementation

In this chapter, implementation of sub-program which arranges DAA is described. Inputs to this subprogram are GPS positions of all aircraft which are currently present in the simulation. The output should be set of the waypoints which will be added to flight plan and through which trajectory of aircraft will change and therefore avoid a collision. Structure of this implementation can be seen in Fig. 5.1.

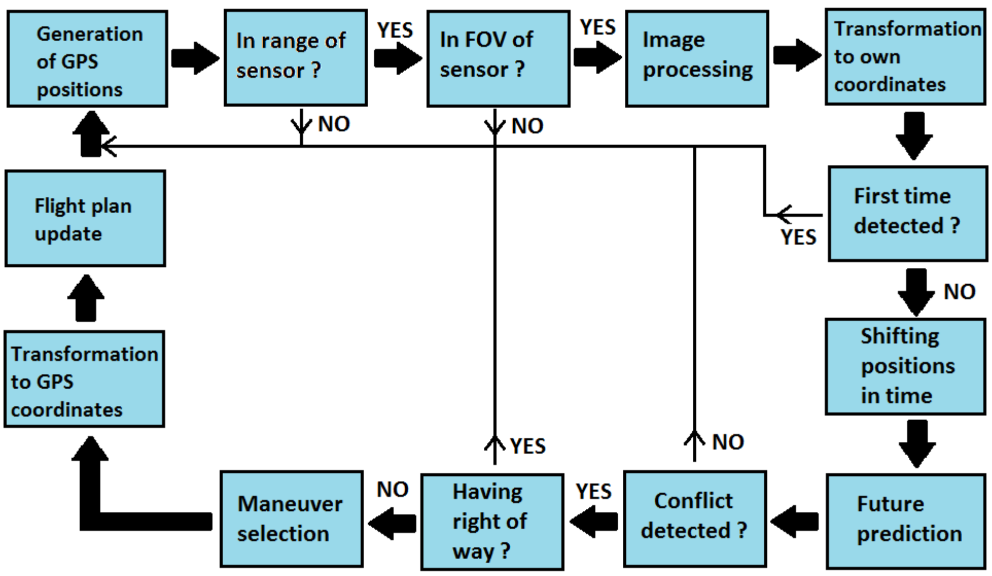

Figure 5.1. Structure of implemented program.

It is important to clarify coordinate system in which we are going to work. Coordinates of local coordinate system are defined following: the direction of movement to the right and left is coordinate x, coordinate y ensures movement up and down, and direction back and to the front represents coordinate z. The center of coordinate system is at the position of UAV. Because the position of UAV is changing in the time, translation to updated coordinate system is needed. Also, value of separation minima has to be established. We will follow the definition of separation minima which was defined in [6], where separation minima are in a cylindrical shape, with values of 500 ft for radius in horizontal plane and 200 ft for height in vertical plane.

5.1 Sensing

Every sensor scans environment repeatedly with certain refresh rate. All GPS positions which are sent by aircraft are filtered out at every time of refreshing and only those which are distant within the range are received. This is done through comparison of distance between GPS positions and range. If the distance is higher than the range of camera, object is not detected and our subprogram returns back to the beginning where it waits for information from next time frame. If distance is less than range, sensor is able to detect object. Subsequently, it is important to check if the sensor would be able to see to the direction from which intruder is coming. Horizontal and vertical FOVs need to be compared to the elevation and azimuth angles between aircraft. Only when both angles are smaller then FOV, aircraft can be seen by camera and its GPS position is transferred into earth-centered, earth-fixed cartesian coordinates system. If intruder position is not within FOV of UAV, subprogram again returns to the beginning and waits for information from following time frame. Refresh rate, FOV, range and other parameters of sensor are set up through configuration files for each sensor separately.

5.2 Image processing

To be able to solve DAA problem, simulation of an image which would be normally received from the implemented camera is needed. This can be done by using a combination of aircraft's position in surrounding environment and parameters of used sensor, in our case camera. For reproduction of the image in pixel form, amount of pixels occupied by aircraft and its center pixel position have to be calculated. Center pixel position in corresponding direction can be determined as the addition of position in our coordinate system and range of camera in corresponding direction, divided by ratio, which represents how many meters are covered by one pixel in corresponding direction. The amount of pixels on which aircraft will appear is computed by following formula:

$$pixels = \frac{realHeight * lensFocal * senzorHeight}{distance * senzorSize}$$

[8],

where all parameters have to be taken in either horizontal or vertical direction. Real height is height in m of scanned object, focal of lens and size of the sensor is taken in mm, sensor height is camera's amount of pixel in corresponding direction and distance refers to the separation distance between camera and scanned object. Because airplane will appear in a circle shape on the image, the radius of this circle is determined as square root of the number of pixels which airplane covers divided by π. Afterward, the image is resolved by reverse process to the one which was described previously when instead of finding position of aircraft on image, its coordinates in the real world are obtained. These coordinates are position of intruder obtained from camera. Because naturally, it can happen that some pixels are only partially covered by aircraft, the decision has to be made about when the pixel is already taken into counting as an occupied pixel or not. Therefore the estimation of real coordinates is getting less accurate with increasing distance between aircraft and decreasing size of detected aircraft, as it is getting harder to recognize if the pixel is occupied by an object or not.

5.3 Data processing

Once the intruder is detected by sensor and its position is received and transferred to earth-centered, earth-fixed cartesian coordinate system, we do another transformation into the local coordinate system, described at the beginning of this chapter. It has a center in the position of UAV from which we are sensing environment. This simplified calculation process because we can work with our position as with stationary position since in each time frame it will have coordinates equal to zero. Because for prediction of movement we need more than one point, in the case when aircraft is detected the first time, its position is saved and process returns back to the beginning where it will wait until it will receive the position of intruder in next time frame. On the other hand, if object was at least one time before detected, all the past positions which were saved, need to be updated to the new updated local coordinate system. This is caused by fact that the center of local coordinate system (which is at the current position of UAV from which we are sensing environment), is moving as this UAV's position is moving. Because we cannot and we also do not need to save an infinite number of past intruder's positions, we will remember only last ten positions which were detected. The reason why we chose number ten is discussed in the following section.

5.4 Safety violation point

To identify the most accurate position of safety violation point, precise prediction of aircrafts' movements is crucial. In our case, we decided to use least square algorithm for predicting the path. The advantage of this method is that it has a relatively easy computational process but the disadvantage is that it can only predict linear path. Therefore it is important to regularly forget positions which were measured further in the past or give to each position weight which depends on how recently the position was measured. Because we chose the option with forgetting points, the decision about how many points we have to take into consideration had to be made. We chose last 10 detected position of aircraft, which should be enough to limit uncertainties in measurement and not too much to sense that turning maneuver has been started recently. Another decision which is needed is how far in future do we need to predict path. According to results mentioned in [5], 25 seconds should be enough in every situation. The safety violation point is identified in that moment when the distance between our aircraft and intruder is in vertical direction less than 200 ft and in horizontal direction less than 500 ft [6]. This situation of horizontal safety violation point is displayed in fig. 5.2, where green dot refers to UAV's position and black to target's position at the moment of safety violation point. Safety violation point can occur in time which we are predicting or there can be no safety violation point in near future. In case that it is not detected, the program returns back to the beginning when it waits for next time frame and update of intruder's position. In case safety violation point is occurring in close future, time and position of both airplanes at which safety violation point is occurring are saved. Subsequently, escape maneuver needs to be chosen.

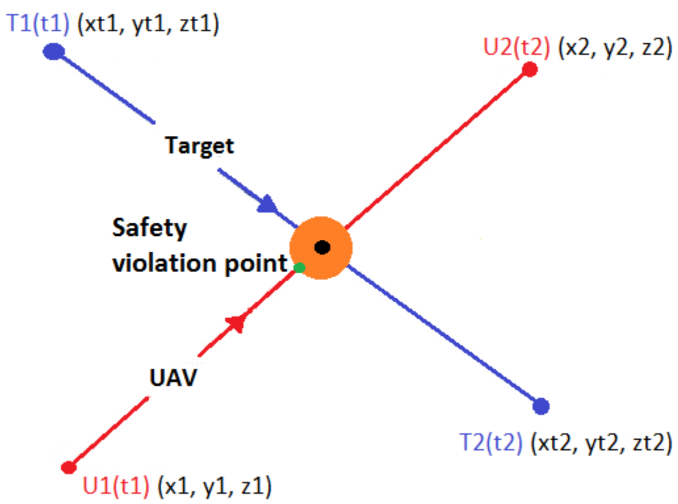

Figure 5.2. Display of safety violation point

5.5 Prescription of escape maneuvers

There can occur five basic conflict situations which we will be solving by prescribed maneuvers designed according to VFR described in chapter 2. In fig. 5.3, the black airplanes represent UAV, which can occur in different positions, compared to the position of an intruder. The intruder is represented by blue airplane. First, it needs to be recognized which situation is happening. If the conclusion is that the UAV has right–of–way, it is expected that conflict situation will be solved by other aircraft and program returns back to the beginning, where is waiting for next refresh rate and updated GPS positions. As it can be seen from the picture, overtaking situation occurs when an intruder is moving with slower speed than UAV's and its position is within 70° to UAV's position in horizontal direction ??. This angle is so big due to fact that slower airplane is not able to see behind yourself. On the other side, head on conflict is defined as approaching head on or nearly head on. This angle is not concretely specified but it should be some smaller angle so we will define it as 20° [13]. When UAV gets into conflict with airplanes number 1 or number 3, the situations are defined as the converging situation. In this case the aircraft with the other on its right–hand side has to give way. This means that we have to only solve situation when UAV is converging from left, as situation number 3 displays. When situation number 1 is happening, a solution of conflict situation is other's aircraft responsibility. Head on situation is happening when we are coming from position number 2. In this case, both airplanes have to shift course to the right. Conflict situations identified as number 4 and 5 are classified as overtaking situations, in which overtaken plane has the right–of–way and the faster plane should pass on right. This means that we have to solve only situation number 5. Situation number 4 is going to be solved by other aircraft. It is important to mention that all avoidance algorithms are designed that way that change of altitude should be minimum.

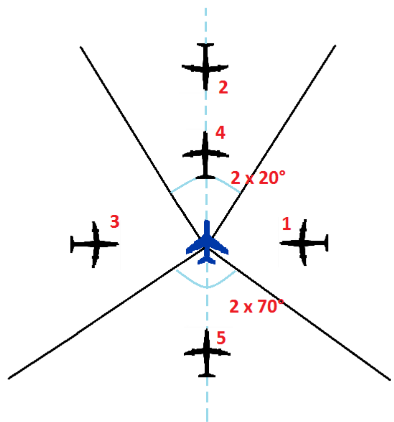

Figure 5.3. Conflict situations

As it was mentioned previously around each aircraft is safety envelope which should be not interrupted. This safety envelope is displayed in fig. 5.4 and fig. 5.5 by green circle around intruder. When aircraft is moving, space which we need to avoid change from a cylindrical shape into cuboid, which is created by moving safety envelope around aircraft as you can see in fig. 5.4, where grey line is original path of UAV and blue line is updated conflict-free trajectory. For complete solution of conflict situation, we need to avoid interruption with this cuboid. We will provide this by identifying beginning and ending point which will be added to flight plan of UAV and this way maneuver will be made. Because recognition of intruder position is not completely precise, addition of δ deviation is needed. Value of this constant deviation should be proportional to the size of aircraft in a conflict situation and to localization precision. Our simulated situations are occurring between two aircraft of Cessna type, which usually has wingspan around 11 m, so we decided to set δ deviation to 10 m.

The beginning point is collision point transferred in the x direction to the right by the difference between safety range in the horizontal direction (SRH) and $\bar{x}$, where $\bar{x}$ is absolute value of the difference between x coordinates of aircraft in conflict plus deviation. The rest of coordinates state the same as coordinates of conflict point are. To be able to calculate ending point, first, we need to find how long it will take until we safely overtake airplane. This can be done by using closing speed between aircraft and basic physics principles. From this, it is easy to conclude that ending point coordinates will be same as beginning point coordinates except for coordinate z. In z direction, we need to move z of beginning point by addition of $2 \cdot SRH$ and distance which was overcome by airplane with right–of–way. Therefore, we can conclude that coordinates of beginning and ending point will be following:

$$begining(x, y, z) = beginning(x_{con} + SHR - \bar{x}, y_{con}, z_{con})$$

$$ending(x, y, z) = ending(x_{con} + SHR - \bar{x}, y_{con}, z_{con} + distance)$$

where index con refers to conflict point and distance means distance which has to be overcome while overtaking.

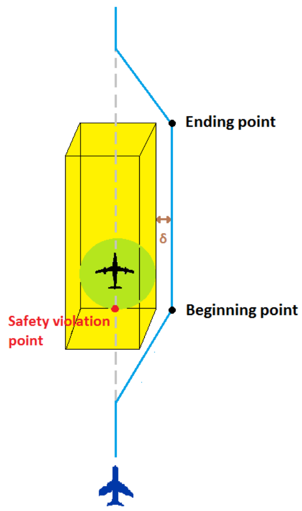

Figure 5.4. Overtaking - conflict situation

In case of head on conflict, beginning and ending point of conflict time has to be defined same way as in overtaking situation. The difference is in a maneuver which has to be done to avoid conflict situation. According to VFR when head-on conflict is happening, both of aircraft have to shift course to the right. Because both of them are shifting to the right, they only need to shift half of the distance compared to overtaking situation. So the coordinates of beginning will be same as coordinates of collision point except for the x coordinate. X coordinate will be move by half of the difference between safety range in horizontal direction (SRH) and $\bar{x}$. Ending point will change in z coordinate compared to the beginning point by subtraction of $2 \cdot SRH$ and distance which was overcome by airplane during this time.

$$begining(x, y, z) = beginning(x_{con} + \frac{SHR - \bar{x}}{2}, y_{con}, z_{con})$$

$$ending(x, y, z) = ending(x_{con} + \frac{SHR - \bar{x}}{2}, y_{con}, z_{con} + distance)$$

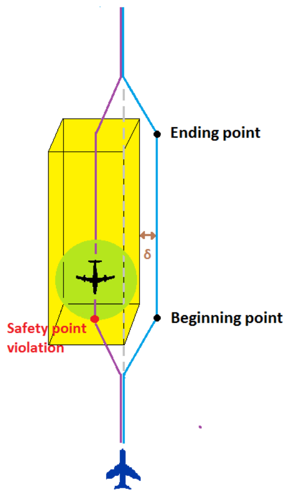

Figure 5.5. Head-on - conflict situation

The last conflict situation in which we are responsible for conflict resolution maneuver is when an intruder is approaching from the right side. In this case, the beginning point is found as an intersection of a tangent line and safety range envelope. Firstly center of safety range envelope needs to be found. In fig. 5.6 this point corresponds with the position of black aircraft marked as number 2. Orange airplane (number 1) is intruder position at the moment when conflict is detected and black airplane is its future position at the moment when collision would occur. Logically we need to avoid safety envelope of the future position of an intruder. For finding this point we will use two right angle triangles drawn on fig. 5.6. Because the time of flight from current position is same for both aircraft in conflict, following equation can be concluded using basic mathematical and physical principles:

$$v_{uav} * s_{uav} = v_{intr} * s_{intr}$$

$$d^2 = (v_{uav} * s_{uav})^2 + (v_{intr} * s_{intr})^2$$

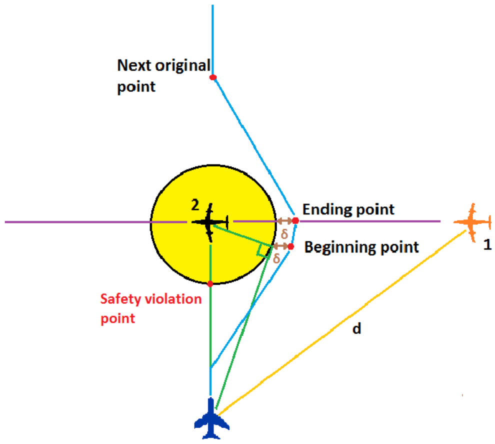

Figure 5.6. Conflict situation with intruder coming from right

where index intr refers to the intruder, d is current distance between aircraft in conflict, v is velocity of corresponding aircraft and s is distance which the corresponding aircraft overcomes in time. Because these distances are unknown, we have two equations with two unknown variables which can be easily solved. After s_{uav} is found, point 2 can be easily found through vector projection by a distance s_{uav} from the current position. Once the position of safety range envelope center is known, the beginning point can be found as a tangent from our current position to this circle. As in previous, we will also add deviation δ. The final point is found as a translation of point 2 positions to the right by SHR and deviation.

After the beginning and end points are determined, they are as at waypoints to the current flight plane. This updated flight plane is then sent to the autopilot which will according to updated flight plan apply an escape maneuver.

Chapter 6
Experiment Methodology

Testing scenarios which we performed, show effects of different closing speed on the minimum distance which is needed to avoid safety envelope around aircraft. Both airplanes are a simulation of aircraft type Cessna with its real parameters like dimensions, speed, turning ability, etc. We will examine conflict situations between two airplanes, UAV, and manned aircraft. While the velocity of UAV, which will perform autonomous escape maneuver states constantly at 20 m/s, the velocity of closing manned aircraft will differ. Concretely we will execute five test simulations with manned aircraft's velocity set up to multiple of 0.5, 0.75, 1, 1.5 and 2 of UAV's velocity performing escape maneuver. Each of test situation will be run in 36 configurations, where each configuration simulates different angle between airplanes' trajectories. Trajectories are designed as straight lines with the required angle at the moment of intersection. These angles differ by 10°. Because escape maneuvers are based on VFR, changes in path plan to avoid conflict situation will be made only in horizontal plane. Therefore altitude in our testing scenarios remains constant during whole simulation and same for all airplanes. In all scenarios, UAV represents aircraft performing escape maneuver encountering under different angles to manned aircraft, aircraft which represents an intruder. All graphs are displayed in such way, that position at the time of safety violation point detection of manned aircraft is in the center of orange circle, which represents safety envelope. The minimum distance needed to avoid safety violation point is measured from UAV's point of view. Yellow zones show this minimal distance from an intruder to UAV when UAV is approaching under different angles. Dashed blue line illustrates the division of configurations into different sectors as it was described in chapter 5. Tests with following set up were performed:

- Test 1
  - Manned aircraft with velocity 10m/s
  - UAV with velocity 20 m/s
- Test 2
  - Manned aircraft with velocity 15m/s
  - UAV with velocity 20 m/s
- Test 3
  - Manned aircraft with velocity 20m/s
  - UAV with velocity 20 m/s
- Test 4
  - Manned aircraft with velocity 30m/s
  - UAV with velocity 20 m/s
- Test 5
  - Manned aircraft with velocity 40m/s
  - UAV with velocity 20 m/s

Figures 6.1 and 6.2 show situations when speed of manned aircraft is smaller than speed of UAV. Therefore escape maneuvers by UAV will be performed between angle 70° and 360°. From angle 70° to 160°, UAV has right–of–way, so according to VFR, it is not responsible for solving collision situation. As it can be seen, the distance needed for maneuver in the overtaking situation is very small. As UAV is approaching more and more from left, more time is needed for maneuver because intruder has to be overtaken from the right side. According to measured results, it seems like that as intruder is moving slower, more time is needed for maneuver. Because of slower movement of an intruder, UAV has less time for maneuver from the same distance and therefore bigger distance for providing maneuver is needed. Another possibility is that this observation is caused only by uncertainties in measurements since the differences are smaller or equal to the distance which is overcome by aircraft in one second.

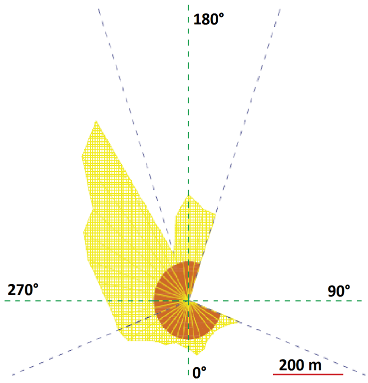

Figure 6.1. Distance needed to avoid conflict-Test 1

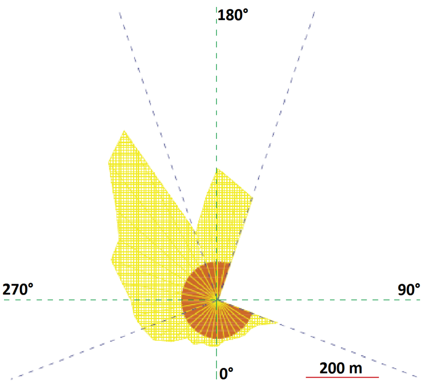

Figure 6.2. Distance needed to avoid conflict-Test 2

Test 3 shows situations when both airplanes are moving at the same speed. As it can be seen in fig. 6.3, interesting peek occurs in configurations between angle 330° and 360°. It would be expected that distance needed for avoidance would increase as UAV is coming more from left. The peak is the result of escape maneuver, which is provided by less or more sharp turning to the right, depending on conflict point. Because of that conflict situations between 330 ° and 360 ° need to take into consideration not only distance to conflict point but also distance to the side between those two airplanes. Therefore the peek is caused by not having enough horizontal distance for turn.

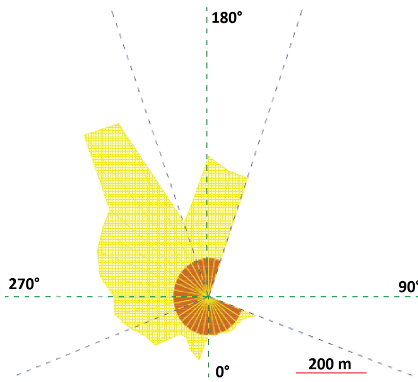

Figure 6.3. Distance needed to avoid conflict-Test 3

Test 4 and test 5 simulate situations when manned aircraft is faster than UAV. Because of this, situations, when UAV would overtake manned aircraft, will not happen. Therefore configurations in which escape maneuver has to be performed by UAV are only between 70° and 290°.

In all scenarios, we can notice some special patterns. The first pattern is, that in the case when UAV is coming from the left side, so it has to give right–of–way, the distance needed to provide escape maneuver increases in a smooth way as UAV is coming more and more from left. This is caused by two factors. Firstly, because we used VFR,

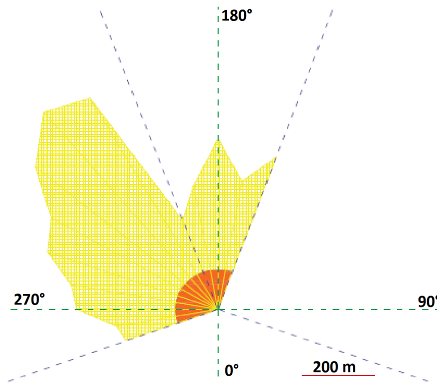

Figure 6.4. Distance needed to avoid conflict-Test 4

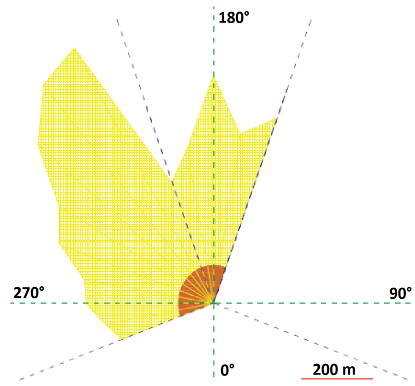

Figure 6.5. Distance needed to avoid conflict-Test 5

distance which is needed to overcome on the right side increases. Another factor is as the conflict is coming from overtaking to head on conflict, closing speed between aircrafts' is increasing. This effect can be observed through increasing distance as the velocity of manned aircraft is increasing through different scenarios.

Another special pattern occurs on the edge of head on conflict and conflict from the right. We can see that in all scenarios between 200° and 210°drop in needed distance occurs. This drop is caused by the change of conflict situation classification from having aircraft on the right side to head on conflict. In case of head on conflict, both aircraft are expected to perform escape maneuver and therefore less distance to avoid conflict is needed. As conflict situation is growing to more straight head on conflict, distance is increasing because closing speed between aircraft is increasing. As it can be seen from results, the distance needed to safely avoid conflict is not symmetrical in head on area, that means between 160° and 200°. This is a direct consequence of the rule, which defines that escape maneuver has to be made to the right side, even though in some situation would be more efficient to go left side. In case of tests 4 and 5, when speed of manned aircraft is bigger than speed of UAV, the distance needed for escape at the edge of head on conflict (around 170 °), starts to grow even though it would be expected to decline since smaller closing speed between aircraft occurs. This could be pattern caused by the fact, that closing speed is not decreasing fast enough to compensate the fact that conflict has to be avoided from the right side, when more distance to the right needs to be overcome.

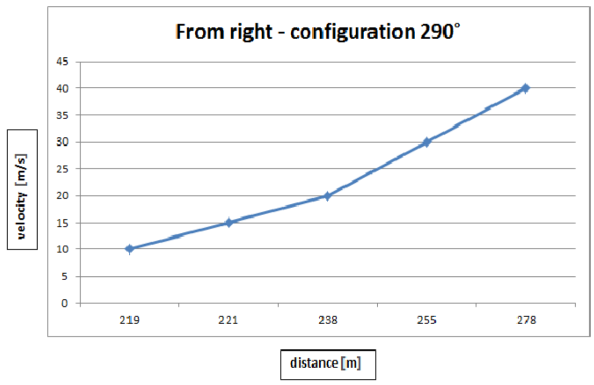

Figure 6.6. Distance–speed dependency for configuration 180°

In figures 6.6, 6.7 and 6.8 dependency on distance through difference scenarios is displayed. It can be seen that for all three configurations, the distance needed to avoid intruder is increasing linearly as the speed of intruder is increasing. Also, it can be noticed that differences between distances needed for escape maneuver are increasing as the closing speed between aircraft is increasing, that means as the aircraft are coming closer to direct head on conflict.

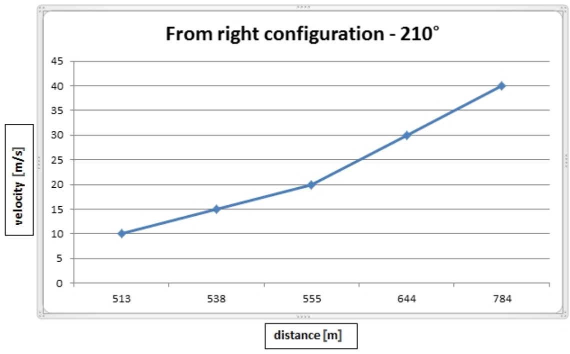

Figure 6.7. Distance–speed dependency for configuration 210°

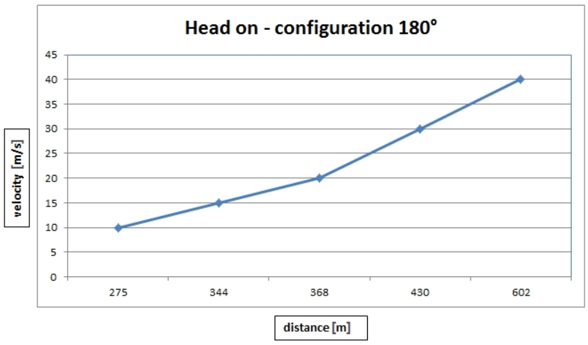

Figure 6.8. Distance–speed dependency for configuration 180°

It is noticeable from all tests that the biggest distance for safe avoidance is needed when UAV is approaching manned aircraft under 210° degrees. For tests from 1 to 5, it is 513 m, 538 m, 555 m, 644 m, 784 m respectively. To these distances, it has to add time interval for detection and data processing. Therefore the actually needed distance will be even bigger and we can conclude that camera which we originally chose in chapter 3.1.3 is not suitable for UAV with our speed 20 m/s because it would be only able to detect an object of the same size (with a height of 2.7 m) and the same type, soon enough with speed of 10 m/s or less. However, it would be able to detect objects soon enough with a height of 5 m if they would be flying with the same speed or slower. Despite this fact, chosen camera is not usable in reality.

This situation could be solved by choosing a camera with better parameters. The most important parameter is pixel resolution. If we would use camera with same parameters as it was chosen in chapter 3, but instead of resolution 1280x720, we would have a 3-megapixel camera, it would be possible to detect airplanes of Cessna type (height of 2.7 m) up to 684 m. This would be soon enough for safe avoidance when approaching aircraft is flying with speed up to 30 m/s. In case of safely avoiding conflict at 40 m/s, we would need 5- megapixel camera. The other solutions would include a choice of camera only for lighter and slower categories of aircraft, and for heavier and faster categories other forms of sensors like radar would be used. Also, it is possible, that better options than using VFR for escape maneuver could exist, therefore smaller distance for escape maneuver would be needed.

Chapter 7
Conclusion and future work

This thesis deals with conflict detection and resolution between UAV and manned aircraft. The main objective was to study distance needed for safe avoidance of conflict between two airplanes. This issue is part of fully autonomous as well as semi-autonomous DAA problem. DAA is system responsible for process starting from sensing surrounding environment, through conflict detection, up to solving possible conflict situation. Details of DAA and different approaches for some subparts were described in chapter 3. To be able to solve conflict safely, it is crucial to start escape maneuver before separation between aircraft in a conflict situation is smaller than RWC distance. The value of this RWC distance was studied in chapter 6 for various closing speed between two aircraft of the same type. Each scenario was executed in 36 configurations, which differed by 10° of the closing angle between aircraft in conflict. Through AGENTFLY framework, the distance needed for safe maneuver was measured among UAV and manned aircraft. Concrete maneuver selection for different situations was described in chapter 5. In all measurement some specific pattern where observed. It could be determined that distance needed for escape maneuver is increasing as closing aircraft is coming more from the right side, closing speed is growing or speed of detected aircraft is increasing. Surprisingly it was found out that biggest distance is not needed when direct approach conflict situation is happening. Instead, conclusion about biggest distance needed in each scenario was in a situation when UAV, which was performing escape maneuver, was approaching manned aircraft under 210°. This is a direct consequence of escape maneuver choice. From concrete values of configuration when the biggest distance is needed, it could be concluded that choice of camera which was made in chapter 3, does not provide range big enough for detection of other aircraft in such a distance that safe escape maneuver is possible. Therefore some suggestions for camera with more suitable parameters or choice of different sensors were made.

As it was mention at the beginning, DAA of UAV is a very complex problem, therefore a lot of research about DAA of UAV can be expected in the future. Concretely RWC problem, which was studied in this thesis has alone a lot of potential for further research. Better analyzation of RWC for a bigger amount of various scenarios would bring better conclusion for a decision which sensors should be implemented in future into UAVs. For this conclusion, different categories of aircraft with flying under different speeds would need to be studied. Also, it would be very interesting to look at the connection between the choice of escape maneuver and distance needed for it. For example, UAV which would not have any human passengers could perform sharper maneuvers than those which would carry human. Another topic for analyzation could be choice of maneuver based on economic cost since maneuvers with changing speed are usually more expensive but in some situation, they could be cheaper.

Glossary

ADS-B – Automatic Dependent Surveillance–Broadcast – technology through which aircrafts periodically broadcast their positions, allowing them to be tracked.

ATC – Air Traffic Control – system which controls and directs air traffic in control space and on the ground.

CAS – Collision Avoidance System – system designed to reduce the severity of an accident.

DAA – Detect and Avoid – abillity to see, detect conflicting objects and take appropriate action to avoid conflict.

EO – Electro-optical – type of passive sensing technology, which works on principle of detecting natural light.

GPSW – Ground Proximity Warning System – system which controls possible collision with ground.

FOV – Field of View - maximal angular size to which object can been seen from entrance pupil.

IFR – Instrument Flight Rules – set of regulations which prescribe operation of aircrafts when pilot is not flying under VFR.

IR – Infrared – type of passive sensing technology, which is based on principle of absorbing detected object heat.

JPDA – Joint Probabilistic Data Association – multitracker algorithm, which derives probability of next situation update as combination of targets' next positions.

MHT – Multiple Hypothesis Tracking – data association algorithm which enumerates all possible associations over time.

MSL – Mean Sea Level – average height about sea surface.

RBCA – Rules Based Collision Avoidance – passive cooperative algorithm based on VFR.

RFS – Random Finite Set – multitracker algorithm which works with set of random variables of random size instead of data associations.

RWC – Remain Well Clear – concept of finding seperation needed to determine what action is necessary to remain an appropriate distance from other aircraft.

TCAS – Traffic Alert and Collision Avoidance System – aircraft collision avoidance system designed to reduce collision between aircrafts equipped by transponders.

UAS – Unmanned Aircraft System – an unmanned aircraft along with the equipment necessary to operate it.

UAV – Unmanned Aircraft Vehicle – an aircraft without a human pilot aboard.

VFR – Visual Flight Rules –a set of rules created for flight in visual meteorological conditions.

VMC – Visual Meteorological Conditions – conditions expressed in terms of visibility, in which pilots have sufficient visibility to fly the aircraft within seperation minima from terrain and other aircraft.

WT – Wake Vortex Turbulence – turbulence which is produced by passage of an aircraft in flight.

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