Bachelor thesis

Simulation of Remote UAS Pilot Station

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BACHELOR‘S THESIS ASSIGNMENT

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II. Bachelor’s thesis details

Bachelor’s thesis title in English:

Simulation of Remote UAS Pilot Station

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Simulace pracoviště operátora bezpilotních prostředků

Guidelines:

1. Study the principles of remote pilot station for control of UAS operating beyond visual line of sight (BVLOS).
2. Study existing graphics standards used to display information about surrounding traffic on display.
3. Design placement of appropriate graphical control elements on the display to allow UAS control.
4. Implement designed graphical interface.
5. Integrate this interface with AgentFly simulation framework.
6. Validate the impact of assisting technologies for situational awareness improvement on pilot performance during traffic avoidance maneuvers.
7. Validate system features on experiments with human pilots.

Bibliography / sources:

[1] Qaisar Raza Waraich. Heterogeneous Design Approach for Ground Control Stations to Marginalize Human Factors Mishaps in Unmanned Aircraft Systems, Dissertation thesis, George Washington University, 2013.
[2] Lachter, Joel & Brandt, Summer & Battiste, Vernol & Ligda, Sarah & Matessa, Michael & Johnson, Walter & V Ligda@nasa, Sarah & Com, Walter & , Gov. Toward Single Pilot Operations: Developing a Ground Station. 2016.
[3] Lee, E., Kim, S. and Kwon, Y.: Analysis of Interface and Screen for Ground Control System. Journal of Computer and Communications, 4, 61-66, 2016.

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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

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Author statement for undergraduate thesis:

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Prague, date.............. ....

signature

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Abstract

Ability to maneuver and detect surrounding traffic is necessary for safe aircraft piloting. When piloting unmanned aerial vehicles, pilot is not situated in the cockpit of the aircraft, therefore it is necessary to present traffic to the pilot in a graphic way. The aim of this work is to design and implement a display that will provide pilots operating from a Ground Control Station with the ability to detect surrounding threats and safely maneuvre with the controlled aircraft. Display must be able to depict surrounding aircraft and information about them, predict threats in form of potential collisions and suggest safe trajectories of flight. The first part of this thesis focuses on principles and standards in traffic depiction, existing types of displays, their attributes and assisting features. The second part describes the implementation of display, its features and abilities. Display features are then tested in experiment consisting of two scenarios that must be accomplished by human pilots in a safe manner. Emphasis is put on validating the impact of assisting features on pilot's performance. The final part of the work evaluates results of experiment and discusses further display extensions.

Key words: unmanned aircraft systems, unmanned aerial vehicles, ground control station, detect and avoid, display, maneuver, pilot

Abstrakt

Pro bezpečné pilotování letadla je nutné, aby pilot dokázal detekovat a případně se vyhýbat okolním letadlům. U bezpilotních prostředků, kdy se pilot nenachází v kabině letadla, je nezbytné zobrazovat okolní leteckou dopravu pilotovi grafickým způsobem. Cílem této práce je navrhnout a implementovat displej, který umožní pilotům operujícím z pozemní stanice detekovat okolní hrozby a bezpečně manévrovat s řízeným letadlem. Displej musí umět zobrazovat okolní letadla a informace o nich, predikovat hrozby v podobě možných srážek a navrhovat bezpečné trajektorie letu. V první částí práce jsou rozebrány principy a standardy zobrazování okolní dopravy pilotovi, existující typy displejů, jejich vlastnosti a asistenční služby. V druhé části práce jsou popsány způsoby implementace displeje, jeho vlastnosti a schopnosti. Vlastnosti displeje jsou poté otestovány v experimentu, který obsahuje dva scénáře, které musí být piloti splnit za bezpečných podmínek. Důraz je kladen na validaci asistenčních služeb, které mají pilotům pomoci bezpečně dokončit trasu. V závěru práce jsou zhodnoceny výsledky experimentu a návrhy na možné rozšíření implementovaného displeje.

Klíčová slova: bezpilotní systémy, bezpilotní letadla, pozemní stanice, detect and avoid, displej, manévr, pilot

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List of abbrevations:

ACAS	Airborne Collision Avoidance System
ANOVA	Analysis of Variance
ATC	Air Traffic Control
BVLOS	Beyond Visual Line of Sight
CPA	Closest Point of Approach
C2	Command and Control link
DAA	Detect and Avoid
DAIDALUS	Detect and Avoid Alerting Logic for Unmanned Systems
GCS	Ground Control Station
HMD	Horizontal Miss Distance
JADEM	Java Architecture for DAA Modeling and Extensibility
JOGL	Ground Control Station
MIDCAS	Mid Air Collision Avoidance System
RPAS	Remotely Piloted Aircraft Systems
TCAS	Traffic Collision Avoidance System
TSD	Tactical Situation Display
UAS	Unmanned Aircraft Systems
UAV	Unmanned Aerial Vehicle
VLOS	Within Visual Line of Sight

Chapter 1

Introduction

As technology is continuously evolving, Unmanned Aircraft Systems (UAS, also called Remotely Piloted Aircraft Systems, RPAS) are increasingly becoming a part of our lives, offering new and exciting opportunities as well as number of challenges.

In UAS operating beyond Visual Line of Sight (BVLOS) in uncontrolled airspace, it is necessary to provide the pilot the information about surroundings of the unmanned aerial vehicle (UAV) in a graphic way. Since pilots are not situated in the cockpit, they operate the aircraft using a Ground Control Station (GCS, Figure 1.1). GCS is a sea- or land-based control centre providing pilots with facilities allowing them to control UAVs. GCS usually consists of one or more screens (monitors or displays) with software providing pilots with the ability to mission control and "detect and avoid" (DAA) other traffic, as a substitution for "see and avoid" which is used in manned aircraft where pilots are situated in the cockpit.

This thesis focuses on designing and implementing a DAA display similar to what can be found in GCSs and validating the impact of its features on pilot's performance when performing avoidance maneuvers.

Coming out from several studies, alerting symbology and traffic depiction standards as well as basic DAA display properties and requirements are described. Furthermore, existing DAA configurations and display types which were subjects of surveys are mentioned.

Based on listed standards and requirements, DAA display is designed and implemented. Display offers basic properties such as monitoring other traffic within defined lateral range and displaying actual information about intruder aircraft to the pilot, including proper traffic symbology and alerting standards. It also provides advanced assisting features such as lateral and vertical bands indicating headings and altitude levels that are predicted unsafe and safe heading and trajectory predictions.

Implemented DAA features are then tested and validated in experiments consisting of several scenarios where pilot is required to complete a mission in a safe manner. During the flight, pilot will take part in many encounters where it is necessary to execute avoidance maneuvers to maintain well clear from other traffic. Using DAA features provided by the display, pilot is expected to successfully complete the mission, that means without any collision. Emphasis is put on validating the impact of DAA features on pilot's performance during avoidance maneuvers.

1.1 Unmanned Aircraft Systems

Unmanned aircraft systems consist of GCS, command and control (C2) link and other systems that are required to operate. UAV (Figure 1.2) are a component of an UAS as well and can come in many variations and sizes. However, common for all UAVs is that the pilot is not on-board. In every possible way, just like with any aircraft, UAVs must be flown in perfectly safe way in order not to endanger its surroundings.

This brings many responsibilities and challenges that must be fulfilled in order to maintain desired safety. In addition to this, operations with UAVs happen either within the Visual Line of Sight (VLOS) or BVLOS.

When an UAV is operated VLOS, pilots are required to see the aircraft for the whole time since take off until landing. The pilot must be able to monitor the flight path of the aircraft and its surroundings to safely maneuvre to prevent a conflict from happening. Opposite to that, operating BVLOS means the aircraft is not clearly seen by the pilot, thus the pilot is not able to see or detect a potential threat and execute a maneuver.

It is also important to distinguish whether an aircraft is flying in controlled or uncontrolled airspace. Controlled airspace is airspace in which Air traffic control (ATC) services are provided. The aim and purpose of ATC is to prevent collisions, organize the flow of air traffic and provide pilots information and other support. The opposite is uncontrolled airspace where ATC services can not be provided or are not considered necessary.

In order to allow BVLOS piloting of UAVs under maximal safety even in uncontrolled airspace, it is necessary to provide pilots with technologies allowing them to see other aircraft, detect and predict potential threats or conflicts and determine and execute suitable avoidance maneuvers. System providing technologies mentioned above are referred to as "Detect and avoid" (DAA) systems. Airborne Collision Avoidance System X (ACAS X, or ACAS Xu optimized for UAS, ([ACAS, 2015])) and Mid Air Collision Avoidance System (MIDCAS, ([MIDCAS, 2015])) are good examples of existing DAA systems.

The integration of UAS into shared airspace is a long term process requiring a lot of research and experiments to determine the Minimum Operational Performance Standards (MOPS) for DAA systems. Main subjects of research were locations of DAA displays, minimum amount of information and impacts of maneuver guidances on pilot's performance. Experiments consisted of simulations that involved experienced pilots to complete scenarios with preplanned flight paths and many intruder aircraft which processed to collision avoidance or self separation alerts. Results and measurements of these experiments are expected to help with determining the MOPS for DAA systems and to finally achieve conditions that will allow the integration of

UAS into shared airspace which would be a big step forward in technology and would open access to many new opportunities.

Figure 1.1: UAS Ground Control Station ([Fern et al., 2015])

Figure 1.2: MQ-9 Reaper / Predator B[1]

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[1] photo by Paul Ridgeway, U. A. F. (7 August 2008). MQ-9 Reaper / predator B. `http://www.af.mil/News/Photos.aspx?igphoto=2000398487`

Chapter 2

Traffic depiction and alerting standards

2.1 Symbols and alerts

To display other aircraft on a DAA display, specific symbols are used. Aircraft are assigned those symbols based on how far those aircraft are and the risk they pose (for specific treshholds see section 2.2). Since traffic symbology is not officially standardized specifically for UAS, recommendations of standards related to alerting and traffic symbols are derived as best practices from existing collision avoidance systems, such as Traffic Collision Avoidance System (TCAS, [TCAS, 2011]), ACAS Xu or MIDCAS.

According to [NIAG Sub-group 205, 2017], symbols in Figure 2.3 and Figure 2.4 are acceptable and together with symbol in Figure 2.2 might be seen in existing DAA systems as well, but should still be subject to a human factors evaluation. However, symbols might be considered as today's best practice and will be used in this thesis as well.

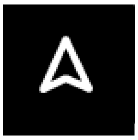


Figure 2.1: Remaining traffic symbol

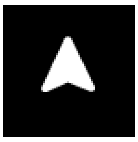


Figure 2.2: Guidance traffic symbol

Figure 2.3: Traffic Advisory Symbols

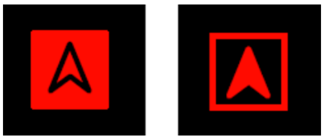


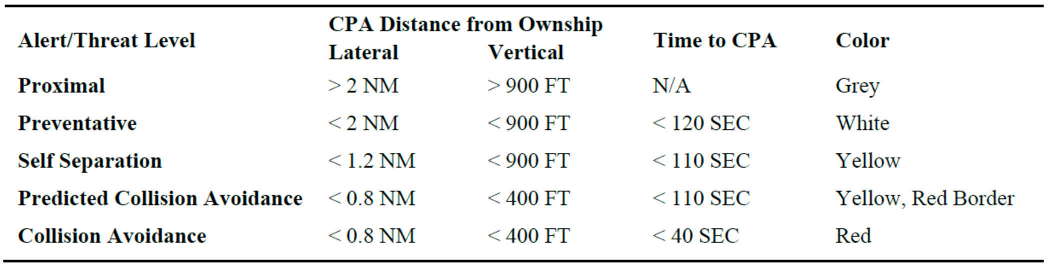
Figure 2.4: Resolution Advisory Symbols

Symbol for ownship is not presented since it might differ among different display implementations. Figure 2.7 shows how symbols might be used in a DAA system.

2.2 Alerting structure and thresholds

To present potential threats to the pilot, specific alerting structures consisting of several alert levels associated with its symbols and thresholds are used. Generally. alerts are defined by three thresholds. First two thresholds are represented by lateral (i.e. horizontal) and vertical distance to the Closest Point of Approach (CPA), respectively. CPA is a location where two aircraft are predicted to be closest to each other. Third threshold is the time until CPA is reached. In order to assign an alert's symbol to an aircraft, all three thresholds must be met at the same time. Aircraft that do not meet thresholds of any alert are usually assigned symbol depicted in Figure 2.1 which means that aircraft poses no threat.

Referring to [Fern et al., 2015], Figure 2.5 shows the multi-level alerting structure used in advanced display conditions. Visual depiction of its alert thresholds is shown in Figure 2.6.



Alert/Threat Level	**CPA Distance from Ownship**		**Time to CPA**	**Color**
	Lateral	**Vertical**		
Proximal	> 2 NM	> 900 FT	N/A	Grey
Preventative	< 2 NM	< 900 FT	< 120 SEC	White
Self Separation	< 1.2 NM	< 900 FT	< 110 SEC	Yellow
Predicted Collision Avoidance	< 0.8 NM	< 400 FT	< 110 SEC	Yellow, Red Border
Collision Avoidance	< 0.8 NM	< 400 FT	< 40 SEC	Red

Figure 2.5: Multi-level alerting structure

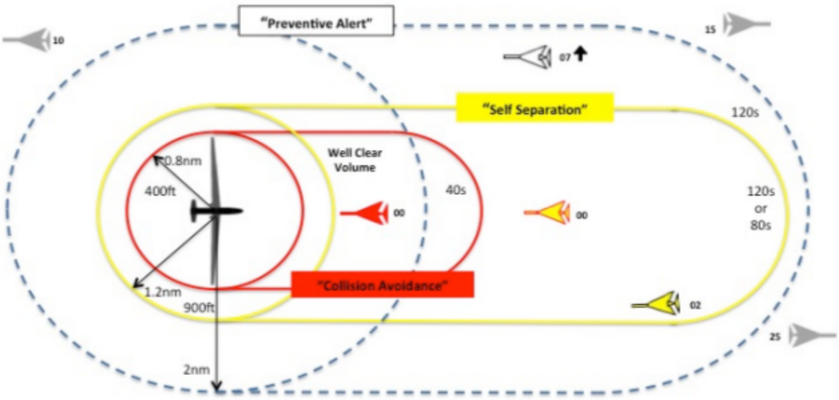
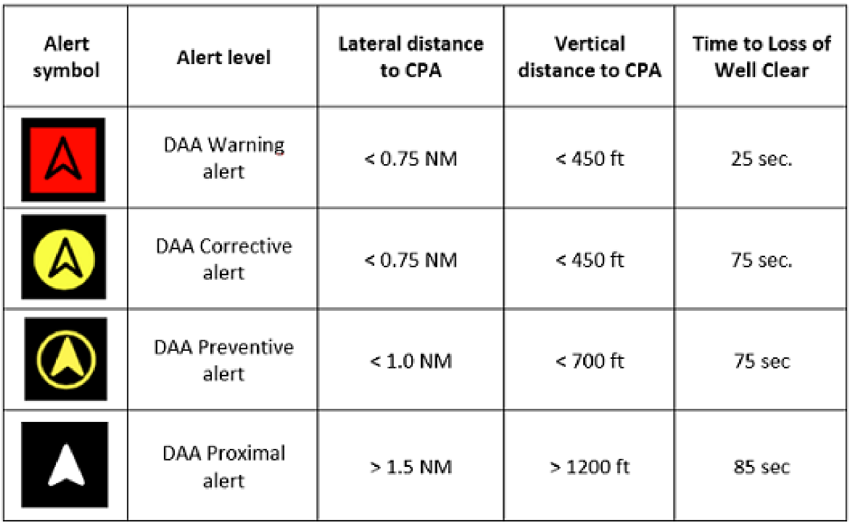


Figure 2.6: Visual depiction of thresholds of alerts in Figure 2.5 ([Fern, 2016])

In another studies, such as in [Monk and Roberts, 2016], the multi-level alerting structure shown in Figure 2.7 supplied by the Java Architecture for DAA Modeling and Extensibility (JADEM, [Santiago et al., 2015]) was used.[1]



Alert symbol	Alert level	Lateral distance to CPA	Vertical distance to CPA	Time to Loss of Well Clear
🟥	DAA Warning alert	< 0.75 NM	< 450 ft	25 sec.
🟡	DAA Corrective alert	< 0.75 NM	< 450 ft	75 sec.
◯	DAA Preventive alert	< 1.0 NM	< 700 ft	75 sec
▲	DAA Proximal alert	> 1.5 NM	> 1200 ft	85 sec

Figure 2.7: Multi-level alerting structure utilized by JADEM

It is important to note that "Time to Loss of Well Clear" and "Time to CPA" thresholds refer to different things. For detailed description and evaluations of alerting and time metrics used for UAS, see [Wu et al., 2017] and [Lee et al., 2016].

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[1] As stated in [Fern, 2016], the term "self separation" was later in 2015 officially removed from SC-228 MOPS and was replaced with "detect and avoid" or "maintain well clear" terms. To follow the convention, the term "self separation" will not be further used.

Chapter 3

Existing DAA display configurations

Previous surveys revealed that location of DAA display could have significant impact on pilot's performance. One of the questions was whether DAA displays should be integrated into the Tactical Situation Display (TSD) or should be on a separate monitor. TSD is a primary display of GCS that does not provide DAA abilities and functionality by default.

According to [Fern et al., 2015], there have currently been developed four configurations that differ in display location and amount of information the display provides to the pilot. Display configurations have been tested on many participants and produced results of measurements in response times to commands.

Developed configurations offer either basic or advanced level of information and differ in locations, either standalone or integrated.

3.1 Standalone DAA display

A standalone DAA display is located on dedicated monitor, separated from TSD and is able only to receive ownship state and trajectory information from the navigation system. The standalone displays are easier to develop which might be an advantage, however, standalone DAA displays bring many disadvantages such as potential confusions if the display and TSD are at different zoom levels, impossibility of integration to GCS C2 interface and necessity to switch attention between different monitors.

3.2 Integrated DAA display

An integrated DAA display is located directly in the TSD and is also integrated with the navigation system, thus it allows the pilot to send commands of maneuver execution using the DAA display. Also, pilot needs to pay attention to one monitor only which seems to be the main advantage. However, as more information and objects are presented in one monitor the amount of clutter might increase and potentially confuse the pilot which confirms the importance of the question, what is the minimum of information that should be depicted on DAA display.

3.3 Basic level of information

Basic level of information contains basic elements that must be provided to the pilot. It does not offer any advanced information or assisting features as in advanced level of information.

According to [Fern, 2016], the following list of information is set as minimum that must be provided to the pilot.

Intruder information

- Location
- Range
- Bearing
- Heading
- Relative altitude
- Vertical trend
- Heading predictor
- Data tag - Vertical velocity
- Data tag - Absolute altitude
- Data tag - Ground speed
- Data tag - Aircraft ID

Ownship information

- Location
- Trajectory
- Heading
- Altitude
- Vertical trend
- Data tag - Vertical velocity
- Data tag - Ground speed

Information elements marked as “Data tag” are shown in the data tag of relevant aircraft and appear either when data tag is selected for an aircraft with proximal or preventive alert or automatically when corrective or warning alert is active.

Combination of basic level of information and different display locations creates two different configurations that can be seen on Figure 3.1 and Figure 3.2.

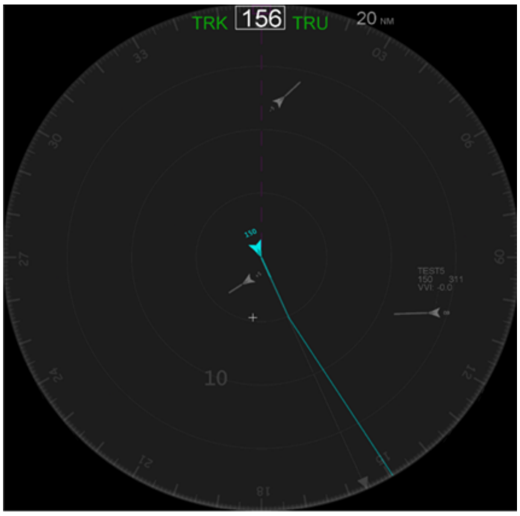


Figure 3.1: Basic standalone display

Figure 3.2: Basic integrated display

3.4 Advanced level of information

Advanced level of information provides additional information elements to the minimum set in basic configuration, including the following list of items:

1. **Predicted location of CPA** - CPA is depicted as a small yellow-colored circle indicating the location, where ownship and intruder are predicted to be closest to each other. It appears when an alert occurs and it automatically disappears once the alert is cleared.
2. **Time to CPA** - A countdown timer indicating the time remaining until CPA is reached. This information is displayed in the data tag of relevant aircraft. Again, it appears when an alert occurs and it automatically disappears once the alert is cleared.
3. **Well Clear ring** - Well Clear ring is a circle with radius of 0.8 NM with center in ownship, providing a visual reference to the collision avoidance threshold. This feature is available only in advanced integrated display configurations.
4. **Vertical situation display** - Vertical situation display is a panel located in the bottom part of DAA display. It displays a vertical profile of traffic ± 1000 ft. vertically from ownship. It also shows traffic icons, heading predictors, CPA locations and appropriate color-coding for alert level.

In advanced display configurations, maneuver guidance is also provided to the pilot. It includes directive guidance providing a single maneuver recommendation in a text format and suggestive guidance providing a range of potential solutions in the form of planning tools. Pilots are not required to follow recommended maneuvers.

1. **Auto-Resolutions** - When an alert is active, a recommended maneuver calculated by Autoresolver-AD (algorithm adapted from [Erzberger et al., 2012]) is provided to the pilot. The maneuver is displayed in a text box in the upper part of display. If more effective maneuver is found, the "Refresh" button starts to flash and when pressed, new maneuver replaces the previous one.

2. **Trial planning tools** - Trial planning tools offer the pilot with two separate planning tools, lateral and vertical. Planning tools automatically engage when an alert is active but pilots are also able to launch them manually. Lateral planning tools consist of an arrow pointing from the nose of ownship to the safe heading calculated by Autoresolved-AD which can be dragged to different headings and gives instant feedback whether heading would result in an alert or not. Lateral planning tools include an altitude table consisting of five altitude options, ± 1000 ft. vertically from ownship with 500 ft. increments. Each altitude level is color-coded according to its predicted safety.

Two different display configurations offering advanced level of information are shown in Figure 3.4 and Figure 3.3.

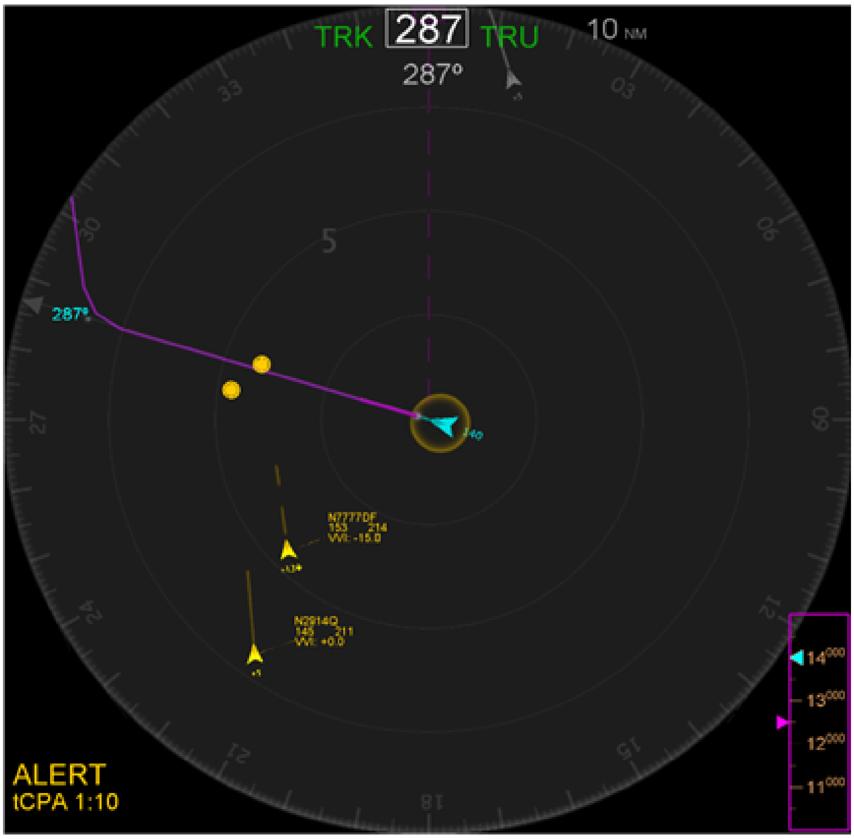
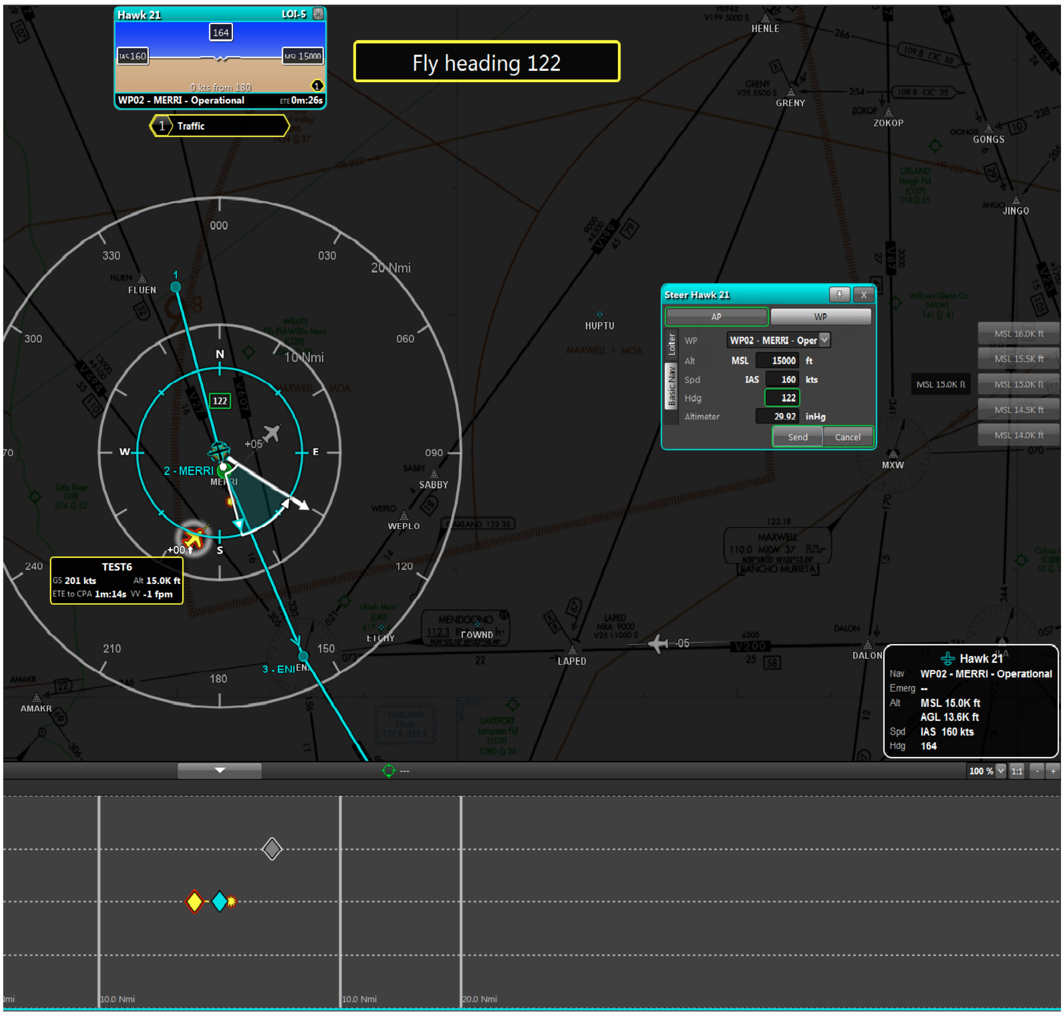


Figure 3.3: Advanced standalone display



Hawk 21 LOI-5
164
IAS 160
MSL 15000
0 kts from 180
WP02 - MERRI - Operational ETE 0m:26s

1 Traffic

Fly heading 122

Steer Hawk 21
WP: WP02 - MERRI - Oper
Alt: MSL 15000 ft
Spd: IAS 160 kts
Hdg: 122
Altimeter: 29.92 inHg

TEST6
GS 201 kts Alt 15.0K ft
ETE to CPA 1m:14s VV -1 fpm

Hawk 21
Nav: WP02 - MERRI - Operational
Emerg: --
Alt: MSL 15.0K ft
AGL 13.6K ft
Spd: IAS 160 kts
Hdg: 164

Figure 3.4: Advanced integrated display

Figure 3.4 shows a TSD with integrated DAA display with active Prediction of Collision Avoidance alert. The small yellow-colored area is the predicted location of CPA. The red border of yellow-colored intruder aircraft represents the “Predicted Collision Avoidance” alert level. Time to CPA can be seen in the intruder aircraft’s data tag. Vertical situation display is located in the bottom part of TSD. The trial planning tools (suggestive maneuver guidance) are represented with the arrow pointing to heading 122 off the nose of the ownship. The recommended maneuver (directive maneuver guidance) is shown in the upper box "Fly heading 122" ([Fern, 2016]).

3.5 Experimental DAA display designs and configurations

In the previous chapter we have described different DAA display configurations that originated from different locations and amount of information they provided and were the subject of the study by [Fern et al., 2015].

As stated in [Fern, 2016], another two main experiments have been made, one examined the impact of suggestive and directive maneuver guidance on pilot's performance and second introduced another four experimental DAA display configurations offering different suggestive maneuver guidance types.

All four display configurations contain the baseline set of minimum information elements described in section 3.3, except heading predictor and vertical velocity.

3.5.1 Informative Only

This configuration offers only baseline set of minimum information described in section 3.3, expect heading predictor and vertical velocity. As seen in Figure 3.5, neither maneuver guidance nor advanced display features such as ’predicted location of CPA’ are provided in this configuration

Figure 3.5: Informative Only (No maneuver guidance)

3.5.2 Stratway+ NoFly bands

Stratway+ NoFly bands configuration is part of Stratway+ system, later renamed to Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS, [Muñoz et al., 2015]). It was used previously to provide pilots with DAA guidance.

In this configuration, pilots are provided with lateral bands and vertical speed bands indicating heading that would result in preventive, corrective or warning alert. Headings that lead to such alerts receive yellow bands, safe headings receive no bands. Vertical speed bands are presented within a vertical speed indicator located on the far right of the display. Both lateral bands and vertical speed bands are shown in Figure 3.6.

In situations where loss of well clear is unavoidable, dashed green "recovery" are added indicating heading that results in quickest resolution. Stratway+ NoFly bands are additive, i.e. allowing the guidance information for more aircraft simultaneously.

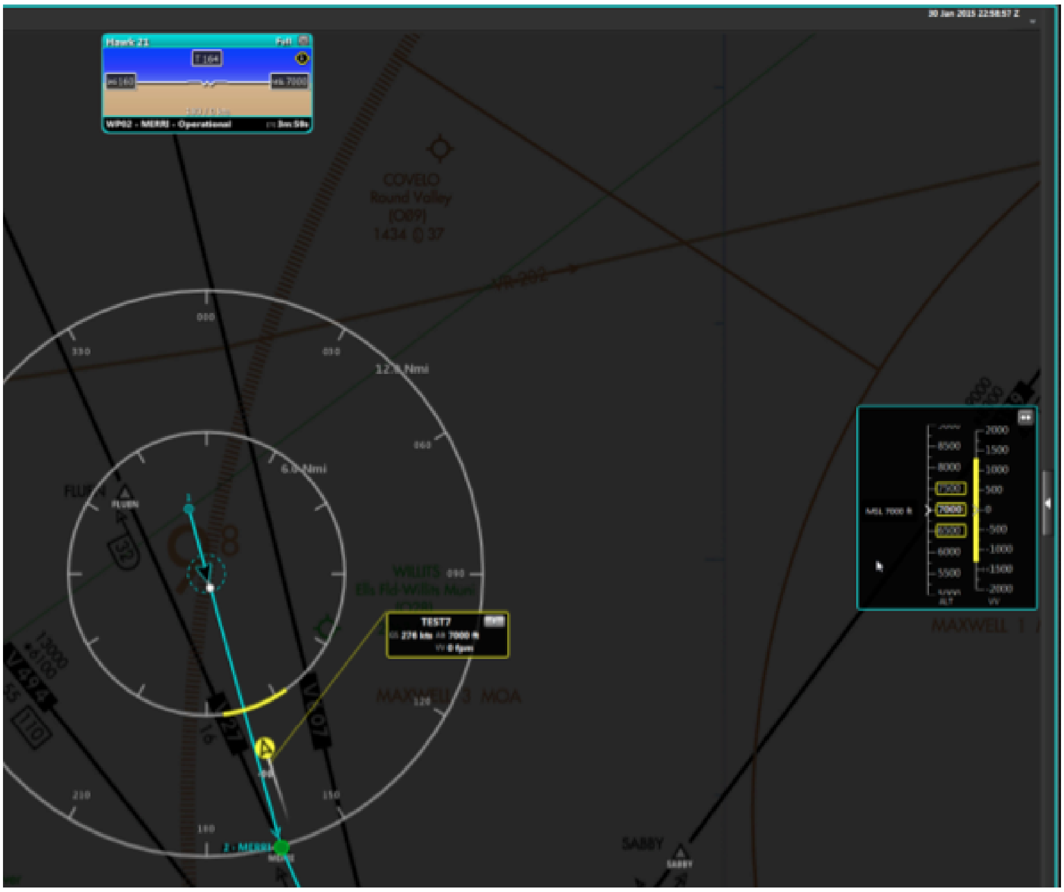


Figure 3.6: Stratway+ NoFly bands

3.5.3 JADEM Omni Bands

Omni Bands, developed by JADEM ([Santiago et al., 2015]), are quite similar to NoFly bands. Instead of one colored bands, OmniBands offer bands in colors corresponding to alerting structure: green (safe), dashed yellow (resulting in DAA Preventive alert), solid yellow (resulting in DAA Corrective alert) and red (resulting in DAA Warning alert).

The main difference between OmniBands and NoFly bands is the vertical guidance. Instead of vertical speed indicator, individual altitude blocks are generated in 500 ft. increments from 1000 ft. bellow controlled aircraft up to 1500 ft. above the controlled aircraft. By clicking on altitude blocks, pilots receive vertical guidance information. OmniBands are also additive, allowing guidance information for more aircraft simultaneously.

Figure 3.7 shows a lateral band created for an intruder aircraft with active DAA Corrective alert, as well as vertical guidance presented as six altitude blocks with red color, indicating that both climb and descend would still result in DAA Warning alert.

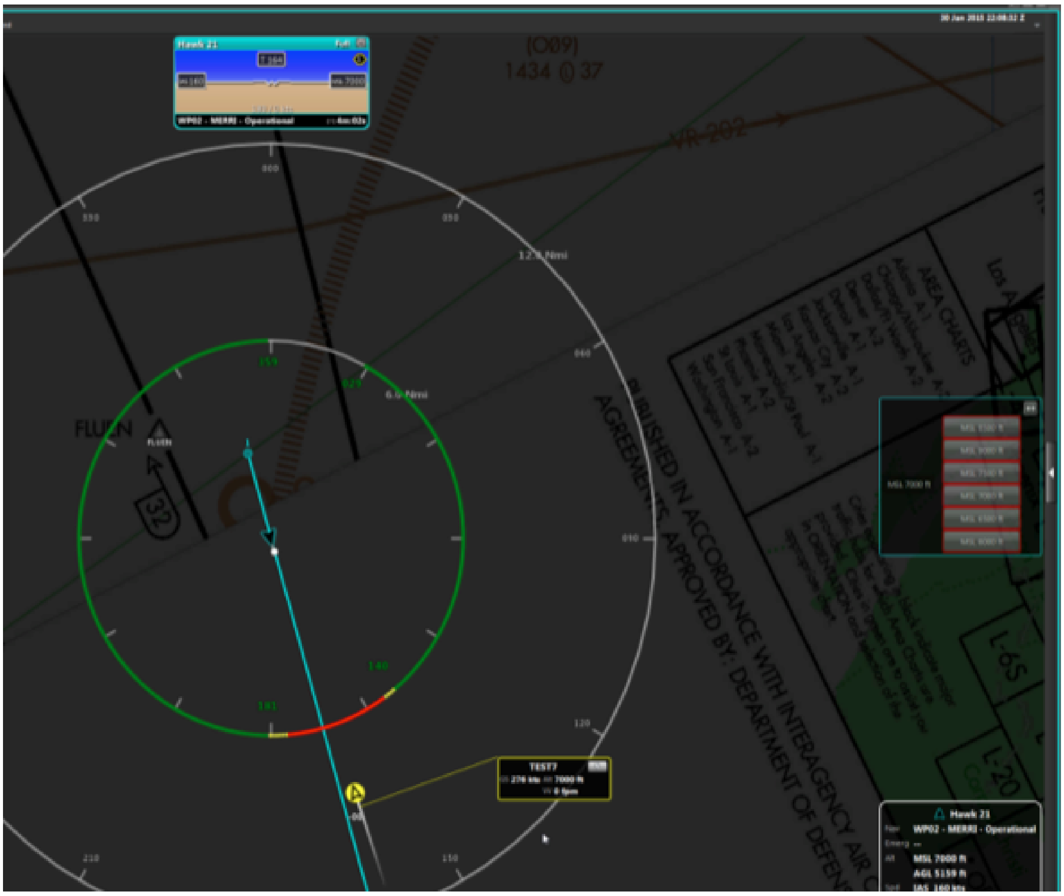


Figure 3.7: JADEM OmniBands

3.5.4 JADEM Vector Planner Tools

Similarly as in Trial planning tools described in section 3.4, Vector Planner Tools developed also by JADEM offer pilots with the ability to test various headings. To do so, pilots have to click and drag a dedicated arrow to different headings and it concurrently changes colors depending on corresponding alerting structure. A text readout next to the arrow tip shows heading that is currently being probed. As shown in Figure 3.8, the green color of arrow indicates that heading 145 is safe.

Same as in OmniBands configuration, individual altitude blocks are generated in 500 ft. increments from 1000 ft. bellow controlled aircraft up to 1500 ft. above the controlled aircraft. By clicking on altitude blocks, pilots receive vertical guidance information.

Figure 3.8: JADEM Vector Planner Tools

Chapter 4

AgentFly simulation framework

This thesis build on an AgentFly[1] simulation framework, which is being developed at the Department of Computer Science, Faculty of Eletrical Engineering, Czech Technical University in Prague. AgentFly simulation framework is used for modeling and simulation of civilian air traffic and unmanned aircraft systems. Part of the AgentFly simulation framework is a visualization system referred as 'visio' that is used to present properties of the simulated environment in a graphic way. Visio is build on JavaFX[2] and uses Java OpenGL[3] (JOGL) wrapper library to allow OpenGL usage in Java. Visio maintains stable 60 frames per second while visualizing Earth surface from any distance or direction, which provides efficient large-scale Earth surface rendering.

For our purpose, we use only specific part of visio, in which the camera uses orthographic view instead of perspective view. To compute two-dimensional coordinates of points, we use stereographic projection which projects the sphere onto a plane with sufficient accuracy for our case.

In this chapter, we will provide a short list and description of basic graphic elements that visio provides and that were used in our display. For further and more detailed description of visio, see [Kaiser, 2018].

LayerProvider LayerProvider is a wrapper class that processes data taken from simulation classes (i.e. classes that generate graphics) into its own scene graph. LayerProvider provides reference to its root layer (i.e. root node of scene graph) and method which commits all changes made in scene graph since the last commit.

Layer Layer represents a single layer containing graphical elememets. Layers are stacked on top of each other and all of them must be inserted in the root layer of relevant LayerProvider in order to be displayed in the scene. Layers also provide option

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[1] `www.agentfly.com`

[2] `http://www.oracle.com/technetwork/java/javase/overview/javafx-overview-2158620.html`

[3] `http://jogamp.org/jogl/www/`

to change its visibility, which display implementation uses for switching visibilities of intruder aircraft.

OrthoScreenLayer OrthoSceenLayer is an extension of Layer, in which its rendering behaves as orthogonal screen aligned view instead of 3D camera view. In our case, Warning Window and Data block of ownship (see subsection 5.1.4 and subsection 5.1.3) both are implemented using OrthoScreenLayer instead of Layer, which provides us the option to align them with the screen and keep them displayed in the same position the whole time.

TransformGroup TransformGroup is a group node that allows a specific transformation such as translation or rotation to be applied to all of its children. In a TransformGroup, other drawable objects (e.g. those mentioned below) can be stored.

AlignedTransformGroup AlignedTransformGroup is an extension of TransformGroup, which operates in 2D space. It provides us the option to align its children with screen, which is widely used when displaying text strings. AlignedTransformGroup is usually wrapped in a TransformGroup, which allows us to apply proper rotation and translatio to it.

Points Points represents points as we all know them, with various sizes, colors as well as shapes. The location of points is based on coordinates that are assigned to them. Display uses points to generate mission waypoints and graphics of predicted location of CPA.

Lines Lines represent a line defined by several coordinates the line connects. Lines can be created in either strip or segment mode. Various colors as well as sizes can be assigned to it. In our case, Lines are used for example to construct display circles and its perpendicular lines.

Text Text instances represent aligned texts with various fonts and sizes. Text instances must be stored in AlignedTransformGroup in which they are properly aligned.

Mesh Mesh is an object with (possibly indexed) vertices, color, texture or other attributes. In our case, we frequently use QuadMesh to create graphics of aircraft symbols. Meshes can be stored in both TransformGroup and AlignedTransformGroup, in which they are rotated, translated or aligned.

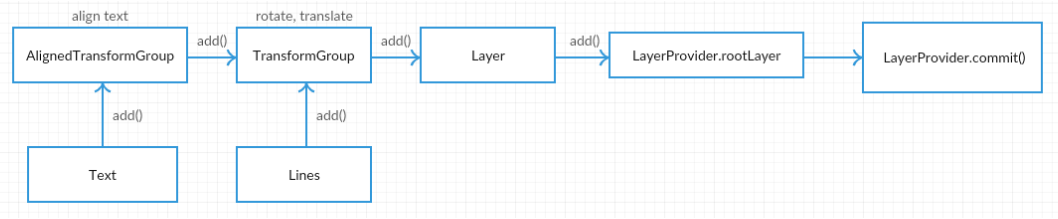


Figure 4.1: Workflow diagram

Figure 4.1 shows, how a line with text would be created and displayed in the scene.

Chapter 5

Display properties

The aim of this thesis is to validate the impact of assisting features of pilot's performance. To achieve the ability to do so, we firstly had to design and implement the display. As some types of DAA displays were already developed, design of our display is highly inspired by them.

Display offers advanced level of information (see section 3.4), providing pilots with additional information than is set as minimum in section 3.3. This is expected to help pilots to detect threats earlier and to achieve more accuracy in maneuver execution. Advanced level of information includes also both suggestive and directive maneuvers indicating pilots headings and altitudes that should not be flown as well as recommended trajectories (see subsection 5.3.2 and subsection 5.3.3).

Since previous studies such as [Monk et al., 2015] revealed that pilots tend to prefer integrated display conditions over standalone, especially when advanced level of information is provided, which in our case is, display is implemented as integrated too.

It is important to mention that integrated condition of our display is a bit different from what it is in real DAA systems. In real DAA systems such as [ACAS, 2015] or [MIDCAS, 2015], integrated condition means that the DAA display is integrated into the TSD (or primary display) and thus integrated with navigation system, making pilots able to send commands of maneuver execution directly through the DAA display, whereas in standalone condition this option is not present. In our case, integrated condition means simply that pilots are provided with only one monitor in which both mission and DAA features are displayed. However, pilots are also presented with standalone condition where mission is displayed on separate monitor, which will be discussed later in chapter 6.

5.1 Graphic components of display

5.1.1 Simulation background

As a background of simulation, map of the Czech Republic is displayed. Map consists of sectors and points with fixed positions loaded from text files. Point usually represents a single airport and might serve for example as orientation points for pilot.

When changing course, simulation background (i.e. background map) rotates correspondingly with the symbol of controlled aircraft.

The whole background map (zoomed out) is shown in Figure 5.1 with inverted colors for better visibility.

Figure 5.1: Simulation background

5.1.2 Controlled aircraft

Controlled aircraft (i.e. ownship) is depicted with cyan-colored symbol with green line that points to direction of current course. Symbol of ownship is surrounded by two circles that serve as visual reference of distance of 5 and 10 nautical miles. Outer circle also contains twelve perpendicular lines that are labelled with a number indicating their headings. For better orientation of pilots, perpendicular lines are displayed on the inner circle as well.

When changing course, only the symbol of ownship with its line rotates. The fact that circles do not rotate at all might lead to better pilot's awareness of where cardinal directions are.

Figure 5.2 shows the controlled aircraft currently heading right to the north.

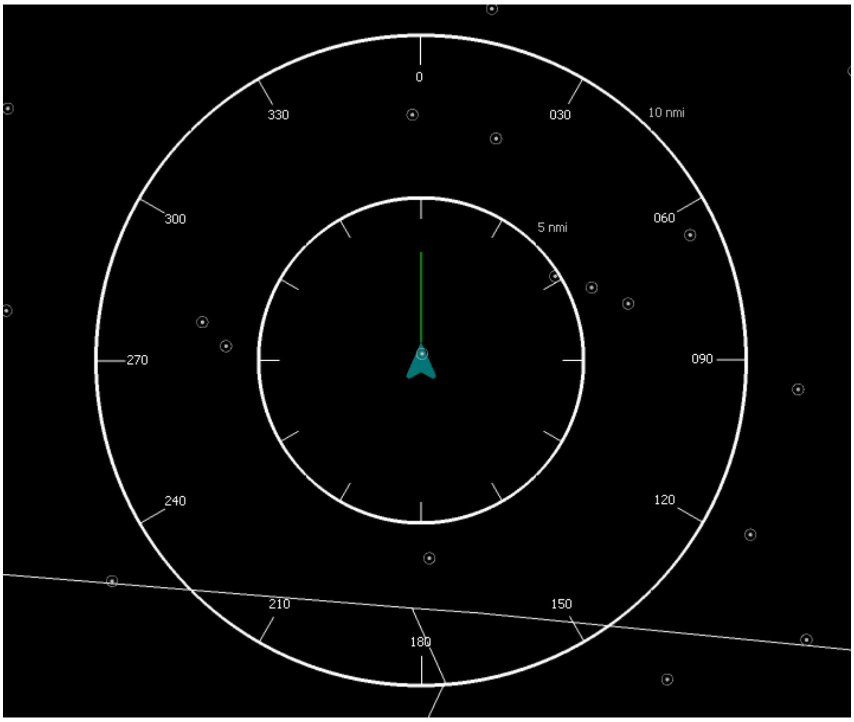


Figure 5.2: Controlled aircraft

5.1.3 Warning window

Warning window is a small rectangular window located in the upper part of display. It is used to visually inform the pilot about currently active alerts. Since alerts have different level of importance, only the alert with highest importance is shown. When there is currently no active alert, a green-colored text "CLEAR" is shown in the warning window. When automatic following of recommended trajectory is selected (recommended trajectories are described in subsection 5.3.3), a cyan-colored text "AUTOMATIC" is shown in the warning window. If manual following of recommended trajectory is selected instead, text changes to "MANUAL" while keeping its cyan color.

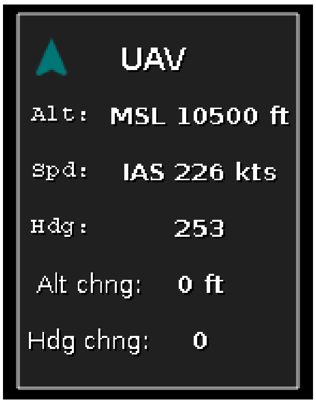

WARNING ALERT ACTIVE

Figure 5.3: Warning window

Figure 5.3 shows how warning window looks like when DAA Warning alert is active.

5.1.4 Data block of controlled flight

Data block of controlled flight (i.e. ownship) is a window located in the left part of display that is used to display current information of controlled flight. It serves as primary source of information for pilot, displaying actual altitude, heading, speed, and lateral and vertical changes in maneuver selected by pilot.



UAV
Alt: MSL 10500 ft
Spd: IAS 226 kts
Hdg: 253
Alt chng: 0 ft
Hdg chng: 0

Figure 5.4: Data block of controlled aircraft

In Figure 5.4, data block displaying current information about controlled flight is shown.

5.1.5 Data tag of intruder flight

Data tag of intruder flight is a small rectangular window connected with a line to the relevant aircraft. As stated in section 3.3, data tag appears as soon as DAA Warning or DAA Corrective alert is active. However, pilots are also able to manually display data tag by clicking on relevant aircraft. In data tag, additional information about relevant aircraft such as vertical velocity, altitude and ground speed is displayed. Similarly as in section 3.4, data tag also provides pilot with a countdown timer indicating time until CPA with relevant aircraft is reached. An example of data tag is shown in Figure 5.5.

TEST 3
Alt: 10.5K ft GS: 226 kts
tCPA: 119 s VV: 0 fpm

Figure 5.5: Data tag of intruder flight

5.2 Basic display features

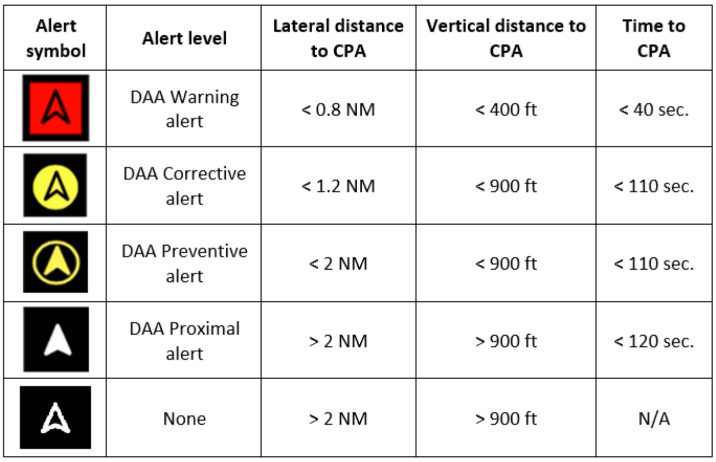
The most important feature that DAA display must provide pilot with is the ability to operate the controlled aircraft. Pilot is able to choose maneuvers using keyboard arrow keys. To change heading, pilot has to press left or right arrow key depending on which direction they want to turn to. To change altitudes, up and down arrow keys must be used. Heading and altitude change of selected maneuver is displayed in the data block of controlled flight, and the maneuver is executed as soon as pilot presses the Enter key.

The second most important feature of DAA display is to provide pilots with ability to detect surrounding traffic. Display is fully capable of displaying surrounding traffic and information about intruder aircraft. Surrounding aircraft are depicted as symbols that are considered today's best practice (see section 2.1) and are assigned to aircraft based on alerting structure presented in subsection 5.2.1.

Speaking about information level, display provides information about majority of features that are set as minimum in section 3.3. However, since flights in simulation do not represent any real vehicles and the whole simulation does not involve weather conditions, ground speed is considered as indicated air speed and vice versa. In addition to this, as vertical velocity of ownship when climbing or descending is constant, the data tag of ownship is left out completely because all necessary information are already contained in data block of controlled flight.

5.2.1 Alerting structure

For our experiment, alerting structure shown in Figure 5.6 is created as combination of both alerting structures described in section 2.2. From the reason mentioned in Figure 1, names of alerts are taken from Figure 2.7, whereas thresholds are taken from corresponding alerts of Figure 2.5.



Alert symbol	Alert level	Lateral distance to CPA	Vertical distance to CPA	Time to CPA
	DAA Warning alert	< 0.8 NM	< 400 ft	< 40 sec.
	DAA Corrective alert	< 1.2 NM	< 900 ft	< 110 sec.
	DAA Preventive alert	< 2 NM	< 900 ft	< 110 sec.
	DAA Proximal alert	> 2 NM	> 900 ft	< 120 sec.
	None	> 2 NM	> 900 ft	N/A

Figure 5.6: Alerting structure used in display

5.3 Advanced display features

To help pilots to detect forthcoming threats, display functionality involves advanced features as well. Advanced features are inspired by those described in section 3.4 and include predicted location of CPA and both suggestive and directive maneuver guidance. Advanced features are applied to all aircraft within lateral range of 15 nautical miles and vertical range of ±1000 feet from current position of controlled aircraft.

5.3.1 Predicted location of CPA

Predicted CPA is location where ownship and relevant aircraft is predicted to be closest to each other. It is depicted as a small point that has either red or yellow color, which is assigned based on the distance between ownship and relevant aircraft in the predicted location of CPA. In order to comply with alerting structure, if both lateral and vertical distance in CPA violate the threshold of DAA Warning alert, red color is assigned, otherwise yellow color is assigned.

CPA automatically appears as soon as an DAA Corrective or DAA Warning alert occurs, and automatically disappears once the alert of relevant aircraft is cleared. For DAA Preventive or DAA Proximal alert, predicted location of CPA is not depicted. Location of CPA is predicted for each aircraft individually, meaning that more CPA might be concurrently displayed if more aircraft create at least DAA Corrective alert.

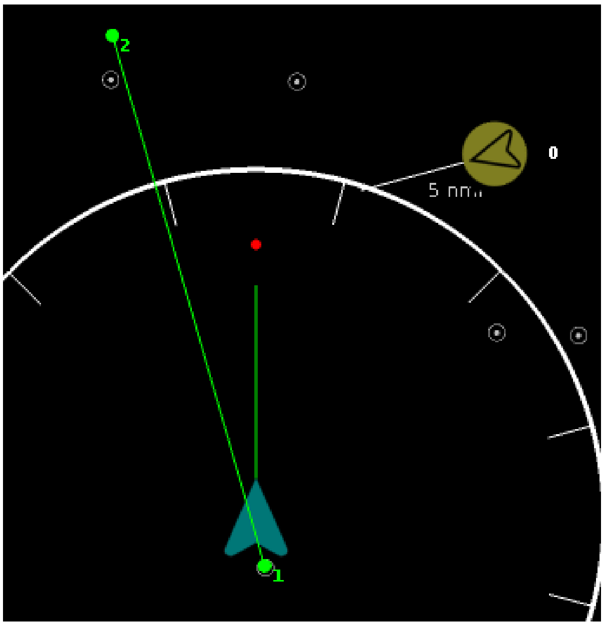


Figure 5.7: Predicted location of CPA

Figure 5.7 shows an aircraft with active DAA Corrective alert for which the predicted location of CPA is calculated and depicted as a red point.

5.3.2 Suggestive maneuver guidance

Pilot is offered with suggestive maneuver guidance in form of bands which serve as a visual reference to headings and altitudes that would result in DAA Corrective or DAA Warning alert. Suggestive maneuver guidance is implemented very similarly as in subsection 3.5.3, with the only difference that DAA Preventive alert does not create any bands.

5.3.2.1 Lateral bands

Lateral bands are used to improve pilot's estimate of headings that should not be flown. As soon as DAA Corrective or DAA Warning alert occurs, lateral band is created for the aircraft that causes the alert.

Lateral band consists of two colors. Yellow color indicates headings that, if flown, would result in violation of lateral threshold of DAA Corrective alert. Red color indicates headings that would result in violation of lateral threshold of DAA Warning alert.

If there is DAA Corrective or higher alert present for more aircraft simultaneously, lateral band is created for each aircraft individually. If two or more bands overlap each other, red color has always the priority over yellow color. However, a band is not guaranteed to end in headings that would not result in another alert, if flown.

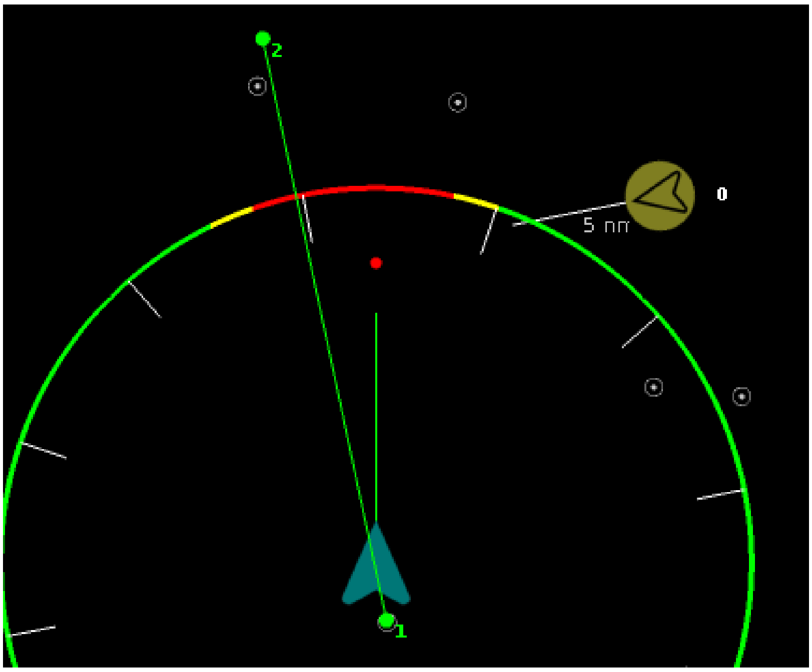


Figure 5.8: Lateral bands

Figure 5.8 shows a lateral band created for an aircraft with an active DAA Corrective alert.

5.3.2.2 Vertical bands

Vertical bands are presented as six altitude blocks with 500 ft. increments, in range of ±1500 feet from current altitude of ownship. The altitudes displayed in altitude blocks represent their lower bounds, meaning that the ranges of altitude blocks are up to 500 feet above their currently displayed altitude. Symbol of ownship is always located in the fourth altitude block from the bottom and indicates current altitude level. Exact altitude level is also displayed above altitude blocks so that pilot does not have to estimate the altitude by where the blue symbol is located.

As soon as an alert occurs, borders of altitude blocks that contain altitudes within vertical threshold of active alert are assigned red or yellow color, for DAA Warning and DAA Corrective respectively. DAA Preventive and DAA Proximal alerts do not cause any vertical bands.

Similarly as lateral bands, also vertical bands are created for each aircraft individually. If more vertical bands overlap each other, altitude blocks assigned red color are always visible over those with yellow color assigned. Vertical bands

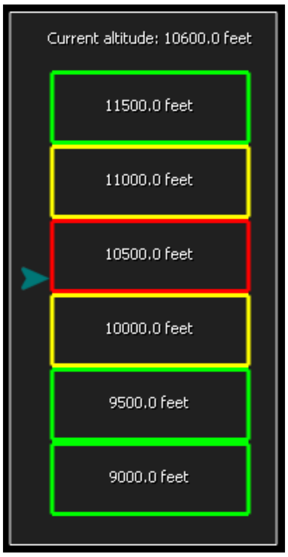


Figure 5.9: Vertical bands

In Figure 5.9, we can see an example of vertical bands created for an aircraft with an active DAA Warning or DAA Corrective alert.

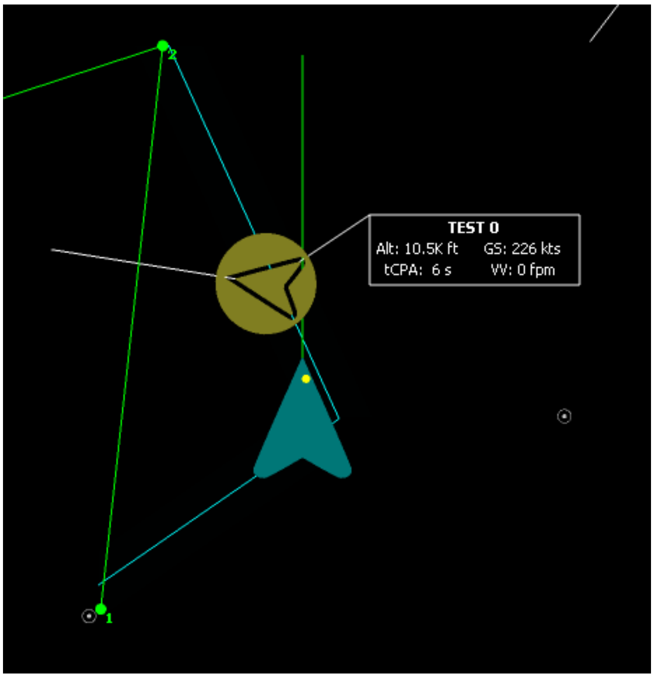
5.3.3 Directive maneuver guidance

Directive maneuver guidance in section 3.4 is presented as a text box (see Figure 3.4 and its description) with recommended heading calculated and predicted as safe. In our display, directive guidance involves lateral trajectory planning to the following scenario mission point, up to 15 nautical miles away from current position. In order to prevent planned trajectory getting out-of-date, trajectory planner keeps recommending new trajectories each second, until pilot finally selects one. Trajectory can be selected easily with a single mouse click on it.

Once pilot selects recommended trajectory, aircraft follows selected trajectory automatically until the destination point of selected trajectory is reached. However, pilot has the option to switch from automatic following to manual following which would keep trajectory displayed but it would be pilot's responsibility to follow the trajectory. Pilot is also able to stop following recommended trajectory and trajectory planner starts to offer him new and updated trajectories.

However, as we do not know the physical model of aircraft, trajectories calculated by Trajectory Planner do not consider maneuver durations and the fact that their execution starts in advance. So if automatic trajectory following is selected, there is a chance that aircraft get a little closer to each other than calculated, which results DAA Corrective alert threshold violation. This is caused by (possibly) sharp angles in positions where the trajectory bends, which, in order to follow the trajectory, forces maneuver execution to start before reaching the bending point, which is not directly crossed because of that. That might allow aircraft to get closer to each other than the threshold is set. However, those threshold violations caused by sharp angles are narrow (in range of meters or tens of meters at maximum) and thus neglected.

Figure 5.10 shows an example of situation where due to almost 90° maneuver turn the DAA Corrective alert threshold might be violated.



TEST 0
Alt: 10.5K ft GS: 226 kts
tCPA: 6 s VV: 0 fpm

Figure 5.10: Situation where trajectory bend point is not crossed

5.3.3.1 Trajectory planner

Trajectory planner is implemented as Theta* algorithm, a variant of A* that propagates information along grid edges without constraining the paths to grid edges ([Nash et al., 2010]). The preference of Theta* over A* results in smoother trajectories that look more realistic and are easier to follow for a pilot. Examples of trajectories calculated using A* and Theta* are shown in Figure 5.11 and Figure 5.12.

In order to gain the ability to apply graph search algorithm, we firstly had to construct graph from our simulated 3D space. As all display's advanced features are applied to lateral range of 15 nautical miles, we took a grid with edge length of 30 nautical miles, with center in current position of controlled flight and split it into number of smaller grids with edge length of a tenth of nautical mile. Each of these smaller grids is considered as an unique graph node defined by coordinates of its center. A set of edges consisting of outcoming edges to all adjacent graph nodes (respectively its centers) is assigned to each graph node, since graph represents a grid where only adjacent fields are reachable. Each node is also assigned heuristic value that equals the straigth line distance from the destination node. Graph is undirected and weigth of edge of two adjacent graph nodes is computed as distance between their centers.

Now, when the graph is constructed, trajectory planning may start. Based on current position of controlled aircraft, start node is selected. As a destination node we consider graph node where following point of scenario mission is located, if it is in range of 15 nautical miles or graph node that is the closest to following point of scenario mission, if it is out of monitoring range. This ensures that trajectory always leads to completition of following mission point that must be reached in order to complete the scenario.

Since we are looking for path in a grid that actually represents a space where other aircraft are present as well, algorithm has to consider that some graph nodes are not accessible (i.e. blocked) for certain times. Otherwise, planned trajectory would obviously lead straight to destination point. This involves the algorithm to remember current position of all aircraft located in the grid as well as current position and speed of controlled aircraft, in the moment when trajectory planning starts. Since the cost to reach a graph node is equal to sum of weigths of edges of each pair of adjacent graph nodes that must be traversed to reach desired graph node, and current speed of controlled aircraft is known, we can simply calculate the time that controlled aircraft needs to reach any graph node from start node as cost of desired node divided by speed of controlled aircraft. That provides us the ability to estimate future positions of other aircraft, based on their origin position and speed when the trajectory planning started. Based on that we can determine if certain graph node is accesible or not in concrete times.

Since graph nodes are defined by theirs center coordinates and edges always connect centers of graph nodes, trajectories planned by Trajectory Planner were not straigth at all and consisted of many sharp bends (as shown in Figure 5.11) that would be impossible to follow for a pilot, considering the time that aircraft needs to change course. This is solved by applying Theta* algorithm and its trajectory smoothing. Theta* algorithm is very similar to A* algorithm, with the main difference of allowing a parent of graph node to be any other graph node, whereas in A* algorithm only adjacent graph nodes of a graph node are allowed to be its parent nodes. However, this is constrained by a line of sight that must connect those two graph nodes. Line of sight between two nodes exists if and only if none of graph nodes crossed by line of sight is blocked. In our case, where graph nodes are accesible or blocked for different times, line of sight between two graph nodes is constructed as $n = distance(Node1, Node2)/(nodeEdgeLength/8)$ positions that are evenly distributed on the imaginary line that connects those nodes. For each position individually, positions of other aircraft are estimated. If all positions are distantied far enough from estimated position of other aircraft to be considered safe, line of sight between two relevant graph nodes exists.

In real world, where more things must be considered and finding simply the fastest path in graph is not enough, planning trajectories for UAV or another autonomous vehicles is much more difficult task. Some approaches of diverse trajectory planning for UAV are discussed in [Tožička and Komenda, 2016].

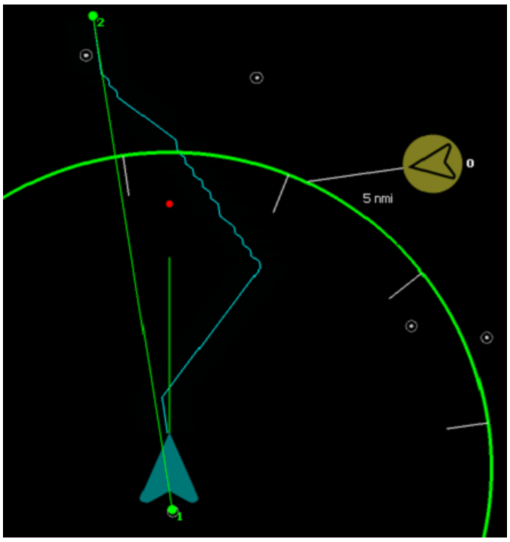


Figure 5.11: Trajectory planner using A* algorithm

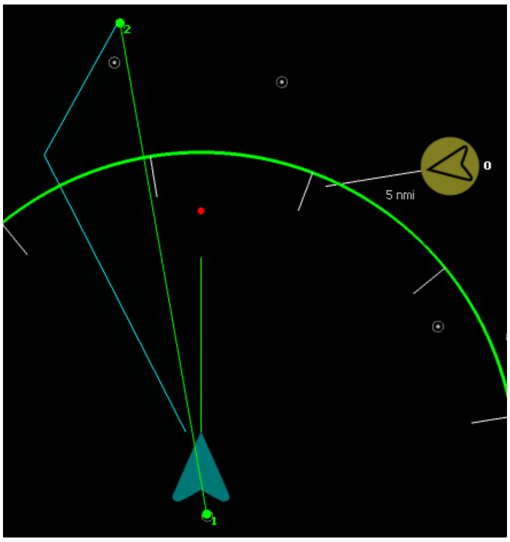


Figure 5.12: Trajectory planner using Theta* algorithm

Chapter 6

Experiments

The purpose of experiments was to validate the impact of assisting features provided by the DAA display on pilot's performance. As an assisting feature we consider a functionality that suggests pilot possible solutions of forthcoming threat in either suggestive or directive manner. Assisting features provided in our DAA display include suggestive maneuver guidance in form of bands and directive maneuver guidance in form of trajectory planning, both described in subsection 5.3.2 and subsection 5.3.3.

Assisting features were tested by two metrics - **total distance traveled** until destination point of mission is reached and **average horizontal miss distance (HMD)** across all aircraft included in scenarios. Vertical miss distance was left out, because we do not know the physical model of aircraft and thus we can not specify or decide, when to prefer vertical maneuver over horizontal maneuver.

This involved pilots to complete two different scenarios with a total count of four different display configurations (denoted as C1, C2, C3, C4). The order of presentation of the four display configurations was counterbalanced to account for order and learning effect.

C1: Informative only First configuration was only informative (similarly as in subsection 3.5.1) and offered only basic features provided by the display, except for predicted location of CPA which is considered an advanced feature.

C2: Bands Second configuration offered pilots with suggestive maneuver guidance in form of lateral and vertical bands, providing a visual reference to headings and altitudes that would result in at least DAA Corrective alert, if flown.

C3: Recommended trajectories In third configuration, pilots were offered with directive maneuver guidance which was presented as recommended trajectories calculated by Trajectory Planner. This configuration provided pilots with the ability to both automatically and manually follow recommended trajectory.

C4: Bands + Recommended trajectories Fourth configuration was combination of previous two configurations, offering pilots both suggestive and directive maneuver guidance at once.

Observed data among different configurations were processed into confidence intervals to determine statistical significance of their differences, if there is any. Participant's subjective opinions and attitudes towards individual display configurations are also discussed later in section 6.5.

6.1 Experimental design

Both examined metrics were analyzed utilizing repeated measures Analysis of Variance (ANOVA)[1] with pairwise comparisons. Results are interpreted using confidence intervals[2] with confidence level of 95% used for all analyses.

6.2 Participants and their task

Experiment included eight participants to take part in operating simulated UAV. Participants were introduced to all features provided by the DAA display, explained their meaning and purpose. They were also trained how to use the software properly on a training scenario. Although display offers vertical maneuvers as well, participants were told to prefer horizontal maneuvers over lateral maneuvers to allow better comparison among individual configurations.

The task consisted of operating a simulated UAV along two pre-planned scenarios. Participants were responsible for navigating the aircraft through all points of scenario mission while responding to alerts caused by other aircraft. Each participant had to complete both scenarios four times, each time with different display configuration offering different assisting features.

6.3 Scenarios

Three scenarios were created for this experiment. Each scenario consisted of different mission with different number of intruder aircraft that must be avoided.

First scenario served as a training scenario for pilots and was not expected to produce any results. Pilots were expected to gain skills in operating the aircraft, estimating maneuver sizes and getting familiar with features provided by the display.

Second scenario consisted of approximately 27 kilometers long mission with 3 intruder aircraft. All intruder aircraft were set to progress to DAA Corrective alert and then to DAA Warning alert.

Third scenario consisted of a longer mission of approximately 39 kilometers and involved 5 intruder aircraft. Four intruder aircraft progressed to DAA Corrective

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[1] `http://www.statisticshowto.com/probability-and-statistics/hypothesis-testing/anova/`

[2] `http://www.statisticshowto.com/probability-and-statistics/confidence-interval/`

alert and then to DAA Warning alert, while one progressed only to DAA Corrective alert. However, one aircraft was set to change course during its flight which could cause another alert, depending on pilot's previous maneuvers and current position of controlled aircraft.

In all scenarios, aircraft were already set to altitude level of MSL 10500 feet. Intruder aircraft did not climb or descend at all and majority of them did not even change course during their flight.

Intruder aircraft were added (i.e. started their flight) gradually after a mission point was completed. This was done to eliminate cases where intruder aircraft would not eventually progress to an alert due to pilot's different or unexpected maneuvering. With this approach, intuder aircraft are guaranteed to progress to desired alert no matter what maneuvers are executed before.

Third scenario, its mission and intruder flights are shown in Figure 6.1.

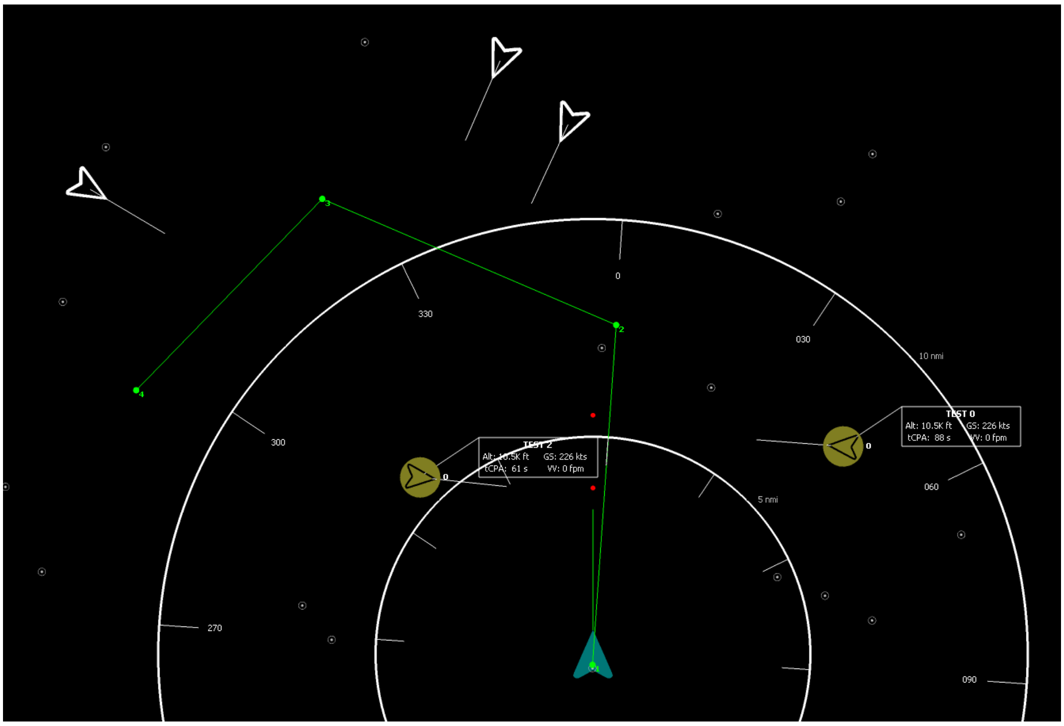

Figure 6.1: Mission and intruder flights of Scenario 2

6.4 Results

Results of experiment were not far away from our expectations. From measured data shown in Appendix A we computed confidence intervals for both examined metrics - **average HMD from intruder aircraft** and **total distance traveled**. Confidence intervals are computed from both scenarios together, since we expect display configurations to have similar effect in every scenario. Null hypothesis H_0 :

$\mu_{C1} = \mu_{C2} = \mu_{C3} = \mu_{C4}$ is rejected as means of all display configurations differ from each other and alternative hypothesis $H_a : \exists i \neq j \in \{1, 2, 3, 4\} : \mu_{Ci} \neq \mu_{Cj}$ is accepted.

If confidence interval does not contain zero, we can say that there is a statistically significant difference between compared configurations. Otherwise, there is not a statistically significant difference (equivalent to $p > 0.05$) and we can not say if one configuration produced better results than the other one.

Results between compared configurations are described and discussed in individual paragraphs for each metric separately. If more configuration pairs produced very similar results, they are grouped to one paragraph together. Confidence intervals of individual comparisons are shown in Figure 6.3 and Figure 6.2.

6.4.1 Metric 1: Total distance traveled

One of examined metric is the total distance that is traveled by controlled aircraft until destination point of scenario mission is reached. Logically, pilots should want to travel as least as possible while keeping maximal safety. Thus, the less the pilot travels with certain configuration, the better we consider the configuration to be, using this metric.

C1-C2 There was not a significant difference in total distance traveled between configurations C1 and C2. Both configurations produced similar results in total distance traveled, which was caused mainly by the advanced feature predicted location of CPA (described in subsection 5.3.1) which was present in all display configurations. If CPA location was currently displayed, pilots knew that current course is not safe and should be changed. However, although difference between configurations C1 and C2 is not significant, bands provided in C2 configuration led to better maneuver size estimation and thus to much lower amount of maneuver uploads.

C1-C3, C1-C4, C2-C3, C2-C4 As shown in Figure 6.2, there was a significant difference in total distance traveled between configurations C1 and C3, C1 and C4, C2 and C3, and C2 and C4. This result was quite expected because configurations C3 and C4 both offered pilots with recommended trajectories. Since recommended trajectories are computed as shortest paths in graph, it is expected that the distance traveled on its path will be minimal. As recommended trajectories are possible to be followed automatically, it also eliminates cases where pilot travels more due to wrong or inaccurate maneuvering. Pilots traveled approximately 4.5 km to 5.5 km less when recommended trajectories were provided.

C3-C4 There was not a significant difference in total distance traveled between configurations C3 and C4. This result was also expected because both configurations offer recommended trajectories. Also, as the benefit of automatic following recommended trajectories highly exceeds the benefit of bands, which resulted in fact that bands were almost ignored.

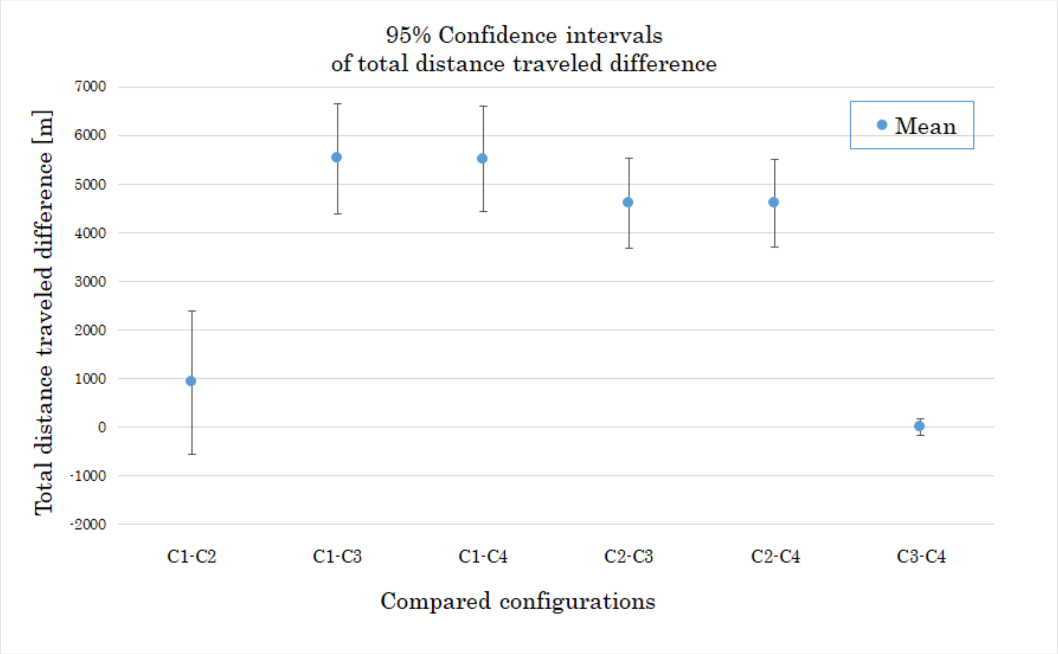

Figure 6.2: 95% Confidence intervals of total distance traveled difference

6.4.2 Metric 2: Average HMD from intruder aircraft

The other examined metric is the average HMD from intruder aircraft. Values of this metric for individual configurations must not necessarily be the lowest. Greater emphasis is put on keeping safely distanced from other aircraft than reaching minimal HMDs. However, to gain good results in total distance traveled too, optimal average HMD would be the lowest distance that is still considered safe.

C1-C2 There was not a significant difference in average HMD from intruder aircraft. Similarly as for the other metric, pilots estimated their maneuvers using advanced feature predicted location of CPA which caused that bands did not produce any significant difference in average HMD, except for the number of maneuver uploads.

C1-C3, C1-C4, C2-C3, C2-C4 There was a significant difference in average HMD from intruder aircraft between configurations C1 and C3, C1 and C4, C2 and C3, and C2 and C4. Similarly as for the other metric, it was expected that configurations offering recommended trajectories would produce lower values of average HMD than those who do not, since recommended trajectories are also the shortest trajectories that are still considered safe and thus intruder aircraft are avoided by the lowest possible distances.

C3-C4 There was not a significant difference in average HMD from intruder aircraft between configurations C3 and C4. Just like in the other metric, this result was expected and was caused by the higher benefit of recommended trajectories which led to ignoring bands almost completely.

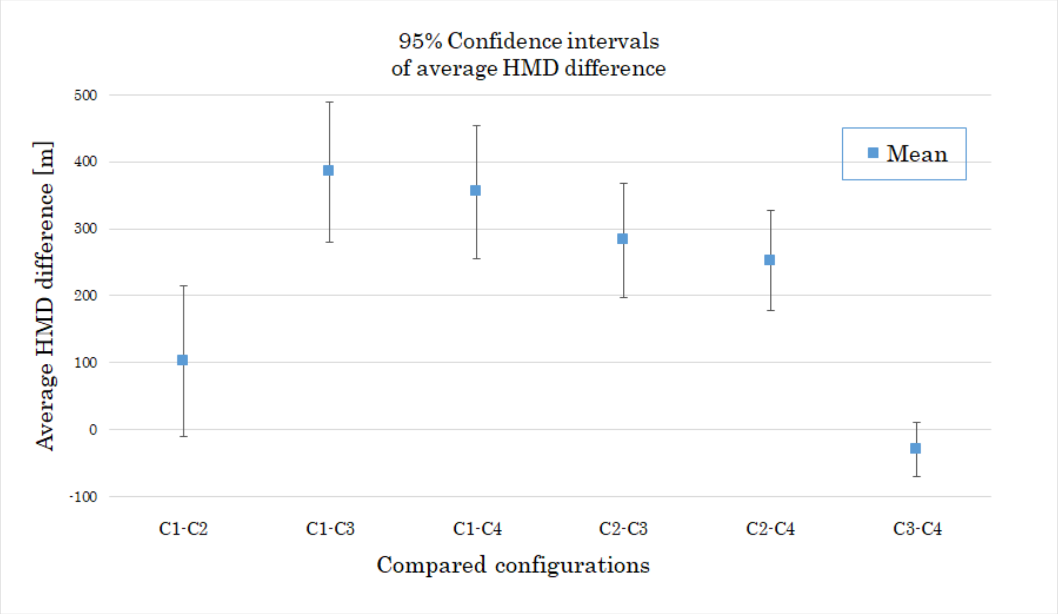

Figure 6.3: 95% Confidence intervals of average HMD difference

6.5 Summary

Experiment consisted of eight participants that took the role of an UAV pilot and operated a simulated UAV along two pre-planned scenarios. Each scenario consisted of different mission and of different number of intruder flights. Pilots must have completed both scenarios with a total count of four different display configurations, each of them offering different features. Configuration 1 (C1) was only informative, configuration 2 (C2) and configuration 3 (C3) offered pilots with bands and recommended trajectories respectively, and configuration 4 (C4) offered both bands and recommended trajectories. Data were measured for all configurations and can be seen in Appendix Appendix A.

Measured metrics for all display configurations were total distance traveled and average HMD from intruder aircraft. Measured metrics produced similar results that were intrepreted using confidence intervals with 95% of confidence.

With configurations C3 and C4, unambiguously better results using both metrics were reached, compared to configurations C1 and C2. Main reason was that configurations C3 and C4 provided pilots with recommended trajectories that could be either automatically or manually followed. However, every pilot preferred automatic over manual trajectory following. Compared to each other, results were almost identical, which can be also seen in Figure 6.2 and Figure 6.3.

Configurations C1 and C2 have not shown significant difference compared to each other which was caused mainly due to the presence of advanced feature predicted location of CPA in both of them. With configuration C1, predicted location of CPA was frequently used to correct the maneuver, as the initial maneuver size estimation was mostly inaccurate. This led to high number of maneuver uploads until desired course was reached. Accurate initial maneuver size estimation was the main benefit of C2 configuration.

All pilots have sucessfully completed both scenarios with all configurations and all of them managed to avoid collisions. Also, none of pilots failed to avoid DAA Warning alert threshold violation, from which we can conclude that individual flights were quite safe. However, few narrow DAA Corrective alert threshold violations happened, from which some were caused by automatic trajectory following and some by pilot's inaccurate estimations and maneuvering. Violations of DAA Corrective alert threshold caused by automatic trajectory following were left out from tables of measured data (Table A.3 and Table A.4) in order not to distort the results of experiments.

On top of main purpose of the experiment, although display is implemented preferably as integrated, pilots were introduced to both standalone and integrated display conditions (described in chapter 3). Integrated display condition consisted of all information contained in one display, whereas standalone display condition had its mission located on dedicated monitor which could help to reduce the amount of clutter that might appear at once (e.g. when traffic is frequent). Since switching attention between two monitors seemed to be less comfortable than possible clutter, pilots agreed on preference of integrated display condition which was used during the whole experiment because of that.

Overall, pilots seemed most comfortable when recommended trajectories, especially with the option to automatically follow the trajectory. However, they agreed on that even if automatic trajectory following was not possible, they would still prefer to have recommended trajectory displayed as only an 'orientation route'. The main benefit of bands was seen in estimations of maneuver sizes, which led to less number of maneuver uploads compared to informative only configuration. Also, advanced feature predicted location of CPA turned out to have been frequently used by pilots to detect unsafe headings as well as correct inaccurate maneuvers.

Although observations were gathered during the experiment, the main issue of the experiment was the lack of experienced pilots. Eigth participants altogether is really insufficient number for an experiment, which also makes the observed data less valuable. Also, further effort should be put into more complex scenarios, which should take longer to complete, should consist of more intruder aircraft and should also involve different altitude levels of intruder aircraft as well as vertical maneuvers, which was left out of our experiments. Beside counterbalancing, more different and complex scenarios might also help to reduce the learning effect.

Chapter 7

Conclusion and future work

In this thesis, we implemented a DAA display and tested its features in an experiment with human pilots, with emphasis put on assisting features and their impact on pilot's performance.

At first, we took a look at existing standards in alerting and traffic depiction for UAS. To display surrounding traffic to pilot, specific symbols and alerting structures are used, derived as best practices from existing DAA systems such as [ACAS, 2015], [MIDCAS, 2015] or [TCAS, 2011].

Then, we described general requirements of DAA display as well as existing DAA display configurations. Display configurations were subjects of three main experiments described in [Fern, 2016] and offered different advanced features, which were tested for their contribution to pilot's performance. Specific features offered by individual display configurations were detailedly broken down.

One of the chapters was also devoted to the AgentFly simulation framework, using which the whole display was implemented. Framework offers tools for creating basic elements of vector graphics such as lines, points, texts or meshes as well as textures and materials, together with their effective rendering.

After that, we described display properties. Firsly, we mentioned graphic components of display and explained their purpose. Then, we described basic display features and the alerting structure that was implemented in the display and was used throughout the whole experiment. Advanced display features were also broken down, with focus put on suggestive and directive maneuver guidances which serve as assisting features for pilots and were described in more detail.

Finally, we proceed to the experiment itself. For the experiment, we created two scenarios with different missions and intruder flights (example shown in Figure 6.1). Eight participants were given the task to operate simulated UAV and safely navigate the UAV along scenario mission. Both scenarios had to be completed four times by the pilots, each time with different display configuration, denoted as C1, C2, C3 and C4. Configuration C1 was only informative and did not provide any maneuver guidance. Configuration C2 offered pilots with suggestive maneuver guidance which is presented as lateral and vertical bands. Configuration C3 provided pilots with directive maneuver guidance presented as recommended trajectories. Configuration C4 offered both suggestive and directive maneuver. For each configuration, we measured two different metrics - total distance traveled and average HMD from intruder aicraft. Vertical miss distance was left out due to unknown physical model of aircraft. Measured data (shown in Appendix A) were pairwise compared among all configurations for each metric separately and produced results in confidence intervals that estimated significance of differences between compared configuration pairs.

Results of experiments appeared to be similar to what we expected. As can be seen in Figure 6.2 and Figure 6.3, configuration C3 and C4 that both offer directive maneuver guidance produced better results in total traveled distance metric as well as in average HMD from intruder aircraft metric than combination C1 or C2. Combinations C1 and C2 did not show any significant difference compared to each other, which was caused by the presence of advanced feature predicted location of CPA. Neither combination C3 and C4 showed any significant difference compared to each other, since both configurations offered recommended trajectories that could be automatically followed. Overall, pilots expressed their interest mainly in directive maneuver guidance and in predicted location of CPA, when directive maneuver guidance was not present. However, configuration C2 offering bands led to less number of maneuver uploads which is also benefical. Experiments lacked a larger number of participants, which would make observed data much more valuable and accurate. Also, individual configurations should have been tested on more complex and real-based scenarios.

In future work, display should be extended to consider aircraft model, its physics and limitations. In the current stage of display, aircraft maneuvers are not continuous and their process is far from reality. To allow more accurate measurements, aircraft physics as well as both horizontal and vertical maneuver costs should be taken in account. In addition to this, if physical model of aircraft and maneuver costs are known, TrajectoryPlanner should be extended so that it considers the maneuver execution process and its duration, which would prevent the situations where alert thresholds are violated while automatically following recommended trajectory from happening (issue is more detailedly described in subsection 5.3.3). Also, as we would know the decision border when to prefer vertical or horizontal maneuver, trajectories calculated by TrajectoryPlanner should involve vertical maneuvers as well.

Furthermore, the environment in which simulations are running should include real conditions such as air conditions, wind direction or weather generally. In addition to this, scenarios should include intruder flights with real based trajectories including altitude and course changes. Also, more complex scenarios should be created, offering situations of different complexity levels as well as necessity of both horizontal and vertical maneuver execution.

This work will be used for future research of UAS integration into shared airspace carried out at the Department of Computer Science, Faculty of Eletrical Engineering, Czech Technical University in Prague.

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Appendix A

Measured data

This appendix contains measured data that were used for comparisons of individual display configurations and from which confidence intervals were computed. Data were collected from scenarios that participants had to complete with each display configuration.

Data are sorted to individual tables by corresponding display configuration.

C1: Informative only				
Participant	Average HMD [m]	Warning alert violations	Corrective alert violations	Total distance traveled [km]
Scenario 1, 3 intruder flights, 27.431 km length				
1	2853.33	0	0	35.045
2	2722.33	0	0	32.834
3	2625.67	0	1	36.989
4	2817	0	0	37.684
5	2557.33	0	1	36.781
6	2341	0	1	33.154
7	2667.33	0	1	34.514
8	2635.33	0	0	35.514
Scenario 2, 5 intruder flights, 39.468 km length				
1	3218.6	0	0	47.457
2	2753.4	0	0	48.615
3	2995.2	0	0	51.454
4	3072.4	0	0	53.874
5	2894	0	0	52.495
6	2762.6	0	0	46.599
7	2765.2	0	0	48.987
8	3090	0	0	49.754

Table A.1: Table of configuration 1 results

C2: Bands				
Participant	Average HMD from aircraft [m]	Warning alert violations	Corrective alert violations	Total distance traveled [km]
Scenario 1, 3 intruder flights, 27.431 km length				
1	2393.67	0	1	35.230
2	2576	0	1	34.818
3	2614	0	1	35.939
4	2489.33	0	0	33.785
5	2609.33	0	0	34.645
6	2584.33	0	0	34.989
7	2559.67	0	1	36.848
8	2627.67	0	1	34.484
Scenario 2, 5 intruder flights, 39.468 km length				
1	2690.8	0	1	52.928
2	2737.2	0	0	45.739
3	3243	0	0	50.306
4	2694.4	0	0	47.941
5	3031.2	0	0	46.926
6	2683	0	1	47.140
7	2683.6	0	0	48.389
8	2912.2	0	0	46.974

Table A.2: Table of configuration 2 results

C3: Recommended trajectories				
Participant	Average HMD from aircraft [m]	Warning alert violations	Corrective alert violations	Total distance traveled [km]
Scenario 1, 3 intruder flights, 27.431 km length				
1	2331.67	0	0	30.375
2	2346.67	0	0	30.645
3	2317.33	0	0	30.659
4	2312.67	0	0	30.344
5	2365.33	0	0	30.657
6	2374.33	0	0	30.546
7	2335	0	0	30.278
8	2298.33	0	0	30.214
Scenario 2, 5 intruder flights, 39.468 km length				
1	2328.4	0	0	43.122
2	2459.4	0	0	43.441
3	2489.8	0	0	43.617
4	2511.4	0	0	43.471
5	2499.6	0	0	43.745
6	2584.6	0	0	44.775
7	2560.6	0	0	43.564
8	2493	0	0	43.986

Table A.3: Table of configuration 3 results

C4: Bands + Recommended trajectories				
Participant	Average HMD from aircraft [m]	Warning alert violations	Corrective alert violations	Total distance traveled [km]
Scenario 1, 3 intruder flights, 27.431 km length				
1	2314	0	0	30.272
2	2306.67	0	0	30.460
3	2376.67	0	0	30.556
4	2359.33	0	0	30.224
5	2393	0	0	30.415
6	2367	0	0	30.781
7	2286.67	0	0	30.178
8	2342.67	0	0	30.515
Scenario 2, 5 intruder flights, 39.468 km length				
1	2458	0	0	43.412
2	2468.8	0	0	43.225
3	2495.2	0	0	43.512
4	2536	0	0	43.958
5	2791.2	0	0	44.552
6	2589.6	0	0	44.417
7	2522.4	0	0	43.272
8	2505.6	0	0	43.716

Table A.4: Table of configuration 4 results

Appendix B

DVD Contents

This chapter contains list of files that are contained on the disc.

/src.zip	Archive with source codes of display implementation.
/thesis.pdf	Thesis in PDF format.
/thesis_src.zip	Archive with source codes of this thesis.