TRAFFIC VISUALIZATION IN HELMET-MOUNTED DISPLAYS IN SYNCHRONIZATION WITH NAVIGATION DISPLAYS

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Abstract

One of the major challenges for helicopter pilots are low level flights and landings in degraded visual environments. Without proper assistance systems, the pilots are prone to lose their situational awareness when fog, heavy precipitation, limited sunlight and stirred-up sand or snow degrades their view. In recent years, various synthetic and enhanced vision systems were developed so as to assist the pilots in these demanding situations. We enhance the existing systems by proposing a concept for the visualization of traffic information in head-mounted displays. The intuitive representation provides additional cues about the environment and decreases the pilots' workload, especially during flights in offshore windparks or while search and rescue operations with many other vehicles operating within a small range.

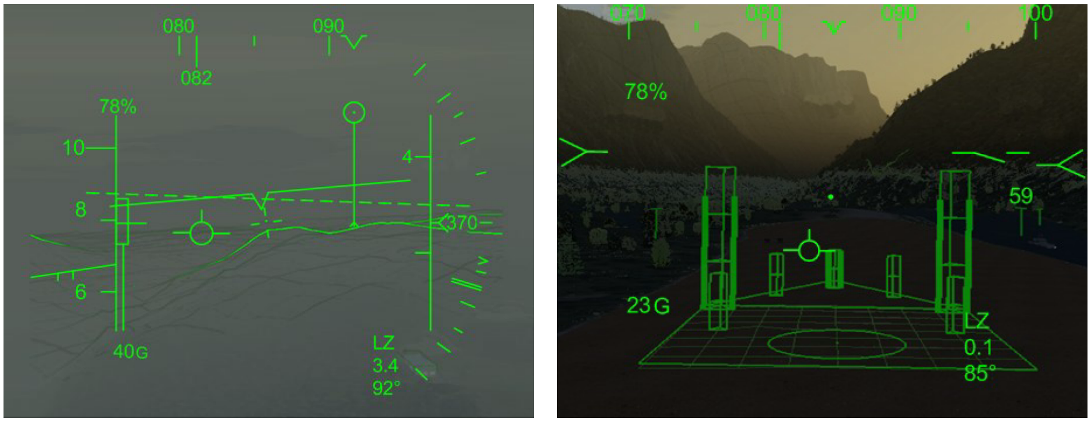
Introduction

In modern helicopter flight decks, Enhanced Vision Systems (EVS) incorporating head-tracked Head-Mounted Displays (HMDs) are used to improve flight safety, especially during operations in Degraded Visual Environments (DVEs) such as brownout landings and flights during night-time or in adverse weather conditions [1], [2]. These displays decrease the pilot's head-down time and increase his situational awareness by displaying important information virtually superimposed on the out-the-window view. As can be seen in Figure 1, this involves simple two-dimensional symbols like the speed and altitude tapes but also three-dimensional symbology. The latter conforms with the real world behind in order to highlight terrain contours or a desired landing location.

Within the framework of the Next Generation Air Transportation System (NextGen)[3] and the Single European Sky ATM Research (SESAR)[4], a new aeronautical surveillance system called Automatic Dependent Surveillance-Broadcast (ADS-B) has been introduced. This satellite-based technology allows for precise determination of an aircraft's, ground vehicle's or ship's position, speed and supplemental data, which is then broadcast to be received by air traffic controllers and other vehicles in the vicinity.

Our key idea is to combine the benefits of these two existing technologies by visualizing received ADS-B data of surrounding traffic on an HMD. Such a system will assist helicopter pilots flying in offshore windparks or taking part in search and rescue operations where many other vehicles operate within a small range. Example situations are given in Figure 2.

Since the pilots have to cope with high workload during such scenarios, the traffic visualization has to present the required information in a way that is easy and intuitive to use and does not unnecessarily distract the pilot. To achieve this and to conform with additional requirements of head-mounted see-through symbologies, we developed an integrated traffic visualization concept: a head-down and a head-mounted display complement each other in their roles so as to combine the advantages of both representations. For the synthetic ADS-B input data, we adapt a clustering algorithm to analyze the high-dimensional traffic data in order to identify groups of similar traffic that can be visualized by a single symbol in the HMD. This cluster information is used to avoid display clutter by decreasing the number of rendered symbols. In addition, we present a special symbology that offers supplemental information about the cued traffic group. This includes parameters such as the number and type of the contained vehicles as well as a measure of the formation's threat potential, based on the predicted closest point of approach. To further



(a) (b)

Figure 1. The head-mounted symbology of the *SFERION*® pilot assistance system by Airbus Defence and Space [2]. (a) 3D conformal symbology (terrain grid with contour lines) overlaid with 2D symbology. (b) 3D conformal landing symbology with doghouse.

(a) (b)

Figure 2. Exemplary scenarios where a head-mounted traffic display increases the situational awareness. (a) A close formation of Coast Guard helicopters [5]. (b) Two helicopters operating inside an offshore windpark [6].

decrease the pilot's workload by avoiding distracting changes in the visual representation of clusters, a smooth transition visualization algorithm is developed for splitting and merging clusters.

Related Work

Related work includes an explanation of the ADS-B technology, a presentation of the TCAS and a brief overview of cluster analysis. Furthermore, work related to head-mounted displays for increasing situational awareness in helicopters is presented.

Automatic Dependent Surveillance-Broadcast: According to ICAO Doc 9924 [8], an Aeronautical Surveillance System "provides the aircraft position and other related information to Air Traffic Management (ATM) and/or airborne users". In its simplest realization, it provides only the aircraft's position at a certain time. More advanced designs allow the user to get information on the identification, the speed, the intent and other characteristics of the aircraft. Depending on the technologies used, it can be distinguished between three major types of aeronautical surveillance systems: Independent Non-Cooperative Surveillance, Independent Cooperative Surveillance and Dependent Cooperative Surveillance [7].

While Independent Non-Cooperative Surveillance systems do not rely on the co-operation of the aircraft, which means that an aircraft does not have to be equipped with any on-board surveillance equipment to be detect-able, Independent Cooperative Surveillance systems communicate with the aircraft to be identified. Therefore, it is possible to request

Table I. Overview of aeronautical surveillance systems [7].

Category		Technology
Independent	Non-Cooperative	Primary Surveillance Radar (PSR) Multi-Static Primary Surveillance Radar (MSPSR)
	Cooperative	Secondary Surveillance Radar (SSR) (Mode A, C, S) Wide Area Multilateration (WAM) Multi-LATeration (MLAT)
Dependent	Cooperative	Automatic-Dependent Surveillance Broadcast (ADS-B)

supplemental data such as the identification or the current airspeed. To do so, each aircraft hast to be equipped with a radio receiver and transmitter, referred to as transponder. Examples of independent cooperative surveillance technologies are Secondary Surveillance Radar (SSR), Wide Area Multilateration (WAM) and Multi-LATeration (MLAT) [7], [9].

The ADS-B system we require for our traffic visualization approach is a Dependent Cooperative Surveillance system. This kind of surveillance systems depend on a system that enables the on-board determination of the vehicles position, for instance a GPS receiver. This information is then broadcast together with supplemental data. The data provided by the ADS-B system and used for our visualization is the identification ID, position, velocity, air/ground state and heading of the vehicle.

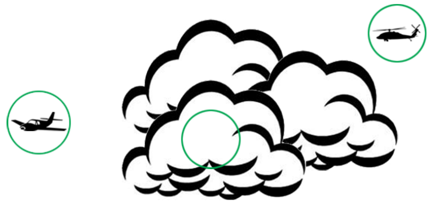
Traffic Alert and Collision Avoidance System:
TCAS is an Airborne Collision Avoidance System that works independently of airborne navigation equipment and ground-based systems, only based on the direct communication of aircraft via their transponders.

The central TCAS unit processes all responses and applies a special logic to the classification of each intruder into three categories: *Proximate Traffic*, *Traffic Advisory (TA)* and *Resolution Advisory (RA)*. The remaining aircraft are declared *Other Traffic*. According to this classification, an intruder is highlighted on the Cockpit Display of Traffic Information, triggers an aural annunciation (TA) or even initiates the display of instructions on how to solve the conflict (RA). The TCAS threat detection is based on the concept of the warning time τ, which is an approximation of the time to the Closest Point of Approach (CPA) between ownship and intruder. The lower this measure, the higher is the threat potential of the target aircraft. The full TCAS description as well as the definition of the different dimensions of the spaces for RA and TA and the threat resolution logic is given in the ACAS Guide [10].

Cluster analysis:
Cluster analysis is one of the central methods used in the field of data mining, which is a key step within the discovery of knowledge in databases [11]. It has been utilized in various fields of science including image segmentation, artificial intelligence research, big data analysis on data derived from different fields such as geology or biology. This vast number of applications with different prerequisites and requirements yields numerous algorithms for the identification of clusters in large data sets. For our work, the DBSCAN algorithm introduced by Ester et. al [12] is applied to the classification of traffic information. For a more thorough description of existing clustering methods one can consider [13], [14], [15] and [16].

Head-Mounted Displays for Increasing Situational Awareness:
Melzer [17] describes HMDs as "powerful tools that can unlock the pilot from the interior of the cockpit or the forward line of sight of the Head-up Display". As a result, the displays "can enable the pilots to do their job more effectively while simultaneously decreasing workload" [17]. One major goal in the development of HMD symbologies is the improvement of the pilot's situational awareness.

A particular challenge is the development of pilot assistance systems that increase the pilot's situational



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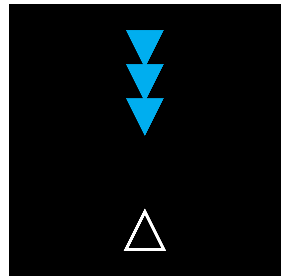

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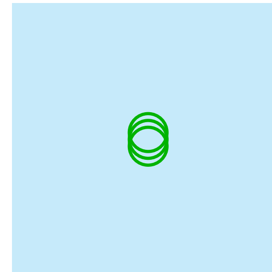


(c)

Figure 3. Illustration of a possible traffic situation causing overlapping symbols on the HMD. (a) A basic traffic visualization on the HMD - visible and invisible traffic highlighted with circles. (b) Head-down Display - top view. (c) Head-mounted Display - overlapping symbols.

awareness during low level flights and landings in DVE. Degraded vision due to fog, heavy precipitation, limited sunlight and stirred-up sand or snow can cause spatial disorientation and lead to fatal accidents. The German Aerospace Center (DLR) as well as Airbus Defence and Space conduct research within this field so as to enhance the pilot's performance in such situations [1], [2]. Both follow a three-dimensional, visual-conformal visualization approach since this scene-linked presentation of information is a proofed concept that facilitates the mental processing and fusion of both impressions, the outside scene and the symbology [18]. It implies that, for instance, obstacle symbols on the HMD are virtually superimposed on the underlying real world scene so that they appear at the location where the pilot would see the real obstacle if the view was not degraded.

Overview

For the visualization of our cluster approach, we use renderings on a head-mounted display as well as on a head-down display (HDD). Target aircraft are cued by displaying a symbol superimposed on the real aircraft in the outside view. In Figure 3a such a visual-conformal symbology is sketched that highlights other aircraft with a framing circle. For the Head-Down Display rendering every vehicle with a certain symbol is sufficient (Figure 3b), while in the Head-Mounted Display such visualizations could lead to cluttering effects (Figure 3c).

Both display types, HMD and HDD, play complementary roles in the integrated traffic visualization concept:

Head-Down Display:

- Provides an overview of the traffic situation, from which the pilot can easily estimate horizontal distances and tracks of other aircraft.
- Incorporates an interface through which the pilot can select nearby aircraft so as to receive additional information and highlight them in the head-down and in the head-mounted visualization.
- Adapts the aircraft symbol according to the threat potential of the intruder.

Head-Mounted Display:

- Supports quick locating of relevant traffic.
- Includes as much important information as possible in order to decrease the pilot's head-down time, but not more than needed to avoid cluttering.
- Allows the pilot to de-clutter the display by excluding irrelevant traffic.
- Applies a clustering algorithm and an advanced symbology in order to avoid overlapping traffic symbols and to densely pack available traffic information.

System Architecture: The ADS-B traffic visualization software is designed as an add-on to Airbus Defence and Space' advanced synthetic vision system [19]. The ADS-B traffic visualization implementation comprises five major modules: Traffic Input, Traffic Processing, Head-Down visualization, Basic

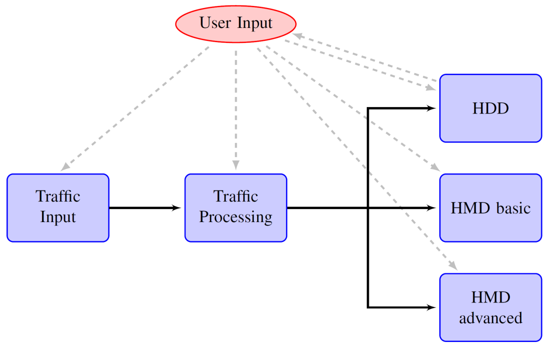


Figure 4. The system architecture of the ADS-B traffic visualization software.

HMD rendering and Advanced HMD visualization. The relations between these subsystems as well as an additional user input are sketched in Figure 4.

The Traffic Input module receives and converts ADS-B messages broadcast by surrounding aircraft and ground vehicles. One current ADS-B message for each traffic participant is generated and sent to the subsequent module. Within the Traffic Processing subsystem, the received ADS-B messages are further processed and the parameters required by the traffic displays are derived. The output comprises all quantities included in the synthetic ADS-B data as well as additionally computed parameters such as the distance to the ownship. The values can either be based directly on last message received or be derived from an interpolation between the last two stored messages. An interpolation of these values yields the possibility of a smooth visualization. For different displays types, varying visualizations are provided: The HDD traffic visualization is inspired by current Cockpit Display of Traffic Information designs, with additional features so as to support the concept of the integrated head-mounted and head-down traffic visualization. For the HMD we implemented a straight-forward traffic visualization approach as given in Figure (3a) and (3c) as reference for our more sophisticated visualization. This more advanced HMD subsystem is the key part of our work. This subsystem incorporates all processing required to realize a head-mounted traffic symbology that presents valuable information to the pilot. This includes clustering as well as the generation of a de-cluttered, smooth traffic representation. The user is able to adapt the appropriate parameters for the Traffic Processing as well as the configuration for the visualizations.

Advanced Traffic Visualization in Head-Mounted Displays

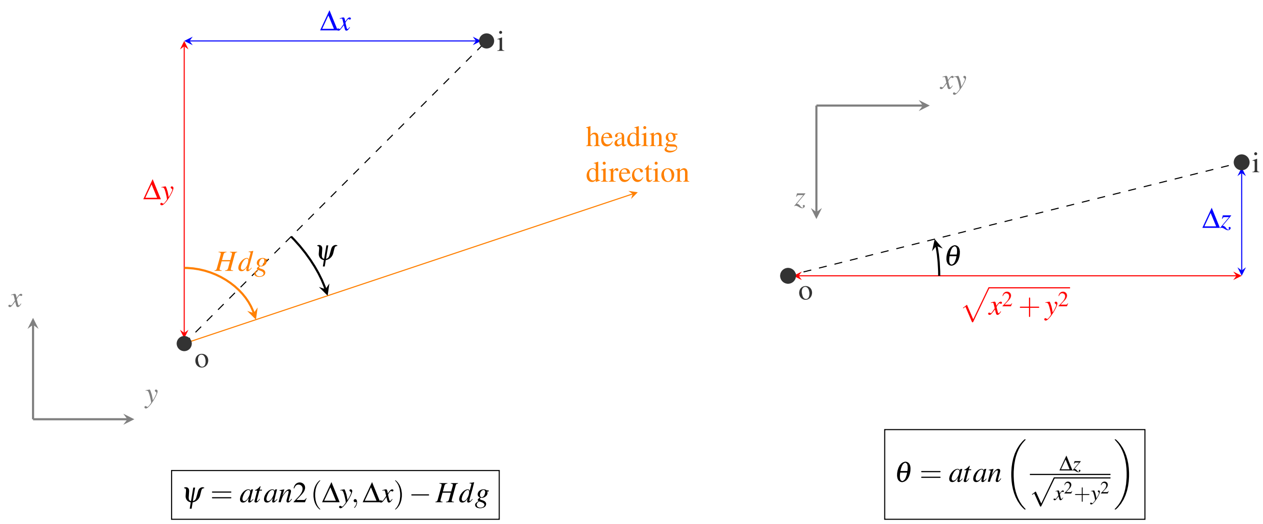
This section describes the development and implementation of the advanced traffic visualization in HMDs. As stated above, this module is integrated with the head-down traffic display. Recalling the role definition of the head-mounted module within the overall traffic visualization concept, the central requirement is that the advanced traffic visualization in head-mounted displays should include as much important information as possible in order to decrease the pilot's head-down time, but not more than needed to avoid cluttering. Thus, the definition of an advanced visualization strategy is started with the identification of methods for de-cluttering the HMD while presenting all relevant information in a way that conforms with the requirements of head-mounted see-through symbologies.

De-Cluttering of the Display:
Rendering the received position data of all surrounding ADS-B-equipped vehicles can lead to many overlapping traffic symbols and unnecessary information on the HMD. Figure 5 shows such a traffic situation, where 11 other ADS-B equipped vehicles are visible for the pilot: two groups of ground vehicles below, three aircraft flying towards the ownship, three intruders crossing the own flightpath from left to right and one single aircraft departing from the ownship on the left side. For head-mounted renderings, we propose to group intruders that operate close to each other and in a similar way and represent them by a single HMD traffic symbol instead of overlapping icons.

Due to the movement of the own and other aircraft, groups of similar traffic will be split up into new clusters, others will fuse as well as various groups will overlap on the screen occasionally. This emphasizes the need for a strategy for **merging and dividing** different clusters and visualizing that process smoothly for the pilot not to get distracted.

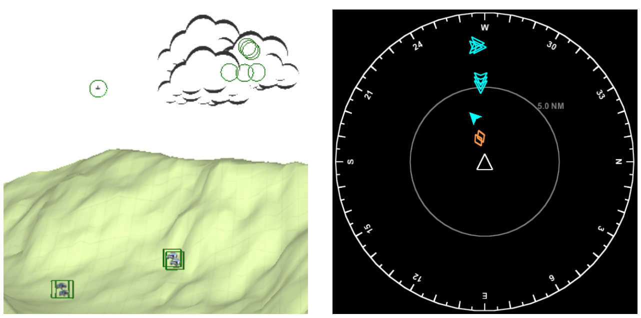
In summary, the realization of a visualization method for groups of similar traffic can be divided into three steps:

1) Identification of traffic groups
2) Graphical representation of these clusters
3) Smooth visualization of cluster fusions and splittings



(a) Azimuth ψ. (top-down view) (b) Elevation θ. (side view)

Figure 6. The calculation of the three-dimensional bearing (ψ, θ) of an intruder i relative to ownship o based on their positions (x, y, z) in a world-fixed North-East-Down frame of reference.



(a) (b)

Figure 5. Example of a traffic situation resulting in cluttering. (a) Cluttered visualization of two groups of ground vehicles (squares), two groups of airborne traffic and one single aircraft (circles). (b) Head-down traffic display showing a top-down view of the same situation as in (a).

Clustering to Identify Groups of Similar Traffic: In general, clustering algorithms try to group a set of *patterns*, here the feature vector of an aircraft, into different *clusters* based on their *similarity*. The result is that objects which are similar to each other belong to one cluster while objects that are dissimilar are assigned to different clusters. It can be stated that a group of similar traffic should contain vehicles that operate **close to each other** and **in a flight formation**. Additionally, further investigations revealed that these vehicles must also appear **close to each other on the HMD**. The features we use can be derived from the basic received ADS-B data:

- **Spatial proximity:**
  Geometric position
- **Similar flight formation:**
  Track angle
  Speed
  Air/Ground state
- **Closeness on the HMD:**
  Relative three-dimensional bearing

All aircraft belonging to one group operate nearby the other members of their group. However, this must not be the only feature to be compared because different aircraft formations fly close by each other, for example when their routes cross. Thus, solely spatial proximity does not form a group of similar traffic. Similar behavior of the group members is ensured by clustering vehicles based on their track angle and speed. Moreover, the air/ground state broadcast via ADS-B is a suitable feature to separate airborne from surface traffic. Finally, the proximity of the cluster members on the HMD is covered through the relative three-dimensional bearing (ψ, θ). The calculation of this feature, which represents the azimuth and elevation angle of a vehicle as seen from the ownship, is illustrated in Figure 6. The features used for clustering can individually changed.

Clustering Procedure:
For the clustering of the vehicles into groups of similar traffic the DBSCAN [12] algorithm is adapted. The main reasons for choosing this algorithm are that it does not require prior knowledge about the number of clusters, that it relies on one input parameter only and that it is able to detect clusters of arbitrary shape as well as noise. Furthermore, its density-based notion of clusters allows for the development of an adapted algorithm which is intuitively to use. We adapted the Euclidean distance function that is used by the DBSCAN to be able to handle different scales than metric scales.

The selected features comprise a binary value, the air/ground state, and many values with continuous data types measured on different scales, for instance the speed expressed in knots or the track angle in degrees. To derive a composite dissimilarity measure, one can normalize all continuous values to a range from 0 to 1 and combine the results based on a chosen weighting to one single dissimilarity measure. The Gower similarity coefficient is a well-known example of such a composite measure [20]. Nevertheless, such an approach implicates the additional challenges of how to weight the different features and how to choose a threshold for this complex distance measure.

To avoid these problems, a different idea is pursued by our work. Instead of a single distance, the region query checks the dissimilarity of all selected continuous features i separately against an associated threshold ε_i. This means that for the assessment of the spatial proximity, the Euclidean distance between the three-dimensional ownship and intruder positions is compared with the chosen threshold $\varepsilon_{Position}$. Likewise, the differences between the track angles, the speed and the bearing angles are checked. Only if every test succeeds, the respective vehicle belongs to the ε-neighborhood. To separate airborne from ground traffic, both types of vehicles are clustered individually.

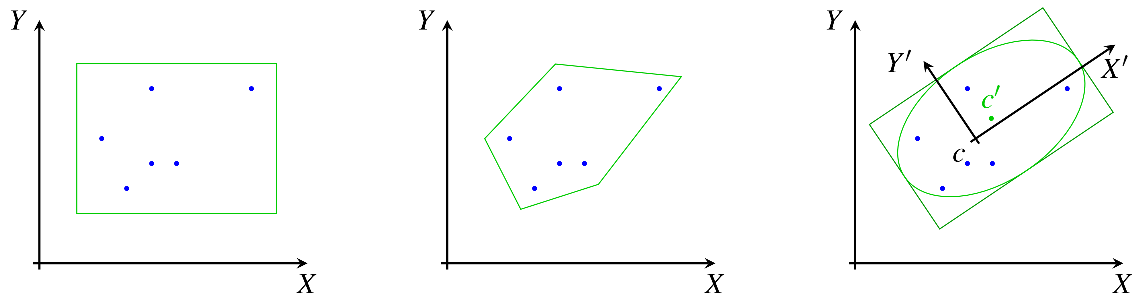
The `minPts` parameter of the DBSCAN is set to two, implying that only single vehicles without any other vehicle in their ε-neighborhood are labeled as noise. In a post-processing step each of these vehicles receives a unique cluster ID which is a requirement for the input of the smooth transition visualization.

Traffic Group Symbology

In order to represent the identified groups of similar traffic on the HMD screen, we developed a visualization with two-dimensional symbols. These symbols are used to support the pilot in the detection of surrounding traffic by indicating the position of the cluster. Figure 7 shows a few approaches which were developed to fulfill this task. Each sub-figure sketches the same traffic situation in window coordinates (X, Y), while the projected positions of the six vehicles, represented by red dots, are framed by a different symbol in each case.

The straight-forward approach in Figure 7a applies a rectangle enclosing all vehicles. However, the box, which is aligned with the axes of the window coordinate frame, also covers areas where no vehicles reside. The convex hull, sketched in Figure 7b, overcomes this drawback by finding the surrounding polygon, for instance by means of the gift wrapping or Jarvis march algorithm [21]. This results in a great many symbols of various, continually changing shapes, which depend on the number and arrangement of the involved vehicles. Therefore, defined symbols like the ellipse and the rectangle presented in Figure 7c are favored for the visualization of traffic in HMDs. In order to resolve the problems encountered in the first approach, the symbol is turned in the direction of the principal axes X', Y' of the traffic group. To clearly differentiate airborne from ground traffic, we decided to visualize air traffic by an ellipsoidal and ground traffic by a rectangular symbol. As can be seen in Figure 7c, the parameters of the ellipse and the rectangle are defined in the principal coordinate system. This direction, where the data shows the largest variance, can be found by performing a PCA [22].

Smooth Merging and Splitting of Traffic Groups:
With the knowledge about the clustering and the group symbology, all methods needed for the realization of an advanced traffic visualization that decreases the occurrence of overlapping symbols are available. By rendering the ellipse or rectangle for each cluster every time, new ADS-B information is retrieved, yields abrupt changes of the traffic symbols if two or more clusters merge to one single cluster or if a cluster splits up into several smaller traffic groups. This poses the risk of distracting the pilot by



(a) (b) (c)

Figure 7. Different approaches to the visualization of a traffic group. (a) A framing rectangle aligned with the window coordinate frame. (b) The convex hull of a traffic group. (c) An ellipse and a rectangle oriented to the principal axes of the traffic group.

unnecessarily drawing his attention to these events. To avoid these undesired sudden changes of the cluster representation, we present a procedure for the smooth visualization of the transitions between partitioned and merged traffic.

The smooth visualization is conducted in intervals of a certain length or number of iterations N. In the first iteration of each interval, when $i = 0$, the current traffic is clustered and the fusion and splitting processes to be visualized within this interval are determined. During all following iterations $(0 < i < N)$ until the end of the interval no clustering is performed again. Instead, the unchanged group symbols are rendered and the identified transitions between the traffic groups are visualized incrementally. This stepwise change from the initial to the final symbols of the particular fusion or splitting is controlled by the Smooth Transition Progress, which represents a ratio of elapsed to total time of the interval.

The scenario comprises three aircraft represented by red dots (Figure 8), which constituted two clusters after the previous visualization interval. The clustering performed in the first iteration of the current interval delivered a new cluster comprising all three aircraft. The corresponding symbol, which shall be the final result of the transition process, is illustrated by the black ellipse in the left image of Figure 8. The standard visualization of the clustering results would instantaneously draw this new cluster, the smooth visualization proposed here, however, visualizes a successive transition from the initial to the final traffic symbols.

Figure 8 sketches a timeline of the step-wise transformation of the traffic symbols, from the initial ellipse and circle on the left side to the final ellipse on the right side. At the beginning of the visualization interval the two input symbols are opened up. Afterwards, during the visualization iterations of the current interval, the resulting curves are adapted incrementally until the final symbol shape is reached. Figure 9 shows an excerpt of the same merging process as above, however with additional information on important details of the smooth transition algorithm.

Each traffic symbol is composed of several line segments connecting two adjacent vertices. During the creation of the traffic group symbols, these corner points are determined in the local principal coordinates (X', Y') of each symbol and afterwards transformed back to window coordinates (X, Y) for drawing. In Figure 9, the vertices of the two input symbols, $\mathbf{S}_{1,j}$ and $\mathbf{S}_{2,j}$, an ellipse and a circle, are illustrated by the light blue dots, while black dots show the vertices of the output ellipse, $\mathbf{S}_{0,k}$. Furthermore, the corner points of the currently drawn symbols, $\mathbf{S}'_{1,i}$ and $\mathbf{S}'_{2,i}$, are illustrated by the dark green dots on the green lines. Finally, the geometric centers C_1, C_2 and C_0 of the symbols S_1, S_2 and S_0 are depicted as dark blue dots. The algorithm for the computation of the current vertices to draw can be divided into three tasks:

1) Find the points where the two input symbols are opened up (magenta dots).
2) Determine a starting point for the mapping of the input to the output vertices (orange dot) and assign each point of the input symbols to a vertex of the output symbol (gray lines).
3) Interpolate the resulting points of the currently drawn shape (green dots) based on the previously determined mapping.

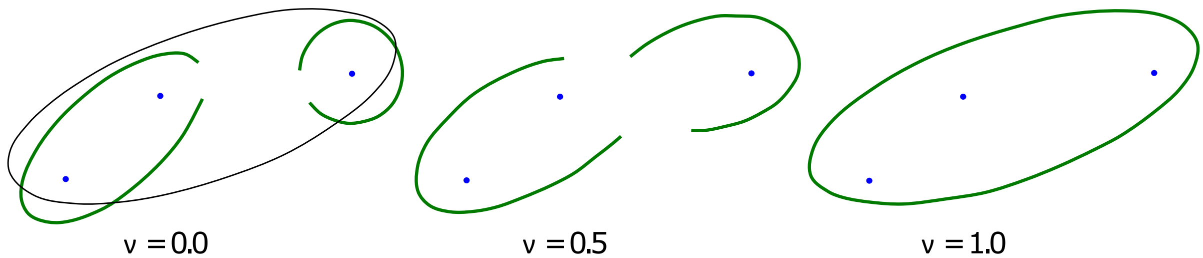


Figure 8. The step-wise transformation of the traffic symbols beginning with a clustering iteration ($v = 0.0$) followed by several visualization iterations ($v = 0.5$ and $v = 1.0$). The convex hull of the detected cluster is depicted as a black line.

The fusion and splitting algorithm presented above has two constraints that need to be considered for the determination of the transitions to be visualized in the subsequent visualization interval. First, only two symbols can be merged at once and a cluster can only be split up into two distinct parts during a single visualization interval. Second, a symbol can only be involved in one transformation process simultaneously; it can not be part of a fusion and a splitting in the same interval. The method we propose to generate such transitions between the previous and the current clusters is shown by the example scenarios in Figure 10.

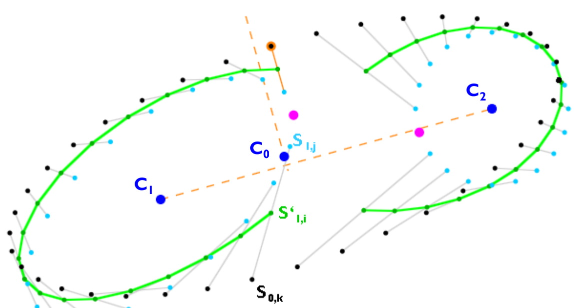


Figure 9. Details of the smooth transition algorithm.

By comparing the initial constellation with the desired final result, three separate transition processes can be identified:

- fusion of the previous cluster p_0 and the left part of the previous cluster p_1 to the current cluster c_0.
- splitting of the previous cluster p_1.
- merging of the previous clusters p_2, p_3 and the right part of p_1 to the current cluster c_1.

The required symbol transformations conflict with both constraints of the smooth transition visualization stated above. First, the final cluster c_1 is a result of the fusion of more than two input symbols. Second, the previous cluster p_1 is part of two fusions and one splitting process at the same time. Consequently, the final traffic group symbols detected by the clustering can not be reached within this visualization interval. Instead, all fusions and splittings which are permitted simultaneously will be determined and forwarded for drawing. This status is saved as initial constellation for the following visualization interval, which implies that all transformations that are not performed now will be made up later if the clustering does not change in the meantime. In conclusion, the whole transition process of the symbols in this example spans over two visualization intervals with an intermediate step as depicted in the right half of Figure 10.

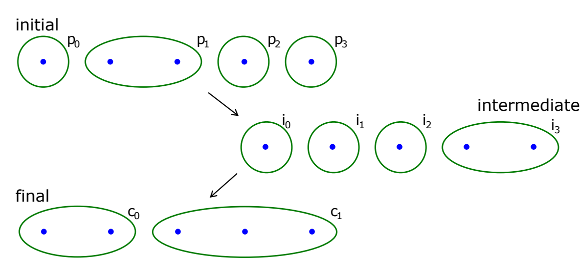


Figure 10. Example of a multiple fusion and splitting process with intermediate visualization step.

The whole process is predicated on the comparison between the resulting situation of the previous visualization interval and the new desired constellation determined by the current clustering. These initial and final situations are contrasted by means of the assignment of the vehicles to the clusters. For the implementation it must be noted that the clustering does not ensure that the same traffic groups receive the same Cluster ID in two consecutive visualization intervals, which means that even vehicles that remain in the same cluster can have different Cluster IDs in the previous and the current situation.

With this information at hand, the algorithm can be divided into two consecutive parts for the identification of splittings and fusions. Splittings are processed first since this decreases the number of required intermediate steps in many situations. The smooth visualization of the situation in Figure 10, for instance, would necessitate two additional intermediate steps if the order was reversed.

For the detection of splittings, each previous cluster with more than one member is checked. A splitting occurs if the current cluster IDs are not the same for all vehicles of the respective previous cluster. In other words, the vehicles of this traffic group are now part of at least two different clusters, which requires the visualization of a splitting. To avoid that this previous cluster will be used for a fusion later, it is marked as processed before the two output clusters are identified. Finally, the whole splitting process is stored for visualization.

In the example scenario this part of the algorithm recognizes that vehicle 1 and 2 in the previous cluster p_1 received different cluster IDs c_0 and c_1. Thus, it triggers the splitting of the cluster into i_1 and i_2 and marks p_1 as processed.

The consecutive identification of fusions works in a similar way by checking which final cluster is constructed of at least two previous symbols that were not part of a splitting before. However, the determination of the input and output symbols is different as the algorithm must account for situations were the current cluster is composed of three or more previous clusters. In this case, not all incoming symbols can be fused at once but pairs of two clusters can iteratively be merged until fewer than two are remaining. The same problem is coming up, if a cluster splits up in more than two new clusters as given in Figure 11.

Since only one of the three occurring splittings can be executed in the first interval, it is important to choose a proper partitioning of the four involved vehicles into the two intermediate clusters. The favorable subdivision for this exemplary case is depicted on the right side of Figure 11. First, the algorithm avoids overlapping symbols because it keeps the adjacent vehicles 0 and 1 as well as 2 and 3 merged. Second, the procedure allows for a simultaneous execution of the two remaining splittings as it distributes the four vehicles evenly over the two intermediate clusters. If three aircraft were grouped into one intermediate cluster, two instead of one additional visualization interval would be needed to reach the desired final state. Without going into the exact details, the basic idea of the algorithm is to first find the two final clusters with the greatest distance in between, here c_0 and c_3. Subsequently, the chosen clusters are used as seeds for constructing the two intermediate symbols as the respective nearest remaining final clusters, here c_1 and c_2, are alternately distributed between them.

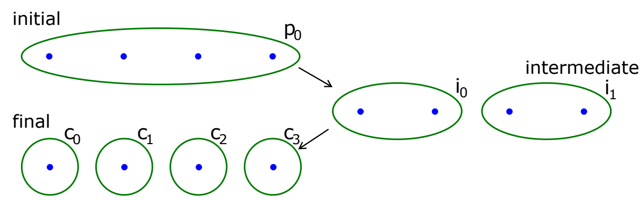


Figure 11. Splitting a cluster into more than two distinct traffic groups.

Visual Threat Potential

The second major part of the advanced traffic visualization in HMDs besides the de-cluttering is the visual coding of important traffic parameters which are not directly visible from a simple perspective projection of the traffic positions. A suitable traffic visualization on the HMD must employ additional techniques to present the required information to the pilot: The threat potential measure.

One could label every traffic symbol with additional information such as altitude or vertical speed trend as it is done in the head-down traffic display. Such an approach was chosen by Wong et al. [23]. Moreover, the size of the symbol could be increased as the intruder comes closer to the ownship or the flight direction could be visualized by using arrows as traffic symbols. However, for our approach it was decided to condense all this information to one single measure, the threat potential, so as to reduce display clutter. Supplemental data on every target aircraft shall be retrieved from the HDD.

This approach follows the maxim that only the most important information is visualized head-mounted.

Threat Potential Measure The main question for a pilot facing an intruder in the vicinity of his aircraft is, if the other aircraft poses a potential threat and if he is required to take any corrective action or if he can continue his flight as planned. This is influenced by many parameters such as positions, speeds and tracks of both the ownship and the intruder. Only certain combinations of these parameters make a nearby aircraft a potential threat. However, the pilot needs to decide in short time if he must react or if he can ignore a target aircraft. Therefore, TCAS provides a Threat Potential Measure calculation method that is based on the Closest Point of Approach (CPA). The approach taken by the TCAS is highly affected by the restricted knowledge of the encounter geometry. Because of ADS-B providing complete position and velocity vectors, a three-dimensional vector analysis of the scenario can be performed instead of using the TCAS approach of dividing the range by the range rate.

To simplify the computations, the positions and velocities of the involved aircraft (ownship o, intruder i) are transformed to a relative frame of reference, whose static origin is located at the intruder position (Figure 12). The point of the predicted closest approach of intruder and ownship is represented by the position vector $\mathbf{p}$. In terms of the known relative position $\mathbf{x} = \mathbf{x}_o - \mathbf{x}_i$ and the relative velocity $\mathbf{v} = \mathbf{v}_o - \mathbf{v}_i$, it can be expressed as

$$\mathbf{p} = \mathbf{x} + t_{cpa} \cdot \mathbf{v} \tag{1}$$

where t_{cpa} is the unknown time at which the closest point of approach is reached.

In order to derive an equation for the determination of this parameter, the vector $\mathbf{w}$ is introduced. As can be seen in Figure 12, t_{cpa} can now be described as the ratio between the lengths of the vectors $\mathbf{w}$ and $\mathbf{v}$

$$t_{cpa} = \frac{|\mathbf{w}|}{|\mathbf{v}|}. \tag{2}$$

Furthermore, $|\mathbf{w}|$ is related to $|\mathbf{x}|$ via basic trigonometry $|\mathbf{w}| = |\mathbf{x}| \cdot \cos\phi$, where $\cos\phi$ can be expressed through the scalar product of the adjacent vectors as $\cos\phi = \frac{-\mathbf{x}\circ\mathbf{v}}{|-\mathbf{x}|\cdot|\mathbf{v}|}$. Combining these two expressions, substituting the result into Equation 2

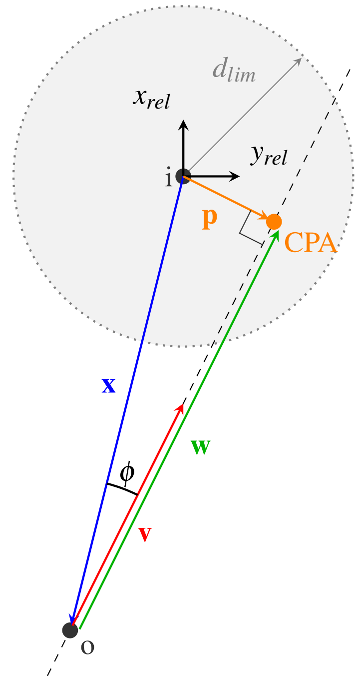


Figure 12. Definition of the parameters used by the Euclidean vector algebra method (w parallel shifted for better visibility).

and reducing the resulting fraction yields a simple equation for the time of the closest point of approach:

$$t_{cpa} = -\frac{\mathbf{x}\circ\mathbf{v}}{|\mathbf{v}|^2} \tag{3}$$

As it turns out, this definition of t_{cpa} is similar to the one derived by [24], however via a different approach.

Finally, the calculated t_{cpa} is substituted into 1 in order to compute the miss distance of both aircraft at CPA

$$d_{cpa} = |\mathbf{p}| = |\mathbf{x} + t_{cpa} \cdot \mathbf{v}|. \tag{4}$$

The final Threat Potential Measure is the normalized value of t_{cpa}, that is color-coded for visualization purposes.

Results

In summary, the preceding chapter presented several methods for the de-cluttering of the HMD and for the graphical representation of important information in a way that fulfills the head-mounted see-through requirements. The former includes a range and altitude filter function, a relevance filter via the threat potential and a method for identifying groups of similar traffic which can be visualized by a single symbol. The latter includes reference lines to support the qualitative assessment of an intruder's relative position as well as the graphical representation of a threat potential, which constitutes an intuitive way to quickly recognize the most relevant intruders. This section illustrates how all these features are combined to the final prototype version of the advanced traffic visualization where the HMD symbology is connected to the head-down visualization.

Figure 13. The traffic visualization as seen by the pilot wearing an HMD.

Figure 13 shows a screenshot of the developed symbology. The image was recorded in a flight simulator at Airbus Defence and Space, into which the software is integrated. For demonstration purposes, the outside view is overlaid with the head-mounted symbology in order to simulate the pilot's view of the scene through the combiner of the HMD. In general, airborne traffic is highlighted by ellipsoidal shapes whereas ground traffic is represented by rectangular symbols. The head-mounted visualization of both vehicle types can be switched off separately on the implemented HDD. In this exemplary situation a group of airborne traffic with a high threat potential is visible in the upper left corner. To the right of this cluster, a single aircraft with a medium threat potential measure can be seen. Finally, the fusion of two ground vehicles is captured on the right side of Figure 13.

As mentioned above, the head-mounted traffic representation is connected to the implemented head-down traffic display. Figure 14 illustrates the realization of this connection via a selection mechanism. A selected vehicle is visualized by a magenta HMD symbol. At the same time, it is highlighted magenta

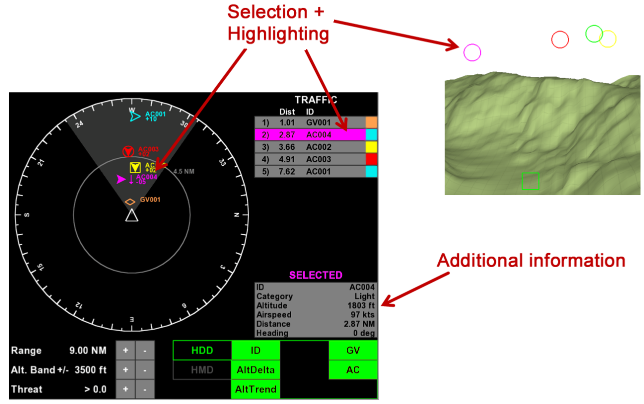
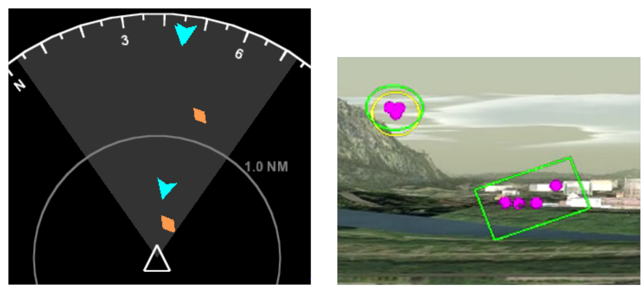


Figure 14. The connection between HMD and HDD.

within the traffic list and the heading rose on the HDD. Supplemental information about the selected vehicle can be retrieved from the head-down info box.



(a) (b)

Figure 15. An exemplary traffic situation showing the effects of different clustering strategies for ground and airborne traffic. (a) The HDD with ground vehicles (tan diamonds) and airborne traffic (cyan arrows). (b) The situation seen through the HMD. (traffic positions indicated by magenta dots for demonstration purposes only).

Figure 15 presents the effects of different clustering strategies for ground and airborne traffic. The features on which the clustering is based can be selected easily and combined in many ways. In the depicted case, the ground traffic is grouped subject to its position on the HMD only. Thus, the three surface vehicles in the foreground and the vehicle in the background, which appear clearly separated on the HDD, are represented by one rectangular head-up symbol. By contrast, the three visible aircraft are visualized by two distinct icons on the HMD, despite their overlapping. The reason for this behavior is the clustering strategy checking not only the screen position but also the behavior (track angle, speed) as well as the spatial proximity, which is not given in this case.

For this Figure 15, the symbology designed for color HMDs is illustrated. The monochrome visualization applies a decreased transparency to aircraft with a lower threat potential. Furthermore, the number of vehicles represented by a group symbol can be coded visually via the line width.

Evaluation

The number of primitives, that is the amount of traffic symbols, drawn by the advanced traffic visualization can never exceed the quantity of primitives in the basic approach, which indicates every vehicle by a single symbol. Again, the extent to which the primitive count is reduced depends on the specific situation. For example, displaying a cluster of two aircraft with one group symbol instead of two single symbols decreases the number of primitives by 50% while in case of four *similar* aircraft the quantity can be reduced by 75%. For each cluster comprising N vehicles, the relation is given by

$$n_{Adv} = n_{Bas} \cdot \frac{1}{N} \quad (5)$$

where n_{Adv} and n_{Bas} are the number of primitives drawn by the advanced and the basic traffic visualization respectively. Figure 5 shows a scenario where the number of rendered icons is lowered by 55%, from 11 to 5. Similarily, the number of rendered pixels can be reduced by our advanced approach. Additionally, the computation time measurements revealed that the proposed algorithms are capable of running in real-time.

Conclusion

In our work we present a prototype implementation of an integrated traffic visualization concept on both head-down and helmet-mounted displays. The main focus of our work is placed on the development of methods for de-cluttering the HMD and increasing the information content of the head-mounted symbology by coding important parameters visually. The realized functions are integrated into a flight simulator, the proposed algorithms are evaluated in terms of their effectiveness and run-time efficiency.

The central idea of the developed traffic visualization concept is to combine the strengths of both involved display types – head-mounted and head-down – while simultaneously diminishing their individual weaknesses. The role of the HMD is to support the pilot in *seeing and avoiding* other aircraft even if the view is degraded. Additionally, it shall help to keep the *head-mounted* and the *eyes out* during the flight. The head-down traffic display complements the role of the HMD by providing an overview of the traffic situation and presenting additional information that can not be displayed head-mounted.

In order to automatically de-clutter the HMD, a technique for clustering the nearby vehicles into groups of similar traffic is developed. To do so, the existing DBSCAN algorithm is expanded to deal with non-metric scales. Furthermore, a graphical representation of the identified traffic clusters on the HMD is suggested. To achieve time coherency and to avoid distracting, sudden changes of the symbology, the cluster representation is dynamically adapted to the varying clustering results. The developed algorithm generates a smooth visualization of the symbol transitions when clusters merge or split. Also, our work deals with the visual coding of important parameters on head-mounted displays. The relevance of an aircraft is expressed by one single measure that is intuitive to use: the threat potential. For the computation of this property, the well-known TCAS II logic [24] is further developed so that it makes full use of the comprehensive traffic data provided by ADS-B. The clustering and the group symbol calculations of the advanced traffic visualization method require more computation time than the basic visualization approach. However, the realized de-cluttering methods are effective and the proposed algorithms are still fast enough to be real-time capable even for high numbers of vehicles to be processed.

In conclusion, our approach provides a complete prototype of a traffic visualization system, which is in many ways adaptable to the pilot's needs and comprises newly developed algorithms that basically fulfill the requirements for a potential certification. Future work will focus on integration of the algorithms into an operational synthetic vision system so as to conduct further tests with real ADS-B data. Furthermore, a thorough validation of the visualization concept by means of a simulator study is required.

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