

A Review of Low-Cost Collision Alerting Systems and their Human-Machine Interfaces

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Abstract

Mid-air collisions still are a regular cause of accidents in parts of the aviation community. Yet advances in the miniaturization and the declining cost of electronics and microprocessors over the past decade have spawned several collision alerting systems specifically tailored to the needs and constraints of sports aviation. In this paper, the current state of technology in low-cost collision alerting systems in this branch of aviation is briefly reviewed. The FLARM system is one of several systems in widespread use today. Due to its low cost and widespread proliferation within the gliding community, this system is discussed in more detail. Here it is identified that most developments associated with the FLARM system are either hardware-related or pertaining to the development of flight-phase identification and traffic-conflict detection algorithms. According to available literature the human-machine interfaces (HMIs) of FLARM and other low-cost collision alerting systems are designed pragmatically. No insight into the requirements and the design of HMIs of low-cost collision alerting systems is found in literature. Based on this fact, several questions pertaining to HMI design are formulated. As a result, a study of commercially available HMI devices was performed, revealing several HMI categories and potential problems on HMI usability. The paper concludes in stating that experimental analysis is required to properly gauge HMI efficacy for different piloting tasks in sport aviation.

Abbreviations

ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependent Surveillance – Broadcast
ATC	Air Traffic Control
BFU	German Federal Bureau of Aircraft Accidents Investigation
EFIS	Electronic Flight Information System
FSR	Institute of Flight Systems and Automatic Control
GPS	Global Positioning System
HMI	Human-Machine-Interface
IFR	Instrument Flight Rules
LED	Light Emitting Diode
PDA	Personal Data Assistant
SA	Situation Awareness
SSR	Secondary Surveillance Radar
TA	Traffic Awareness
TIS-B	Traffic Information Service – Broadcast
VFR	Visual Flight Rules

Introduction

A large share of aviation activities and corresponding flight missions are concerned with the fulfillment of rational goals,

such as providing commercial air services, personal transportation, national defense or police duties. Yet sport aviation — which can be defined as “flight for fun, or interest’s sake” [1] — lacks such rational driving forces by its very definition^a. The categories of aircraft operated for sport aviation are far strung, ranging from single and multi-engine airplanes to gliders, gyrocopters, ultralight airplanes, hot air balloons, parachutes, etc.

Much of sport aviation is performed by pilots who have received less rigorous training than is demanded of other pilots, particularly in systems management. In some countries the regulatory environment for such sport flying operations also is less restrictive. Many regulations, such as the US sport pilot / light sport aircraft rules or European ultralight / ecolight / microlight rules, only allow for sport flights to be conducted in compliance with visual flight rules (VFR). Also, sport aircraft are often owned by individuals or small groups of individuals (such as flying clubs, etc.). The financial means available by these individuals or groups for aircraft operation in sport aviation is usually much more limited than in other branches of aviation.

A regular (but not the major) cause of accidents in sport aviation are mid-air collisions. The German Federal Bureau of Air-

^aSport aviation is a subset of general aviation. General aviation, in turn, is defined by the International Civil Aviation Organization as all civil aviation which is not operated for commercial air transport or aerial work [2]

craft Accidents Investigation (BFU) alone released 22 accident investigation reports between the years of 1999 and 2011 pertaining to accidents resulting from mid-air collisions and near misses^b involving sport aircraft^c. The list of involved sport aircraft classes includes single engine airplanes, helicopters, gliders, touring motorgliders and ultralight airplanes. All sport aircraft are operated under VFR.

Collision avoidance in sport aviation

Several operational means of ensuring airborne separation and collision avoidance in aviation have evolved over time. For sport aviation operations operating under VFR, these means can be broken down into three categories: the “see-and avoid” principle, traffic information and separation provided by air traffic control (ATC) and collision alerting systems.

By far the oldest means of providing collision avoidance in aviation is the “see-and-avoid” principle. Here, pilots are responsible for visually detecting conflicting traffic and ensuring self-separation. Nevertheless, factors which are physiological and psychological in nature hamper “see-and-avoid” in deterministically preventing mid-air collisions [3].

ATC is a further source of traffic information for sport pilots. Even in airspaces where radio communication with ATC is not required for VFR flights (airspaces classes E, F and G), pilots can often request traffic information. This service is usually offered on a workload-permitting basis by ATC and is supposed to assist in self-separation from other traffic operating under VFR or instrument flight rules (IFR). In higher airspace classes (A, B, C, and D), ATC provides different levels of separation service.

Collision alerting systems are perhaps the youngest means of aiding sport pilots in collision avoidance. The past decade has seen a surge in low-cost, non-certified, airborne systems which aid sport pilots in the detection and avoidance of other traffic. Every system consists of some form of traffic sensor, processing unit with conflict detection algorithms, and a human-machine-interface (HMI) for relaying information to the pilot. In order for collision alerting systems to be viable for sport aviation operations, several demands must be fulfilled. These demands are discussed in more detail in the proceeding sections.

Human factors considerations

For most mid-air collisions it is often impossible to blame a single cause, event or person for the accident. The characteristic model of the failure of a complex system is often called the “Swiss cheese model” [4, 5] in which holes in multiple layers of defense have to line up for a failure to occur. Nevertheless, the theoretical understanding of the mechanisms leading up to mid-air collisions and the conditions favoring such events is thorough. The simple fact that visual target acquisition is a stochas-

tic process [6,7] implies that adequate separation cannot be guaranteed deterministically for those flight operations relying on the “see-and-avoid” principle as their sole means of ensuring airborne separation. Some factors influencing the stochastic target acquisition rates are target size and visibility, distance to the target, atmospheric visibility, pilot alertness as well as pilot experience [6, 7].

Also, the setup of the human visual system and its reaction to different stimuli directly influence the identification of potentially conflicting traffic. Targets exhibiting a relative motion to the observer tend to attract visual attention and are therefore more likely to be identified by the pilot [8]. Yet most often collision geometries cause aircraft to maintain a stationary bearing from one another [9], making target acquisition less likely.

Traffic awareness (TA) can be considered as a subset of situation awareness (SA). This allows SA models to be used in describing pilot behavior in situations with conflicting traffic. Endsley provides a comprehensive theory of SA [10]. SA is described as a multi-layered process. At the first layer is the level of perception. Applied to TA, a pilot must perceive other aircraft in order to be aware of their presence. Second comes the level of comprehension. In the case of TA, the pilot must comprehend that an acquired aircraft may be a potential threat from which to remain separated. The highest level in the process of SA is the level of projection. In order to successfully deconflict from potential mid-air collisions, the pilot must adequately predict the conflicting aircraft’s trajectory.

Also directly related to the concept of SA is the concept of the mental model. In human factors research it is supposed that each human has some form of model of how a given (technical or non-technical) system works. According to Endsley, this mental model directly influences the levels of comprehension and projection of the SA theory [11]. Relating to the research of TA, this means that each pilot has an expectation of how the air traffic system works. In practice, this mental model assists the pilot in comprehending that a visual target aircraft flying parallel to a runway at an altitude of 1000ft above ground level with a horizontal offset of 1nm is most likely flying in an airport traffic pattern. At the level of prediction, the same model of the air traffic system will allow the pilot to predict that aircraft’s turn from downwind to base leg in the traffic pattern and plan accordingly.

An illustration of Endsley’s SA and mental model theories applied to the case of TA is given in Fig. 1.

While the SA/TA concept presented above has so far been discussed as a stand-alone concept, it shall be pointed out that it is closely intertwined with the concepts of workload and pilot performance. Durso and Alexander [12] note that a change in SA, workload or pilot performance will lead to changes in the other two. Furthermore, Casner [13] voices concerns about the possible detrimental effects of advanced cockpit systems — such as collision alerting systems — in general aviation environments on SA and workload. Casner also mentions that these systems not necessarily reduce error rates and that alarms and alerts often provided by advanced cockpit systems may lead to unintended

^bOne ultralight airplane suffered structural failure of the wing in the wake vortices of an F-4 Phantom fighter after a near miss with the jet.

^cGerman Federal Bureau of Aircraft Accident Investigation. Investigation Reports (website). URL: http://www.bfu-web.de/cln_030/nn_223648/DE/Publikationen/Untersuchungsberichte/untersuchungsberichte_node.html?_nmm=true [cited 23 January 2012].

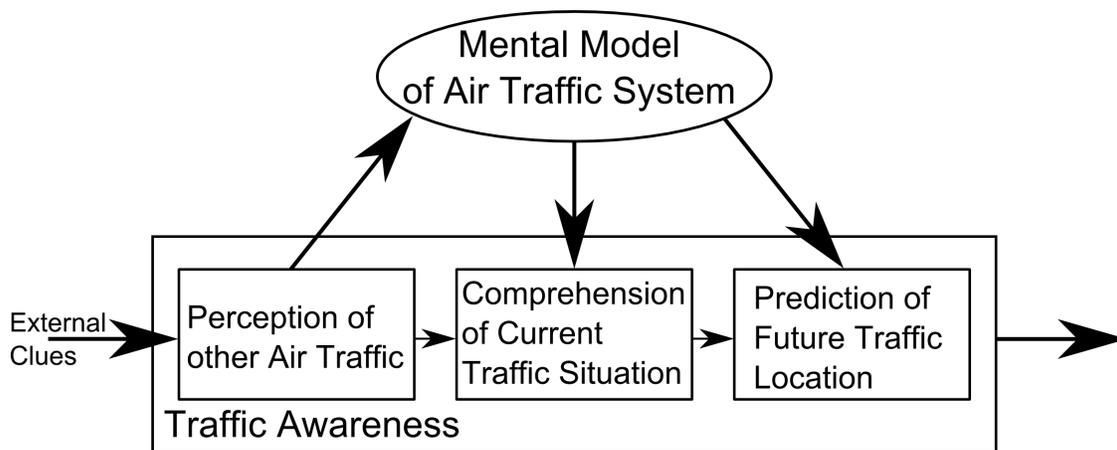


Figure 1 Concept of TA applied to Endsley's SA and Mental Model Theories (derived from Ref. 9).

pilot behavior, such as startle.

Contemporary collision alerting systems

A technological approach to aiding the pilot with the perception of other traffic is the introduction of collision alerting systems. These augment the human visual sensors (the eyes) with additional technical sensors. Ideally, this leads to earlier perception of other air traffic — or even perception of traffic that would otherwise have been missed visually by the pilot — and therefore increases pilot TA. This happens on the perception level. Furthermore, if the system offers different levels of conflict alerts it directly influences comprehension level of TA. Depending on the design of such collision alerting systems, predictions of other traffic locations also might be made, also aiding on the prediction level. Additionally, collision alerting systems are intended to act as an additional layer of defense within the “Swiss cheese model.”

A central technical question during the design of a collision alerting system is the selection of adequate sensors for identifying, locating and tracking of potentially conflicting aircraft. Here, a wide range of sensor technologies exist. These include primary air search radars, infrared and visual sensors or the standard Airborne Collision Avoidance System (ACAS). Nevertheless, the technologies mentioned above are either too heavy, consume too much power, are too complex to operate and interpret or are too expensive to be of current interest for sport aviation collision alerting purposes and will not be discussed further. However, research at the Lincoln Laboratory of the Massachusetts Institute of Technology aims to expand ACAS functionality to some general aviation applications [14]. Regardless of this, advances in modern electronics and microprocessing have spawned a whole series of low-cost collision alerting devices specifically designed for sport aviation use within the last decade.

Demands of collision alerting systems for sport aviation

Any collision alerting system intended for use in sport aircraft has to be designed to comply with the typical restrictions of sport aviation operations. The following restrictions have been found by the authors to have significant influence on the design of existing systems:

Size and Mass The low payload capacity of many sport aircraft may not be further burdened by the installation of heavy or cumbersome equipment. Instrument panel space for additional displays is also severely limited in many aircraft.

Power Consumption Particularly gliders have to rely on batteries as their sole source of electrical power. Power consumption needs to be low enough to allow uninterrupted operation of the collision alerting system for several hours of flight time while relying mostly on battery power.

Ease of Operation Time available for training on a collision alerting system is severely restricted for sport pilots, who often are flying only tens of hours per year. Hence, interaction with the system must be very intuitive to the pilot. Also, it may not draw too much attention away from other tasks, yet shall improve TA.

Financial Burden Considering that at the lower end of the financial spectrum, used aircraft might have a value of several thousand Euros, it seems unlikely that an aircraft will voluntarily be equipped with a collision alerting system if the unit price of such a system is within the proximity of the remaining aircraft value.

Precision of Relative Traffic Position Indicated traffic positions must be precise enough to allow for swift and distinct identification of potentially conflicting traffic. Large discrepancies between indicated and actual position might cause the pilot to initially search the wrong “patch of the sky,” thereby wasting valuable time for deconfliction.

Reliability/False Alarms If the rate of false alarms rises above a critical threshold, pilots tend to see the system as a nuisance [15]. Pilots ignoring the warnings provided or even disabling such systems may be the consequence. At the other hand, if the system does not identify conflict situations properly, it does not reach its design motivation.

Availability Availability is only limited to a certain geographic region or phase of flight, significantly lowering the usability of a given collision alerting system. Ideally, the system's services are available during all phases of flight and in all geographic areas where a given flight takes place.

Legal Implications If the system is to issue compulsory commands to the aircrew involved, this raises questions of responsibility and ultimately liability. The same is true for any automated intervention into the flight controls. As a result, certification burdens are extremely high for compulsory directives or automatic intervention.

Sensing technologies

Before discussion of the sensing technologies commences, it shall be noted that all presented technologies are "cooperative". Hence, potential threat aircraft only can be identified by a collision alerting system if the threat aircraft is specially equipped and the equipment is operational. All ensuing sensing technologies more or less fulfill the demands of the previous section "Demands of Collision Alerting Systems for Sport Aviation" for certain applications in sport aviation.

SSR-transponder signal analysis

Secondary surveillance radar (SSR) transponders form the basis for most ground-based ATC services and flight tracking [15]. When interrogated by a ground-based radar, the transponder replies with its 4-digit Ident-code ("Squawk," Mode A). In Mode C, the transponder will provide further its pressure altitude. Mode S transponders also are uniquely identifiable through a 24-bit aircraft address transmitted with each interrogation reply.

Utilization of transponders also is a prerequisite for flight operations in some parts of the airspace system, ensuring that all aircraft operating in the airspace elements are cooperative and can be detected by transponder-based collision alerting systems. High-end ACAS systems — mandated for most commercial flight operations — determine the slant distance to a potential target by interrogating nearby transponders and measuring the reply times. On the other hand, most low-cost, non-certified collision alerting systems relying on transponder signal analysis determine distance on the basis of transponder signal strength [16]. The relative direction to a potential target can be determined by automated direction finding equipment. Yet some low-cost collision alerting systems solely provide non-directional range data. Relative altitude to the potentially conflicting traffic can be determined from the pressure altitude of the Mode C reply. If the

target aircraft transponder only replies in Mode A, no altitude information is available.

Previous research at the Institute of Flight Systems and Automatic Control (FSR) [17] quotes error magnitudes for transponder-based signal analysis. Inherent uncertainties of up to 27° in determining relative bearing, slant distance errors of up to 250ft for reply time measurements and errors in relative altitude of 270ft are provided. Furthermore, systems relying on signal strength measurements for determining the slant distance to a target are occasionally prone to errors in the order of magnitude of 1nm [18]. These errors only allow for transponder-based collision alerting systems to be used in situations where aircraft are sufficiently spaced.

GPS-based position broadcasting

Position and velocity measurements based on the Global Positioning System (GPS) have become commonplace within many technological applications over the past decade. It is easily possible to transmit the measured position through predefined radio protocols and therefore make a receiving party aware of the sender's position.

ADS-B / TIS-B Automatic Dependent Surveillance – Broadcast (ADS-B) is a new airspace surveillance technology based on automatic position and velocity reports being broadcast by the participating aircraft. The broadcast position data is provided by an external navigation source, such as a GPS receiver or inertial navigation system. Though originally intended as an air traffic monitoring tool to assist ATC, by now several commercially available collision alerting devices are able to detect conflicting traffic on an ADS-B basis.

The ADS-B standard is internationally certified and standardized between ATC organizations. Accordingly, the protocol documentation for ADS-B transmitted is freely available [19]. Yet certification costs are reflected in the pricing of ADS-B-conformal equipment.

ADS-B receivers also may receive traffic information from ground based transceiver units operated by ATC. This allows the traffic information available in ADS-B-equipped aircraft to be enhanced with traffic data about non-ADS-B aircraft, generated through ATC's SSR. Such enhanced ADS-B service is known as Traffic Information Service – Broadcast (TIS-B). In order for TIS-B to be available, the receiving aircraft must be within range of a ground based transceiver unit [20].

FLARM The FLARM^d system also relies on the transmission of GPS-based position information. Additionally, each unit identifies its current phase of flight (straight and level, turning flight, gradual turn, etc.) and calculates a forecast position accordingly. This predicted position also is transmitted by each FLARM unit. However, in contrast to ADS-B the signal strength

^dFLARM is manufactured by FLARM Technology GmbH of Baar, Switzerland. To avoid confusion between the FLARM system and FLARM Technology GmbH, the company is referred to as the "FLARM manufacturer" in this paper.

of the message transmitted is much lower and it is transmitted on a concession-free radio frequency. Also, FLARM's radio protocol is proprietary, allowing messages to be received only by equipment endorsed by the manufacturer [21]. Due to the low signal strength, typical detection ranges for the FLARM system vary between 3km and 5km [22], which is significantly lower than the detection ranges of the other systems.

FLARM has been originally developed for application within the soaring community, as a non-certified collision alerting system. Due to its low costs and simplicity in operation FLARM has become a quasi-standard within the world gliding community, with installed units also spreading to light airplane, ultralight, helicopter and aerial sports applications. Its threat detection algorithms are specifically designed to the requirements of sport aviation.

Coordinate systems

All collision alerting systems evaluate geometric conditions in order to assess the threat presented by a sensed aircraft. This implies that coordinate systems are attributed to the geometric analysis. The orientation of these coordinate systems is dependent strongly upon the sensors utilized and influences the information which can be passed to the pilot.

Transponder direction finding equipment, due to its aircraft-fixed installation, will provide parameters in body axes. Yet Mode C relative-altitude information is given in earth axes. Slant distance measurements, by definition, are non-oriented. GPS-based signal analysis also can take place in a variety of coordinate systems. Yet many GPS-based low cost collision alerting systems lack access to the ownship's attitude information, and therefore cannot provide alerts in body axes. Instead, earth axes, flight path axes or related coordinate systems are used.

Literature review

Due to the popularity and the rapidity with which FLARM has proliferated in parts of the aviation community, a review of literature on the system was performed. The system was developed in 2003 in Switzerland in response to a series of fatal glider mid-air collisions [23]. Development appears to have been driven by a pragmatic "trial-and-error" approach, typical of a young startup company. A detailed review of scientific literature on the system reveals that only few publications deal with the FLARM system or collision alerting systems for sport aviation in general. The most comprehensive set of documentation is that provided by the FLARM manufacturer. Part of this literature is aimed at the pilots and operators confronted with the installation, operation and maintenance of the FLARM units in each aircraft [22, 24]. Another part of manufacturer literature is intended as a description of the design philosophy [21] and documentation of the serial data port, allowing the FLARM system to be interfaced with other devices and systems [25].

Other scientific and technical literature found on the subject is noted as follows.

- A research project initiated by the German Federal Ministry of Transport, Building and Urban Development analyzed the state of collision avoidance in German sport aviation between 2003 and 2004. At the time of publication in the spring of 2004, FLARM was just being introduced into the market. The research project's final report quotes FLARM as being the most promising and advanced of four low-cost collision alerting systems discussed. The other three systems did not reach market maturity. Also, the authors recommend that future research into the FLARM system should be considered once more widespread operational experience with the system is available and a higher number of aircraft is equipped with the system [8].
- In their 2007 report to the Fédération Aéronautique Internationale, Hearne and Strachan [26] discuss the potential of GPS-based position broadcasting technologies for sport aircraft. They see ADS-B and FLARM as being able to significantly and cost-efficiently enhance safety for sport aircraft by providing surveillance functionality to ATC as well as being usable for onboard collision alerting.
- The FLARM manufacturer, together with the Swiss Federal Institute of Technology, Zurich, developed new algorithms for estimating the wind influence from GPS data. This wind influence is then used in refining flight phase identification and trajectory prediction [27].
- A company specializing in simulating complex dynamic systems was tasked by the FLARM manufacturer with analyzing the operational characteristics and limitations of the FLARM system. Particularly, cases of high traffic densities and their influence on the proprietary radio communications protocol were studied [28, 29].
- A German-registered patent not associated with the FLARM manufacturer concerns itself with an optimized FLARM antenna, which can be remotely mounted on the aircraft canopy [30].
- A plethora of pilot reports for collision alerting devices exist in online forums. These reports are of variable scientific quality and usability. Yet also popular aviation print media routinely discuss the subject [18, 31].
- FLARM compatible avionics devices will often also document some technical aspect of the interfaced FLARM system [32].
- Several patents and publications propose a FLARM receiver as a traffic sensor and further process the data provided by the FLARM receiver for manned and unmanned operations [33–35].

Two other documents of interest on the topic of low-cost collision alerting, though not directly related to FLARM, were also found.

- In 2000, a German-registered patent proposes a collision alerting system also intended for glider operations. However, the relative location of a threat is not identified via GPS, but much rather on the principles of radio direction finding. The receiver’s proposed HMI already features a circular array of light emitting diodes (LEDs), similar to the HMI integrated current FLARM units [36].
- Proposed changes in the structure of aviation in the Republic of China and the opening of lower airspace for light aircraft have spurred concerns about mid-air collisions there. Hence development of an ADS-B-based collision alerting system has also commenced there [37].

From the list of available publications on the subject, it can be seen that the introduction of FLARM has mostly been accompanied by practical considerations and little theoretical research. The few scientific documents that do exist primarily concern themselves with the improvement of prediction algorithms, radio protocol limitations and improved hardware.

Literature on HMI development

Even though a multitude of external displays and other HMI concepts exist and are available on the market for use with FLARM units, no single publication concerns itself with the design of such an HMI. Expanding the review to low-cost collision alerting systems for sport aviation in general did not reveal additional literature. Discussion with aviation accident investigation experts and avionics experts from the BFU and representatives of avionics manufacturer Garrecht Avionik GmbH and HMI manufacturer Butterfly Avionics Ltd.⁶ further support the suspicion that comprehensive scientific literature on the subject of HMI development for low-cost collision alerting systems does not exist. From this lack of scientific understanding, several questions arise:

- How do existing and commercially available HMIs differ? How are these interfaces designed?
- How effective are the available HMIs for increasing pilot TA? How do they affect SA in general? Do they detract attention from other piloting tasks?
- Can recommendations be made on how to improve the design of HMIs? Is it possible to optimize the HMI design process, which currently relies heavily on “trial-and-error” methodology?

HMIs for low-cost collision alerting systems

In order to answer the first of the questions posed above on “How do existing and commercially available HMIs differ?” a market analysis of currently available devices and their respective HMIs was performed. The results of this study, presented

⁶Both companies cooperate closely with the FLARM manufacturer

below, also serve to offer a first insight into the design of HMIs for low-cost collision alerting systems in sport aviation.

The purpose of the HMIs is to present data on sensed traffic and potential collisions in a form that is understandable to the pilot. During the analysis of these HMIs it was found that they could be divided into two primary categories; auditory HMIs and visual HMIs. Each of these two categories can be further divided into clearly defined sub-categories.

Other available human sensory channels, such as haptics and tactility appear to remain unused for the use of relaying traffic information to the pilot. However, most commercially available devices utilize the visual and auditory channels simultaneously. In most real-world HMI designs, one can differentiate between a primary and secondary channel; the primary channel being the one through which the majority of the traffic and conflict information is relayed to the pilot. Often, a primarily visual device will utilize some sort of auditory message to attract attention to the visual data depicted. Primarily auditory devices will often use visual elements to confirm the operating status of the device.

Auditory traffic HMIs

Many devices utilize a simple audio speaker (“beeper”) or “gong signal” to attract attention to a visual display. Hence, the pilot is informed of the existence of priority information, even when currently not scanning the instrument panel.

Another means of conveying auditory traffic information is plain voice output. Prerecorded messages or message fragments are triggered to inform the pilot of the position of other traffic and conflict situations.

Traffic displays

Traffic information also can be displayed visually on displays in the cockpit. Here one can differentiate between displays which are solely dedicated to displaying traffic information and information on the operating state of the collision alerting system or non-dedicated displays, where further non-traffic-related information is displayed.

Dedicated traffic displays

Dedicated displays are often directly integrated into the receiver units of low-cost collision alerting systems. Yet integration is no prerequisite. Displays and receivers can be mounted with spatial separation. Dedicated traffic displays are most often installed in the pilot’s primary field of view. Example sketches of dedicated displays are given in Fig. 2 and are discussed below.

Low-Complexity (Fig. 2(a)) Such displays arbitrarily can be defined as having a maximum of 30 individually controllable visual elements to relay information on sensed traffic and the operating state of the collision alerting system to the pilot. Typical of this category is the current HMI integrated into FLARM units, which features a circular array of twelve LEDs to indicate the relative horizontal location of traffic and a column of four LEDs

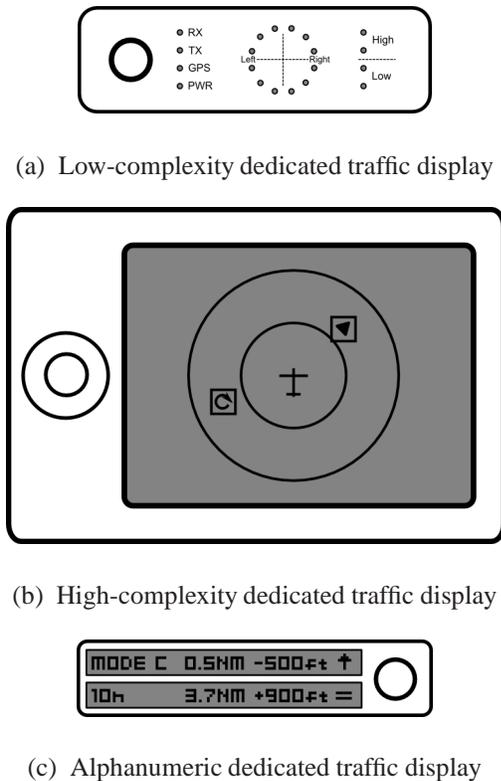


Figure 2 Example sketches of dedicated traffic displays

for indicating relative vertical traffic position. Furthermore, four LEDs indicate the operating status of the FLARM unit. Legacy FLARM units still in operation today feature a horizontal row of eight LEDs to indicate the relative horizontal traffic location instead of the circular array. Range information is usually not explicitly provided by low-complexity displays. Due to the limited number of individually controllable visual elements, it is often only possible to present one threat aircraft to the pilot, making an automated prioritization of threats necessary.

High-Complexity (Fig. 2(b)) In contrast to low-complexity displays, high-complexity dedicated traffic displays consist of a significantly higher number of individually controllable visual elements. This is usually realized through a polychromatic liquid crystal display matrix. One typical representative of the high-complexity dedicated traffic displays is the Butterfly Display, manufactured by Butterfly Avionics Ltd. Due to the nature of the devices, it is possible to display multiple sensed aircraft and adjust the presented screens dynamically, depending on the current traffic situation and threat level. Threat information can be provided through symbolical or through alphanumeric elements. Furthermore, it is easy to provide relative distances to each of a multitude of threats.

Alphanumeric (Fig. 2(c)) While high-complexity displays tend to depend heavily on symbolical concepts for relaying traffic data to the pilot, alphanumeric displays do so primarily

through the use of letters and digits. Nevertheless, a limited number of low level symbols (such as arrows) might also be utilized.

Alphanumeric dedicated traffic displays are often made up of a monochromatic display that allows only the depiction of a strictly limited number of potential targets. Usually no more than four lines of alphanumeric symbols are displayed. Typical representatives of these HMIs are the PCAS MRX and PCAS XRX displays manufactured by Zaon Flight Systems.

Non-dedicated traffic displays

Due to the flexibility of modern integrated electronics, it is also possible to display traffic information on systems not solely dedicated to the task. The list of non-dedicated displays below by no means shall be intended to be fully comprehensive in terms of non-dedicated traffic displays in sport aviation. It much rather offers an insight into the possible fusion of traffic information with other data.

Integrated glide computer or EFIS displays Many modern high performance gliders are equipped with integrated glide computers which combine data streams from air data and GPS sensors to allow for final glide calculations and assist in tactical decisions. Analogous systems tailored to the needs of powered light aircraft are often available as electronic flight information systems (EFIS). Both systems' displays usually take up significant amounts of available panel space and feature different "pages" for depicting data. The possibility of displaying traffic ranges from dedicated traffic pages to integrated traffic information on moving map pages. The LX 9000 FLARM of LXNAV is representative of such a modern glide computer with the mentioned capabilities while the MT Vision Air of Moving Terrain Air Navigation Systems represents an example light airplane EFIS allowing for the display of traffic information.

PDA software solutions and PDA displays As a low-cost alternative to the integrated glide computers, personal data assistants (PDAs) often take up analogous tasks of assisting in tactical decision processes for glider pilots. However, the PDAs require external GPS data as input. Due to the fact that many of the aircraft in which PDAs are utilized are also equipped with FLARMS, the enriched GPS data stream — including traffic information — can be fed by the FLARM unit to the PDA. Several software products display this information in dedicated traffic pages or on integrated pages. PocketStrePla by 8F Computer is a software product which can be run on a plethora of different PDA devices and also has the capability of displaying sensed traffic to the pilot.

Moving map GPS displays The idea of overlaying traffic information onto maps of the surroundings of the aircraft, such as terrain, airspace, etc. is apparently well accepted by pilots. Therefore numerous moving map GPS units allow traffic information to be fed onto their displays and be overlaid onto the

map. Systems capable of this are, for example, the GPSmap 39x/49x/69x Series produced by Garmin.

On HMI usability

While studying the marketed HMIs for low-cost collision alerting systems, it became obvious that no HMI explicitly provides information on the coordinate system that its information is presented in. Instead, information on the coordinate systems is often only provided in operating manuals and system descriptions.

Considering that time available for training and systems familiarization is often limited for sport pilots, and that collision alerting systems are usually not covered by ground school syllabi, it must be assumed that many sport pilots only have a limited understanding of the internal workings and coordinate systems of collision warning devices. Furthermore, the aircraft-fixed mounting of HMI devices might lead sport pilots to assume that traffic information is presented in a body coordinate system. Yet, as discussed previously, only systems relying on radio direction finding or being fed with attitude information can provide information in body coordinates. This gives rise to the hypothesis that many sport pilots have incorrect mental models of collision alerting systems. If this hypothesis proves to be true, detrimental effects on traffic awareness can be expected, as per Endsley's SA theory.

Contrary, if a pilot understands that information is not provided in body coordinates, the information must be mentally transformed relative to the pilot's fixed position in the aircraft. Current research at the Institute of Psychology of Technische Universität Darmstadt studies the mental load of test subjects required for transforming traffic information presented on a low-complexity dedicated traffic display to their surroundings [38]

Conclusions

From the numerous questions derived in the section "Literature on HMI Development," only the question of how existing HMIs differ is answered in detail. Furthermore, the discussion of HMI categories also offers an initial insight into the many options presented to the HMI designer. Yet the questions of particular interest from an engineering point-of-view — "How effective are these HMIs?" — could not be answered so far. The wide variety of parameters expected to influence HMI efficacy ranges from the pilot's senses stimulated by the HMI, to pilot workload and mental models, traffic mix, flight mission and meteorological conditions. Due to a lack of comprehensive theoretical work on these peculiarities of traffic situations in VFR flying tasks, it is believed by the authors that the presented questions and hypotheses can be best answered by empirical study.

Summary and Outlook

This paper reviews the current state of low-cost collision alerting systems for sport aviation and their HMIs. Mid-air collisions still are a common cause of accidents, even under optimal VFR conditions. Due to the stochastic nature of the human visual

scan, "see-and-avoid" cannot provide absolute protection from mid-air collisions. Therefore, a technical necessity for assisting pilots in helping to spot other air traffic does exist. A human factors framework is provided by modifying Endsley's SA and mental model theories to the case at hand.

All mature collision alerting systems in sport aviation are cooperative and utilize GPS-based position broadcasting or SSR-transponder signal analysis to sense other traffic. These are the only technologies that can comply with the specific demands of collision alerting systems in sport aviation and are viable for the purpose of collision avoidance.

Particular attention is given to available literature on FLARM, a non-certified collision alerting system. Scientific publications accompanying its development have focused on the advancement of hardware and algorithms, as well as analyzing the limits of the proprietary radio protocol. After identifying that HMI development for FLARM is not treated in literature, the literature review is expanded to include HMI development for low-cost collision alerting systems in sport aviation. The expanded review does not provide meaningful insight into HMI design and development. Instead it aids in formulating several questions pertaining to HMI design.

Nevertheless, a multitude of different HMI devices for low-cost collision alerting systems do exist. These only use the auditory and visual channels to provide the sport pilot with traffic information and warnings. Furthermore, each device can be categorized into a specific category, depending on its design and the primary human sensory channel it excites.

A need for empirical study of HMI efficacy exists. In response to this need, the authors are currently in the process of designing an experimental setup. At the core of this setup is FSR's newly procured Diamond DA 40-180 flight simulator.

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References

- [1] J. F. Welch and L. Bjork. *Van Sickle's Modern Airmanship*. McGraw-Hill, 8th edition, 1999. Chap. 1.
- [2] Annex 6 to the convention on international civil aviation: Operation of aircraft: Part I: International commercial air transport — aeroplanes. International Civil Aviation Organization, International Standards and Recommended Practices, No. 28, November 2003.
- [3] Limitations of the see-and-avoid principle. Australian Transport Safety Bureau, Research Report 0 642 16089 9, April 1991.
- [4] J. Reason. *Human Error*. Cambridge University Press, Cambridge, England, UK, 1990. Chap. 7.
- [5] J. Reason, E. Hollnagel, and J. Pariés. Revisiting the 'Swiss Cheese Model' of Accidents. Eurocontrol Experimental Centre, EEC Note 13/06, Bruxelles, Belgium, October 2006.
- [6] J. W. Andrews. Modeling air-to-air visual acquisition. *The Lincoln Laboratory Journal*, 2(3):475–482, 1989.

- [7] J. W. Andrews. Unalerted air-to-air visual acquisition. Massachusetts Institute of Technology Lincoln Laboratory, Project Report ATC-152, November 1991.
- [8] J. Janke et al. Abschlussbericht BEKLAS: Die Erkennbarkeit von Segelflugzeugen und kleinen motorisierten Luftfahrzeugen. Bundesministerium für Verkehr, Bau- und Wohnungswesen, Forschungsbericht FE-Nummer L-6/2002-50.0300/2002, Bonn, Germany, April 2004.
- [9] Review of midair collisions involving general aviation aircraft in Australia between 1961 and 2003. Australian Transport Safety Bureau, Research Report B2004/0114, May 2004.
- [10] M. R. Endsley. Towards a theory of situation awareness in dynamic systems. *Human Factors*, 37(1):32–64, 1995.
- [11] M. R. Endsley. Situation models: An avenue to the modeling of mental models. In *Proceedings of the 14th Triennial Congress of the International Ergonomics Association and the 44th Annual Meeting of the Human Factors and Ergonomics Society*, San Diego, 2000. Human Factors and Ergonomics Society.
- [12] F. T. Durso and A. L. Alexander. Managing workload, performance, and situation awareness in aviation systems. Chap. 8 in *Human Factors in Aviation*, 2nd Ed., edited by E. Salas and D. Maurino, Elsevier, Burlington MA, USA, 2010.
- [13] F. T. Casner. General aviation. Chap. 19 in *Human Factors in Aviation*, 2nd Ed., edited by E. Salas and D. Maurino, Elsevier, Burlington MA, USA, 2010.
- [14] T. B. Billingsley, M. J. Kochenderfer, and J. P. Chryssanthacopoulos. Collision avoidance for general aviation. In *30th Digital Avionics Systems Conference*, pages 1.D.1–1 – 1.D.1–10, Seattle, WA USA, October 2011. IEEE.
- [15] M. R. Endsley, B. Bolté, and D. G. Jones. *Designing for Situation Awareness: An Approach to User-centered Design*. Taylor & Francis, London, 2003. Chap. 9.
- [16] H. Flühr. *Flugführungssysteme*. Springer-Verlag, Heidelberg, 2010. Chap 6.
- [17] P. M. Lenhart. Räumliche Darstellung von Flugführungsinformationen in Head-Mounted-Displays. Dissertation, TU Darmstadt, 2006.
- [18] T. Borchert and M. Nass. ‘Traffic!’ Kollisionswarner im Test. *Fliegermagazin*, pages 43–45, July 2011.
- [19] Surveillance Data Exchange — Part 12 — Category 021: ADS-B Reports. Eurocontrol, Eurocontrol Standard Document SUR.ET1.ST05.2000-STD-12-01, ed. 1.3, March 2009.
- [20] New technology — ADS-B, TIS-B, and FIS-B. Federal Aviation Administration, Air Traffic Bulletin ATB 50-3, August 2005.
- [21] FLARM compatibility considerations, v1.10f. FLARM Technology GmbH, Baar, Switzerland, January 2008.
- [22] Operating manual FLARM collision warning unit. FLARM Technology GmbH, Baar, Switzerland, March 2011.
- [23] K. Scherer. Eine Erfolgsgeschichte voller Idealismus: Die FLARM-Biographie. *Segelfliegen*, (5):25–27, May 2006.
- [24] S. Böhnisch. FLARM — Einbau, Wartung und Pflege. *Segelfliegen*, (1), October 2011. Online magazine.
- [25] FLARM Data Port Specifications: Preliminary. FLARM Technology GmbH, Baar, Switzerland, March 2011.
- [26] P. Hearne and I. Strachan. General and sport aviation and the use of satellite-based systems (particularly in air traffic management). Fédération Aéronautique Internationale, Lausanne, Switzerland, October 2007.
- [27] T. I. Baumgartner and U. Maeder. Trajectory prediction for low-cost collision avoidance systems. In *28th Digital Avionics Systems Conference*, pages 1.C.5–1 – 1.C.5–8, Orlando, FL USA, October 2009. IEEE.
- [28] L. Schuler. Die Wirksamkeit von Warnsystemen durch Simulation erhöhen. In *Warnung bei Aussergewöhnlichen Naturereignissen*, Eidgenössische Forschungsanstalt WSL, Birmensdorf, Switzerland, 2007, edited by C. Hegg and J. Rhyner, pp 93–97.
- [29] C. D. Berweger and L. Schuler. Simulationen zur Verbesserung des FLARM-Funkprotokolls. *Segelfliegen*, (3):30–33, March 2008.
- [30] B. Dolba and T. Vaupel. Planare aufklebbare Richtantenne für das FLARM System. German Patent Application, Patent Number DE 20 2009 004 658 U1. Filed 3 April, 2009.
- [31] M. C. Lee. When airplanes collide: Avoiding the unexpected. *Plane & Pilot*, 47(9):65–70, October 2011.
- [32] TRX-1090 — ADS-B Receiver Data Port Specifications, Rev. 0.3. Garrecht Avionik GmbH, November 2010.
- [33] Z. Perrottaf. On-board electronic apparatus for surveillance of air traffic, has connection unit provided for connecting personal computer (PC) tablet to communication devices, receivers and electronic control unit (ECU), and biometric recognition unit. Italian Patent Application, Patent Number IT1379098-B, filed 17 April 2007. Biofly SRL, Ardea, Roma, Italy.
- [34] A. Lenz and G. Kügemann. Method for conflict recognition in air space, involves outputting information to driver of own aircraft when conflict arises, where information refers to occurrence of possible conflict in case of direction change. German Patent Application, Patent Number DE 10 2009 045 755 A1, filed 16 October 2009. ESG Elektroniksystem- und Logistik-GmbH, Fürstenfeldbruck, Germany.
- [35] F. M. Adolf and F. Thielcke. A sequence control system for on-board mission management of an unmanned helicopter. In *AIAA Infotech@Aerospace 2007 Conference and Exhibit*, Rohnert Park, CA, USA, 2007. American Institute of Aeronautics and Astronautics, Inc. AIAA paper No. 2007-2769.
- [36] K. Porod. Kollisionswarnsystem für Flugzeuge, insbesondere Segelflugzeuge. German Patent Application, Patent Number DE 201 17 525 U1. Filed 26 October 2001.
- [37] C. E. Lin and Y.-Y. Wu. Collision avoidance solution for low-altitude flights. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 225(7):779–790, 2011.
- [38] V. Schochlow. Spatial processing of traffic information in sport aviation – a randomized controlled study of mental rotation processes in non-pilot participants. Bachelor Thesis, Institute of Psychology, TU Darmstadt, Germany, 2012. In preparation.