Abstract
A collision between aircraft is one of the most sudden and catastrophic transportation accidents imaginable. These tragic events are rarely survivable – hundreds of people may die as the two aircraft are destroyed. Some airborne systems have been developed and are currently in use to prevent mid-air collisions. This article focuses on the widely fielded, crucial technology called the Traffic Alert and Collision Avoidance System (TCAS). TCAS has had extraordinary success in reducing the risk of mid-air collisions. Now mandated on all large transport aircraft, TCAS has been in operation for more than two decades and has prevented several catastrophic accidents. TCAS is a unique decision support system in the sense that it has been widely deployed (on more than 25,000 aircraft worldwide) and is continuously exposed to a high-tempo, complex air traffic system. TCAS is the product of carefully balancing and integrating sensor characteristics, tracker and aircraft dynamics, maneuver coordination, operational constraints, and human factors in time-critical situations. Missed or late threat detections can lead to collisions, and false alarms may cause pilots to lose trust in the system and ignore alerts, underscoring the need for a robust system design.

Introduction
Over the years, air traffic has continued to increase. The developments of modern air traffic control systems have made it possible to cope with this increase, whilst maintaining the necessary levels of safety. The risk of collisions is mitigated by pilots exercising the “see and avoid” principal and staying away from other aircraft and by ground based Air Traffic Control (ATC) which is responsible for keeping aircraft separated. Despite technical advances in ATC systems, there are cases when the separation provision fails due to a human or technical error. Any separation provision failures may result in an increased risk of a mid-air collision.

To compensate for any limitations of “see and avoid” and ATC performance, an airborne collision avoidance system, acting as a last resort, has been considered from the 1950s. In 1955, the use of the slant range was proposed between aircraft divided by the rate of closure or range rate for collision avoidance algorithms, i.e. time rather than distance, to the Closest Point of Approach (CPA). Today’s airborne collision avoidance system is based on this concept [1].

In 1956, the collision between two airliners, over the Grand Canyon in the USA, prompted both the airlines and the aviation authorities to advance the development of an airborne collision avoidance system. It was determined in the early 1960s that, due to technical limitations, the development could not be progressed beyond the overall concept.

During the late 1960s and early 1970s, several manufacturers developed prototype aircraft collision avoidance systems. Although these systems functioned properly during staged aircraft encounter testing, it was concluded that in normal airline operations, these systems would generate a high rate of unnecessary alerts in dense terminal areas. This problem would have undermined the credibility of the system with the flight crews.

In the mid-1970s, the Beacon Collision Avoidance System (BCAS) was developed. BCAS used reply data from the Air Traffic Control Radar Beacon System (ATCRBS) transponders to determine an intruder’s range and altitude. In 1978, the collision between a light aircraft and an airliner over San Diego, California led the US Federal Aviation Administration (FAA) to initiate, three years later, the development of TCAS (Traffic Alert and Collision Avoidance System) utilizing the basic BCAS design for interrogation and tracking with some additional capabilities.

Despite the terrifying prospect of a mid-air collision, aviation travel is incredibly safe. A person who flew continuously on a jet transport aircraft in today’s environment could expect to survive more than 11,000 years of travel before becoming the victim of a mid-air collision. This accomplishment has only recently been realized. The number of hours flown annually by jet transport aircraft has
more than quadrupled since 1970, but the rate of mid-air collisions over that period of time has dropped by an order of magnitude. The result is that today we can expect one mid-air collision every 100 million flight hours. Such an exceptional safety level was achieved through advances in air traffic surveillance technology and relentless attention to improving operational procedures. TCAS is one component of a multi-layered defense against mid-air collisions. The structure of airspace and operational procedures provide the first strategic layer of protection. Traffic flows are organized along airways at segregated altitudes to aid air traffic controllers in managing aircraft and predicting potential conflicts well before problems arise. Aircraft are normally kept three to five miles apart laterally or 1000 ft vertically, to provide sufficient safety margins. Air traffic control ensures that separation minima are not violated by issuing tactical commands (including altitude restrictions and heading change vectors) to the pilots in response to nearby traffic. Should these nominal traffic separation processes fail, the TCAS system aids pilots in visually acquiring potential threats and, if necessary, provides last-minute collision avoidance guidance directly to the flight crew.

It is obviously imperative that TCAS alert the flight crew early enough that evasive action can be taken. But it is also important that TCAS does not alert unnecessarily. Collision avoidance alerts represent high-stress, time-critical interruptions to normal flight operations. These interruptions, in addition to distracting the aircraft’s crew, may lead to unnecessary maneuvering that disrupts the efficient flow of traffic and may over time also cause pilots to distrust the automation. Monitoring and safety assessments led to a series of changes resulting in the latest international version of TCAS – referred to as Version 7.1, or the Airborne Collision Avoidance System (ACAS). Starting in January 2003, the International Civil Aviation Organization mandated the use of ACAS worldwide for all turbine-powered aircraft with passenger capacity of more than 30 or with maximum take-off weight exceeding 15,000 kg. In January 2005, that mandate was extended to cover aircraft with more than 19 passenger seats or maximum take-off weight of more than 5700 kg [2].

The real challenge lies in integrating new collision avoidance technologies with the existing systems and procedures. The Überlingen accident demonstrated the catastrophic outcome that can result from dissonance between two different decision makers in a time-critical situation: namely, an air traffic controller’s decision to request a descent and TCAS’s Resolution Advisory to climb. While this specific problem is being solved by improving pilot training to comply with RAs and refining the TCAS algorithms, related problems are likely to surface as unmanned aircraft and enhanced collision avoidance technologies mix. Ensuring compatible operation also extends well beyond TCAS or aviation to many integrated sensing and decision support system applications.

Conclusion
TCAS represents a clear success story in aviation safety. Its successful design was achieved through detailed consideration of sensor characteristics and the coupled dynamic interactions among pilots, air traffic controllers, and aircraft. The result is a fine balance that provides sufficient time to take action and that minimizes alert rates. As the Überlingen accident shows, however, safety can not be taken for granted, and areas of improvement will always exist in systems that rely on integrating humans and automation for information processing and decision making.

References
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