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A survey of autonomous vision-based See and Avoid for Unmanned Aircraft Systems

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ABSTRACT

This paper provides a comprehensive review of the vision-based See and Avoid problem for unmanned aircraft. The unique problem environment and associated constraints are detailed, followed by an in-depth analysis of visual sensing limitations. In light of such detection and estimation constraints, relevant human, aircraft and robot collision avoidance concepts are then compared from a decision and control perspective. Remarks on system evaluation and certification are also included to provide a holistic review approach. The intention of this work is to clarify common misconceptions, realistically bound feasible design expectations and offer new research directions. It is hoped that this paper will help us to unify design efforts across the aerospace and robotics communities.

Contents

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1. Introduction

The fundamental reason for developing any unmanned aircraft systems is to remove the pilot from the aircraft in order to realise a number of key operational benefits. First, some unmanned aircraft can stay airborne for longer hours (days) and travel greater distances, without inducing pilot fatigue. Second, they may be operated in close proximity or within environments that are either inhospitable or potentially harmful, without the associated human risk. Third, some platforms may be operated at considerably low cost and human resource. These benefits make unmanned aircraft an attractive alternative to conventionally piloted or manned aircraft (CPA) for typically dull, dirty and dangerous civilian applications. They also open up the possibility of new tasks, impossible with manned aircraft. However, a number of technological, social and regulatory barriers must be addressed to ensure that the full potential of unmanned aircraft can be realised.

From an application specific perspective, the issues concern whether the intended task can actually be accomplished successfully. The task itself may be considerably difficult for unmanned aircraft due to onboard sensing (and payload) limitations, operator workload and power constraints or a demanding physical environment. For example, many issues still remain for robust aerial manipulation, payload delivery, remote sensing (inspection) and adverse weather (dust, rain, visibility, etc.) management. Many of these challenges are currently being addressed in the robotics community to bring technology to a satisfactory level required for success, and ensure unmanned aircraft remain useful [1,2].

From a regulatory perspective, a more general issue concerns whether the unmanned aircraft can operate both legally and safely in the intended environment [3]. For indoor operations, rules and regulations do not exist as such flights are not considered as aviation. For outdoor operations, dedicated regulatory bodies[1] determine the rules and regulations for all aircraft operations within their respective airspace. For these operations, it is infeasible to suggest that existing air traffic management systems are modified in light of this new airspace user [4]. Unmanned aircraft must therefore comply with existing practices and procedures [5,6] such that they operate seamlessly with other airspace users and existing infrastructure. This means that UAS must operate at an equivalent level of safety (ELOS) to manned aircraft so as to not degrade the overall safety of the current air traffic management system. This requirement introduces a significant number of non-trivial issues that must be addressed. These issues are generally application independent, but often overlooked when designing unmanned systems.

Multiple attempts have been made to enumerate each specific issue [7,8], define the equivalent level of safety and suggest possible solutions [9,10]. Despite such efforts, most UAS still lack sufficient capability to adequately perform all of the key functions required by the regulator. Arguably the most difficult of these functions is the lack of See and Avoid (SAA) capability [11]. As See and Avoid is a particular type of pilot-centric collision avoidance, by removing the pilot from the aircraft the task is made considerably difficult. So in fact, the main motivation for developing unmanned systems is also their major drawback from a regulatory perspective. The problem is being addressed in many research and industry communities, with major efforts in the robotics and aerospace disciplines. This diversification helps promote novel ideas and innovative solutions, but has also led to some infeasible approaches. The problem itself may be misunderstood, overly simplified or inappropriately framed. To this end, the contributions of this paper are to:

1. Clearly articulate the vision-based See and Avoid problem, identifying unique constraints, design considerations and common misconceptions.
2. Provide a comprehensive review of visual sensing (detection, tracking and estimation) in the context of practical See and Avoid.
3. Provide a comprehensive review of collision avoidance systems (decision and control) in the context of practical See and Avoid.
4. Offer future research directions to help unify design efforts for vision-based See and Avoid systems.

This paper is structured as follows. Section 2 provides a technology focused description of the See and Avoid problem. Section 3 highlights the limitations of visual sensing including the expected performance of recent detection, tracking and estimation algorithms. Sections 4 and 5 review human, aircraft and robot collision avoidance and resolution strategies in the context of vision-based See and Avoid. The implications of each review are presented as future research directions in Section 6, with concluding remarks given in Section 8.

2. See and Avoid

Collision avoidance and separation assurance is a multi-layered process at the core of aviation safety. One of the key collision avoidance layers that is consistently identified as a major roadblock to civil UAS integration is the absence of See and Avoid (SAA) capability. It is considered the last line of defence against a mid-air collision once all auxiliary layers of the collision avoidance process have failed. In short, it is a form of decentralised short term collision avoidance in which the pilot must independently identify and avoid any unplanned hazard, be it static or dynamic. It involves the pilots visual system, recollection of regulatory procedures and pilot knowledge and skill. It does not rely on existing infrastructure (primary radar, etc) onboard surveillance equipment (TCAS, ACAS, ADS-B, etc.) or air traffic services. The SAA function is thus a particular type of collision avoidance constrained by pilot ability and behaviour.

The See and Avoid task itself is typically dissected into a subset of functions including Detect, Decide and Act (DAA) or Observe, Orient, Decide and Act (OODA) [12]. Taking a more generic approach, the system components can be positioned in the common collision avoidance system framework namely Detection (Detect or Observe and Orient), Avoidance (Decide and Act) and Resolution. Detection involves the visual acquisition of a potential collision threat. Avoidance involves the decision of how to act in response to the threat and the implementation of that action. This may mean the alteration of the aircraft path or indeed no action at all. Resolution, in this work, denotes when the collision can be considered over or resolved and the aircraft is free to cease the avoidance behaviour and return to its original path. The alignment of some proposed See and Avoid architectures with the traditional collision avoidance framework is depicted in Fig. 1.

See and Avoid systems are not exempt from the requirement to demonstrate an equivalent level of safety (ELOS) to that of manned aircraft. This means that either a pilot remains in the loop, or the system performs this task autonomously with satisfactory performance. Considering that a pilot's ability to adequately See and Avoid has also been deemed questionable [13,14], research has focused on how an automated system may be able to aid, augment [15] or replace the pilot completely [16]. This presents its own set of difficult problems [17]. Indeed, defining the technical design and performance requirements remains as challenging as developing the systems themselves, and they continue to be refined simultaneously [18].

[1] International Civil Aviation Organisation (ICAO), Federal Aviation Administration (FAA), Civil Aviation Safety Authority (CASA) and EUROCONTROL (Europe).