A Survey of Collision Avoidance Approaches for Unmanned Aerial Vehicles

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Abstract-**The ability to integrate unmanned and manned aircraft into airspace is a critical capability that will enable growth in wide varieties of applications. Collision avoidance is a key enabler for the integration of manned and unmanned missions in civil and military operation theaters. Large efforts have been done to address collision avoidance problem to both manned and unmanned aircraft. However, there has been little comparative discussion of the proposed approaches. This paper presents a survey of the collision avoidance approaches those deployed for aircraft, especially for unmanned aerial vehicles. The collision avoidance concept is introduced together with proposing generic functions carried by collision avoidance systems. The design factors of the sense and avoid system, which are used to categorize methods, are explained deeply. Based on the design factors, several typical approaches are categorized.**

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are viable solutions for the future civil and military applications. UAVs may potentially be used as a low-cost solution where manned aircraft are currently used. Many of these applications for UAVs require the ability to navigate in urban or unknown terrain where many moving and/or stationary obstacles of different types and sizes may endanger the safety of the mission. UAVs must have the ability to autonomously plan trajectories that are free from collisions with stationary obstacles as buildings, trees or unlevel ground. Furthermore, any UAV enters commercial airspace must meet strict requirements. One of these requirements is that the UAV must be able to sense and avoid potential conflicts.

Much of the research in collision avoidance approaches for UAV systems had been imparted from the air traffic management, maritime and mobile ground robot research community. Collision Avoidance Systems (CASs) employed among UAVs usually assume cooperative behavior in which inter-agent communication of position, heading, waypoints, and proposed trajectory is allowed. This is a common trait in collision avoidance methods for cooperative UAV systems, cooperative mobile ground robots and ATM systems. However, from the mobile ground robot standpoint, fixed wing aircraft complicates the CAS problem by added dynamic constraints of having to maintain a minimum speed to maintain enough lift to stay aloft.

Some efforts towards describing and understanding the differences among proposed approaches have been introduced in the literature. Zeghal [1] provides a review of the differences among force field collision avoidance methods. Warren [2] conducted an evaluation among three conflict detection methods. Furthermore, Krozel [3], Kuchar [4, 5] conducted detail surveys of conflict resolution methods. Sislak [6] describe the differences and similarities among four current protocol based collision avoidance methods.

This paper provides a survey and discussion of major approaches from the up to date literature that address collision avoidance problem. The intent is to categorize approaches into what type it is designed as well as point out its advantages and disadvantages. Furthermore, the paper identifies common issues that should be considered in CAS design process.

II. FUNCTIONAL UNITS OF COLLISION AVOIDANCE SYSTEM

The global objective of the CAS system is to allow UAVs to operate safely within the non segregated civil and military airspace on a routinely basis. For this purpose, the UAV must be able to identify and be identified by the surrounding traffic as well as by the Automatic Traffic Control (ATC).

The diversity of UAVs and their missions involve a wide-range of system operating concept. Current unmanned aircraft range in size from small hand launch vehicles to large fixed-wing UAV with a wing span similar to Boeing 737. In addition, some UAV autonomously, semiautonomous or completely guided by ground pilot. Furthermore, unmanned vehicles cruise speed, climb/dive rate and operating altitudes are similarly varied [7]. Algorithms, which most likely functioning autonomously will be needed to ensure that the unmanned aircraft avoids other cooperative traffic while also avoids fixed and moving obstructions such as terrain, obstacles and no flying zones.

CAS system must detect and predict traffic conflicts. A conflict is defined as the event in which the Euclidean distance between two agents is less than the minimum desired separation distance. CAS system must be able to detect conflicting traffic in sufficient time to perform an avoidance maneuver and then propose a course of action and maneuver autonomously so as not to create collision. Depending on the level of autonomy inherent in the UAV, these functions could fall into wide range from simple conflict detection and warning to full autonomous conflict detection and avoidance.

The basic idea of CAS monitoring operation involves monitoring the environment for any encounter including cooperative aircraft as well as stationary and moving obstacles in a shared airspace. An example of a shared airspace is that a UAV is performing an operation within the airspace segment that includes both manned and unmanned aircraft together with no flying zone, as depicted in Figure 1. When a UAV gets too close to any moving or stationary obstacles, a potential collision may occur.

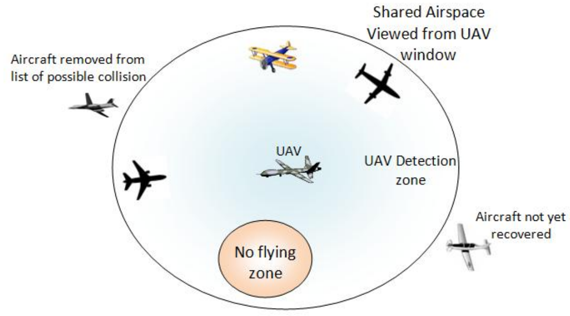

Figure 1. Shared Airspace as viewed from UAV

The unmanned aircraft's CAS system is composed of five key functions. These functions include sensing, detection, awareness, escape trajectory estimation and maneuver realization. Figure 2 illustrates the generic functional architecture of the CAS system for autonomous UAV.

The main role of avoidance function is to evade a collision. This function will be invoked after a near future collision is detected. It determines how and what action should be performed. The maneuvering of the UAV will be performed based on the scheduled flight plan along with the level of responsibility assigned by the ground controller, which is further depends on the level of UAV autonomy[8].

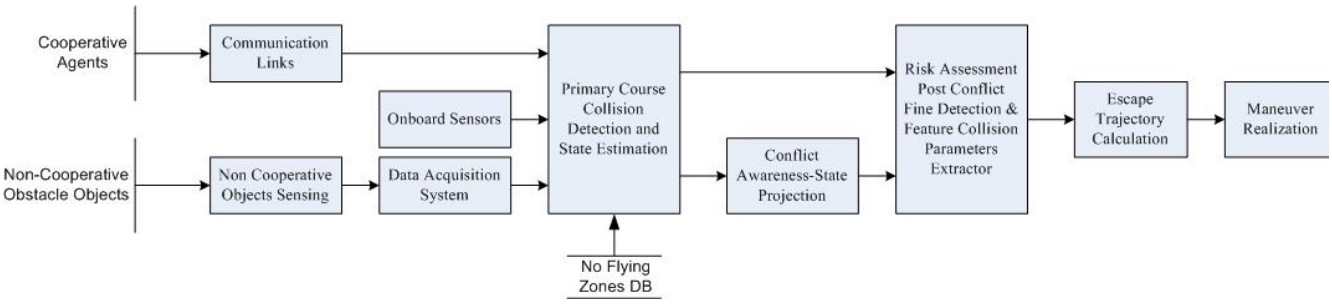

Figure (2): Demonstrates the main functional units implemented in Collision Avoidance System

The sensing function refers to the ability of the system to monitor the environment and collect appropriate current state information for encounters, e.g. aircraft position, velocity and heading, about the environment surrounding UAV. This is done through the utilization of active and/or passive sensors and communication equipments.

The detection function is the ability for the system to acquire the sensed data, process it to extract useful information and discover and manage collision risks to the UAV. Whereas, awareness function is used to dynamically projects the states into the future to check whether a potential conflict will occurs in the near future or not. It also extracts the collision parameters in case of a potential conflict detected. In addition, it handles the process of when action should be taken.

III. DESIGN FACTORS OF UNMANNED AIRCRAFT COLLISION AVOIDANCE SYSTEMS.

A fully automated collision avoidance system must address five problems, as stated above. The approaches are organized in terms of these five main design factors. These factors, that will discussed in details in the following subsections, represent principal categories by which approach differ. Figure (3) shows the main and sub divisions of these factors.

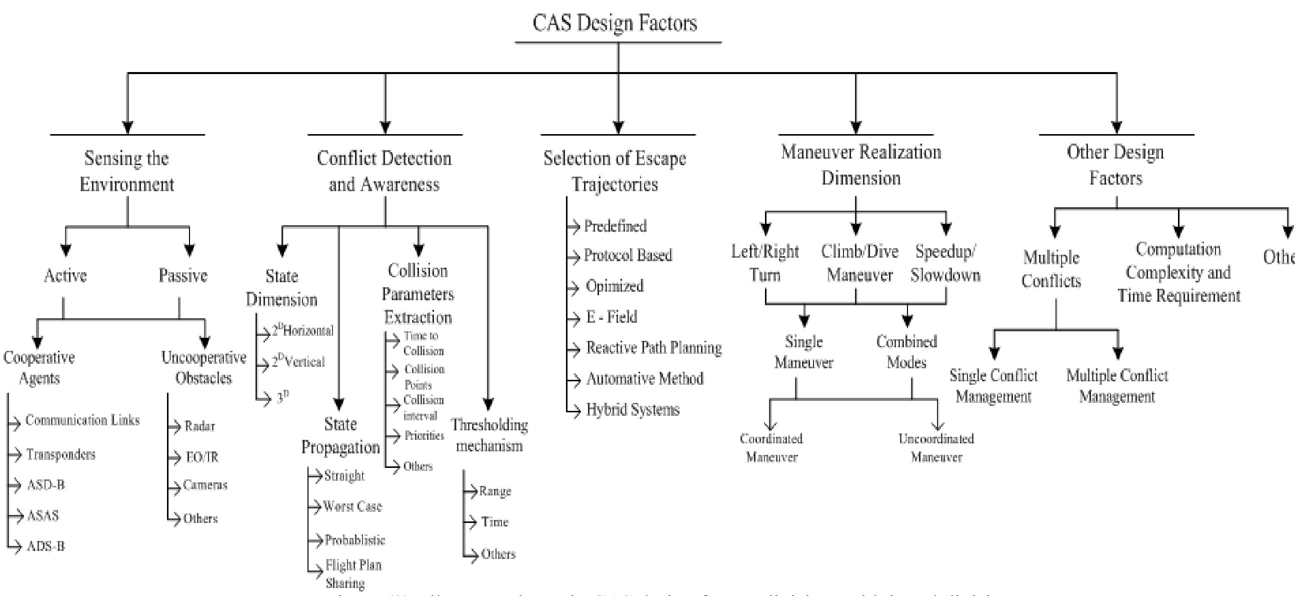

Figure (3): Illustrates the main CAS design factors divisions with its subdivisions.

Many methods have been proposed by various researchers to address collision avoidance problem. These methods have been developed not only for aerospace, but also for ground vehicles, robotics, and maritime applications. That is because the fundamental collision avoidance issues are similar across different transportation systems.

Some of the existing operational systems in use or which have been evaluated in the field are: Airborne Information for Lateral Spacing (AILS) [9], County Technical Assistance Service (CTAS) [10], Ground Proximity Warning System (GPWS) [11] and its recent enhanced version (EGPWS) [12], Precision Runway Monitor (PRM) [13], Traffic alert and Collision avoidance system (TCAS) [14-17], Traffic and Collision Alert Device (TCAD) [18], User Request Evaluation Tool (URET) [19], and a prototype conflict detection system for Cargo Airline Association [20]. The other approaches range from abstract concepts to prototype conflict detection and resolution systems being evaluated and used in laboratories. Some approaches were developed for robotics, automobile or naval applications [21-24], but are still not applicable to aviation [7].

A. Sensing Mechanism.

The sensing function refers to the ability of the system to provide traffic information about surrounding environment around unmanned aircraft system. There are a wide variety of sensors those were deployed for aircraft, which is mainly divided into two main categories: Cooperative and non-cooperative traffic sensors.

Cooperative traffic Sensors includes all communication equipments those enable exchange information between the cooperative agents like position, heading, speed and waypoints. These devices like transponders mode S or emerging technologies like Airborne Separation Assistance Systems (ASAS) and Automatic Dependant Surveillance Broadcast (ADS-B) [25-27]. As an example, ADS-B transfers the information: location, speed, UAV identification from UAV to other agents and ATC.

UAVs not fitted with such communication equipment may use non-cooperative traffic sensors to get knowledge about surrounding environment. In this case, the solution needs new sensors to replace communication links. Sensing the environment can be done in a variety of ways from the available technologies for non cooperative traffic including laser range finders, optical flow sensors Electro-Optical/Infra-Red (EO/IR), radar systems or stereo camera pairs or moving single camera. Laser range finders are commonly used to detect obstacles and are effective if they can be scanned. The use of a single fixed laser range finder is of limited capabilities to detect the environment. Moreover, this type of sensors is considered costly.

Alternatively, the utilization of radar system for active sensor detection [28] is used to detect any moving/stationary obstacles whether they are cooperative or not. However, it is not used in small scale UAV due to its weight and size. As the advances of new powerful processing units, cameras can be used as a passive sensor to detect the obstacles around UAV. Many efforts are already being conducted to use camera in CAS systems found in [29, 30]. Video cameras are light and inexpensive and thereby fit to the UAV requirements especially the small one. Video camera can be configured for obstacle detection as a stereo pair, or a moving single camera. However, video cameras provide information in a way that requires significant data processing to be useful for autonomous control for unmanned aircraft.

The accuracy of data available from sensors is limited and depends on the type of sensor used. The accuracy required depends on aircraft packing density. The data update rate received from other aircraft is important, so that the aircraft are working on timely data. The safety distance between aircraft can be increased to account for sensor inaccuracy.

B. Encounter Sensing Dimension

This dimension demonstrates whether the monitoring of the environment used in a given approach is in two dimensional horizontal plane (2D-H), two dimensional Vertical Plane (2D-V) or three dimensional state information (3D). The majority of the developed CAS approaches cover either 3D or 2D-H. However GPWS focuses on the 2D-V.

The coverage of a certain dimension doesn't necessary mean complete description of the situation in that dimension is available. For example, TCAS uses range measurements and range rate estimates to determine if a conflict exists in the horizontal plane. A better prediction of the threat condition could be obtained if additional information were available such as bearing.

C. Encounter Current information projection

One of the main CAS factors is the prediction of the future. That is because it specifies the way of dynamic projecting states of UAV and encounter into the near future and check for collision risk. Four fundamental prediction methods have been identified. These methods are, as illustrated in figure (4): worst case, straight projection, probabilistic and flight plan sharing.

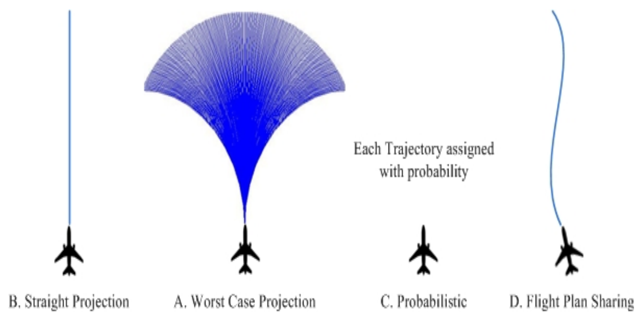

Figure (4): Methods used for projecting current encounter's information

In the straight projection method, the states are projected into the future along a single trajectory, without direct consideration for uncertainties, as shown in figure (4.a). This will simplify the problem but it is can be only used in situations in which aircraft trajectories is very predictable and for short period of time. That is because the CAS approach that uses straight projection doesn't account for the possibility that an encounter can do any maneuvering in predicted time.

The other extreme is the worst case projection illustrated in figure (4.b), which assumes an aircraft will perform any range of maneuvers. If anyone of these trajectories could cause a conflict, then a conflict is predicted. It should be limited to a short period projection time to limit the computation requirement for risk assessment.

In the probabilistic method, the uncertainties are modeled to describe risk variation in the future trajectory of aircraft, as shown in figure (4.c). This method is based on developing a complete set of possible future trajectories, each weighted by a probability of occurring, making a probability density function. The advantages of this method is that decisions can be made on the fundamental likelihood of conflict; safety and false alarm rate can be assessed and considered directly. However, the disadvantage is that the logic behind this method may be difficult to model the probabilities future trajectories.

The advancement of the technology allows for the forth method of encounter states projection using path plan sharing, as depicted in figure (4.d). It is a method of providing path trajectory (flight plan segment) and aircraft specific information (like position, heading and velocity) to all other aircraft in the vicinity. Data from each aircraft will be sent to ground stations for monitoring and all neighboring aircraft as a broadcast. This will leads give all aircraft a 3D picture of neighboring aircraft movements, precise projection of encounters' states and exact collision parameters extraction. As an example ADS-B that is proposed to be fully deployed in aircraft by the year 2020 to support free flight capability [31]. However, the focus needs to be on removing the complexity of data exchanges and the quantity of data required to ensure safe maneuvers. Clearly, the more data needed to be exchanged in collision situation, the more complex and prone to error the system becomes.

D. *Assessment of Collision Risk and Collision Parameters Extraction*

The design of any collision avoidance system should include some form of assessment of collision risk. This is a complex issue that receives considerable attention in the literature. An example is given by Carlson [33]. Merz [34] describes a method of avoiding collision given the increased likelihood of collision as aircraft numbers and packing densities increase. The limit on packing density where these algorithms no longer work is examined by Bowers and smith [35, 36].

Approaches may use an extremely simple criterion like range information to determine when a conflict exists or may use a more complex threshold or set of logic. Some of them uses concept of a simple threat detection zone around each aircraft and determines a maneuver that ensures adequate separation even if one aircraft does not maneuver. This provides safe separation even if the link to one aircraft fails.

E. *Escape Trajectories Calculation Approaches*

Various approaches have been proposed in the collision avoidance literature for choosing escape trajectories that generates the solution to a conflict. Six main categories of the escape trajectory approaches are introduced in this paper, which are: Predefined, Protocol Based, optimized, E-filed, automotive and hybrid systems. These approaches will be discussed in details in the next section.

F. *Maneuver Realization Dimension*

A maneuver is the combination of actions by all aircraft in the vicinity. Initiating a resolution maneuver requires at least one aircraft to change its flight plan. The maneuver dimensions include: horizontal plane, turn left/right; vertical maneuver, climb/dive; and/or speedup slowdown commands. These maneuvers, depends on the CAS approach used, may be issued separately (e.g. change of only one dimension) or combined maneuvers may be performed (e.g. speed and vertical and horizontal planes). Furthermore, the combined maneuvers can be performed simultaneously or in sequence.

Issues such as coordinated and uncoordinated maneuvers also need to be addressed. Coordinated maneuver refers to the choice of the direction when there is a choice of two alternative versions of maneuver. As an example in TCAS in which the preferred maneuver might be for aircraft A to climb while aircraft B descends. While the uncoordinated maneuver refers to the worst case scenario, in which the other aircraft does not respond and only the computing aircraft should do all the maneuvering commands.

G. *Other Design Factors*

One of the other important CAS design factors is that, complex computation performed by an approach versus time requirement to resolve the conflict. The designed approaches should take into consideration finding the solution in real time. This means compromise between two factors must be done. That is the complexity of the calculation needs to be bounded, to provide an approach that is effective and robust but reasonably simple.

Another important design factor is the consideration of the CAS system for detection and accordingly resolving conflicts in multiple encounters scenarios. It describes how an approach handles traffic situations with multiple aircraft. It is divided into two types: Single conflict management approaches in which multiple sequential conflicts are avoided sequentially in pairs, and multiple conflict management approaches in which the entire situation is handled simultaneously. The general problem raises questions such as does this maneuver work on multi aircraft? Is there a maximum packing density where maneuvers no longer work and is it dependent on aircraft type or separation criteria?

IV. CATEGORIZATION OF THE DEVELOPED COLLISION AVOIDANCE APPROACHES

To provide insight into different CAS approaches, a literature review of previous research models and current developmental and operational systems is performed. Based on the collision avoidance system design factors as illustrated in Figure 3, the approaches were catalogued according to their fundamental approaches to each phase of CAS function. The major collision avoidance approaches are categorized into four main methods. These methods are explained together with their advantages and disadvantages in the following subsystems.

A. *Predefined Collision Avoidance*

This type of collision avoidance is based on a fixed set of predefined rules without performing any additional computation to determine an escape trajectory. The advantage is on minimizing the response time to avoid the conflict. In the other hand the disadvantages will be on less effectiveness and less optimal than the maneuvers which are computed in online. That is because there is no way to alter the commanded maneuver, which is very essential to account for unexpected events. As an example, GPWS issues a standard climb warning when a conflict with terrain exists. Other examples can be found in the references [9, 13, 37].

B. Protocol Based Decentralized Collision Avoidance

This type offers a very elegant solution to conflict free navigation for a team of agents, each agent represent an aircraft. Inter-agent communication includes sharing position, velocities, waypoints and heading. Agents make decisions based on a common set of rules decided priori. This method is decentralized, highly scalable and guarantees safety. However, the trade off is that unnecessary long trajectories can be generated long mission completion times. [6, 38-42] are examples use this kind of collision avoidance approach.

C. Optimized Escape Trajectory Approaches

In this type, the collision avoidance problem is often formulated as an optimization problem and many different optimization problems can be applied .These approaches generally combine a kinematic model with a set of constraints. An optimal resolution strategy is then computed based on most desired optimization constraint. For example at present, the TCAS system does not seek to define an escape trajectory, instead requesting a climb or dive maneuver [43, 44]. It searches through a set of potential climb or descent maneuvers and selects the least-aggressive maneuver that provides adequate protection. The idea implies that somehow the system knows that the path planned towards the goal without taking account of intruders would be unsafe. An aircraft will head for its goal until a collision threat is detected and then find a trajectory that will avoid the collision. Path planning should be more elegant, that is finding a safe trajectory that still reaches the goal.

Tomilin [45] presents an approach using game theory for controller design that covers simple moving obstacles. Although it is interesting, it does not appear practical at present. Another well-known safe navigation method originating from mobile ground robot research community is the dynamic window approach, presented by Fox [46]. This approach takes into account the dynamic model and kinematic constraints of aircraft to determine a safe control action.

Other optimized conflict resolution approaches utilize techniques such as genetic algorithms, expert systems, or fuzzy control to the problem. These techniques may be complex and therefore would require a large number of rules to completely cover all possible encounter scenarios. This may leads to a very power computational processing demanding. Resulting in difficult to certify that the system will always operate as intended.

Pre-mission path planning is often formulated as an optimization problem and many different optimization problems can be applied. Path planning for UAVs is difficult problem because it requires the ability to create paths in environments containing obstacles or no-flying zones. Additionally, UAVs are constrained by minimum turning radius, minimum speed, and maximum climb rate constraints. Generally, CAS algorithms are used to sparsely search the space for solutions and then the best solution is chosen.

D. E-Field Methods

Many methods have been proposed for safe navigation in static obstacle strewn environment. Most popular obstacle avoidance methods are artificial potential field methods. Researchers have considered the force field to map the volume between aircraft in terms of a potential field. The methods treat each aircraft as a charged particle and the repulsive forces between aircraft are used to generate maneuvering trajectories. This type is considered as a path planning technique that estimates the trajectories by creating trajectory estimation filters based on the previous paths. Trajectories with low flex densities can be then selected as the preferred courses. The method shows some success through the sense that conflict avoidance is continuously available using simple electrostatic equations. However, the algorithms presented have limited relevance due to sharp discontinuities in the commanded maneuvers may occurs. Furthermore, it requires a high level of flight guidance, leads to increase in complexity beyond issuing simple maneuvering commands.

Artificial potential field methods were first presented by Khatib [47]. Other methods utilize same escape method can be found in references [48-51]. Obstacle and other agents are modeled as repulsive forces and waypoints as attractive forces; the gradient of the summation of these forces yields the control command. These methods provide very simple and elegant solutions to general collision avoidance scenarios. However, the existence of local minima could trap a robot for infinite time [52]. Potential field like methods that didn't have local minima were later demonstrated [53, 54]. The designed for multi-agent systems presented in [55], in which the repulsion force from neighboring agents is replaced by a gyroscopic force from the nearest neighbor. This force will enable an agent to spin free in symmetric conflict scenarios.

E. Other CAS Approaches

Most other methods of escape trajectory maneuvering rely on trajectory estimation filters based on previous intruder path history, position versus time. However, actual intended intruder path data, position; heading; and future waypoints, offers a much more reliable basis for path planning than trying to estimate where the intruder might go given its previous history.

In addition to the above most famous approaches, there are several other CAS approaches to be considered. Like automotive collision avoidance, that offers some interesting analogies for aircraft but does not appear to have been considered for this purpose in the literature. It attempts to predict the vehicle trajectory using historical information or forward looking sensors [56].

Another method uses hybrid CAS systems as presented by Tomlin [38, 45]. This type of realization is concerned with the modeling and control of systems combining continuous and discrete states. In this method, vehicle and its maneuver is modeled as a hybrid system and its reachable sets of states is filtered based on safety specifications to get a safe subset of the reach set. Then Hamilton-Jacobi equations are employed to calculate control commands that can guarantee UAV will remain in its safe set. Although this method is decentralized and guarantees safety it scales poorly for large UAVs.

V. CONCLUDING REMARKS

This paper presents a survey of collision avoidance approaches from different scientific areas and communities related to collision avoidance algorithms applicable to autonomous UAV. The survey and categorization is based on the main CAS design factors which are also handled in this paper. However, it is important for a future work to make a comprehensive review of the developed methods considering a larger set of CAS factors.

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