A REVIEW ON AERONAUTICAL DECISION-MAKING AND ARTIFICIAL INTELLIGENCE FOR UNMANNED AIRCRAFT

Thiago Toshio Matsumoto
Escola Politécnica da Universidade de São Paulo – EPUSP
Av. Prof. Luciano Gualberto – Trav. 3, 158, +55 11 3091-5395, ttmatsumoto@usp.br

João Batista Camargo Junior
Escola Politécnica da Universidade de São Paulo – EPUSP
Av. Prof. Luciano Gualberto – Trav. 3, 158, +55 11 3091-5401, joaocamargo@usp.br

ABSTRACT

We present a review of decision-making concepts with focus on Aeronautical Decision-Making (ADM), traditionally performed by humans, and possible decision-making methods presented in Artificial Intelligence (AI) literature, with focus on collision avoidance. Additionally, from the human decision-making model used in ADM, we perform a comparison with AI methods with the objective of identifying advantages and disadvantages of replacing a human by an AI-based system within an aircraft. The identification of the state of the art on those subjects will be used as basis to future researches on unmanned aircraft autonomous operation.

Keywords: Aeronautical decision-making, artificial intelligence, UAS.

1. INTRODUCTION

As evidenced by the Committee on Autonomy Research for Civil Aviation National Research Council (2014) of the National Research Council, due to the expectation of significant benefits in terms of safety, reliability, efficiency, affordability and previously unattainable mission capabilities, a wide variety of organizations is making advances in the development of technologies that are directly related to increasingly autonomous[1] systems for civil aviation. Besides, due to the increasingly interest for possible applications of Unmanned Aircraft Systems (UASs), we consider the use of increasingly autonomous systems within the unmanned aircraft will be indispensable. Although the International Civil Aviation Organization (ICAO) considers only remotely-piloted aircraft will be able to integrate the international civil aviation system in the foreseeable future (ICAO, 2011), it is worth observing that the contingency options described by ICAO (2015) for a scenario of loss of Command and Control (C2) link would demand an automatic behavior of the aircraft, similarly to an increasingly autonomous system.

However, it is important to notice that the Committee on Autonomy Research for Civil Aviation National Research Council (2014) identifies several barriers to the increased use of autonomy in civil aviation systems. Most of those barriers is related to technological issues, such as:

- Bandwidth of wireless communications and data links.
- Vulnerability to cyberphysical attacks, impairing safety and reliability of increasingly autonomous systems.
- Lack of generally accepted design, implementation and test practices for granting decision-making capabilities to adaptive/nondeterministic systems.
- Limitation related to machine sensory, perceptual and cognitive systems, which would have to replace those capabilities of a human.
- Lack of verification and validation methods applicable for advanced increasingly autonomous systems.

Additionally, the Committee identifies non-technological barriers such as those related to regulation and certification (e.g. lack of a certification process that considers the special characteristics of an advanced increasingly autonomous system) and those related to political or social issues.

In this work, we selected the technological barrier related to implementation of decision-making capabilities within an increasingly autonomous system as the main subject. Therefore, the objective of this work is to identify in the literature the state of the art of approaches used to implement decision-making capabilities within an (increasingly autonomous) aircraft. However, as decision-making within aviation encompasses a wide variety of aspects, we decided to focus on decision-making for collision avoidance.

The subsequent sections of this work are organized as follows: section 2 presents concepts associated to decision-making and decision models applied within the aeronautical environment; section 3 describes collision avoidance methods that are closely related to the aviation environment and that are intended for use in the near future; section 4 presents a discussion regarding the concepts presented in the previous sections; section 5 presents our final remarks; finally sections 6 and 7 present, respectively, our acknowledgements and the references consulted for this work.

2. DECISION-MAKING CONCEPTS

In this section, we present concepts identified in the academic literature and in aeronautical reference documents related to decision-making. It is worth noticing that firstly we consider decision-making in a broad sense, not being restricted to increasingly autonomous systems and artificial

[1] The Committee on Autonomy Research for Civil Aviation National Research Council (2014) uses the term "increasingly autonomous systems" for referring to those systems whose capabilities lies between those of a theoretical fully autonomous system, capable of operating independently within civil airspace, and those of a current automatic system (e.g. remotely piloted aircraft).

intelligence. In this regard, we identified the approach used by people for decision-making in the aeronautical environment as a comparison basis for AI methods (discussed in section 4).

2.1. Normative decision theory and descriptive decision theory

As presented by Peterson (2017), decision theory represents an interdisciplinary field of study for which professionals of different areas – such as philosophers, psychologists and computer scientists – present contributions. However, Peterson (2017) presents a distinction between **normative decision theory** and **descriptive decision theory**, which are briefly described below:

- **Normative decision theory**: a decision theory that seeks to describe how a **rational agent** must proceed for decision-making. The normative decision theory is related to decision-making approaches that are based on maximizing (or minimizing) the expected value of a utility function. The ACAS X (discussed in section 3.2) is an example of such an approach.
- **Descriptive decision theory**: decision theory that focuses on describing how people actually makes decisions. In this regard, it is worth observing that not all decisions made by people are strictly rational, independently of the proficiency of the decision-maker. The naturalistic decision making discussed in following sections is an example of this kind of decision theory.

2.2. Naturalistic Decision Making

As presented by Klein (2008), the concept of Naturalistic Decision Making (NDM) emerged in 1989 as a research field that seeks to identify the decision-making strategies applied by people in real-world settings. One important aspect indicated by Klein (2008) is the fact that, even though not adherent to optimal performance principles (based on probability and maximization of expected value), people are still capable of making decisions under adverse conditions, such as time limitation and uncertainties. As presented by Orasanu (2010), decisions vary from intuitive (dependent on pattern recognition based on experience) to analytic depending on the nature of the situation in which they are made.

2.3. Aeronautical Decision-Making

Within the aviation environment, the Advisory Circular AC 60-22 (FAA, 1991) and chapter 17 of the Pilot's Handbook of Aeronautical Knowledge (FAA, 2008), both issued by the Federal Aviation Administration (regulatory agency for civil aviation in the United States), present the concept of Aeronautical Decision-Making (ADM), which is defined as a "systematic approach to risk assessment and stress management" (FAA, 2008). We notice that those documents focus on behavioral training for the pilot. In this regard, those documents indicate that hazard and risk are two defining elements for ADM and present some guidance for pilots to make decisions according to observable risk sources (pilot himself, aircraft, environment and mission/external pressures).

However, it is worth observing FAA (2008) acknowledges the existence of situations in which time is not sufficient to allow for analytical decision-making. Under those conditions, a naturalistic decision-making (also called automatic decision-making by FAA) is applied. In Figure 1, both analytical and naturalistic decision-making are illustrated.

Additionally, it is worth observing that FAA (2008) acknowledges that risk assessment process as preconized in ADM is subject to the pilot's perception of hazards, as different pilots may see a given hazard differently. Besides, the FAA documents also indicate that hazardous attitudes (e.g. failing to recognize own limits) may affect the quality of a pilot's decision.

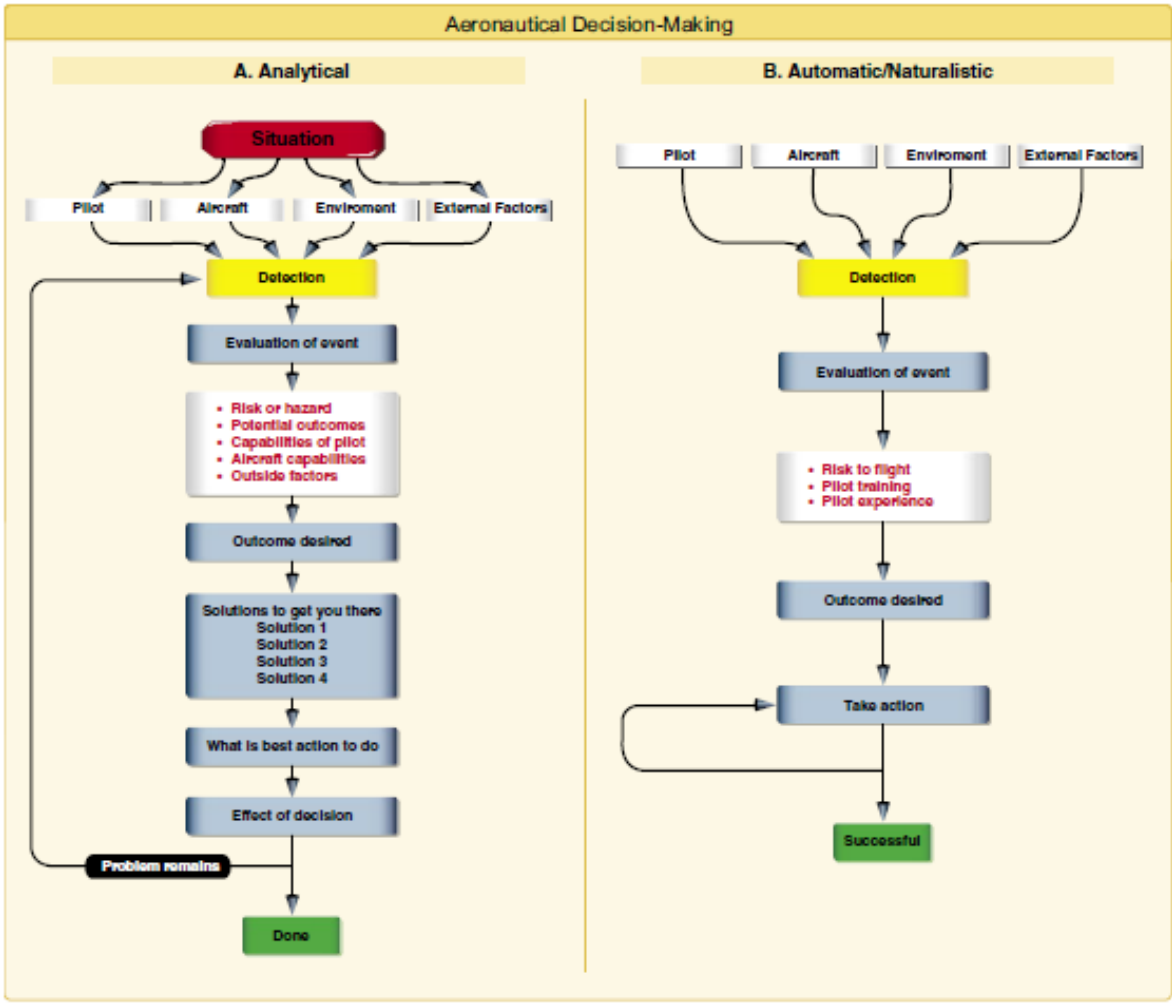


Figure 1: Analytical and automatic/naturalistic approaches for ADM (FAA, 2008).

3. AUTOMATIC METHODS FOR COLLISION AVOIDANCE IN AVIATION

In a previous work (MATSUMOTO; CAMARGO JUNIOR, 2016), we had identified a number of different approaches to control an autonomous aircraft. However, as discussed in that work, we observed that most of the identified approaches focuses solely on the computational problem, without considering ATC concepts. Therefore, for the present work, we considered important to focus on those methods that are more closely related to ATC, as they represent the more suitable candidates for being embedded into an increasingly autonomous aircraft system. In this regard, most of the documents that were consulted in the scope of the present work generally indicate Traffic Alert and Collision Avoidance System (TCAS) and its variants as the resource for collision avoidance in civil aviation. Consequently, this work is focused on that technology, which is discussed in the subsequent sections.

3.1. Traffic Alert and Collision Avoidance System (TCAS)

The beginning of collision avoidance systems development dates from 1950s. In 1956, the collision of two airliners over the Grand Canyon in the United States pushed both airlines and aviation authorities towards the development of an effective collision avoidance system that should serve as a last resource in case of failure of separation services provided by ATC (EUROCONTROL, 2016)(FEDERAL AVIATION ADMINISTRATION, 2011).Through the years, the idea of such a collision avoidance system evolved from passive and non-cooperative concepts, considered to be

impractical in the early 1960s, to a beacon-based system (Beacon Collision Avoidance System, BCAS) in the mid-1970s. Finally, in the beginning of the 1980s, FAA made a decision to develop TCAS utilizing BCAS design as basis for interrogation and tracking, with the addition of some capabilities (FEDERAL AVIATION ADMINISTRATION, 2011). Besides, in parallel, ICAO developed standards for Airborne Collision Avoidance Systems (ACAS). Currently, TCAS II is the only implementation the complies to ACAS standards (EUROCONTROL, 2016)[2].

In relation to TCAS II operating concept, it is based on the interrogation of ICAO compliant transponders in the vicinity. Based on the replies received, TCAS tracks the slant range and relative bearing of surrounding traffic (altitude can be tracked as well if informed in the reply message). From successive replies, TCAS calculates the time to reach the closest point of approach with the intruder, which is the main parameter for issuing alerts (FEDERAL AVIATION ADMINISTRATION, 2011). In this aspect, TCAS can issue two types of alerts (EUROCONTROL, 2016)(FEDERAL AVIATION ADMINISTRATION, 2011):

- Traffic Advisories (TA) – intended to help pilots in visual identification of the intruder aircraft and to alert them for a possible resolution advisory.
- Resolution Advisories (RA) – recommendation of avoidance maneuver, which tells the pilot the range of vertical rates within which the aircraft should be flown to avoid the intruder aircraft. For the issuance of RAs, it is not necessary the intruder aircraft to be equipped with TCAS. However, if it does, both systems will coordinate to select complementary RAs.

It is worth observing that, despite being able to avoid mid-air collisions over the years, TCAS present some limitations. As discussed by Kochenderfer, Holland and Chryssanthacopoulos (2012), on fundamental limitation of TCAS is being based on a deterministic model. Due to this characteristic, it would be necessary to anticipate the entire spectrum of responses from all aircraft involved in the conflict. In this regard, one of the most noticeable exemplification of such a limitation was the collision of two aircraft in 2002 over Überlingen, Germany. In that accident, TCAS of both aircraft had issued complimentary RAs, indicating one aircraft to climb and the other to descend. However, not being aware of TCAS RAs, the ATCo instructed the former to descend, contrary to TCAS RA (EUROCONTROL, 2016)(KOCHENDERFER; HOLLAND; CHRYSSANTHACOPOULOS, 2012). As described by EUROCONTROL (2016), the existing version of TCAS (7.0) at that time was not capable of reversing an RA in that kind of conflict (see Figure 2), limitation that was corrected in version 7.1 (Figure 3).

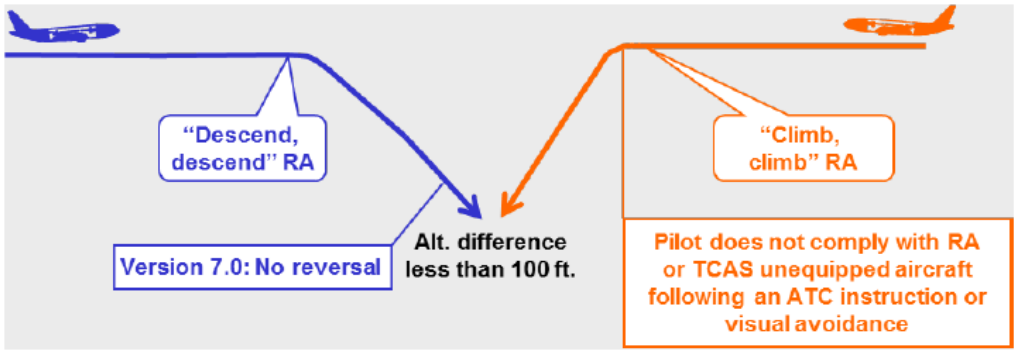


Figure 2: Conflict geometry in which version 7.0 of TCAS does not reverse an RA (EUROCONTROL, 2016).

[2] As discussed by EUROCONTROL (2016), the term ACAS II is typically used to refer to the standard or to the concept, whereas the term TCAS II is used to refer to the implementation. In this work, those terms are used interchangeably.

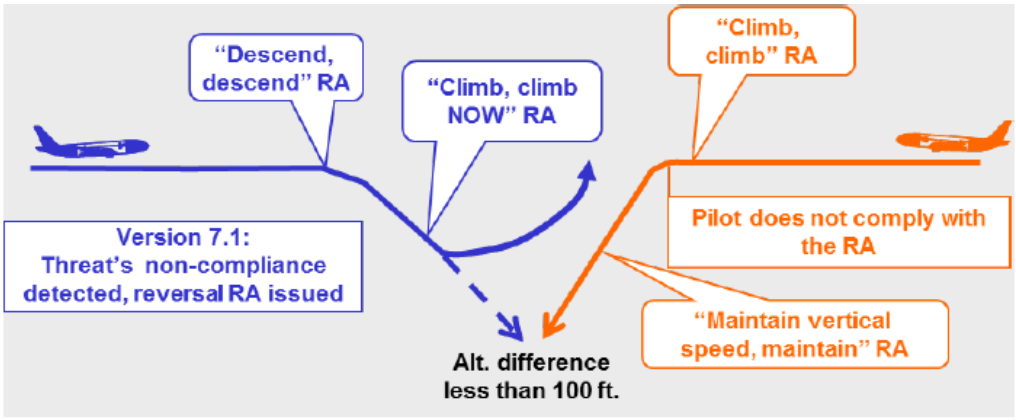


Figure 3: Improved logic for issuing reversal RA in version 7.1 of TCAS (EUROCONTROL, 2016).

Additionally, it is important to consider current TCAS limitations that may become more evident with the evolution of operational concepts in aviation. For example, considering future reduction of spacing between aircraft as a consequence of an increasing airspace population density, it is expected that TCAS II would issue alerts too frequently to be useful (EUROCONTROL, 2016). Besides, another important aspect to consider is the increasingly interest for UAS applications and some particularities of that kind of aircraft. Due to a restricted performance criteria necessary for TCAS (e.g. aircraft must be capable of achieving a climb rate of 2500 ft/min), many unmanned aircraft would not be able to use TCAS (EUROCONTROL, 2016). Moreover, it is important to emphasize the fact that TCAS is not certified for autonomous use (TEMIZER et al., 2010), with a concept of operation that is independent of autopilot and other aircraft systems in general[3] (EUROCONTROL, 2016).

Regarding the limitations of TCAS, FAA has funded research for the development of a new generation of airborne collision avoidance system, which is known as ACAS X. In the next section, we present a description of the main characteristics of ACAS X as identified in the literature.

3.2. Next generation of TCAS – ACAS X

As presented by Kochenderfer, Holland and Chryssanthacopoulos (2012), ACAS X will present major enhancements in terms of surveillance and advisory logic as described below:

- **Surveillance**: as discussed in section 3.1, TCAS was developed using beacon-based surveillance. In the other hand, ACAS X will support other kinds of surveillance techniques, such as those based on satellites (e.g. GPS), and other modalities of sensors, including radar and electro-optical sensors.
- **Advisory logic**: instead of using hard-coded rules of TCAS, ACAS X advisory logic is based upon a numeric lookup table which is generated by means of optimization methods applied to a probabilistic dynamic model of the airspace.

Regarding the probabilistic model used for ACAS X, Kochenderfer, Holland and Chryssanthacopoulos (2012) indicate such a model is represented as a Markov Decision Problem (MDP), which also includes a utility model. Within such a model, the state (e.g. position and velocity) of the aircraft involved defines the model state. Therefore, from each state of the model a set of actions (corresponding to the RAs that ACAS X may issue) is available and, depending on the current state and the action performed, the next state of the model is determined probabilistically. Besides, a reward function is associated for each state transition in the model (for example, transitions that lead to a near mid-air collision would represent a large penalty). Finally, the application of optimization techniques to that MDP generates a lookup table that indicates the best action to take for each state

[3] As presented by EUROCONTROL (2016), Airbus AP/FD TCAS capability is the only exception to TCAS concept of operation as that mode of operation allows for the autopilot to automatically fly the RA.

of the model to maximize the utility function (calculated accordingly to the transition probability and the associated reward). The process of generating the lookup table and selecting the RAs during runtime is illustrated in Figure 4.

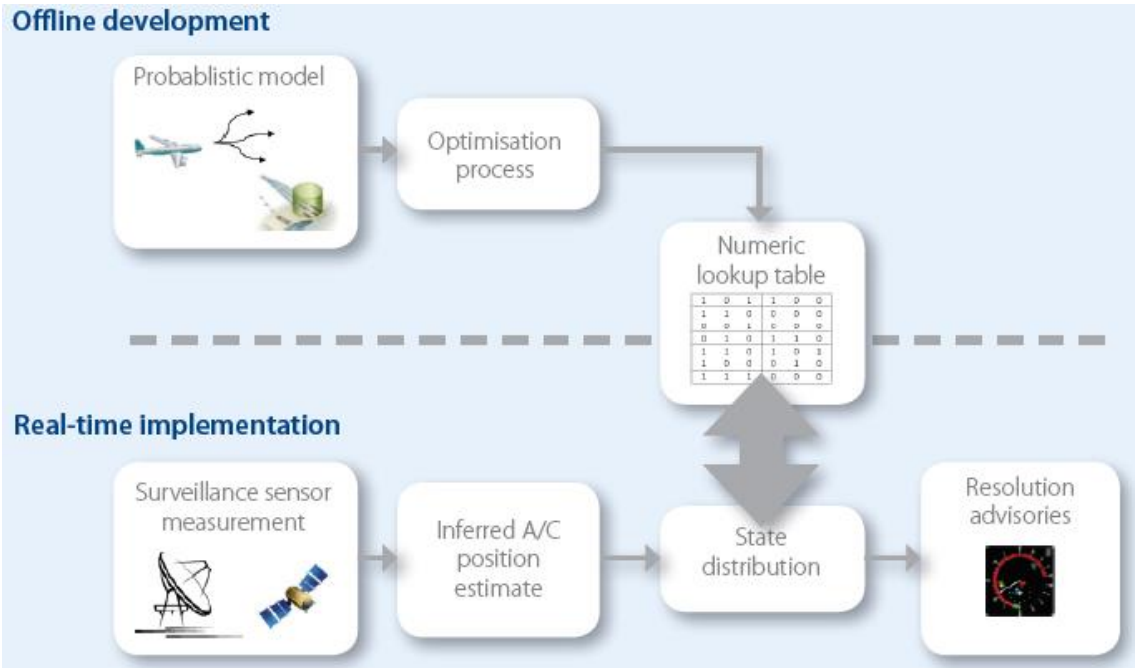


Figure 4: ACAS X collision avoidance logic (EUROCONTROL, 2013).

Moreover, it is worth observing that ACAS X present four variants, each of those intended for different kind of operations as presented in Table 1.

Table 1: ACAS X variants (adapted from EUROCONTROL (2016) and Olson (2016)).

ACAS X variant	***Intended use***	***Surveillance approach***	***Advisories set***	***Schedule***
ACAS Xa	TCAS II successor (general purpose ACAS X)	Beacon-based surveillance with supplementation provided by ADS-B[4]	Same set of advisories of current TCAS II	Standards are expected to be ready by 2018. Expected to be operational in 2020.
ACAS Xo	Extension of ACAS Xa for use in specific operations, such as closely spaced parallel approach	Beacon-based surveillance with supplementation provided by ADS-B	Procedure specific alerts for selected aircraft and global alerting against others	Standards also expected to be ready by 2018.
ACAS Xu	Unmanned aircraft	Potentially radar, electro-optical, infrared, etc.	Vertical and horizontal advisories	Work on standards started in 2016 and is expected to be finished by 2020.

[4] Automatic Dependent Surveillance-Broadcast.

ACAS X variant	*Intended use*	*Surveillance approach*	*Advisories set*	*Schedule*
ACAS Xp	General aviation	Passive ADS-B only. Does not make interrogations.	Reduced advisory set	Longer-term research

It is worth observing that, as presented by Olson (2016), ACAS Xu possesses the capability of responding automatically to RAs, which represents an important aspect associated to increasingly autonomous aircraft systems. One important contribution in this regard was presented by Kotegawa (2016), who reported the results of ACAS Xu proof of concept flight tests executed in 2014. As indicated by Kotegawa, those tests involved several private and public organizations, including FAA and NASA, and represent the first demonstration of a coordinated automatic resolution maneuvers between two unmanned aircraft with ACAS Xu. Another contribution worth noticing was presented by Mueller and Kochenderfer (2016), who explored the capabilities of a multi-rotor aircraft to allow for speed changes as collision avoidance maneuvers.

Finally, with respect to other contributions to ACAS X development, it is worth noticing that we identified some recent works that are focused in verification of ACAS X implementation. As discussed by Jeannin et al. (2015), the task of verifying ACAS X present some challenges, as the size of the lookup table generated by the optimization process makes impracticable the execution of a full verification. Instead, for a given conflict geometry, Jeannin et al. define some "safe regions" to represent geometric configurations for the aircraft that does not result in a near -mid-air collision. Additionally, von Essen and Giannakopoulou (2016) present an approach based on the probabilistic verification. One noticeable aspect discussed in that work refers to the effect on the controller observed by varying the resolution used in state space discretization. In this aspect, von Essen and Giannakopoulou indicates that an increase in altitude resolution for representing aircraft were more effective than increasing the number of climb rates.

4. DISCUSSION

By comparing the ADM process (described in section 2.3) and ACAS X concepts (section 3.2), we consider the optimization method applied for ACAS X to be closely related to the analytical approach for ADM. However, due to being implemented by an automatic system, the selection of the most appropriate solution by ACAS X is not susceptible to external factors or to hazardous attitudes. Besides, such an automatic system can process the collision avoidance logic sufficiently fast to not require the use of suboptimal approaches such as the naturalistic decision-making. Another important improvement presented by ACAS X concept is related to the fact of it not being dependent on deterministic behaviors, which make it capable of handling a broader spectrum of responses as compared to TCAS II. We consider those aspects represent important advantages in the use of increasingly autonomous aircraft systems with focus on collision avoidance.

However, we consider that, due to the model-based nature of ACAS X, its performance for collision avoidance is determined by the quality of the probabilistic model used for generating the corresponding lookup tables. In this regard, it was possible to notice that, in general, the references consulted in the scope of this work indicates that selecting appropriate reward functions for the MDP models is of major importance. Besides, selection of discretization resolution for describing model spaces and identification of verification methods appropriate to being applied to ACAS X approach represent other research challenges.

5. FINAL REMARKS AND FUTURE WORK

This work presented a literature review on concepts related to decision-making in aviation with focus on collision avoidance methods, considering increasingly autonomous systems. We considered concepts from both Aeronautical Decision-Making practices used by human pilots and the artificial intelligence literature, which allowed for a comparison between human and automatic decision-making approaches. However, given the broad spectrum of suitable artificial intelligence methods presented in the literature, we focused on works that are more closely related to the aviation environment, which contributed to narrow our review down to TCAS-like approaches. The main contribution of this work is the identification of the state of the art in that subject and the associated research gaps for future works.

6. ACKNOWLEDGEMENTS

The authors thank Boeing Research & Technology – Brasil (BR&T-Brasil) for the support for this research and for its institutional support to the Safety Analysis Group (GAS) of the School of Engineering of the University of São Paulo (Poli-USP).

7. REFERENCES

COMMITTEE ON AUTONOMY RESEARCH FOR CIVIL AVIATION; BOARD, A. and S. E.; DIVISION ON ENGINEERING AND PHYSICAL SCIENCES; NATIONAL RESEARCH COUNCIL. **Autonomy Research for Civil Aviation : Toward a New Era of Flight**. [s.l: s.n.]. Disponível em: <http://www.nap.edu/download.php?record_id=18815>.

EUROCONTROL. ACAS X – the future of airborne collision avoidance. **NETALERT - the Safety Nets newsletter**, p. 1–10, 2013. Disponível em: <http://www.skybrary.aero/bookshelf/books/2390.pdf>.

EUROCONTROL. **Airborne Collison Avoidance System (ACAS) Guide**. [s.l.] EUROCONTROL, 2016.

FAA. **AC 60-22 Aeronautical Decision Making**, 1991. . Disponível em: <http://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_60-22.pdf>.

FAA. **Pilot's Handbook of Aeronautical Knowledge**. [s.l: s.n.]. Disponível em: <http://www.faa.gov/regulations_policies/handbooks_manuals/aviation/pilot_handbook/media/FAA-H-8083-25A.pdf>.

FEDERAL AVIATION ADMINISTRATION. **Introduction to TCAS II Version 7.1**. [s.l: s.n.]. Disponível em: <http://www.faa.gov/documentLibrary/media/Advisory_Circular/TCAS II V7.1 Intro booklet.pdf>.

ICAO. **ICAO Cir 328, Unmanned Aircraft Systems (UAS)**. [s.l: s.n.]. Disponível em: <http://www.icao.int/Meetings/UAS/Documents/Circular 328_en.pdf>.

[CSL STYLE ERROR: reference with no printed form.]

JEANNIN, J.-B.; GHORBAL, K.; KOUSKOULAS, Y.; GARDNER, R.; SCHMIDT, A.; ZAWADZKI, E.; PLATZER, A. Formal verification of ACAS X, an industrial airborne collision avoidance system. In: 2015 International Conference on Embedded Software (EMSOFT), Acas X, **Anais**...IEEE, out. 2015. Disponível em: <http://ieeexplore.ieee.org/document/7318268/>.

KLEIN, G. Naturalistic Decision Making. **Human Factors**, v. 50, n. 3, p. 456–460, jun. 2008. Disponível em: <http://journals.sagepub.com/doi/10.1518/001872008X288385>.

KOCHENDERFER, M. J.; HOLLAND, J. E.; CHRYSSANTHACOPOULOS, J. P. Next-Generation Airborne Collision Avoidance System. **Lincoln Laboratory Journal**, v. 19, n. 1, p. 17–33, 2012. Disponível em: <https://www.ll.mit.edu/publications/journal/pdf/vol19_no1/19_1_1_Kochenderfer.pdf>.

KOTEGAWA, T. Feature article: proof-of-concept airborne sense and avoid system with ACAS-X U flight test. **IEEE Aerospace and Electronic Systems Magazine**, v. 31, n. 9, p. 53–62, set. 2016. Disponível em: <http://ieeexplore.ieee.org/document/7590301/>.

MATSUMOTO, T. T.; CAMARGO JUNIOR, J. B. Modeling and simulation of autonomous unmanned aircraft to assess risk of collision with other aircraft. In: XV SITRAER - Simpósio de Tráfego Aéreo, São Luís, MA, Brasil. **Anais**... São Luís, MA, Brasil: 2016.

MUELLER, E. R.; KOCHENDERFER, M. Multi-Rotor Aircraft Collision Avoidance using Partially Observable Markov Decision Processes. In: AIAA Modeling and Simulation Technologies Conference, June, Reston, Virginia. **Anais**... Reston, Virginia: American Institute of Aeronautics and Astronautics, 13 jun. 2016. Disponível em: <http://arc.aiaa.org/doi/10.2514/6.2016-3673>.

OLSON, W. **ACAS Xu UAS Detect and Avoid Solution**, 2016. . Disponível em: <https://conferences.ll.mit.edu/atc/sites/default/files/1000-Olson-LL_ATC_Workshop ACAX X_2016 Finalv3 BernsteinA.pdf>.

ORASANU, J. M. Flight Crew Decision-Making. In: **Crew Resource Management**. [s.l.] Elsevier, 2010. p. 147–179.

PETERSON, M. **An Introduction to Decision Theory**. 2 ed. ed. [s.l.] Cambridge University Press, 2017.

TEMIZER, S.; KOCHENDERFER, M. J.; KAELBLING, L. P.; LOZANO-PÉREZ, T.; KUCHAR, J. K. Collision Avoidance for Unmanned Aircraft using Markov Decision Processes. In: AIAA Guidance, Navigation, and Control Conference, Toronto, Ontario. **Anais**... Toronto, Ontario: American Institute of Aeronautics and Astronautics, 2010. Disponível em: <http://hdl.handle.net/1721.1/61341>.

VON ESSEN, C.; GIANNAKOPOULOU, D. Probabilistic verification and synthesis of the next generation airborne collision

avoidance system. **International Journal on Software Tools for Technology Transfer**, v. 18, n. 2, p. 227–243, 17 abr. 2016. Disponível em: <http://link.springer.com/10.1007/s10009-015-0388-8>.