Obstacle Avoidance Framework based on Reach Sets

by

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# Dedication

This work is a commutation of a five-year-long journey. Many sacrifices were made along the way, at least now you may hold the summary of it. The book in your hands is applicable in many areas of the land/sea/air transportation. Please proceed with care and apply the knowledge to empower humankind.

I *dedicate* this work to anyone who is seeking knowledge. I would be glad if it can help you to find the missing piece in the jigsaw of science. You can expect a detailed cookbook with many useful ideas which needs to reach maturity.

The best is yet to come in the field of autonomous systems; the full autonomy is in our grasp. To get there its need to know what are the limits of your maneuverability in a given situation. This work offers you that.

Feel free to *reach* it!

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# Abstract

This work addresses an issue of *event-based/reactive obstacle avoidance* for *Unmanned Autonomous Systems* (UAS) operating in non-segregated airspace.

The *UAS* is controlled through *movement automaton*; this enables trajectory discretization and *control independence*. The movement automaton acts as an *interface* consuming movement *command chain* to control UAS or generate a reference trajectory

for low-level control.

The *sensor readings* and *information sources* are fused through rating-based *data fusion*; this provides *sensor-platform independence*. The situational assessment is projected into operational space.

The UAS *operational space* is represented as a *planar grid*; this is separated into nonuniform cells. The *threats* are tracked for each cell, namely obstacles or intruders presence, geo-fencing or weather impact.

The *avoidance* or *navigation strategy* of UAS is represented as a *reach set* in operational space. The *reach set* is approximated as a tree where the root is initial system state; the nodes are expected states after movements application. The reach set is calculated for a range of initial states prior the flight, giving a low computational footprint, enabling approach implementation on embedded platforms.

The reach set approximation can include various *maneuvering properties*, like *high space coverage* or *trajectory smoothness*, for avoidance or navigation tasks. The *customization* is used to integrate UAS into *controlled airspace*, where *separation requirements* are included in *reach set*.

The basic services of *UAS Traffic Management* like position notification, airspace restriction, directives, and micromanagement are implemented to prove the operational feasibility of approach in controlled airspace.

The *verification of approach feasibility* was proven through *border-line case test scenarios* taken from general aviation practices and experience. The complete simulation environment with wide customization options is presented.

# Resumo

Esse trabalho aborda o *problema de desviar de obst´aculos baseado em eventos e de forma reactiva* para um sistema aut´onomo n˜ao tripulado que opera em *espa¸co a´ereo n˜ao segregado*. O sistema ´e controlado atrav´es de um autˆomato de movimento, dessa forma ´e poss´ıvel d*iscretizar a trajet´oria e controlar o ve´ıculo de forma independente*. O autˆomato actua como uma interface para controlar o sistema aut´onomo e gerar referˆencias de trajeto´rias para um controlador de baixo n´ıvel.

As leituras do sensor e outras fontes de informa¸c˜oes s˜ao combinadas atrav´es de uma t´ecnica de fus˜ao de dados baseado em escala, dessa forma o m´etodo ´e independente da plataforma. A avaliac¸˜ao situacional ´e projetada no espa¸co operacional.

O espac¸o operacional do sistema aut´onomo ´e representado em uma grelha planar, separada em c´elulas na˜o uniformes. Os riscos s˜ao rastreados para cada c´elula, nomeadamente obsta´culos e a presen¸ca de intrusos, geo-fencing ou distu´rbios atmosf´ericos.

A *estrat´egia de evas˜ao ou navega¸c˜ao* do sistema autoˆnomo ´e representada como um conjunto alcan¸ca´vel no espa¸co operacional. O conjunto alcanc¸´avel ´e aproximado como uma ´arvore na qual a raiz representa o estado inicial do sistema e os no´s sa˜o os estados esperados apo´s aplicar os movimentos. O conjunto alcan¸c´avel ´e calculado para um conjunto de estados iniciais antes da execu¸ca˜o da miss˜ao. Devido a baixa carga computacional, ´e poss´ıvel implementar a estrat´egia em plataformas embarcadas.

A *aproxima¸c˜ao do conjunto alcan¸c´avel* inclui diversas propriedades de manobra, como grande cobertura de regio˜es ou suavidade de trajeto´rias, para tarefas de navega¸ca˜o e evasa˜o. A customiza¸ca˜o ´e utilizada para integrar o sistema auto´nomo no espa¸co de controlo a´ereo, onde os requisitos de separa¸ca˜o est˜ao inclu´ıdos no conjunto alcan¸ca´vel.

Os *servi¸cos b´asicos do sistema de controlo de tr´afego a´ereo* como posi¸ca˜o, como notifica¸ca˜o da posi¸c˜ao, restric¸˜ao do espa¸co a´ereo, diretivas e administra¸ca˜o local sa˜o implementadas para provar a possibilidade da estrat´egia ser implementada no espa¸co de

controlo a´ereo.

A verificac¸˜ao da *estrat´egia foi comprovada atrav´es* de cena´rios chaves obtidos de exerc´ıcios de avia¸ca˜o e experiˆencias. O ambiente de simula¸c˜ao completo com uma vasta gama de opc¸˜oes de customiza¸ca˜o ´e apresentado.

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## Nomenclature

This chapter summarize used symbols (tab. 3), acronyms (tab. 1), terminology (tab. 4) and, organizations (tab. 2) mentioned in work.

Acronym

Meaning

|  |  |
| --- | --- |
| UAS | Unmanned Autonomous System(including naval vehicles) |
| RPAS | Remotely Piloted Aerial System(lesser degree of autonomy) |
| LOS | Line Of Sight |
| VLOS | Visual Line Of Sight |
| BLOS | Behind Line Of Sight |
| SAA | Sense And Avoid |
| DAA | Detect And Avoid |
| MAC | Mid-Air Collision |
| ABSAA | Airborne Sense and Avoid |
| GBSAA | Ground Based Sense and Avoid |
| POA | Preemptive Obstacle Avoidance |
| ROA | Reactive Obstacle Avoidance |
| TCAS | Traffic Alert and Collision Avoidance System |
| ACAS X | Airborne Collision Avoidance System X |
| ACAS X*U* | Airborne Collision Avoidance System X for UAS |
| CD&R | Collision Detection and Resolution |
| GPS | Global Positioning System |
| IMU | Internal Measurement Unit |
| LiDAR | Light Detection and Ranging |
| ADS-B | Automatic Dependent Surveillance – Broadcast |
| GSE | Ground Support Equipment |
| ATC | Air Traffic Control |
| ATO | Air Traffic Organization |
| C2 | Control and Communications |
| MOPS | Minimum Operational Performance Standard |

Table 1: List of Acronyms

Acronym

Organization name

|  |  |
| --- | --- |
| ICAO | International Civil Aviation Organization (UN) |
| EASA | European Aviation Safety Agency (EU) |
| JARUS | Joint Authorities for Regulation of Unmanned Systems (EU) |
| FAA | Federal Aviation Administration (USA) |
| LSTS | Laborato´rio de Sistemas e Tecnologia Subaqu´atica (PT) |
| FEUP | Faculdade de Engenharia da Universidade do Porto (PT) |

Table 2: List of Organizations

Symbol

Explanation

|  |  |
| --- | --- |
| *A,B,C,D,...* | Capital letters are used for matrices |
| *A*(*...*)*,B*(*...*)*,...* | Functional matrices, (*...*) denotes parameters |
| *f*(*...*)*,g*(*...*)*,...* | Vector or scalar functions (*...*) denotes parameters  Explicit vector functions, when equation contains both types of scalar and vector functions |
| *t,x,y,z,...* | Vectors or scalar coefficients |
| *~x,~o,~g,...* | Explicit vectors, when function contains both types of scalar and vector parameters. |
| *θ,ϕ* | Greek letters denoting angles in radians |

Table 3: List of symbols

Terminology

Definition

|  |  |
| --- | --- |
| Air Traffic Control | A service operated by appropriate authority to promote the safe, orderly, and expeditious flow of air traffic |
| Aircraft | A device that is used or intended to be used for flight in the air |
| Airspace | Any portion of the atmosphere sustaining aircraft flight and which has defined boundaries and specified dimensions. Airspace may be classified as to the specific types of flight allowed, rules of operation, and restrictions by International  Civil Aviation Organization standards or State regulation |
| Civil Aircraft | Aircraft are other than public aircraft. |
| Collision  Avoidance | The Sense and Avoid system function where the UAS takes appropriate action to prevent an intruder from penetrating the collision volume. The action is expected to be initiated within a relatively short time horizon before the closest point of approach. The collision avoidance function engages when all other modes of separation fail. |
| Communication  Link | The voice or data relay of instructions or information between the UAS pilot and the air traffic controller and other NAS users. |
| Control Station | The equipment used to maintain control, communicate with, guide, or otherwise pilot an unmanned aircraft. |
| Crewmember  (UAS) | In addition to the crewmembers identified in 14 CFR Part 1, a UAS flightcrew member includes pilots, sensor/payload operators, and visual observers, but may include other persons as appropriate or required to ensure safe operation of the aircraft. |

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Terminology

Definition

|  |  |
| --- | --- |
| Data Link | A ground-to-air communications system which transmits information via digitally coded pulses. |
| Detect and Avoid | A term used instead of Sense and Avoid in terms of Reference for RTCA Special Committee 228. This new term has not been defined by RTCA and may be considered to have the same definition as Sense and Avoid when used in this document. |
| ICAO | International Civil Aviation Organization is a specialized agency of the United Nations whose objective is to develop the principles and techniques of international air navigation and to foster the planning and development of international civil air transport. |
| Manned Aircraft | Aircraft piloted by a human onboard. |
| RTCA | RTCA, Inc. is a private, not-for-profit corporation that develops consensus-based recommendations regarding communications, navigation, surveillance, and air traffic management system issues. RTCA functions as a Federal Advisory Committee. The FAA uses its recommendations as the basis for policy, program, and regulatory decisions and by the private sector as the basis for development, investment and other business decisions ([www.rtca.org)](http://www.rtca.org/) |
| See and Avoid | When weather conditions permit, pilots operating instrument flight rules or visual flight rules are required to observe and maneuver to avoid another aircraft. |
| Self-Separation | Sense and Avoid system function where the UAS maneuvers within a sufficient time-frame to remain well clear of other airborne traffic. |
| Sense and Avoid | The capability of a UAS to remain well clear from and avoid collisions with other airborne traffic. Sense and Avoid provides the functions of self-separation and collision avoidance to establish an analogous capability to “see and avoid” required by manned aircraft. |
| Unmanned Aircraft | 1. A device used or intended to be used for flight in the air that has no onboard pilot. This device excludes missiles, weapons, or exploding warheads, but includes all classes of airplanes, helicopters, airships, and powered-lift aircraft without an onboard pilot. 2. An aircraft that is operated without the possibility of direct human intervention from within or on the aircraft. |

Terminology

Definition

|  |  |
| --- | --- |
| Unmanned Aircraft  System | An unmanned aircraft and its associated elements related to safe operations, which may include control stations (ground, ship, or air-based), control links, support equipment, payloads, flight termination systems, and launch/recovery equipment.  An unmanned aircraft and associated elements (including communications links and the components that control the unmanned aircraft) that are required for the pilot-in-command to operate safely and efficiently in the national airspace system. |
| Visual Line of Sight | Unaided (corrective lenses and/or sunglasses exempted) visual contact between a pilot-in command or a visual observer and a UAS sufficient to maintain safe operational control of the aircraft, know its location, and be able to scan the airspace in which it is operating to see and avoid other air traffic or objects aloft or on the ground. |

Table 4: Terminology

*Note. Acronyms* (tab. 1) and *Terminology* (tab. 4) comply with *ICAO*, *FAA*, and, *EASA* definitions, refer to [1] for more detailed information.

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[1] Michael Huerta. Integration of civil unmanned aircraft systems (uas) in the national airspace system (nas) roadmap. *Federal Aviation Administration, Retrieved Dec*, 19:2013, 2013.

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