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 a 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 good 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 non-uniform 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 obstáculos baseado em eventos e de forma reactiva* para um sistema autónomo não tripulado que opera em *espaço aéreo não segregado*. O sistema é controlado através de um autômato de movimento, dessa forma é possível d*iscretizar a trajetória e controlar o veículo de forma independente*. O autômato actua como uma interface para controlar o sistema autónomo e gerar referências de trajetórias para um controlador de baixo nível.

As leituras do sensor e outras fontes de informações são combinadas através de uma técnica de fusão de dados baseado em escala, dessa forma o método é independente da plataforma. A avaliação situacional é projetada no espaço operacional.

O espaço operacional do sistema autónomo é representado em uma grelha planar, separada em células não uniformes. Os riscos são rastreados para cada célula, nomeadamente obstáculos e a presença de intrusos, geo-fencing ou distúrbios atmosféricos.

A *estratégia de evasão ou navegação* do sistema autônomo é representada como um conjunto alcançável no espaço operacional. O conjunto alcançável é aproximado como uma árvore na qual a raiz representa o estado inicial do sistema e os nós são os estados esperados após aplicar os movimentos. O conjunto alcançável é calculado para um conjunto de estados iniciais antes da execução da missão. Devido a baixa carga computacional, é possível implementar a estratégia em plataformas embarcadas.

A *aproximação do conjunto alcançável* inclui diversas propriedades de manobra, como grande cobertura de regiões ou suavidade de trajetórias, para tarefas de navegação e evasão. A customização é utilizada para integrar o sistema autónomo no espaço de controlo aéreo, onde os requisitos de separação estão incluídos no conjunto alcançável.

Os *serviços básicos do sistema de controlo de tráfego aéreo* como posição, como notificação da posição, restrição do espaço aéreo, diretivas e administração local são implementadas para provar a possibilidade da estratégia ser implementada no espaço de controlo aéreo.

A verificação da *estratégia foi comprovada através* de cenários chaves obtidos de exercícios de aviação e experiências. O ambiente de simulação completo com uma vasta gama de opções de customização é apresentado.

Contents

List of Tables

List of Figures

List of Algorithms

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	Laboratório de Sistemas e Tecnologia Subaquática (PT)
FEUP	Faculdade de Engenharia da Universidade do Porto (PT)

Table 2: List of Organizations

Symbol	Explanation
$A, B, C, D, \ldots$	Capital letters are used for matrices
$A(\ldots), B(\ldots), \ldots$	Functional matrices, $(\ldots)$ denotes parameters
$f(\ldots), g(\ldots), \ldots$	Vector or scalar functions $(\ldots)$ denotes parameters
$\vec{f}(\ldots), \vec{g}(\ldots), \ldots$	Explicit vector functions, when equation contains both types of scalar and vector functions
$t, x, y, z, \ldots$	Vectors or scalar coefficients
$\vec{x}, \vec{o}, \vec{g}, \ldots$	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	Another 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.

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 the 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`)
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.

Bibliography

[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.