Chapter 1

(W) Introduction

To be done here:

- Introduce UAV problem of integration into non segregated airspace.
- Open JARUS/NASA requirements and discuss legal framework a little
- Introduce Honeywell interest into topic.

1.1 (W) Motivation

To be done here:

- situation
- trends

1.2 (W) Goals

To be done here:

- Propose abstract obstacle avoidance framework able to avoid obstacles in real time and guaranteeing safe path independent of controlled platform
- Define guarantee of safety margin concept.
- Define requirements for avoidance set.

1.3 (R) Overview

The work is organized like follows:

1. *Introduction* (ch. 1) - the introduction chapter giving overview of work motivation, goals, contributions and *author‘s list of publication.*

2. *Collision Avoidance* (ch. ??) - This chapter gives aerospace related background. The manned aviation is serving as knowledge base for assumption of future UAS Detect & Avoid functionality. The chapter gives overview of airspace classification, which told us where and what we can do or expect. Aircraft operational rules for general are reflected into *separation functionality*. The separation can be passive enforced by Air Traffic Management authority or active enforced by *ACAS-X/TCAS* systems. The *UAS Traffic Management* is parallel to maned aviation practices with additional layer of complexity. The *Event Based avoidance* is introduced to give overview of concepts used later.

3. *Background Theory* (ch. ??) - this chapter outlines background necessary for approach understanding. The *control theory* system models are used as base for the *reach set* calculation. The important concept of *movement automaton* (special case of hybrid automaton) used for prediction, trajectory representation, and, reach set estimation is introduced. The LiDAR related theory and complements are presented at last.

4. *Problem Statement* (ch. ??) - this chapter states the problem solved in this work. The basic definition and terminology is established at beginning with initial problem and assumptions. Incremental problem is introduced with increasing complexity and relaxed conditions. Avoidance and Navigation functional and non-functional requirements are stated at last.

5. *State of Art* (ch. ??) - this chapter covers important results of other researcher works in topics of Movement Automaton, Sensor & Data Fusion, Navigation Algorithm, Reach Sets, and Testing Approach. The *UAS Traffic Management* concept relevant for this work is introduced.

6. *Approach* (ch. ??) - this chapter describes approach, it starts with overview (sec. ??), outlining the block scheme of the system (fig. ??). The discretization of the space, trajectories and system model are covered in (sec. ?? - ??), the following topics are covered:

   a. *Reach Set Estimation* (sec. ??) - the discretization, performance evaluation and generation algorithms.

   b. *Encounter Modeling* (sec. ?? - ??) - static obstacles, intruders, static/moving constraints, and more.

   c. *Collision Avoidance* (sec. ??) - the avoidance/navigation loop with global data fusion procedure, complexity and safety margin calculations.

   d. *Further to Cooperative Operations* (sec. ?? - ??) - the approach to satisfy scalability and *UTM* requirements.

7. *Simulations* (ch. ??) the simulations covers aspects developed in approach, the test plan (tab. ??) summarizes test cases. The results are outlined in (tab. ??), the computation load statistics are summarized in (tab. ??). The test are divided into following categories:

   a. *Non-cooperative Test Cases* (sec. ??) - various obstacles, weather constraints and non-cooperative intruders test cases

b. *Cooperative Test Cases* (sec. ??) - maneuvers in controlled airspace under supervision of traffic management.

c. *Reach Set Estimation Performance and Properties* (sec. ??) - the comparison of various estimation methods, the impact on complexity.

8. *Conclusion and Future Work* (ch. ??) - work conclusion, summarizing achieved results, comparing other approaches, outlining reusable modular parts of approach, utilizing the future work on approach shortcommings.

1.4 (R) Contributions

The *contributions* of this work can be divined into two categories:

Conceptual Contributions: The contributions enhancing and enriching the conceptual level of *Detect & Avoid* systems, namely:

1. *Movement automaton control and prediction* - necessity to abstract the control of the system from the *detect and avoid* systems, leads to customization of hybrid automaton (sec. ??) to *movement automaton* (def. ??). The movement automaton can be adapted to nonlinear system (sec. ??) as a instance (sec. ??). The movement automaton can be also used as a predictor of the system (sec. ??). The *initial state disparity issue* [1] has been addressed in (sec. ??).

2. *Trajectory as a discrete command chain* - the *movement automaton* as a control interface consuming the discrete command chain enabled the *finite discrete representation* of trajectory (eq. ??).

3. *Reach set discretization* - the *infinite reach set* (def. ??) can be represented as a tree of movements from system initial state (def. ??). This tree can have associated properties, like reachibility of each trajectory segment (eq. ??). The advantage of having finite maneuver set, with little precision sacrifice, which can be calculated prior the flight have huge impact on *computation complexity* (sec. ??). Enabling to use approach on different platforms with small computational power.

4. *Operational space assessment* - the operational space is separated by grid into finite set of the cells. Each cell has properties to track like the occurrence of obstacle, presence of intruder or impact of constraint. The *u*niversal data fusion procedure (sec. ??) is enabling accumulation of treat information from various sources.

5. *Hierarchical threat assessment* - the *various threat* sources (obstacles, intruders, constraints) are categorized according to operational environment/rules and their avoidance priority is handled according to that (fig. ??).

6. *UAS Traffic Management* - the architecture proposal for traffic management as cooperative authority (sec. ??) covers some basic maneuvers (sec. ??, ??,??), the more important is the adaptability of presented approach to cooperative (sec. ??) and non-cooperative (sec. ??) avoidance modes, showing adaptability.

Implementation Contributions: The concepts, which solve implementation issues for *Detect & Avoid* systems, namely:

1. *Operational space segmentation* - the *planar grid* (sec. ??) slice (fig. ??) have been selected, because it can be used for fast assessment of LiDAR scan data to estimate, obstacle (??) or visibility (??). The cell volume is increasing with distance from UAS, this gives us decreased space status assessment complexity.

2. *Wave-front algorithm for avoidance estimation* - to estimate reach set the space exploration method has been developed. The *rapid exploration tree* (fig. ??) is employed as *wave-front* expansion (alg. ??). Various shapes and properties of *reach set estimation* can be achieved employing the *constrained expansion functions* for *chaotic* (alg. ??), harmonic (alg. ??), and, *ACAS-like* (alg. ??) reach set approximations.

3. *Encounter and constraints models* - the planar grid used in solution required a development of encounter models for static obstacles, constraints (sec. ??), intruders, moving constraints (sec. ??). The intersection algorithms can be reused in other approaches using unusual grid.

4. *Avoidance process enhancement (Rule engine)* - the air traffic rules are changing based on time and geographic location, the UTM concept is under development. These reasons are calling to use flexible implementation architecture, rule engine (sec. ??). The rule engine can be set to cover any kind of rules (fig. ??).

1.5 (R) List of Publications

This *section* contains the list of published articles, proceedings, technical reports and module projects, relevant to the *thesis topic*.

Article: Alojz Gomola, Joao Borges de Sousa, Fernando Lobo Pereira, and Pavel Klang. Obstacle avoidance framework based on reach sets. In Iberian Robotics conference, pages 768–779. Springer, 2017. [1][1].

Summary: This report on preliminary investigations concerning the development of a LIDAR based detect and avoid (DAA) system with a low computational footprint for small Unmanned Air Systems. The focus is on the integration with nominal flight control systems and on computational feasibility. The proposed system decomposes the SAA problem into the following components detection, space assessment, escape trajectory estimation and avoidance execution. The control logic is encoded with the help of a hybrid automaton. The properties of the system are studied with the help of approximations to time slices of the UAV reach set.

Article: Juraj Števek, Michal Kvasnica, Miroslav Fikar, and Alojz Gomola. A parametric programming approach to automated integrated circuit design. IEEE Transactions on Control Systems Technology, 26(4):1180–1191, 2018. [2][2].

[1]Draft available online: `https://goo.gl/kZujZE`

[2]IEEE copy online: `https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7981386`

Summary: The proposal of an optimization-based slotting approach to automated *integrated circuit* design for generating a power transistor. The original slotting problem is formulated as a mixed-integer linear program. It is solved through parametric optimization with advantage that usage of any commercial optimization solvers on user's side is avoided with short evaluation time and simple implementation. The approach is applied in specific very large scale integration production technology and demonstrated on an example.

Contributions: Point-location algorithm for MPC region selection.

Proceedings: Kristian Klausen, Jostein Borgen Moe, Jonathan Cornel van den Hoorn, Alojz Gomola, Thor I Fossen, and Tor Arne Johansen. Coordinated control concept for recovery of a fixed-wing uav on a ship using a net carried by multirotor UAVs. In Unmanned Aircraft Systems (ICUAS), 2016 International Conference on, pages 964–973. IEEE, 2016, [3][3].

Summary: Ship-based Unmanned Aerial Vehicle (UAV) operations represent an important field of research which enables a large variety of mission types. Most of these operations demand a high level of endurance which normally requires the use of a fixed-wing UAV. Traditionally, a net located on the ship deck is used for recovering the fixed-wing UAV. However, there are numerous challenges when attempting autonomous landings in such environments. Waves will induce heave motion, and turbulence near the ship will make approaches challenging. In this paper, we present a concept using multi-rotor UAVs to move the recovery operation off the ship deck. To recover the fixed-wing UAV, a net is suspended below two coordinated multirotor UAVs which can synchronize the movement with the fixed-wing UAV. The approach trajectory can be optimized with respect to the wind direction, and turbulence caused by the ship can be avoided. In addition, the multirotor UAVs can transport the net at a certain speed along the trajectory of the fixed-wing UAV, thus decreasing the relative velocity between the net and fixed-wing UAV to reduce the forces of impact. This paper proves the proposed concept through a simulation study and a preliminary control system architecture.

Contributions: Ground station manuever implementation, messaging between ground station/UAVs. RTK-GPS for precise navigation integration, Net-release mechanism design, Mechanical parts for 3D printer modeling.

Proceedings: Alojz Gomola. Aspect-oriented solution for mutual exclusion in embedded systems. In Alena Kozakova, editor,ELITECH15: 17th Conference of doctoral students, pages964–973, Bratislava, Slovak Republic, may 2015. Online publication, [4][4].

Summary: Embedded systems are developed for wide range of applications. The best known applications are industrial process control and banking solutions. Fault tolerance is the crucial requirement in long-term embedded systems. This paper presents solution for mutual exclusion in embedded systems. The usual mutual exclusion solution using semaphores is a crosscutting concern. Semaphores are difficult to maintain in code and their failure rate is high. We propose new aspect-oriented solution for mutual exclusion. Our solution utilizes aspect-oriented approach, is usable in other systems and designed to be robust against program changes, and it provides a solution to aspect fragility problem.

[3]Public copy available online: `http://folk.ntnu.no/torarnj/ICUAS2016_singlecolumn.pdf`

[4]Draft available online: `https://github.com/logomo/Elitech15-paper`

Technical report: Alojz Gomola, Pavel Klang, and Jan Ludvik. Probabilistic approach in data fusion forobstacle avoidance framework based on reach sets. In Internal publication collection,pages 1–93. Honeywell, 2017, [5][5].

Summary: The *sensor input* and *information sources* fusion procedure design to obtain rated space assessment for visibility, obstacle occupancy and reachibility evaluation. Unique statistical approach was proposed to couple partial ratings under reading and time uncertainty. The key contribution is scalable approach to evaluate *UAS action space* and *Feasible Trajectories* properties.

Technical report: Alojz Gomola. Model predictive control of unmanned air vehicles with obstacle avoidance capabilities. Technical report, FEUP, 2017, [6][6].

Summary: Initial solution of *predictive control* problem for *UAS* navigation in constrained, non-controlled airspace. The key contribution is *Movement Automaton* (a special type of hybrid automaton) establishment in current form (sec. **??**). The *stability*, *controllability* and *observabillity* properties have been proven. The *feasibility* of *Movement Automaton* as *control interface* and *future state predictor* have been shown trough formal proof and excessive testing.

Technical report: Alojz Gomola. Optimal control of unmanned air vehicles with obstacle avoidance capabilities in partially known environment. Technical report, FEUP, 2017. [7][7].

Summary: The *optimization problem* for *obstacle avoidance* (eq. **??**) to provide satisfy *avoidance requirements* (sec. **??**)

Framework: Feature-based ACAS[8] implementation to support claims of this work has been developed trough course of years *2016-2018.* The framework provides:

1. *Simulation environment* - full support for single/multiple UAS simulation support in controlled/non-controlled airspace.
2. *Mission Control Support* - standard mission control support for *sparse ordered waypoint* mission type.
3. *UAS Traffic Management* - support for *collaborative* weather and collision avoidance with general authority in controlled airspace. The configurable *event handling* trough *rule-engine.*
4. *Encounter Models* - model for *static obstacles* supporting point-cloud generation of LiDAR sensor, various intruders model supporting the ADS-B like encounter model, static/dynamic polygon constraints with altitude range.
5. *Collision Avoidance* - the support for *cooperative* and *non-cooperative* behaviour in controlled airspace, *non-collaborative, non-adversary* bahaviour in non-controlled airspace.
6. *Reach Set Estimation Methods* - four methods for various property focused *Reach Set Estimations.*

[5]Public copy available online: `https://github.com/logomo/Data-Fusion-Report`

[6]Public copy available online: `https://github.com/logomo/Predictive-control---Final-report`

[7]Public copy available online: `https://github.com/logomo/Optimal-Control`

[8]Matlab prototype available online: `https://github.com/logomo/Feature-based-ACAS`

Bibliography

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