Slide: Initial page

Speech:

- Dear (Lady, and Gentlemen), my name is Alojz Gomola and for today I am going to defend thesis with title:
- “Obstacle avoidance based on Reach Sets”,
- Which was lead by
- Joao Sousa from LSTS, and
- Fernando Lobo Pereira from FEUP,

Slide: 01 Overview

Speech:

- Let me start with short overview,
- First there will be an introduction into Detect and Avoid,
- Then I will outline problems which we approached,
- The brief introduction of “Related work and used concepts”
- Is necessary before we go trough “Proposed framework”
- After that the test cases and performance will be shown

Slide: 02 SAA Introduction

Speech:

- The main goal of the thesis was to develop a framework,
- Which is capable to fly in “non-segregated airspace”,
- Lets start with short introduction

Slide: 03 Airspace classification

Speech:

- There is airspace vertical classification based on altitude,
- Different rules and authorities applies on different
- “flight levels”,
- “C class airspace” is where passenger planes operates

Slide: 04 Airspace restictions

Speech:

- The same goes for horizontal plane restrictions,
- Airspace authority can prohibit operations in specific area,
- For example the “orange rectangle” was marked as
- ”Restricted Area”,
- Due the “Military exercise”.

Slide: 05 UAS traffic management

Speech:

- As for the planes there is ATM,
- the similar concept is applied for UAS,
- The UAS Traffic Management system is established by
- “EASA” in EU,
- You can see examples of UAS operations:
- 1. Free flight,
- 2. Corridor like navigation,
- 3. Authority enforcement,
- The latest has been implemented in our work

Slide: 06 Remain well clear:

Speech:

- The aviation is using “Well clear distance”
- The bigger barrel is called “Well clear margin”
- Which is considered as “warning zone”
- No plane should enter that zone
- The smaller barrel is called “near miss margin”,
- Entrance is considered as a “serious incident”

Slide: 07 Actors introduction

Speech:

- The **UAS** is interacting with **obstacles**:
- - **Static** not changing position with time, like buildings,
- - Moving which are not trying to harm us – **Intruders,**
- - Moving which are trying to harm us – **adversaries,**

Slide: 08 Reactive sense and avoid

Speech:

- UAS usually flies mission given as a ordered list of
- “Waypoints”, the UAS is solving:
- 1. **Reactive Avoidance** – immediate threat,
- 2. **Preemptive Avoidance** – long term threat,
- The example shows implementation of both,
- 1. UAS spots an obstacle
- 2. The long term path is not feasible
- 3. Newly calculated avoidance path is taken

Slide: 09 Problems in Detect and avoid

Speech:

- Now lets define the problem which is going to be solved

Slide: 10 Get to the PUB!

Speech:

- The obstacle avoidance can be taken as a “trip to a pub”,
- Lets help this gentleman get into the fine restaurant,

Slide: 11 The situation

Speech:

- We have a simple mission get from the home (red),
- To the “Fine restaurant” (blue),

Slide: 12 Path planning problem

Speech:

- First is “Path planning problem”, we know everything,
- We just need stick to the plan.

Slide: 13 Forgotten man

Speech:

- I have forgotten my map at home, I need to use my eyes,
- “Sensor system” to scan some surroundings,
- I am forced to do “Continuous decision making” and adapt.
- I am limited by my field of the vision (black box)

Slide: 14 First decision

Speech:

- Because I am lazy I am changing my path only on
- “Decision points” (red circle),
- I look around and I see three possible ways,

Slide: 15 Decision was made

Speech:

- I choose the most promising path according to
- “Cost function”,
- I will continue along the way

Slide: 16 Walk a little bit closer,

Speech:

- I reached the next decision point,
- I look around and I see three possible ways,

Slide: 17 Rinse and repeat the process

Speech:

- I choose to go down to my “cost function”,
- I do next “sensor scan”,
- I can see the restaurant,

Slide: 18 Problem of the evolving world

Speech:

- The “Evolving world” leads to “semi-optimal” problem solution,
- Where the path between “decisions points” is “optimal”,
- According to the “cost function”
- This is getting closer to real world navigation where we are limited by our “field of vision”.

Slide: 19 You are not alone on the streets

Speech:

- There are others around us, lets call them “intruders”,
- They are moving, they can harm us, but don’t want to,
- We know their position, heading and body mass,
- For sure, we want to avoid them,

Slide: 20 Multiple information sources

Speech:

- You have contraindicating data,
- The map is outdated, the pub was moved,
- You need to determine what is the true,
- You need to fuse data in “Data fusion”,

Slide: 21 Static restrictions

Speech:

- When we managed to avoid intruders, the problem is,
- Still standing folk, or “static restrictions”,
- There are vigilantes they will fine you,
- They are considered “hard constraints”,
- There are grannies who are just going to tell on you,
- They are considered “soft constraints”,
- The parallel are the airspace restrictions,

Slide: 22 Try to avoid static restrictions,

Speech:

- Try to avoid “static restrictions”, take long detour (red line)

Slide: 23. Weather

Speech:

- We try to avoid hash weather conditions, which acts like:
- 1. “Moving constraint”, or,
- 2. “Static constraint”,
- Some prioritization needs to be implemented in our,
- “Data fusion”,

Slide: 24 Restriction breach

Speech:

- The prioritization of “constraints” is like follow:
- Rather get yelled by granny than catching a cold

Slide: 25 Rules

Speech:

- It is necessary to obey the authority, in traffic, society,
- Especially in “Airspace”,
- The different airspaces implements different rules

Slide: 26 Problem 01

Speech:

- Let say that UAS classifies for every time operational 3D space into four categories:
- 1. Free -where it can move
- 2. Occupied – where crash happens,
- 3. Uncertain – out of our knowledge
- 4. Restricted – other threat,
- The space classification (4.10) is result of “Data fusion” (4.19)

Slide: 27 Problem 02

Speech:

- The UAS is flying a mission given as a set of ordered waypoints (4.6),
- The goal is to keep the distance to any occupied space greater than some margin (4.21),
- Under following assumption:
- 1. Sensor readings are clear,
- 2. There are no intruder for now,
- 3. The airspace is unrestricted,
- 4. The waypoints are reachable,
- 5. UAS constant speed,

Slide: 28 Problem 1 Basic Avoidance

Speech:

- The “Basic avoidance problem” is like follow:
- 1.UAS is equipped with LiDAR sensor, flyes over open space with static obstacles only,
- 2.The “Restricted space” is out of question,
- 3.There is only “vehicle dynamic constraints”
- The following needs to be established:
- 1. Avoidance loop – for immediate decisions (6.6.2)
- 2. Navigation loop - for decision point management (6.6.1)

Slide: 29 Problem 2 Intruders

Speech:

- Let us introduce intruders,
- 1. We read their position over ADS-B broadcast,
- 2. The “Sensor fusion” needs to fuse two sensors,
- 3. “Flight corridors” as added “hard constraints”,
- Problems to be addressed:
- 1. How to model “intruder intersection” in “operational space”,
- 2. including future “corridors”.

Slide: 30 Problem 3 static restrictions

Speech:

- Let us add “static constraints” and restrictions, originating from:
- 1. Terrain Map – from our previous flights
- 2. Obstacle Map – from future UTM,
- 3. Flight restrictions – from airspace authority,
- The data fusion now needs to handle prioritization,
- Evaluate the threat potential,

Slide: 31 Problem 4 Weather

Speech:

- The weather compliance is necessary for controlled airspace integration, considering the average UAS size,
- 1. The weather consists of static phenomenon like focused storm or moving phenomenon like wind gusts,
- This introduces a new type of “moving constraint” which needs to be accounted from greater range,
- 2. Depending on the UAS construction and future durability requirements,
- Some of the weather cases may be ignored, this gives us “soft constraints”.

Slide: 32 Problem 5 The Rules of the air

Speech:

- The final step for airspace integration is authority obedience,
- The avoidance and navigation mechanisms needs to adhere to “rule of the air” dependent on “airspace context”

Slide: 33 Related work

Speech:

- The goal is to provide the answer to given challenges.
- We need a tools for:
- 1. An UAS discrete control,
- 2. Surroundings surveillance,
- 3. Short-term/Long term navigation,
- 4. Reach set estimation/approximation

Slide: 34 RW: Movement Automaton

Speech:

- There is special type of “hybrid automaton” called,
- “movement automaton”, which provides sufficient,
- abstraction to be reused on different platforms
- “Our movement automaton” is based on work of,
- “Emillio Frazolli”,
- Movement automaton hase the finite set of possible,
- movements, which supports determinism (green picture)

Slide: 35 RW: Surveillance

Speech:

- The world map is represented as a set of cells,
- Each cell has a rated property, like visibility, reachability,
- The “Data fusion” procedure which evaluates these properties is based on work of Gustafson and Ramasy,

Note:

- From left to right (examples of properties):
- 1. Intruder intersection rate,
- 2. Obstacle map rate,
- 3. LiDAR hit count,

Slide: 36 RW Navigation algorithm

Speech:

- The navigation is understood as joint of multiple immediate decisions to achieve,
- “long-term safe path” between waypoints.
- The Sabatini and Gardi laid out the base for UAS

Note:

- From left to right:
- 1. Simplified navigation framework structure,
- 2. Simplified navigation activity diagram,

Slide: 37 RW Reach set estimation

Speech:

- The reach set defines where can UAS fly from initial position in given time frame,
- We want to have finite count of possibilities to guarantee finite time solution,
- The “lattice trajectory tree” fulfils this purpose,
- The work of LaValle, Gessel, and, Esposito are used as base for our algorithm.

Slide: 38 Proposed framework

Speech:

- That’s all for the introduction,
- Let us get to the proposed framework,

Slide: 39 Proposed framework schematics

Speech:

- The framework works like follow:
- 1. The entry point is Data fusion (green <plane> box),
- 2. Data fusion gives “Situation overview” to “Avoidance Run”,
- 3. “Avoidance Run” (orange box) stores the situation in “Grid”,
- 4. The “Situational Assessment” (blue box) based on “Goal waypoint” and “rules” selects the most feasible “short-term avoidance trajectory” from the reach set.
- 5. The “Navigation loop” is responsible for long term navigation.
- 6. The movement automaton is responsible for “reference path translation”
- Then let us look on details.

Slide: 40 UAS Model

Speech:

- The controlled plant (sec. 6.2.2) for UAS model, is continuous time system, (dramatic pause, click)

Slide: 41 3D unicycle model (6.2.2)

Speech:

- The UAS model is simple 3D unicycle,
- With position (GCF) and orientation (GCF) as a state (6.1)
- And control input as scalar velocity and angular velocity (6.2),
- The model is then given by set of equations (6.4).

Slide: 42 Movement Automaton (Key enabler)

Speech:

- The UAS is controlled via Movement automaton
- Movement automaton consumes commands – movements,
- In the picture you can see example of simple Copter movement automaton, with four movements,

Slide: 43 Movement set of Automaton

Speech:

- The movement set is a set of automaton states,
- For our model there is a possibility to deriver nine (9) elementary movements (6.11)
- In the picture the red plane shows the position before movement application, other colors after movement application

Slide: 44 Trajectory generated by automaton

Speech:

- The buffer is created by chaining multiple elementary movements as command chain,
- The command chain is stored in Buffer structure (6.12),
- The movement automaton continuously consumes buffer to control UAS over trajectory,
- The trajectory for some initial state and buffer is given as,
- The chain of the state changes with corresponding movement applications (6.13).

Slide: 45 Reach set approximation

Speech:

- The Reach set is used for decision making,
- It can be imagined as “tree of trajectories”,
- Example: Reach set using our method (red) in Field of vision (aquamarine),

Slide: 46 Reach set approximation, space segmentation

Speech:

- The UAS operational space is represented by
- “Avoidance grid” (6.20)
- Avoidance grid represented in planar coordinates is split into the uniform cells with space portion (6.15)

Slide: 47 RSA definition

Speech:

- The avoidance grid example is denoted by red line, the blue plane is in the center.
- Then the Reach set approximation is given as a set of trajectories originating in “initial state” with limited duration (6.23),
- The trajectory is given as a execution of movement chain - “buffer” applied on initial state,

Slide: 48 Reach set approximation trajectory properties

Speech:

- The goal is to have meaning full trajectories in Reach Set Approximation,
- The trajectory relation to the “avoidance grid” is given by its footprint, the set of cells passed by trajectory,
- In the left figure you can see six trajectories going over avoidance grid,
- There are only three unique footprints,
- That means we need only 3 of those trajectories,

- The right figure shows four trajectories with same footprint

Slide: 49 Property based approximations

Speech:

- The trajectory properties are considered when the candidate trajectory for Reach set approximation is selected,
- In the figure you can see selection process based on coverage property,

Slide: 50 Developed RSA 1

Speech:

- Following reach set approximations were developed:
- **1. Coverage maximizing (6.4.4)**
- A. contains trajectories maximizing avoidance capability
- B. Used for intruder/obstacle avoidance
- C. In non-controlled airspace
- **2. Turn minimizing (6.4.5)**
- A. Contains trajectories with minimal turning,
- B. Used for navigation, increases behavior predictability,
- C. Used in non-controlled airspace

Slide: 51 Developed RSA 2

Speech:

- The idea behind combined RSA (6.4.7) is to have properties of both turn minimizing and coverage maximizing RSA.
- To be compatible with controlled airspace, the “ACAS-like” (6.4.6) RSA was developed to emulate horizontal/ vertical/ cross section separations of modern aircrafts.

Slide: 52 Mission plan

Speech:

- To use Reach set Approximation, we need a mission plan,
- The mission plan is given as ordered set of waypoints,
- The example shows a trajectory with multiple decisions

Slide: 53 ADS-B

Speech:

- To evaluate situation, we need some input data,
- For intruder position the ADS-B is used,
- Each air traffic attendant is broadcasting its position and heading,

Slide: 54 LiDAR

Speech:

- LiDAR is a sensor of choice for static obstacles,
- In the example data you can see a small farm,

Slide: 55 Offline maps

Speech:

- LiDAR classification algorithms can be used for the,
- “Offline maps” creation,
- In the example you can see farm data (NW) classification,
- For vegetation (NE), Terrain (SW), Buildings (SE),

Slide: 56 Obstacle map example

Speech:

- There is an example of offline map created by one of my master students,

Slide: 57 Data fusion introduction

Speech:

- Now we have all the ingredients for Data fusion and Avoidance Run
- The Avoidance Run is situation evaluation for one specific decision time point,

Slide: 58 Avoidance run 1/7

Speech:

- First we start with empty avoidance grid,
- The goal is green square,
- The UAS position is blue square,

Slide: 59 AR Threat(Obstacle) assessment

Speech:

- The “Data fusion” provides threat rating (obstacle rating) each cell in avoidance grid
- Red cells are occupied,

Slide: 60 AR Unknow state of the cells

Speech:

- Then we evaluate the unknown as yellow cells,

Slide: 61 AR Reach set projection

Speech:

- Then then we project reach set approximation into avoidance grid,
- The result is trimmed reach set with only safe green trajectories,

Slide: 62 AR Reach set projection over

Speech:

- The green cells which are penetrated by at least one safe trajectory are considered reachable,
- The orange unreachable cells do not have any.

Slide: 63 AR Trajectory selection

Speech:

- The navigation algorithm provides navigation goal (purple star).
- Then in the reachable space a feasible blue avoidance path is selected from constrained reach set,
- The blue star is marked as next decision point,
- We fire up Avoidance Run again there

Slide: 64 Mission control run

Speech:

- The avoidance run is responsible for "Short term navigation", for long term navigation mission control run is used.
- Multiple avoidance runs are executed to create one safe trajectory,
- The cyan trajectory is planned from next decision point,

Slide: 65 UTM management concept

Speech:

- That was all for framework,
- We need to make multiple instances to cooperates, for UAS to be airworthy,
- This schematic shows a concept of centralized UTM,
- UTM is receiving position updates from aircrafts,
- If UTM detects collision its sends "Collision Resolutions",

Slide: 66 Rule engine

Speech:

- Because UAS operates in very complex space we needed a mechanism to tweak navigation/avoidance process,
- The simple rule engine has been implemented which enables code injection in specific joint points
- The example shows slow down rule for "C" class airspace,

Slide: 67 Simulation

Speech:

- That's all for the framework,
- Now lets get to the testing scenarios

Slide: 68 Test plan

Speech:

- We have developed own testing framework enabling us to test:
- 1. Static obstacle collisions.
- 2. Intruder collision,
- 3. Weather avoidance,
- 4. Combination of any previous,
- We have prepared and executed 13 scenarios,

Slide: 69 Obstacles + weather

Speech:

- Firstly, I will show you two scenarios for obstacle avoidance and weather avoidance

Slide: 70 Maze scenario

Speech:

- Lets call it "Standard pizza delivery scenario"
- The "blue plane" is flying over the maze to the green square waypoint,
- The blue line is already flew trajectory
- The red line is planned trajectory for actual decision point
- The non convex obstacles are fed to "LiDAR" sensor

- As you can see the approach has maze solving capabilities

Slide: 71 Storm scenario

Speech:

- The blue plane is approaching magenta storm,
- The storm is considered as moving constraint
- The plane avoids storm

Slide: 72 Rules of the air simulations

Speech:

- To be airworthy UAS needs to adhere some basic traffic rules, I will demonstrate the rules of the air which are valid for “controlled airspace”

Slide: 73 Converging maneuver,

Speech:

- The converging maneuver needs to be executed when the angle of approach is above seventy degrees,
- The right hand rule is applied,
- The red plane has right of the way,

Slide: 74 Converging maneuver resolution

Speech:

- The blue plane start avoidance keeping safe distance

Slide: 75 Converging maneuver leave condition

Speech:

- The blue plane avoids wake turbulence and returns to original path

Slide: 76 Rule based converging

Speech:

- Blue plane avoids magenta plane, which has
- “right of the way”
- The rule engine has been deployed to tweak process,

Slide: 77 Head On approach

Speech:

- The “Head on approach” is triggered when the angle of approach is greater than 130 degrees
- None of planes has the right of the way,
- The virtual round abound concept is used

Slide: 78 Head On approach resolution

Speech:

- Both planes keep safe distance from expected collision point to avoid wake and side turbulences
- The maneuver ends when virtual roundabout is used

Slide: 79 Virtual roundabout (Rule based)

Speech:

- The collision point is used as a center of virtual roundabout
- Both planes start to converge to original waypoint when the collision point is passed,

Slide: 80 Overtake maneuver

Speech:

- Faster blue airplane is overtaking slower red airplane
- Faster blue airplane needs to take detour,
- The standard solution is to follow divergence waypoint and start returning on convergence waypoint

Slide: 81 Overtake maneuver - resolution

Speech:

- It's going like this,
- During overtake both planes should keep constant speed

Slide: 82 Overtake maneuver - resolution

Speech:

- Then it finishes like this

Slide: 83 Rule based overtake

Speech:

- Here you can see overtake maneuver implemented in our framework,
- The blue plane is following the divergence waypoint
- The blue plane returns on convergence waypoint when its wake turbulence does not harm magenta plane

Slide: 84 Different overtake speed impact

Speech:

- The divergence and convergence waypoints are calculated according to vehicle classes and speed difference,
- Here you can see how the overtake trajectory wider with increase of speed difference

Slide: 85 Cooperative vs non cooperative

Speech:

- The multi collision can be solved in cooperative or non-cooperative manner, let's take look on some more complex scenarios.

Slide: 86 Cooperative case scenario

Speech:

- There is a central UTM authority,
- The UAS gives their "Position notification",
- The UAS is enforcing "Directives as a commands",

Slide: 87 Rule based mixed

Speech:

- In controlled airspace, where central authority is present, UAS are forced to cooperate,
- The multi collision case scenario is solved with sufficiently big roundabout,
- The capacity of virtual roundabout is depending on standard cruising speed,
- All planes needs to use same speed while on roundabout

Slide: 88 Non cooperative case scenario

Speech:

- Now lets get to non cooperative mode,
- Each UAS is detecting own collisions, alerting others trough ADS-B
- Each UAS is using our approach to calculate own avoidance trajectory which gave them best possible odds of survival

Slide: 89 Emergency avoidance

Speech:

- Each UAS is using own calculations to increase odds of survival
- They start to react at the last moment around the collision point
- As you can see it seems almost like collision,

Slide: 90 Non cooperative performance scenario

Speech:

- There is a diagram showing mutual distance between UAS
- The blue line represents the crash distance,
- The red line represents safety margin
- The safety margin was not breach in any case
- Therefore, the operation is considered as safe,

Slide: 91 Simulation results 1

Speech:

- For all test cases we have tracked:
- “Safety margin breach” which is primary performance criterion,
- All simulations have passed

Slide: 92 Simulation results 2

Speech:

- The same goes for the cooperative test cases,
- All simulations have passed,

Slide: 93 Conclusion

Speech:

- *TBD on the go