**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