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Alojz Gomola
12th July 2019, Porto

Obstacle avoidance based on Reach Sets

Defense Presentation of Doctoral Thesis in Applied Mathematics

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,

Your Notes:

1

Overview

Sense & Avoid introduction:
- Context of SAA
- Actors
- Reactive Obstacle Avoidance

Problems in Detect & Avoid:
- Explained as a story
- Incremental problem definition

Related work:
- Movement Automaton
- Surveillance
- Navigation
- Reach set estimation

Proposed framework:
- Overview
- Avoidance Run
- UTM Implementation
- Rule Engine

Simulations:
- Test Plan
- Obstacle avoidance
- Weather avoidance
- Rules of the Air
- Cooperative vs. Noncooperative

Conclusion

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This project has received funding from European Union`s Horizon 2020 research and innovation programme, under the Marie Sklodowska-Curie grant agreement No 642153

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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

Your Notes:

2

Sense & Avoid Introduction:

Airspace classification

UAS Traffic Management

Terminology

Reactive Avoidance

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Speech:

The main goal of the thesis was to develop a framework,

Which is capable to fly in "non-segregated airspace",

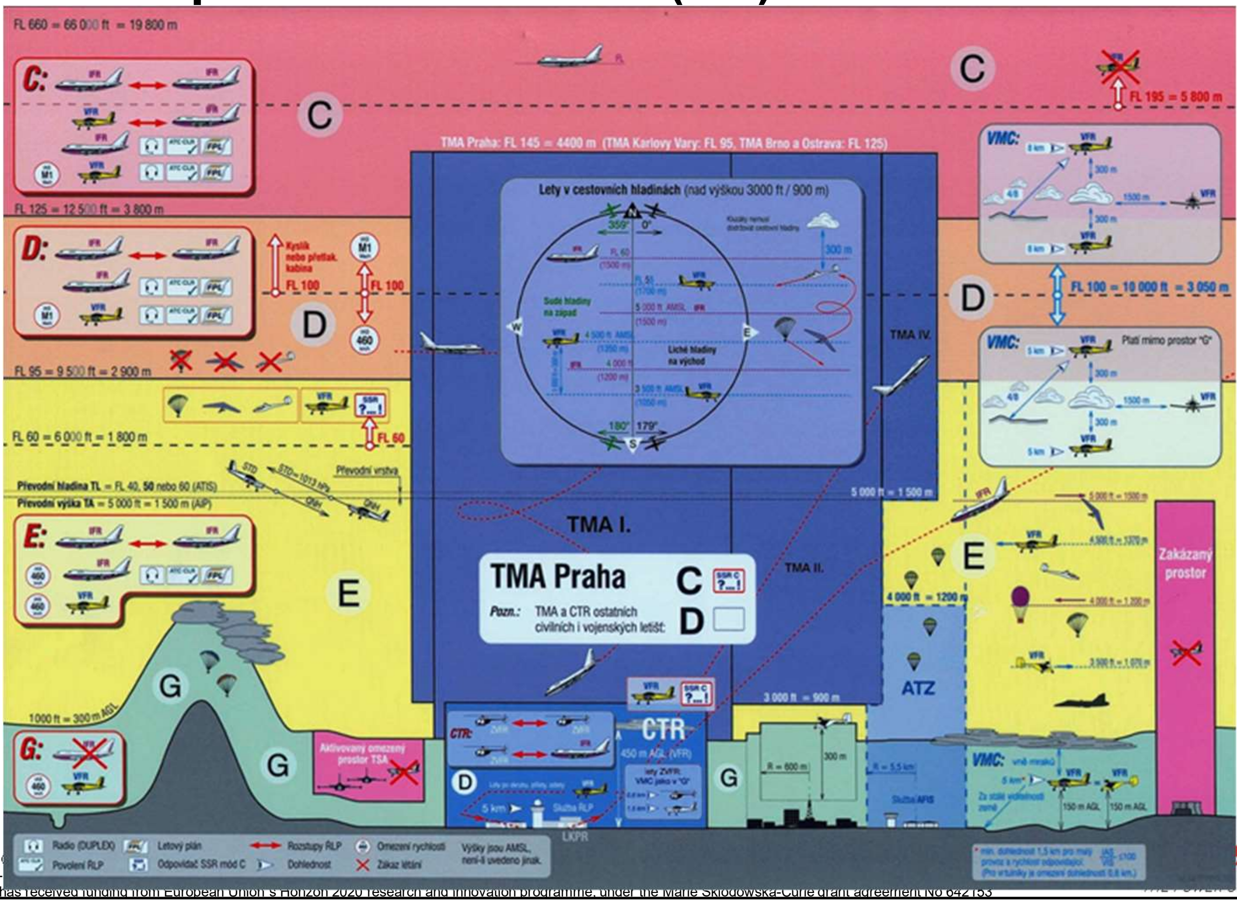
Lets start with short introduction

Note: All Airspace related rules and constraints can be found in chapter 2. This section is only a short introduction.

Your Notes:

3

Context of SAA:
Airspace classification (2.2)



Speech:

There is airspace vertical classification based on altitude,

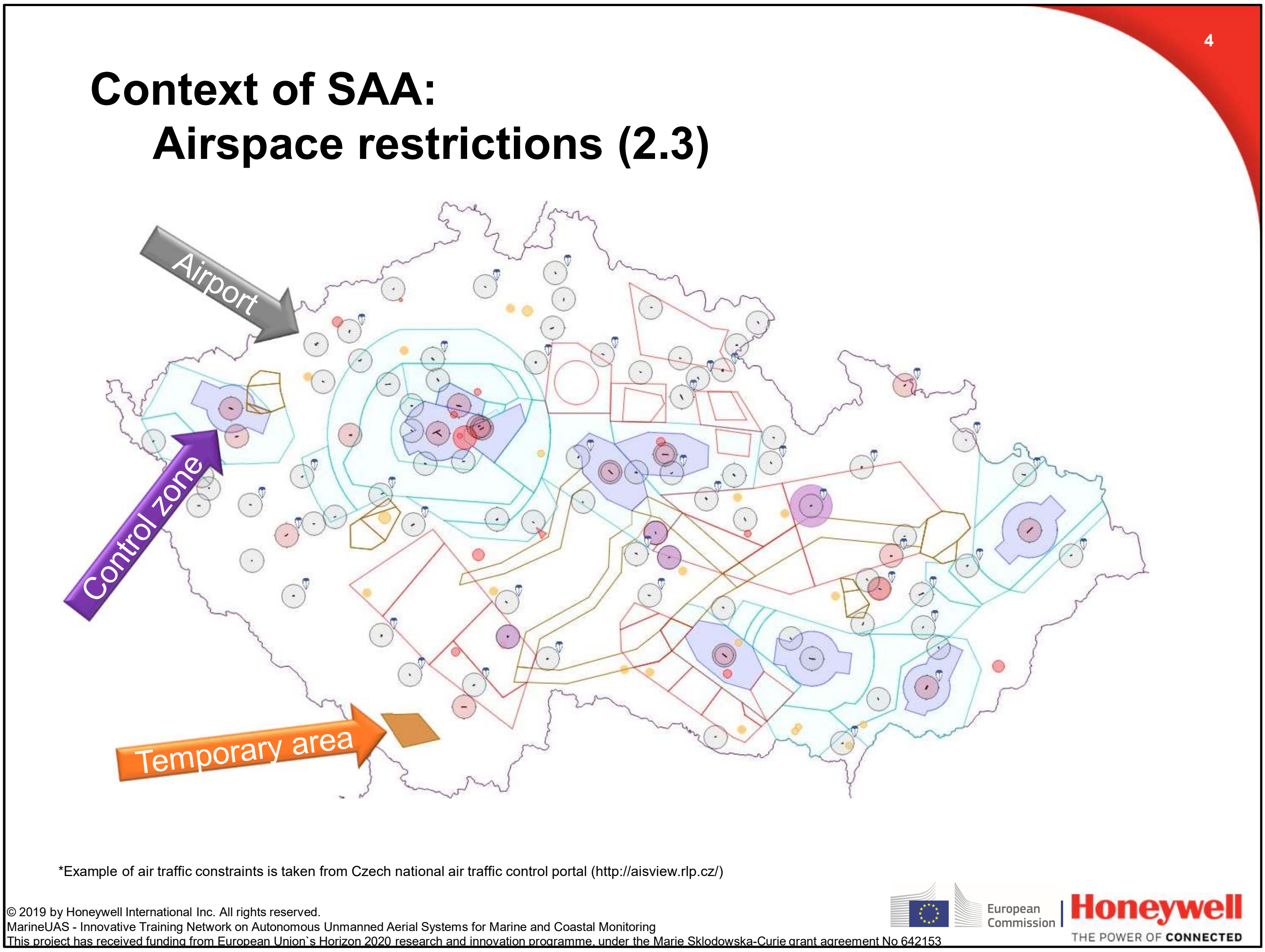
Different rules and authorities applies on different

“flight levels”,

“C class airspace” is where passenger planes operates

Note: There is slight difference between countries, this example is valid for Czech/Slovak Republic.

Your Notes:



Speech:

The same goes for horizontal plane restrictions,

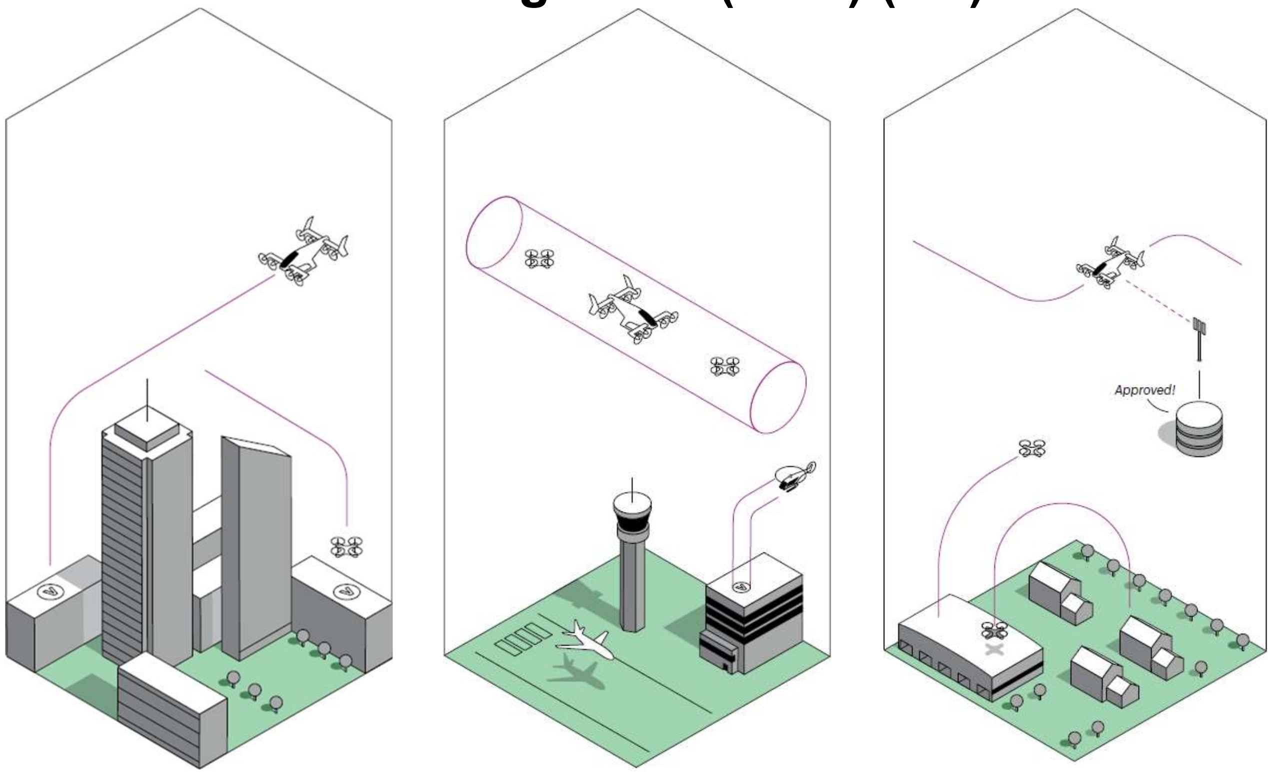
Airspace authority can prohibit operations in specific area,

For example the “orange rectangle” was marked as ”Restricted Area”,

Due the “Military exercise”.

Your Notes:

Context of SAA:
UAS Traffic Management (UTM) (2.5)



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Speech:

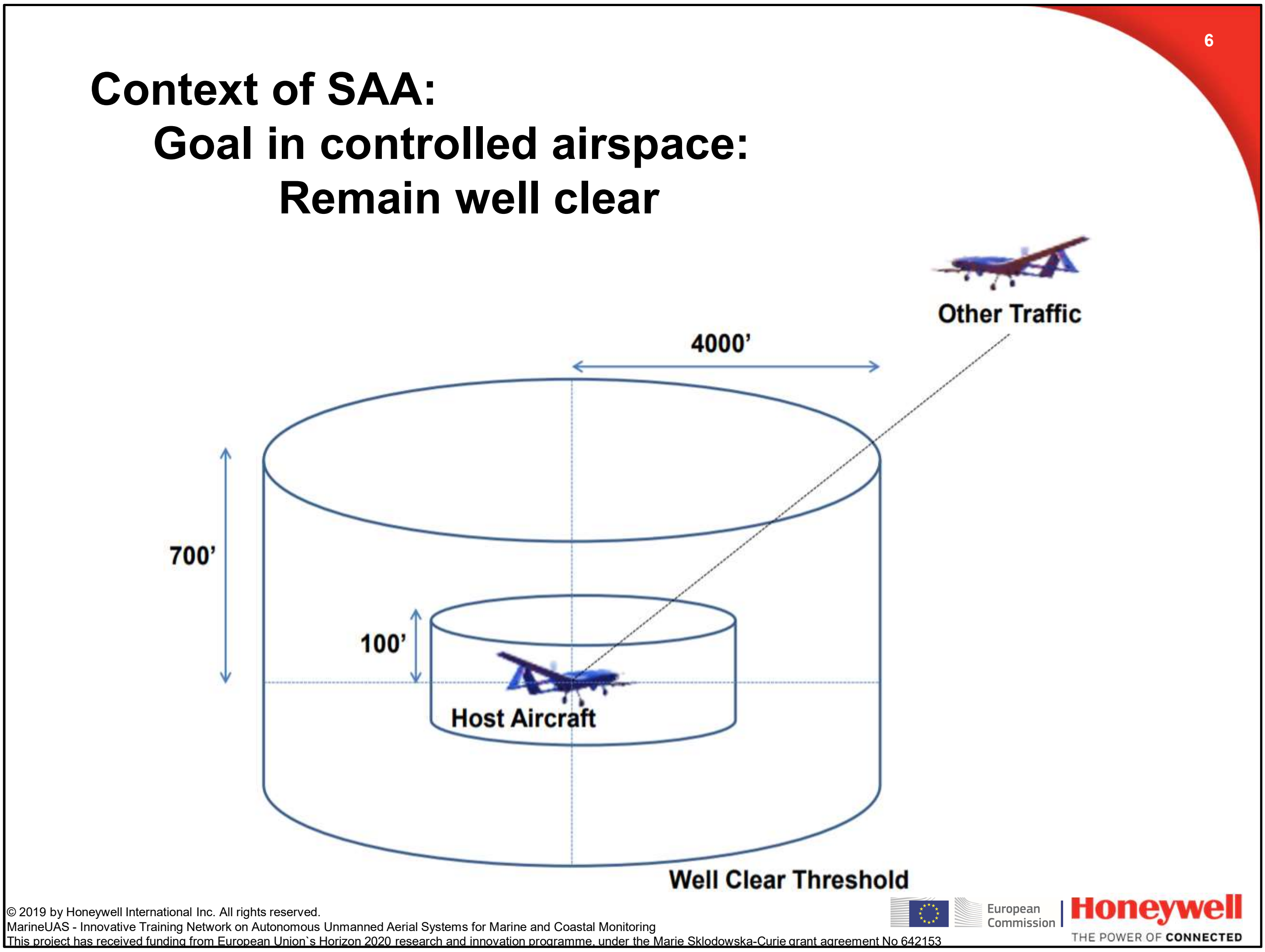
As for the planes there is ATM, the similar concept is applied for UAS, The UAS Traffic Management system is established by "EASA" in EU,

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

Your Notes:



Speech:

The aviation is using “Well clear distance”

The bigger barrel is called “Well clear margin”

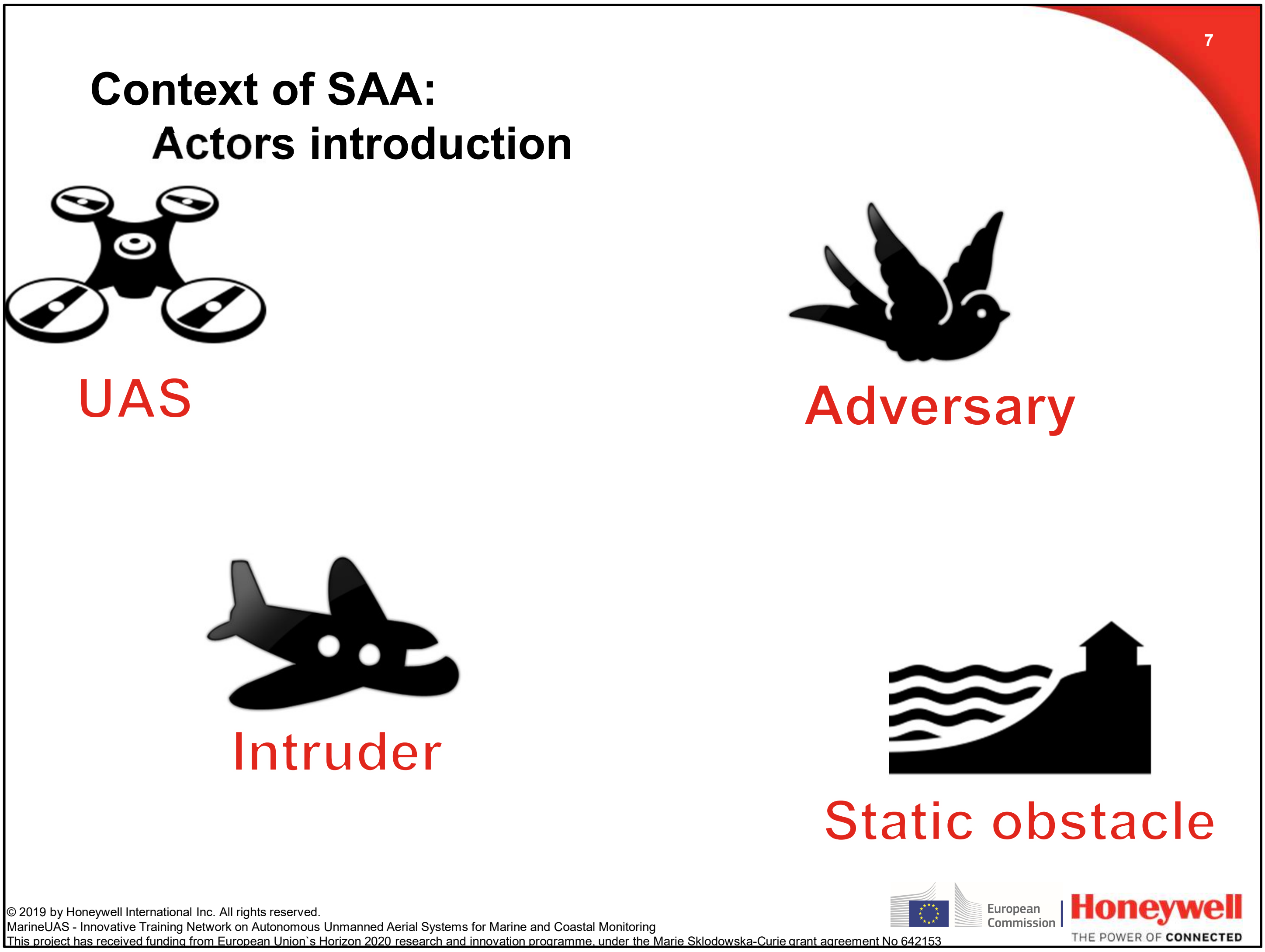
Which is considered as “warning zone”

No plane should enter that zone

The smaller barrel is called “near miss margin”,

Entrance is considered as a “serious incident”

Your Notes:



Speech:

The **UAS** is interacting with **obstacles**:

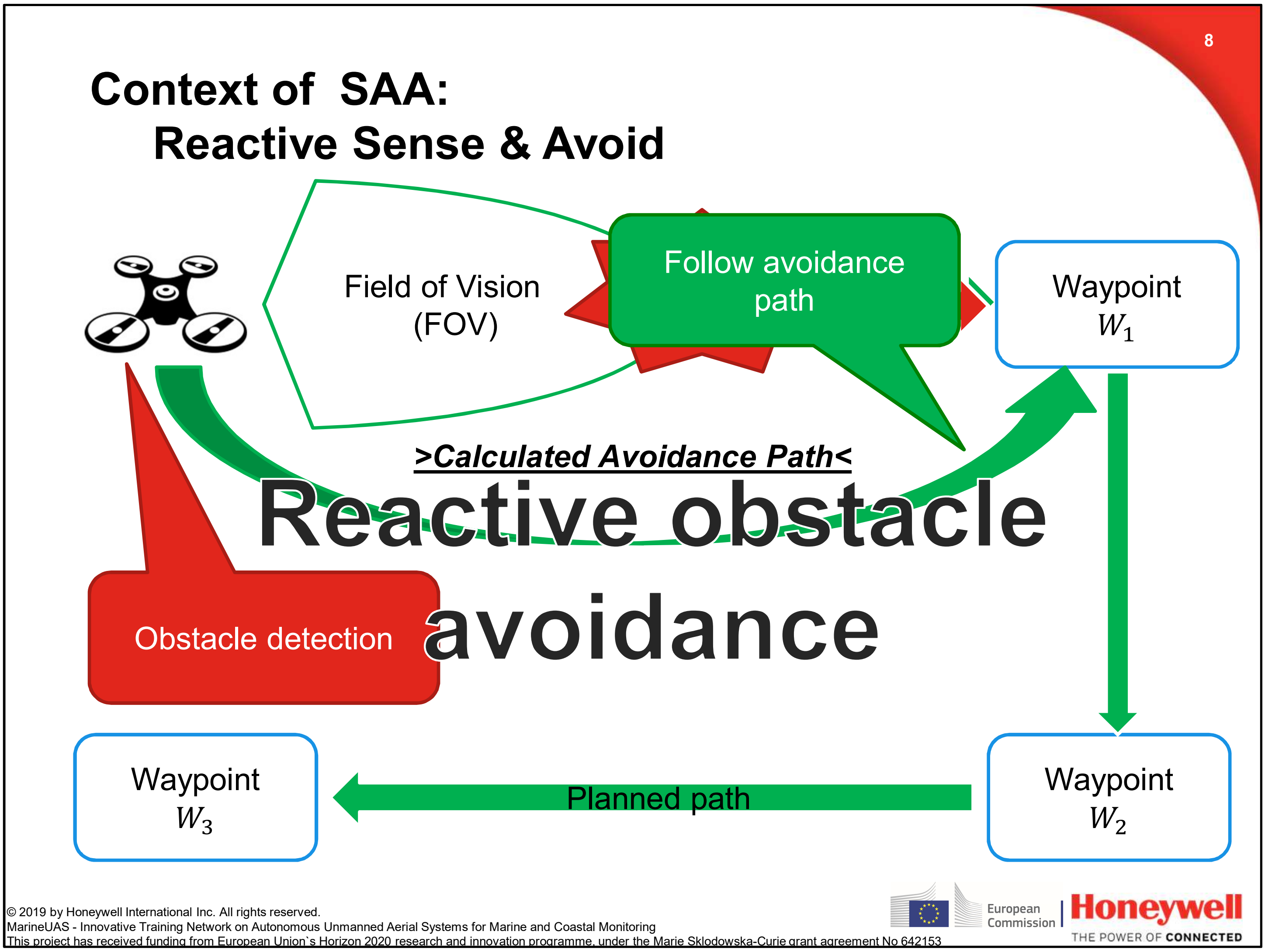
- **Static** not changing position with time, like buildings,

- Moving which are not trying to harm us – **Intruders,**

- Moving which are trying to harm us – **adversaries,**

Note: The work does not consider “adversaries”,

Your Notes:



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

Your Notes:

Problems in Detect & Avoid:

Explained as a story

Incremental problem definition

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Speech:

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

Your Notes:

10

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How this gentleman gets into the Fine Restaurant

[1]https://commons.wikimedia.org/wiki/File:Le_restaurant_V%C3%A9ry_-_ext.png
[2]https://commons.wikimedia.org/wiki/File:A_gentleman,_walking_towards_the_left_and_drawing_his_sword_from_the_sheath,_wearing_a_plumed_hat_and_boots_with_spurs_MET_DP829192.jpg

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Speech:

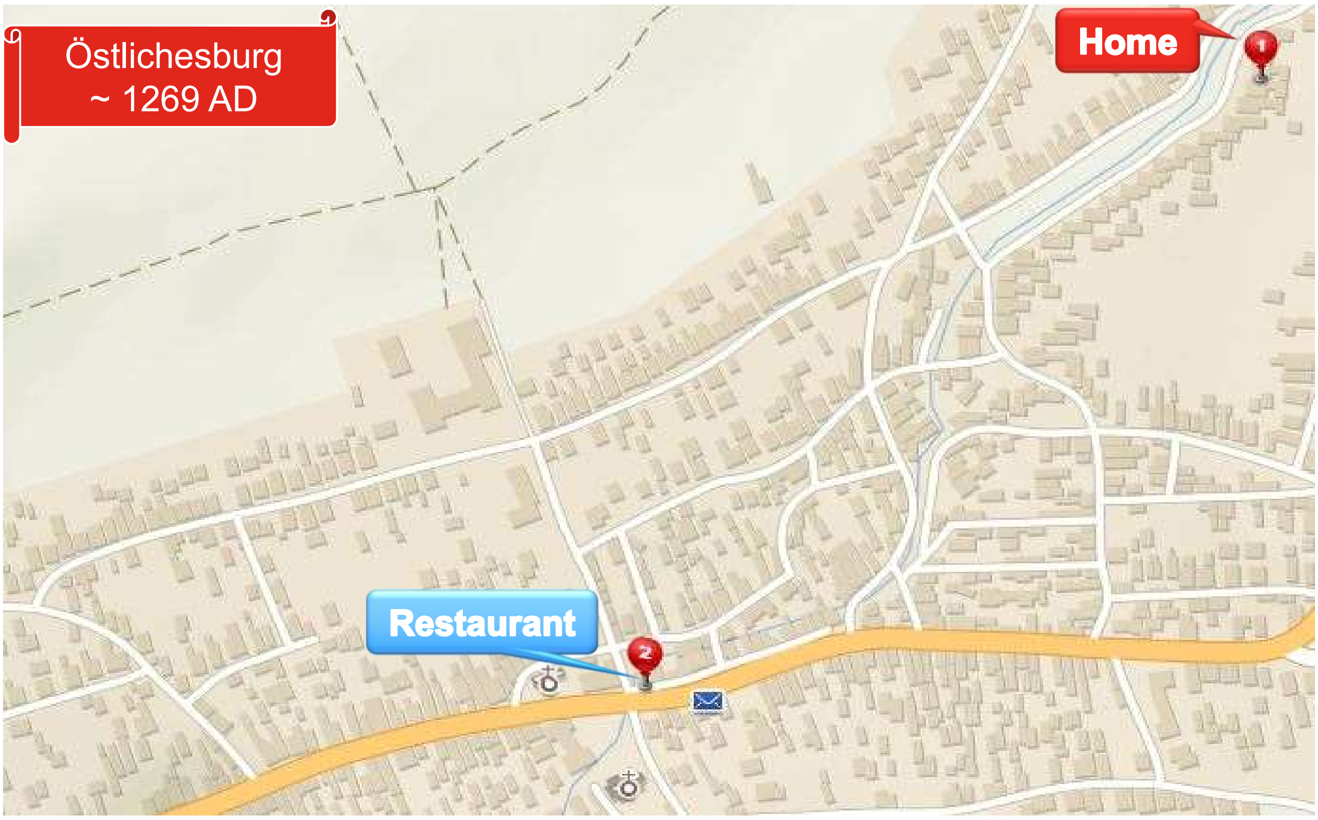
The obstacle avoidance can be taken as a “trip to a pub”,

Lets help this gentleman get into the fine restaurant,

Your Notes:

11

How to get to the fine restaurant ?



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Speech:

We have a simple mission get from the home (red),

To the “Fine restaurant” (blue),

Your Notes:

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No problem, I know a map of my surroundings

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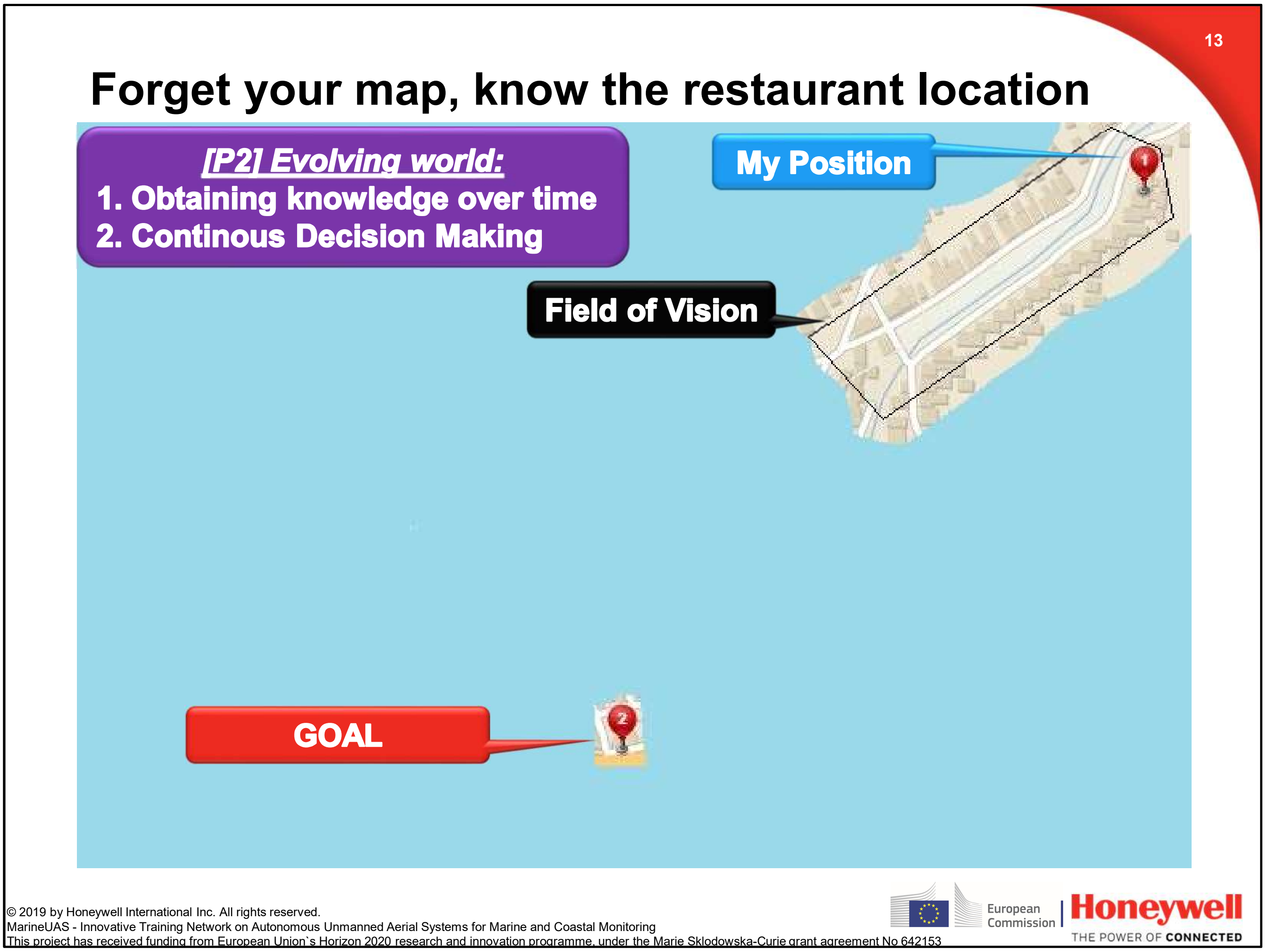
Speech:

First is “Path planning problem”, we know everything,

We just need stick to the plan.

Your Notes:



Speech:

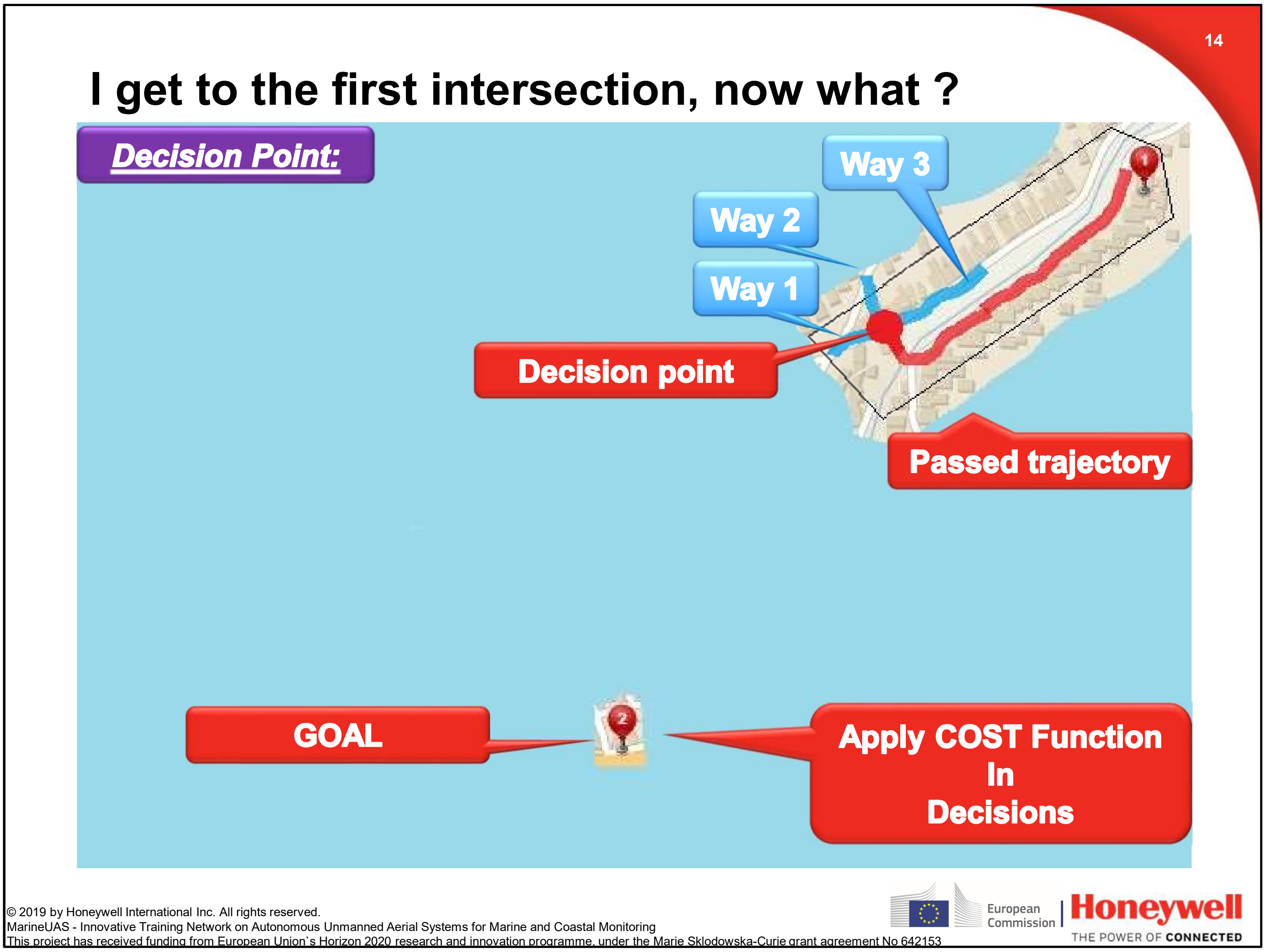
I have forgotten my map at home, I need to use my eyes,

“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)

Your Notes:



Speech:

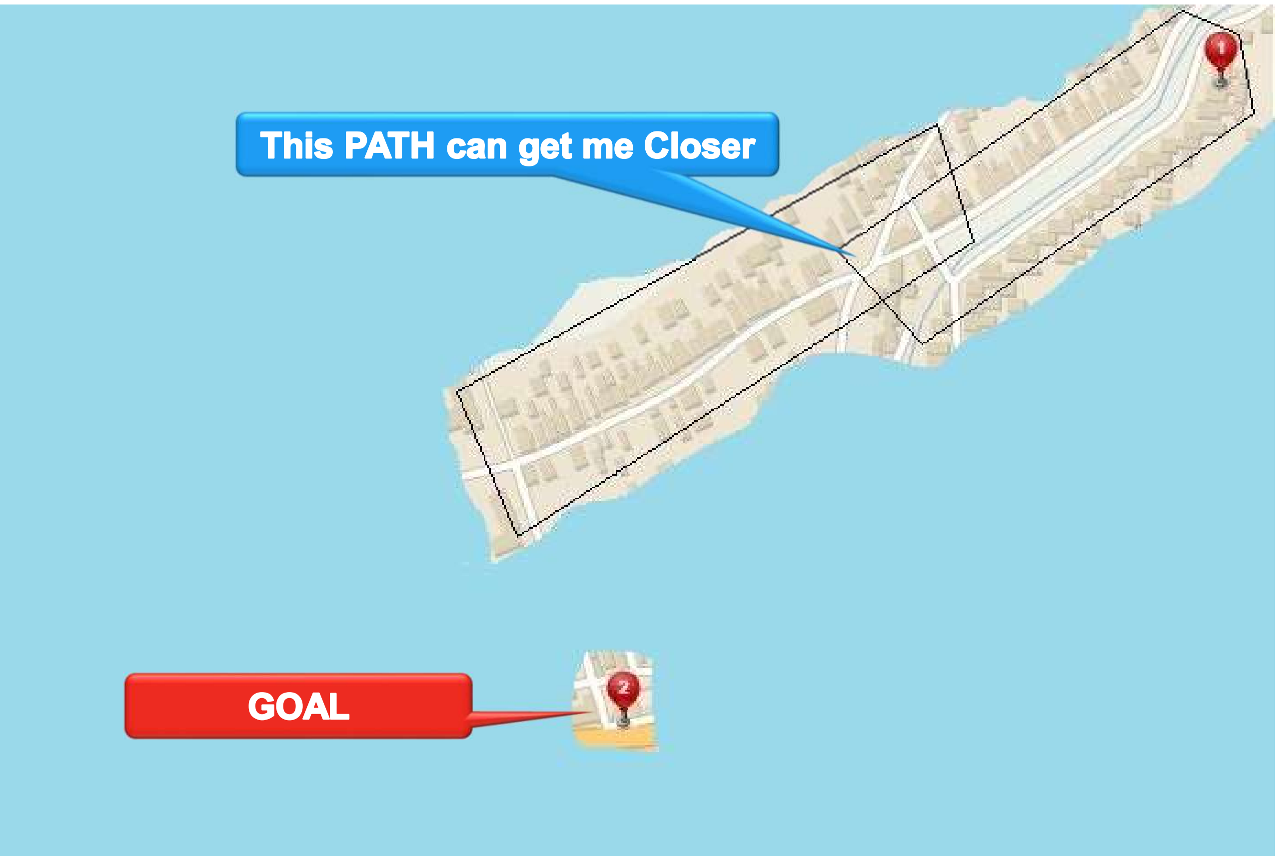
Because I am lazy I am changing my path only on "Decision points" (red circle),

I look around and I see three possible ways,

Your Notes:

15

Look around, get know to your surroundings



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Speech:

I choose the most promising path according to "Cost function",

I will continue along the way

Your Notes:

Speech:

I reached the next decision point,

I look around and I see three possible ways,

Your Notes:

Speech:

I choose to go down to my “cost function”,

I do next “sensor scan”,

I can see the restaurant,

Your Notes:

18

Enjoy a Pint

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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”.

Your Notes:

19

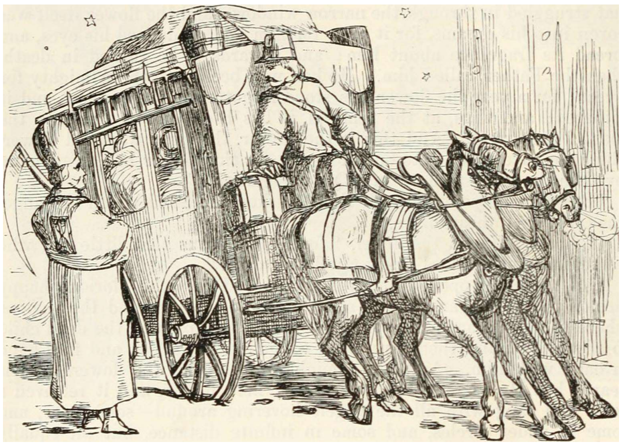
You are NOT alone on the streets !

[P3] Intruder:

You need to avoid:

Carriages and Other people

You can hurt others !



[P3] Intruder:

Reactive obstacle avoidance

Ingredients:

1. **Intruder Position**
2. **Intruder Velocity**
3. **Own position and velocity**

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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,

Your Notes:

20

Multiple source of information – Data Fusion

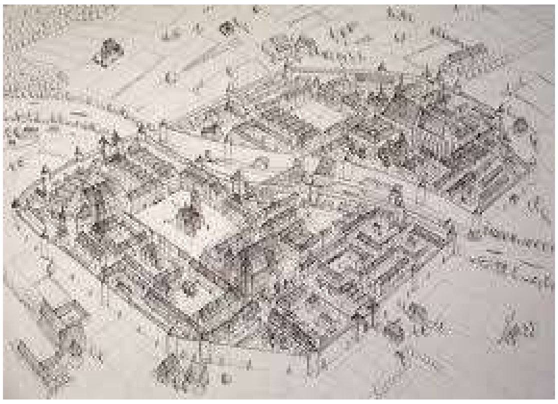
[P3] Data fusion:

So much Information …

So many Whispers …

Need Validation …

Much Verification …



[P3] Data Fusion:

Decisions under uncertainty

1. **Determine what is truth**
2. **Consider all information**
3. **Rank your sources worth**

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Speech:

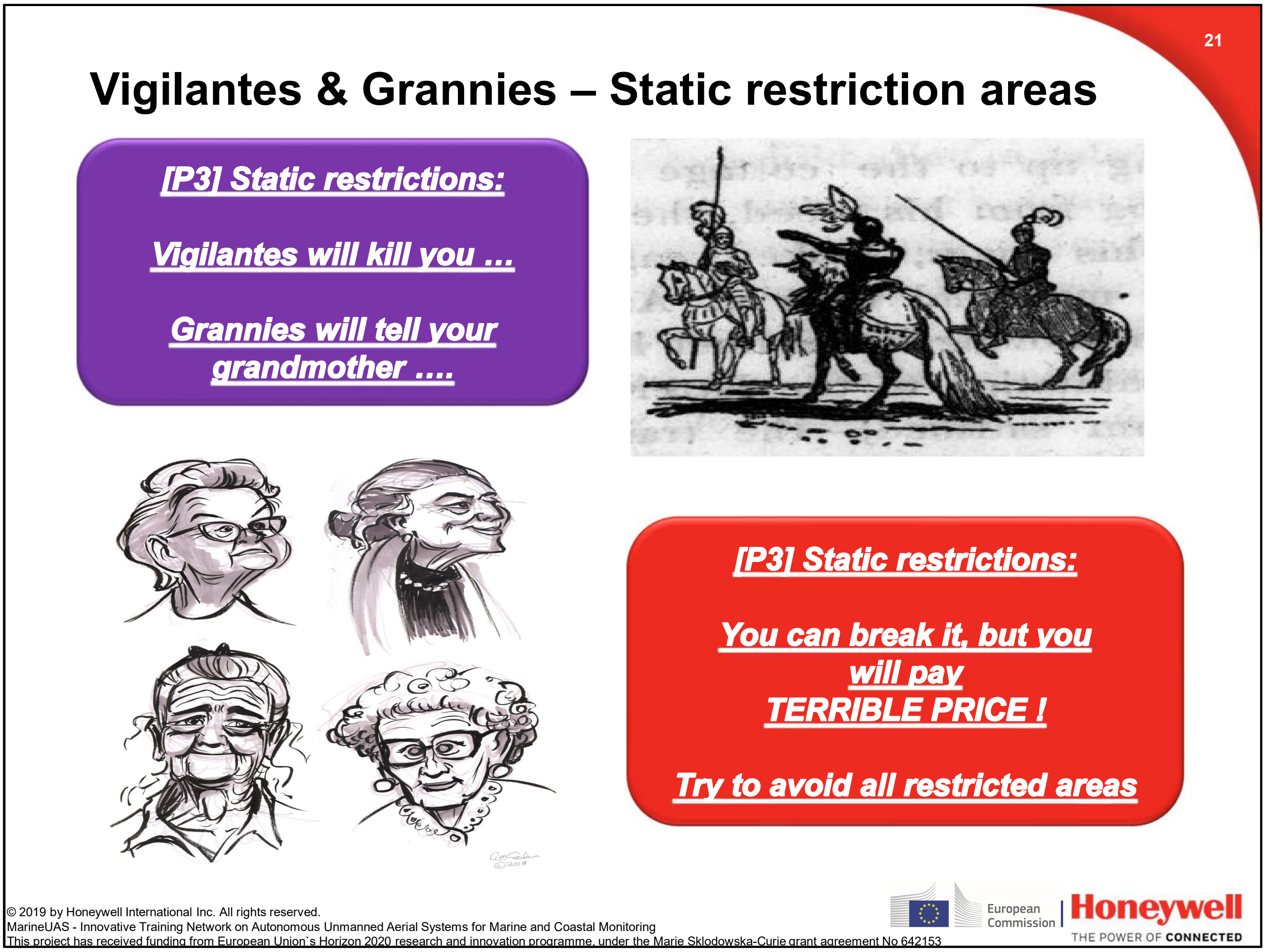
You have contraindicating data,

The map is outdated, the pub was moved,

You need to determine what is the true,

You need to fuse data in "Data fusion",

Your Notes:



Speech:

When we managed to avoid intruders, the problem is,

Still standing folk, or “static restrictions”,

There are vigilantes they will fine you,

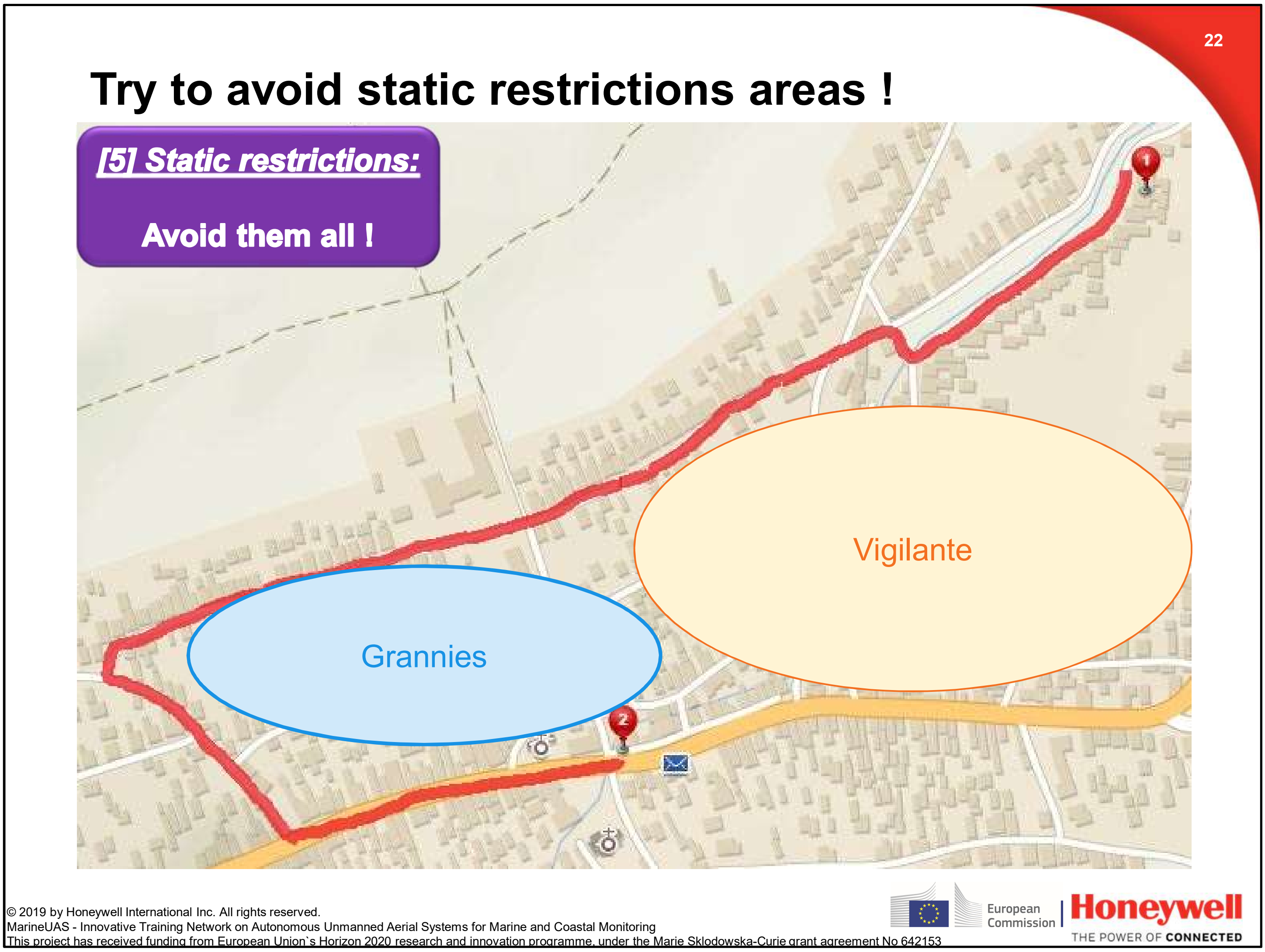
They are considered “hard constraints”,

There are grannies who are just going to tell on you,

They are considered “soft constraints”,

The parallel are the airspace restrictions,

Your Notes:



Speech:

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

Note:

The path is semi-optimal (continuous-decision making) with given restrictions

Your Notes:

23

How about weather ?

[P4] Weather:
Östlichesburg **winter very harsh,**
On the other hand,
Östlichesburg **summer even**
Harsher

[P4] Weather:

Harsh Weather Avoid NOW !

Maybe you will need to break some restrictions

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Speech:

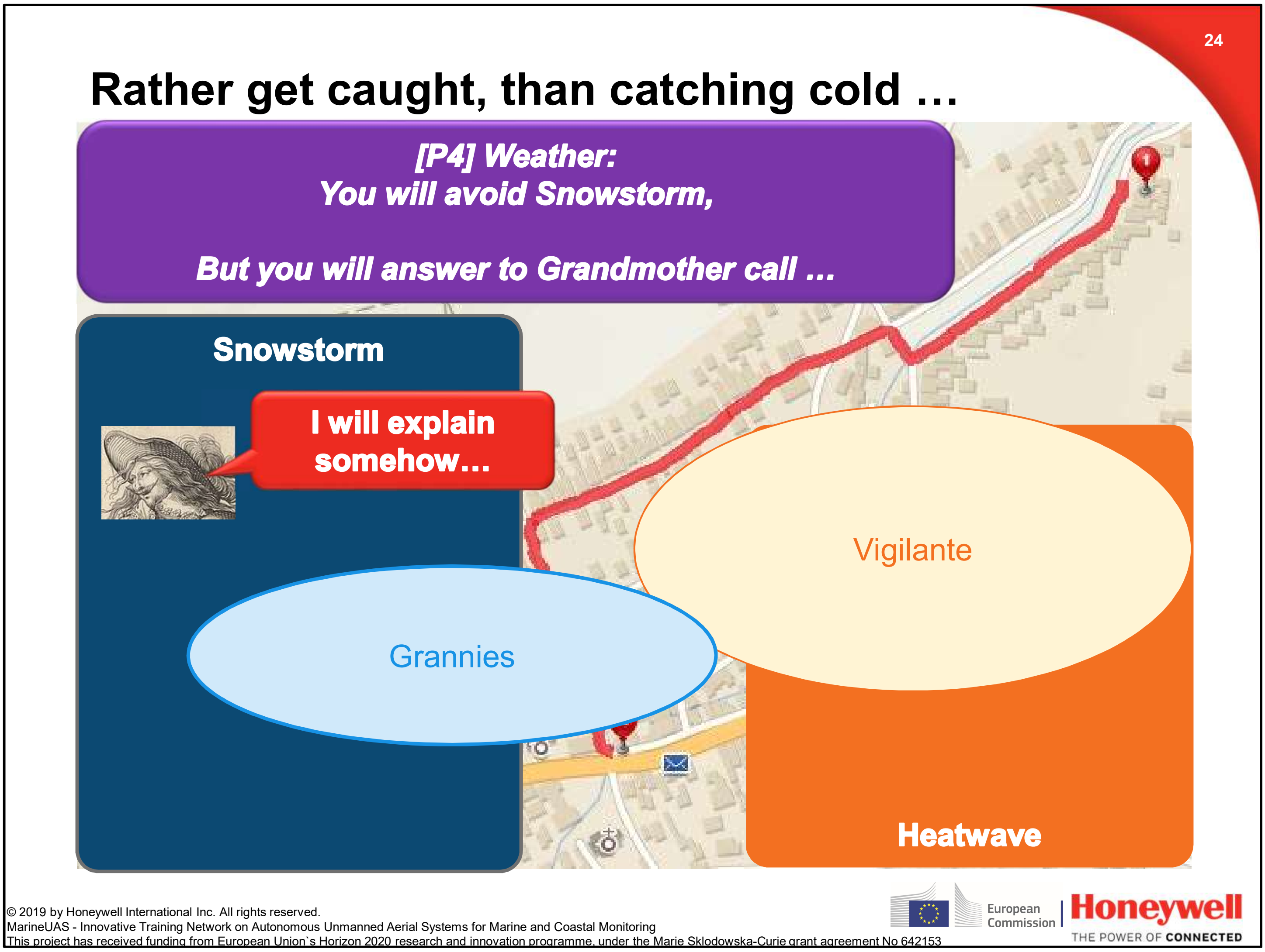
We try to avoid hash weather conditions, which acts like:

1. “Moving constraint”, or,
2. “Static constraint”,

Some prioritization needs to be implemented in our,

“Data fusion”,

Your Notes:



Speech:

The prioritization of “constraints” is like follow:

Rather get yelled by granny than catching a cold

Note:

The red path is crossing grannies territory, breaking “soft static constraint”

25

Stick to the rules !

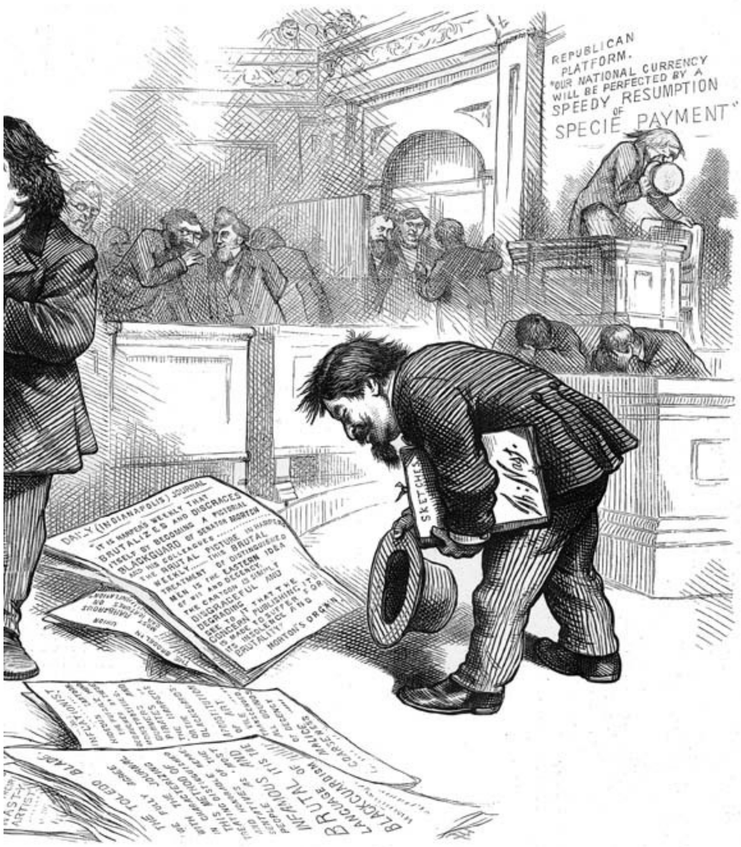
[P5] Rules:

Obey rules while walking

[P5] Rules:

Stick to Written and unwritten rules …

Necessity
for integration into traffic, society, air space



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Speech:

It is necessary to obey the authority, in traffic, society,

Especially in "Airspace",

The different airspaces implements different rules

Your Notes:

Formal problem specification 1/2

The UAS is operating in space _classified into four distinctive subsets_:

$$SpaceClassification : y \in Space \mapsto s \in \{Free, Restricted, Occupied, Uncertain\} \tag{4.10}$$

The space classification is coming from _data fusion procedure_:

$$DataFusion : \begin{bmatrix} InformationSource_1 \times \\ InformationSource_2 \times \\ \times \cdots \times \\ InformationSource_l \times \\ SensorFusion(\dots) \times \\ Weather(\dots) \\ position \times \\ fixed\ time\ t_{fix} \times \\ dataFusionParameters \end{bmatrix} \to \begin{cases} Free(t_{fix}) \\ Occupied(t_{fix}) \\ Restricted(t_{fix}) \\ Uncertain(t_{fix}) \end{cases} \tag{4.19}$$

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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)

Note:

The data fusion will be discussed later,

Your Notes:

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Formal problem specification 2/2

UAS will fly a ***Mission*** given as ordered set of waypoints:

$$Mission = \left\{ \begin{matrix} waypoint_1, waypoint_2, \dots, waypoint_m : \\ \forall_{i=1\dots m} waypoint_i \in Space \end{matrix} \right\}, \quad m \in \mathbb{N}^+, m \geq 2 \tag{4.6}$$

The goal is to have ***path*** satisfying:

$$\forall t \in [missionStart, missionEnd] : \\ distance(x(t), Occupied(t), t) \geq safetyMargin \tag{4.21}$$

Under the ***assumptions***:

1. Filtered sensor reading are available.
2. There are no moving obstacles (intruders) [Relaxed P3]
3. The movement takes place in unrestricted airspace [Relaxed P5]
4. The mission consist of a set of reachable waypoints
5. The UAS is moving with constant velocity [Relaxed P5]

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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,

Note:

Some assumptions are relaxed over time,

Your Notes:

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Incremental problem definition:
[P1] Basic Avoidance

$$KnownWorld: \quad = SensorFusion(t) \forall point \in KnownWorld(t)$$
$$= Free(t) \cup Occupied(t) \cup Unknown(t)$$
$$Mission: \quad = \forall waypoint \in Mission \text{ are reachable}$$
$$Sensors: \quad = \{LiDAR\}$$
$$SensorFusion: \quad = \{\text{Clasificaiton function}\}$$
$$HFlightConstraints: \quad = \{\text{vehicle dynamic}\}$$

1. *Known world* - consisting from Free, Occupied, Unknown sets.
2. *Mission* - Assumptions 1-5 are valid.
3. *Sensors* - LiDAR sensor is introduced as source of information.
4. *Sensor fusion* - classification function implementation
5. *Hard Flight constraints* - UAS dynamic only.

Problems addressed:

- Navigation Loop Implementation (sec. 6.6.2).
- Avoidance Loop Implementation (sec. 6.6.1).

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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)

Your Notes:

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Incremental problem definition: [P2] Intruders Introduction

$$KnownWorld: \quad = SensorFusion(t) \forall point \in KnownWorld(t)$$
$$= Free(t) \cup Occupied(t) \cup Unknown(t)$$
$$Mission: \quad = \forall waypoint \in Mission \text{ are reachable}$$
$$Sensors: \quad = \{LiDAR, ADS-B\}$$
$$SensorFusion: \quad = \{\text{Advanced joint sets}\}$$
$$HFlightConstraints: \quad = \{\text{vehicle dynamic}\}$$
$$HardConstraints: \quad = \{\text{intruder corridors}\}$$

1. *Sensors* - ADS-B added enabling intruder detection.
2. *Sensor fusion* - union of obstacle space and individual intruder spaces.
3. *Hard constraints* - intruder corridors, changing over time.

Problems addressed:

- Intruder Intersection Models (minimal operation requirements achieved): Linear Intersection Model (app. C.1), Body-volume intersection (app. C.2), Maneuverability uncertainty intersection (app. C.3).
- Flight Corridors (sec. 6.5.3).

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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”.

Your Notes:

30

Incremental problem definition: [P3] Static restrictions

$$
\begin{aligned}
KnownWorld: &\quad = DataFusion(t)\forall point \in KnownWorld(t) \\
&\quad = Free(t) \cup Occupied(t) \cup Unknown(t) \cup Restricted(t) \\
Mission: &\quad = \forall waypoint \in Mission \text{ are reachable} \\
Sensors: &\quad = \{LiDAR, ADS-B\} \\
SensorFusion: &\quad = \{\text{Advanced joint sets}\} \\
InformationSources: &\quad = \{TerrainMap, ObstacleMap, FlightRestriction\} \\
DataFusion: &\quad = \{\text{Advanced data fusion}\} \\
HFlightConstraints: &\quad = \{\text{vehicle dynamic}\} \\
HardConstraints: &\quad = \{\text{intruder corridors}, \text{terrain}, \text{obstacles}\} \\
Softconstraints: &\quad = \{\text{protection zones}\}
\end{aligned}
$$

1. Known world - added restricted space portion evolving over time
2. Information sources - added *Obstacle Map* (fig. 6.13), *Visibility Rating Concept* (fig. 6.12) and *Static Constraints* (sec. 6.5.3).
3. Data fusion - the rating implementation of the data fusion (sec. 6.5.4).
4. Hard constraints - added obstacles and terrain constraints.
5. Soft constraints - added airspace restrictions and geo-fencing/

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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,

Note:

Refer to the map from the introduction for “restricted airspace”.

The supplement ratings needed to be introduced, like visibility (6.13) and static constraints (6.5.3)

The final form of data fusion has been outlined (6.5.4)

Your Notes:

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Incremental problem definition: [P4] Dynamic restrictions

$$KnownWorld: = DataFusion(t) \forall point \in KnownWorld(t)$$
$$= Free(t) \cup Occupied(t) \cup Unknown(t) \cup Restricted(t)$$
$$Mission: = \forall waypoint \in Mission \text{ are reachable}$$
$$Sensors: = \{LiDAR, ADS-B\}$$
$$SensorFusion: = \{\text{Advanced joint sets}\}$$
$$InformationSources: = \{TerrainMap, ObstacleDatabase, FlightRestriction, Weather\}$$
$$DataFusion: = \{Advanced\ data\ fusion\}$$
$$HFlightConstraints: = \{\text{vehicle dynamic}\}$$
$$HardConstraints: = \{\text{intruder corridors, terrain, obstacles, protection zones}\}$$
$$Softconstraints: = \{\text{protection zones}\}$$

1. Information sources - the weather adding *moving constraints* (def. 20) example *Weather Avoidance Case* (app. E.1).
2. Hard constraints - protection zones against severe weather conditions
3. Soft constraints - protection zones against mild weather conditions

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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”.

[Note]

Weather covers all types of constraints due its phenomena variability.

32

Incremental problem definition: [P5] Rules of the air

$$
\begin{aligned}
KnownWorld: &\quad = DataFusion(t)\forall point \in KnownWorld(t)\\
&\quad = Free(t) \cup Occupied(t) \cup Unknown(t) \cup Restricted(t)\\
Mission: &\quad = \forall waypoint \in Mission \text{ are reachable}\\
Sensors: &\quad = \{LiDAR, ADS - B\}\\
SensorFusion: &\quad = \{\text{Advanced joint sets}\}\\
InformationSources: &\quad = \{TerrainMap, ObstacleDatabase,\\
&\quad FlightRestriction, Weather\}\\
DataFusion: &\quad = \{Advanceddatafusion\}\\
HFlightConstraints: &\quad = \{\text{vehicle dynamic}\}\\
SFlightConstratins: &\quad = \{\text{airspaces, rules of the air}\}\\
HardConstraints: &\quad = \{\text{intruder corridors, terrain, obstacles, protection zones}\}\\
Softconstraints: &\quad = \{\text{protection zones}\}
\end{aligned}
$$

1. *Soft flight constraints* - different behavior in *airspace classes* added, *rules of the air* implementation added, introduction in *UTM Implementation* (sec. 6.7), *Rule Engine for UAS* (sec. 6.8.1) and *Rule Implementation* (sec. 6.8.2).

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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”

Your Notes:

Related work:

Movement Automaton

Surveillance

Navigation

Reach set estimation

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Speech:

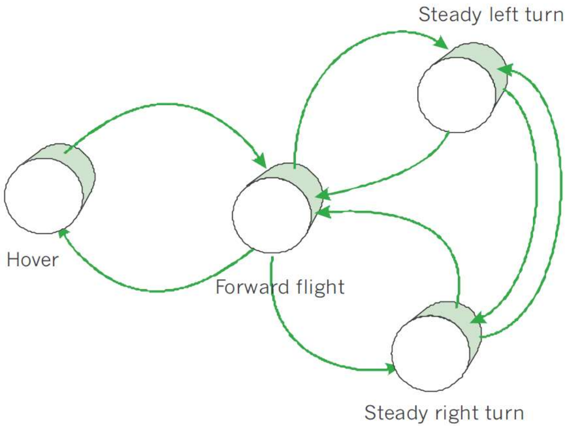
The goal is to provide the answer to given challenges.

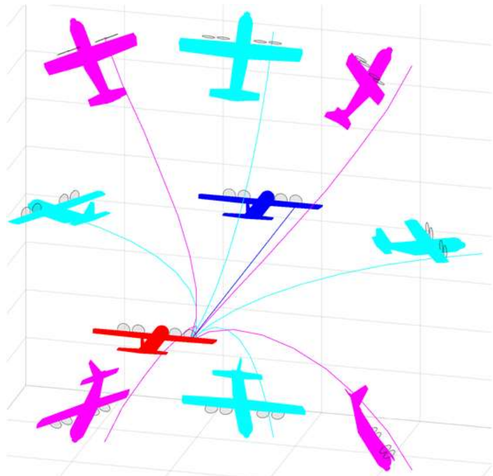
We need a tools for:

1. An UAS discrete control,
2. Surroundings surveillance,
3. Short-term/Long term navigation,
4. Reach set estimation/approximation

Your Notes:

Related work:
Movement automaton (5.1)





Related work:

[15] Emilio Frazzoli. Robust hybrid control for autonomous vehicle motion planning. PhD thesis, Massachusetts Institute of Technology, 2001.

[91] Emilio Frazzoli, Munther A Dahleh, and Eric Feron. Trajectory tracking control design for autonomous helicopters using a backstepping algorithm. In American Control Conference, 2000. Proceedings of the 2000, volume 6, pages 4102-4107. IEEE, 2000.

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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)

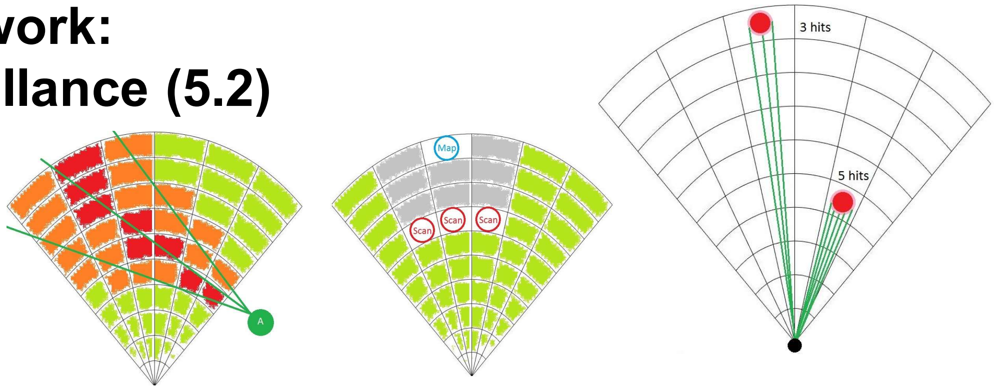
Note:

In the picture you can see the example of used movement set [red plane is origin], [cyan/magenta plane after movement]

Your Notes:

35

Related work:
Surveillance (5.2)



Related work:

[98] Fredrik Gustafsson. Statistical sensor fusion. Studentlitteratur, 2010.

[99] Subramanian Ramasamy, Roberto Sabatini, Alessandro Gardi, and Trevor Kistan. Next generation fight management system for real-time trajectory based operations. Applied Mechanics and Materials, 629:344-349, 2014.

[100] Yuriy Chynchenko, Tatyana Shmelova, and Oksana Chynchenko. Remotely piloted aircraft systems operations under uncertainty conditions. Proceedings of the National Aviation University, 1(1):18-22, 2016.

[101] T Shmelova, D Bondarev, and Y Znakovska. Modeling of the decision making by UAS operator in emergency situations. In Methods and Systems of Navigation and Motion Control (MSNMC), 2016 4th International Conference on, volume 1, pages 31-34. IEEE, 2016.

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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,

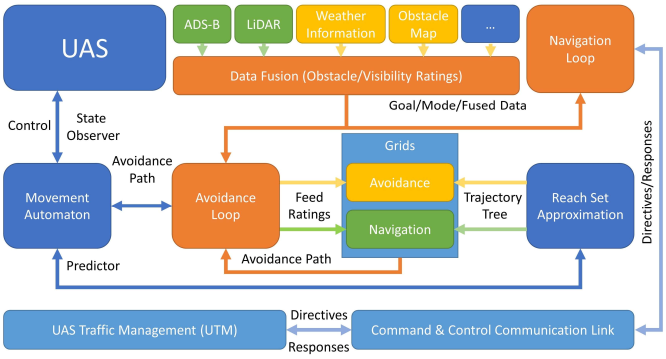
Note:

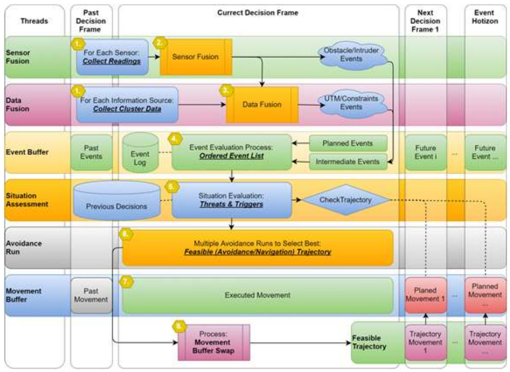
From left to right (examples of properties):

1. Intruder intersection rate
2. Obstacle map rate
3. LiDAR hit count

Your Notes:

Related work:
Navigation (5.3)





Related work:

[167] Roberto Sabatini, Celia Bartel, Anish Kaharkar, Tesheen Shaid, and Subramanian Ramasamy. Navigation and guidance system architectures for small unmanned aircraft applications. International Journal of Mechanical, Industrial Science and Engineering, 8(4):733-752, 2014.

[168] Roberto Sabatini, Alessandro Gardi, and M Richardson. Lidar obstacle warning and avoidance system for unmanned aircraft. International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering, 718-729,2014.

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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:

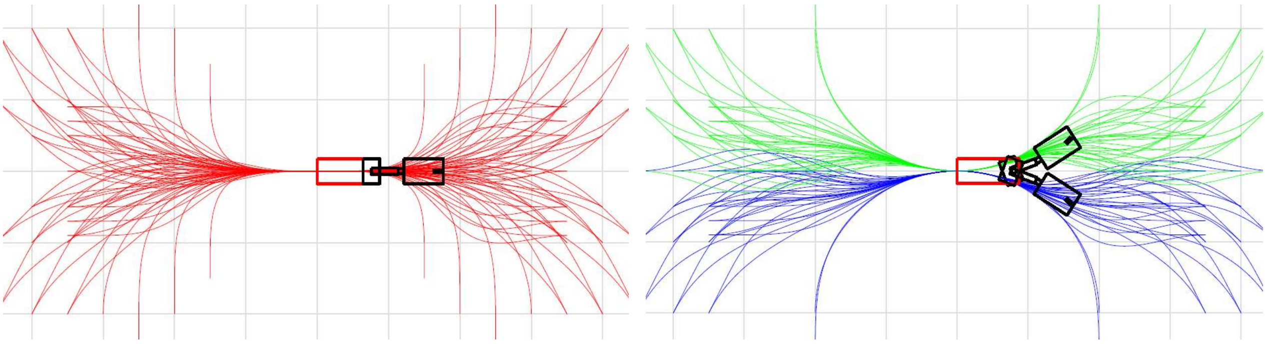
From left to right:

1. Simplified navigation framework structure,
2. Simplified navigation activity diagram,

Your Notes:

37

Related work:
Reach Set Estimation (5.4)



Related work:

[108] Steven M LaValle, Michael S Branicky, and Stephen R Lindemann. On the relationship between classical grid search and probabilistic roadmaps. The International Journal of Robotics Research, 23(7-8):673-692, 2004.

[109] Ira M Gessel. A probabilistic method for lattice path enumeration. Journal of statistical planning and inference, 14(1):49-58, 1986.

[110] Floriana Esposito, Donato Malerba, Giovanni Semeraro, and J Kay. A comparative analysis of methods for pruning decision trees. IEEE transactions on pattern analysis and machine intelligence, 19(5):476{491, 1997.

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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.

Note:

On the picture the “reach set approximation” for truck in different starting positions

Your Notes:

38

Proposed Framework:

Overview

Avoidance Run

UTM Implementation

Rule Engine

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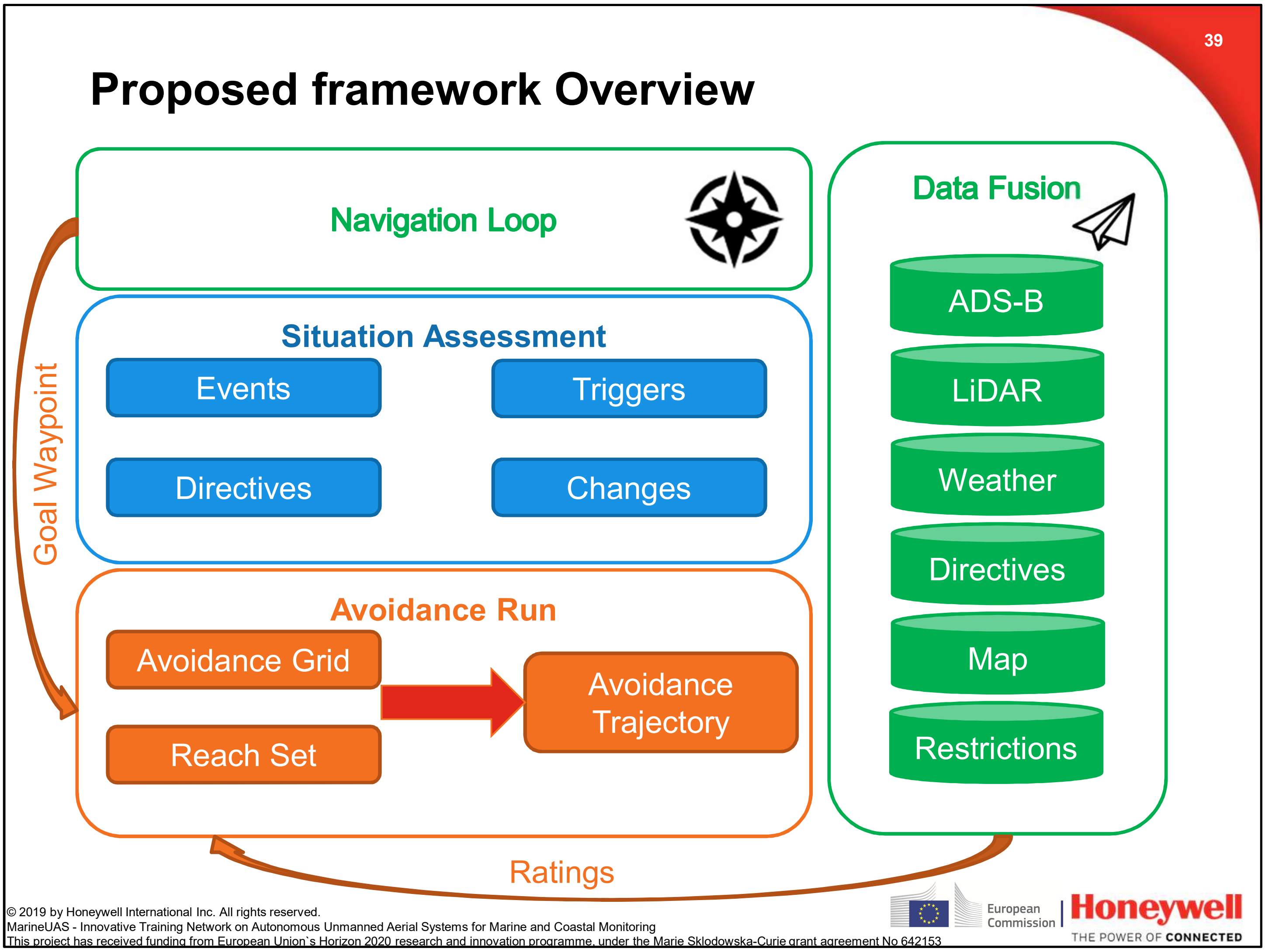
Speech:

That's all for the introduction,

Let us get to the proposed framework,

Your Notes:



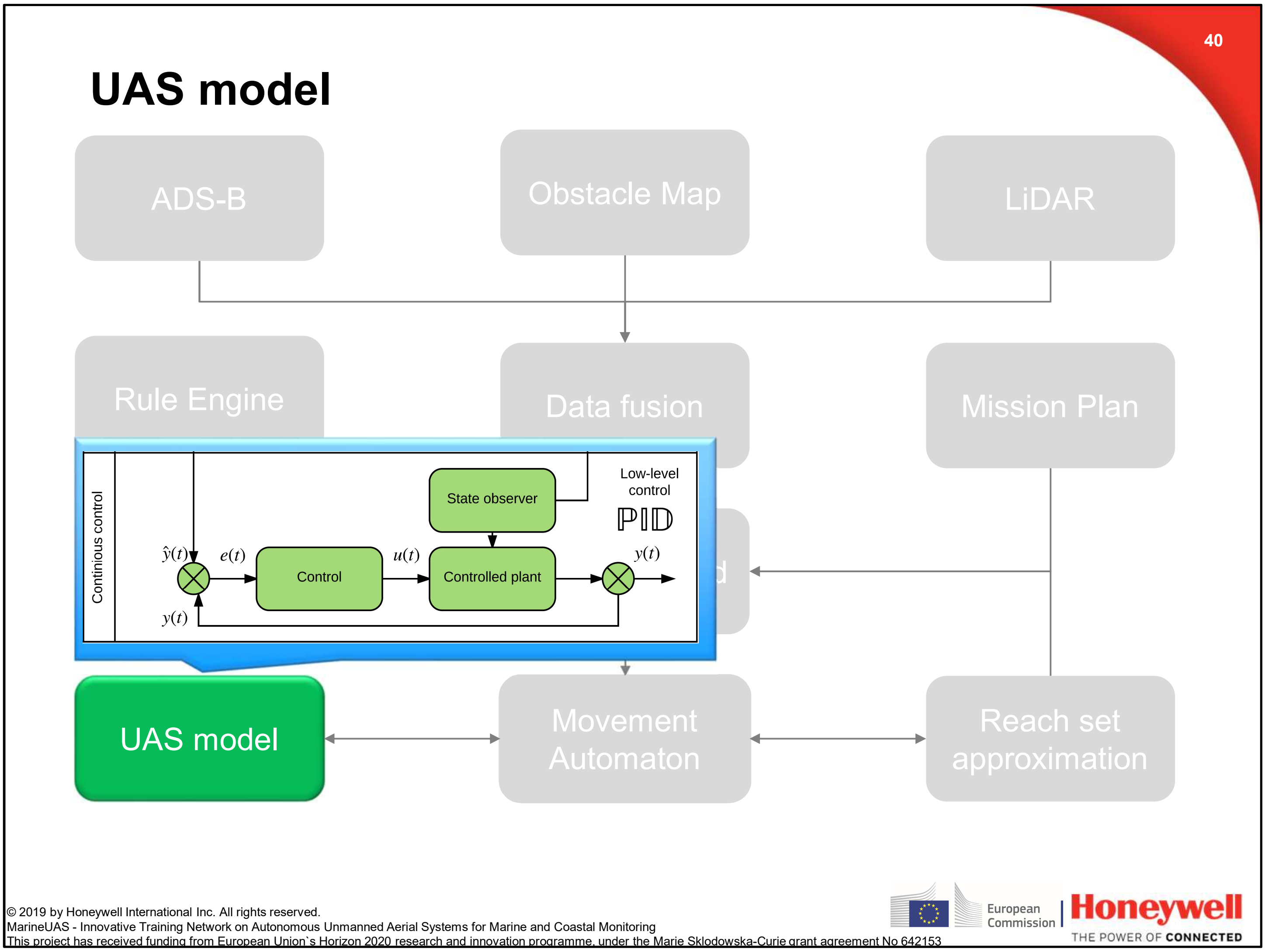
Speech:

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.

Your Notes:



Speech:

The controlled plant (sec. 6.2) for UAS model, is continuous time system, (dramatic pause, click)

Your Notes:

41

UAS model:
3D unicycle (6.2.2)

The ***UAS model*** is defined like follows:

$$state = [x, y, z, roll, pitch, yaw]^T \tag{6.1}$$

$$input = [v, \omega_{roll}, \omega_{pitch}, \omega_{yaw}]^T \tag{6.2}$$

$$\begin{aligned} \frac{\mathrm{d}x}{dtime} &= v\cos(pitch)\cos(yaw); & \frac{\mathrm{d}roll}{dtime} &= \omega_{roll}; \\ \frac{\mathrm{d}y}{dtime} &= v\cos(pitch)\sin(yaw); & \frac{\mathrm{d}pitch}{dtime} &= \omega_{pitch}; \\ \frac{\mathrm{d}z}{dtime} &= -v\sin(pitch); & \frac{\mathrm{d}yaw}{dtime} &= \omega_{yaw}; \end{aligned} \tag{6.4}$$

The **state** is *position* in GCF (x,y,z) and orientation in GCF (roll, pitch yaw).

The ***input*** is *linear velocity* (v) and *angular speed* in LCF $(\omega_{roll}, \omega_{pitch}, \omega_{yaw})$

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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),

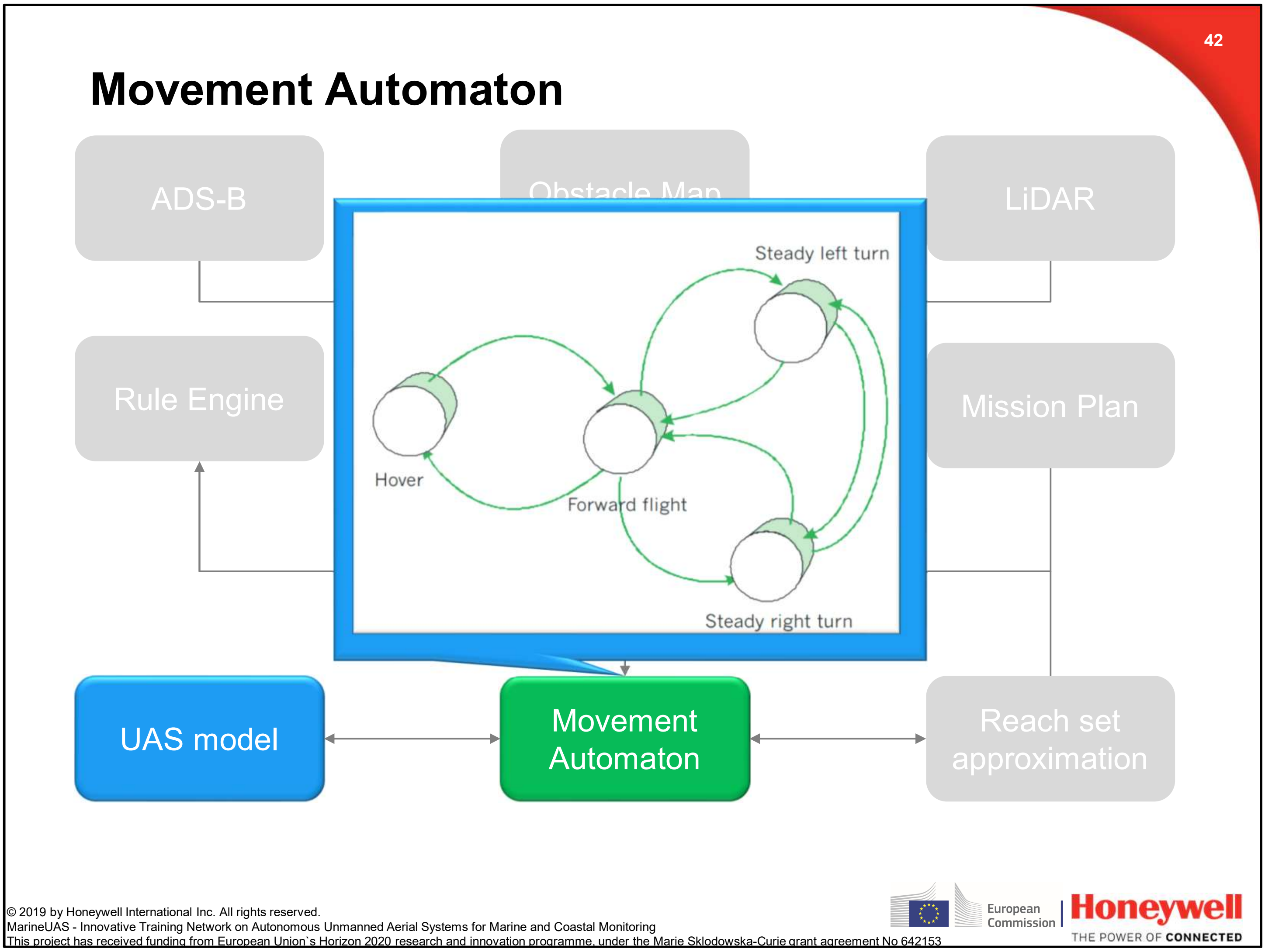
The model is then given by set of equations (6.4).

Note:

The simple model was used to ease reach set estimation experimentation,

The angular velocities are decoupled,

Your Notes:



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,

Note:

The movement automaton is just hybrid automaton with enforced state changes.

Your Notes:

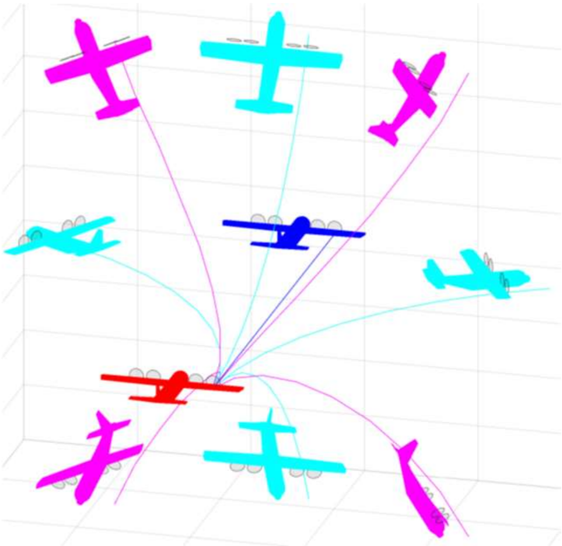
43

Movement Automaton: Movement set (6.2.3)

A ***movement set*** have been implemented containing movements lasting 1s:

$$MovementSet = \left\{ \begin{matrix} Straight, Left, Right, Up, Down, \\ DownLeft, DownRight, UpLeft, UpRight \end{matrix} \right\} \qquad (6.11)$$

The ***movement execution***, with *initial state* represented as a red plane, looks like follow:



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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

Note:

Similar movement set can be achieved for many UAS models,

Movement Automaton: Trajectory (6.2.3)

A ***buffer*** is an *ordered list of movements* to be executed by UAS:

$$Buffer = \left\{ movement(j) : \begin{matrix} movement(j) \in MovementSet(eq.6.11), \\ j \in 1 \dots n, n \in N^+ \end{matrix} \right\} \quad (6.12)$$

The ***trajectory*** for some *initial state(0)* and *buffer* is given as:

$$Trajectory(state(0), Buffer) =$$

$$\left\{ \begin{aligned} state(0) &= state(0), \\ state(1) &= applyMovement\left(state(0), movement(1)\right), \\ state(2) &= applyMovement\left(state(1), movement(2)\right), \\ \vdots &= \vdots \\ state(n-1) &= applyMovement\left(state(n-2), movement(n-1)\right), \\ state(n) &= applyMovement\left(state(n-1), movement(n)\right) \end{aligned} \right\} \quad (6.13)$$

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Speech:

The buffer is created by chaining multiple elementary movements as command chain,

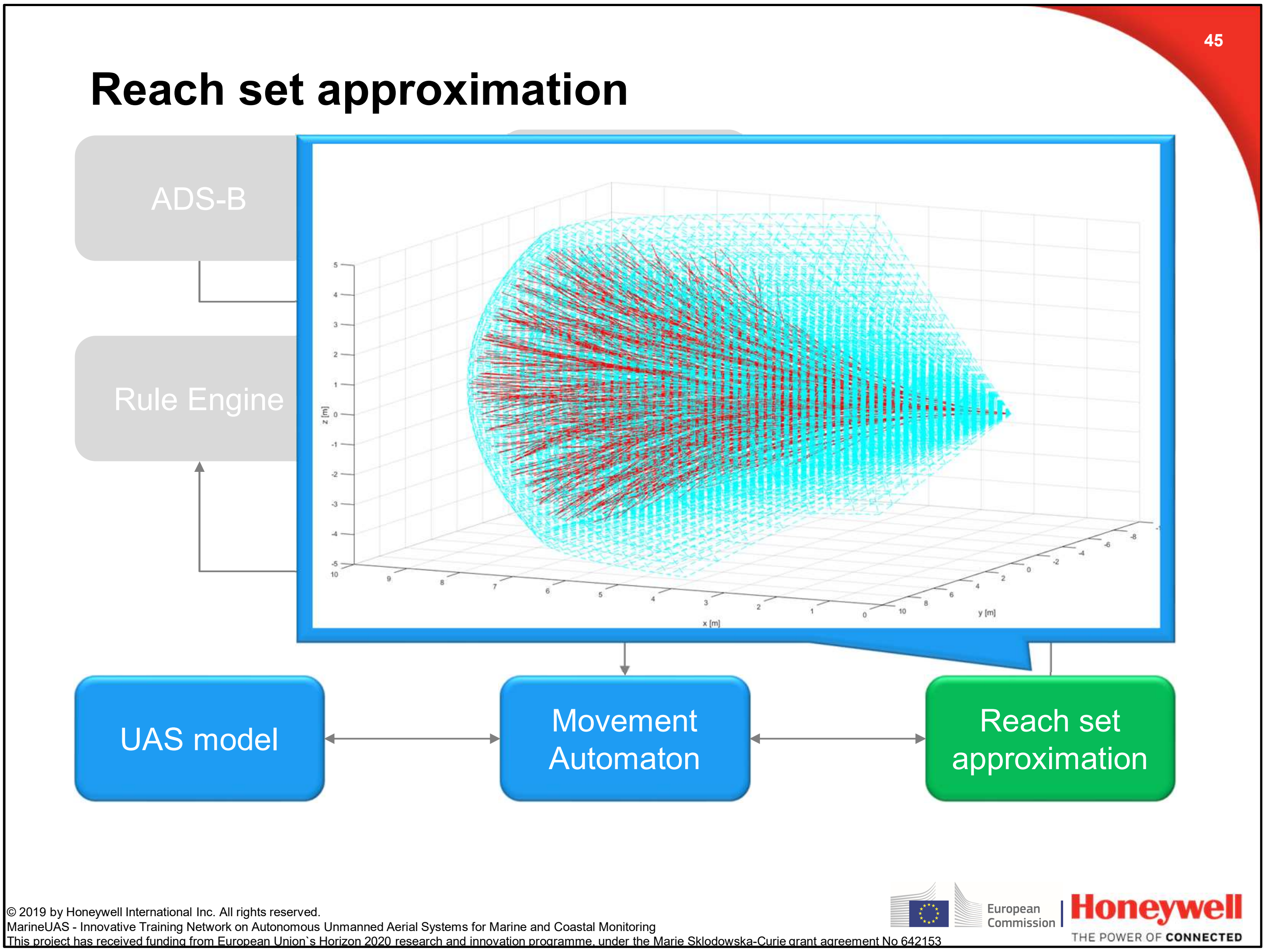
The command chain is stored in Buffer structure (6.12),

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).

Your Notes:



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),

Your Notes:

46

Reach set approximation

Space segmentation – Avoidance Grid (6.3)

An intermediate operational space is segmented into ***avoidance grid***:

$$AvoidanceGrid = \left\{ cell_{i,j,k} : \begin{matrix} i \in 1 \dots layerCount \\ j \in 1 \dots horizontalCount \\ k \in 1 \dots verticalCount \end{matrix} \right\} \quad (6.20)$$

$$\forall cell_{i,j,k}, cell_{m,n,o} : cell_{i,j,k} \cap cell_{m,n,o} = \varnothing, i \neq o \vee j \neq n \vee k \neq o \quad (6.21)$$

One ***cell space portion*** is bounded by:

$$cell.spacePortion = \dots$$
$$\left\{ \begin{matrix} point \in \mathbb{R}^3 \text{ where :} \\ \begin{pmatrix} cell.distance_{start} < & point.distance \leq & cell.distance_{end}, \\ cell.horizontal^{\circ}_{start} < & point.horizontal^{\circ} \leq & cell.horizontal^{\circ}_{end}, \\ cell.vertical^{\circ}_{start} < & point.vertical^{\circ} \leq & cell.vertical^{\circ}_{end} \end{pmatrix} \end{matrix} \right\} \quad (6.15)$$

Refer to (def. 11,12)

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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)

Note:

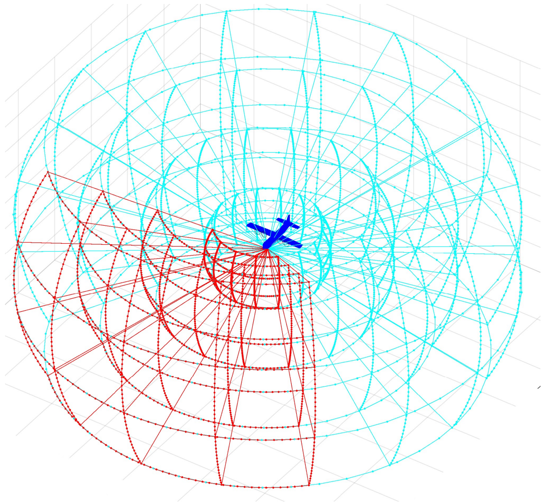
The space bounded by cells is exclusive (6.21).

Your Notes:

47

Reach set approximation
The RSA definition

In segmented discrete operational space represented as *avoidance grid*:



The ***reach set approximation*** is a *set of trajectories* with common origin:

$$ReachSet(\tau, time_0, state_0) = \left\{ Trajectory(state_0, buffer) : \begin{array}{c} \text{duration}(buffer) \\ \leq \\ (time_0 - \tau) \end{array} \right\} \quad (6.23)$$

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Speech:

The avoidance grid example is denoted by red line, the blue plane is in the center.

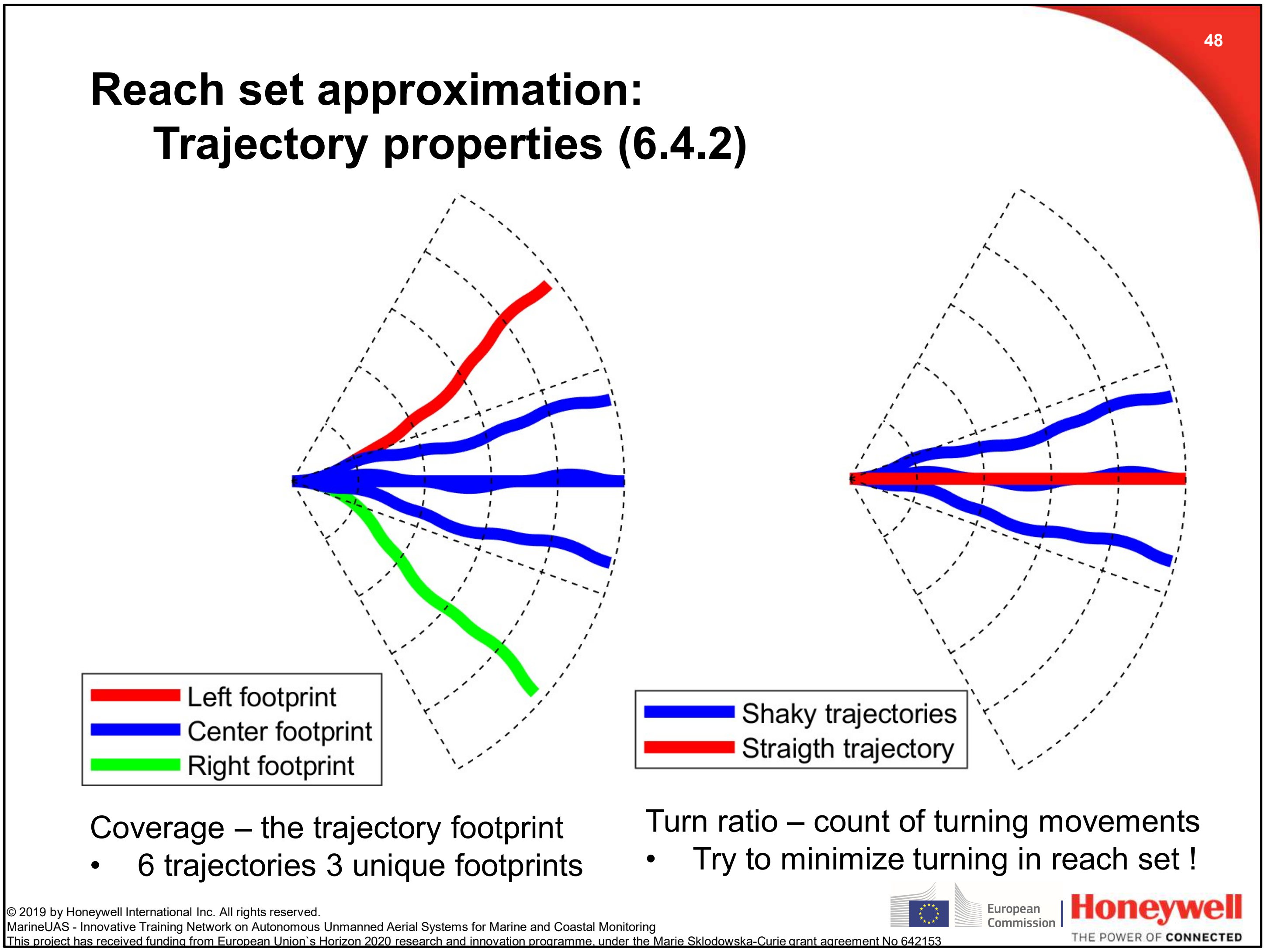
Then the Reach set approximation is given as a set of trajectories originating in “initial state” with limited duration (6.23),

The trajectory is given as a execution of movement chain - “buffer” applied on initial state,

Note:

Refer to section (6.4.1) for detailed explanation.

Your Notes:



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,

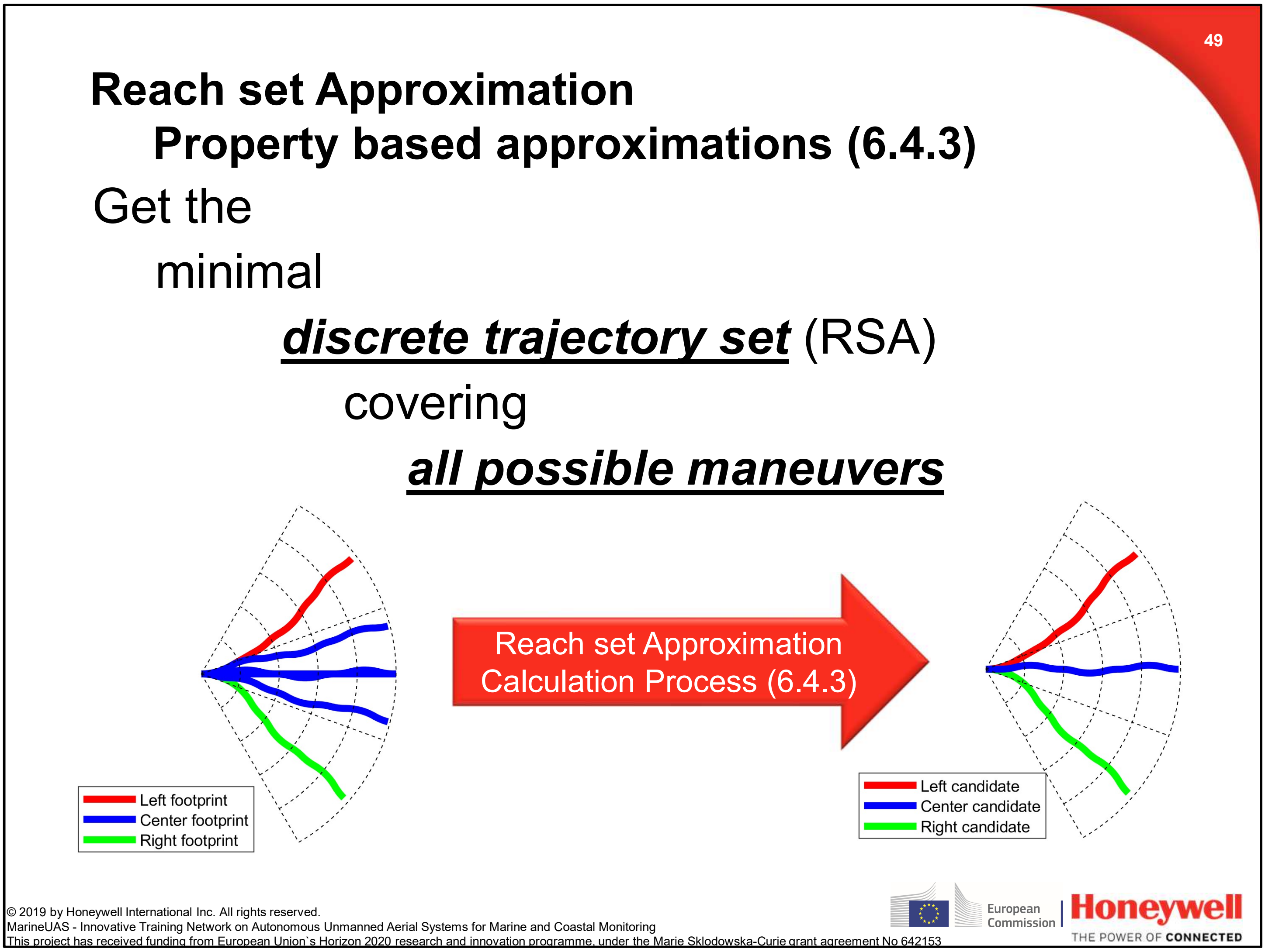
In the left figure you can see six trajectories going over avoidance grid,

There are only three unique footprints,

That means we need only 3 of those trajectories,

The right figure shows four trajectories with same footprint

Your Notes:



Speech:

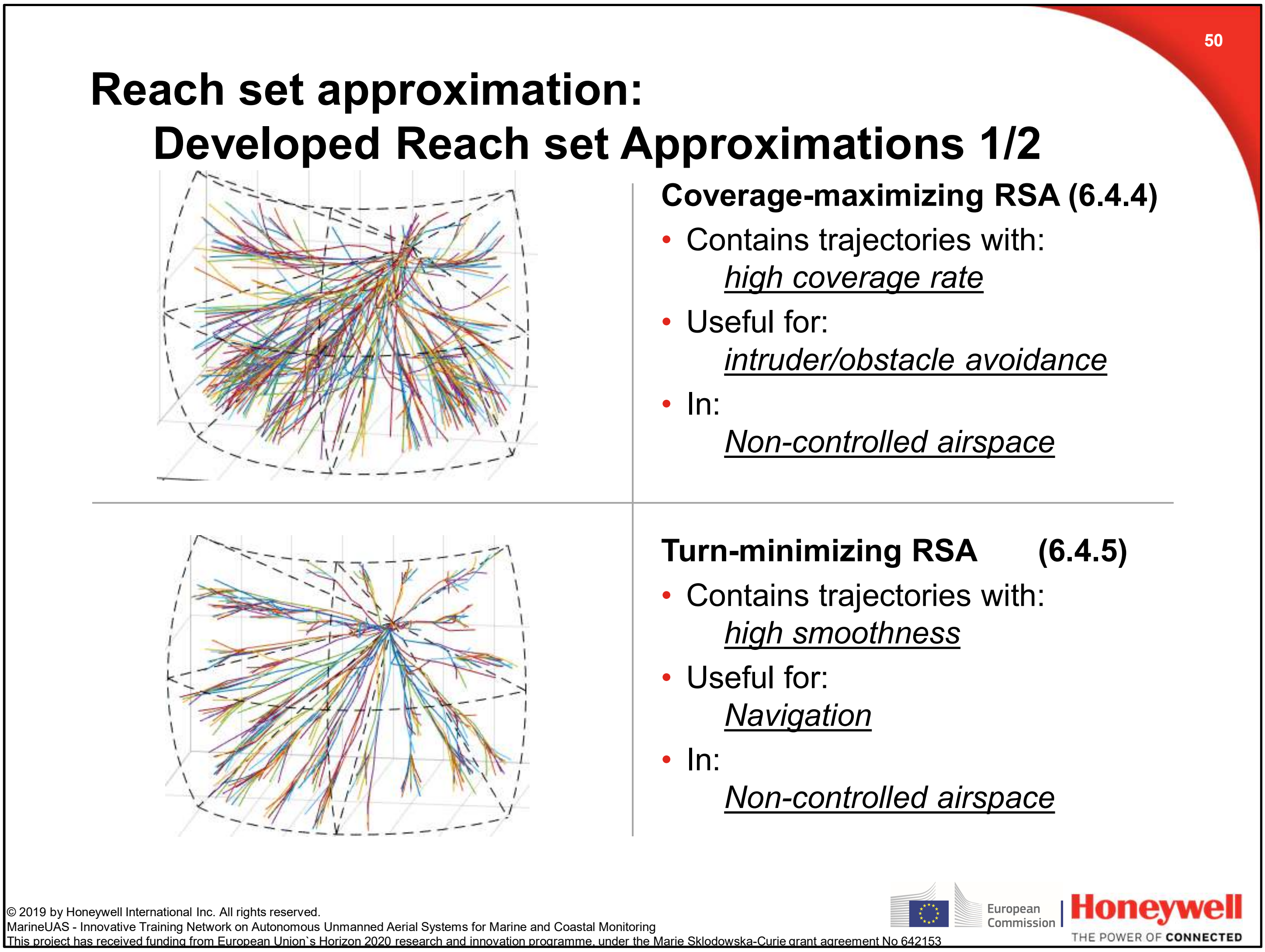
The trajectory properties are considered when the candidate trajectory for Reach set approximation is selected,

In the figure you can see selection process based on coverage property,

Note:

You can track any property of the trajectory in relation to operational space or airspace, as you will see later,

Your Notes:



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,

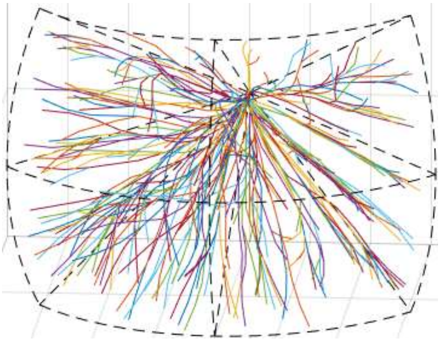
B. Used for navigation, increases behavior predictability,

C. Used in non-controlled airspace

Your Notes:

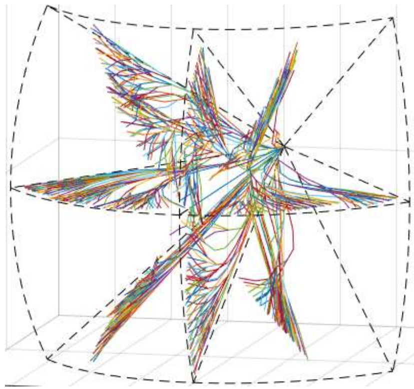
51

Reach set approximation: Developed Reach set Approximations 2/2



Combined RSA (6.4.7)

- Contains trajectories with:
  TM + CM RSA combination
- Useful for:
  avoidance/navigation
- In:
  Controlled airspace in case of Emergency



ACAS-like RSA (6.4.6)

- Contains trajectories with:
  ACAS behavior
- Useful for:
  Navigation/UTM Resolutions
- In:
  Controlled airspace

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Speech:

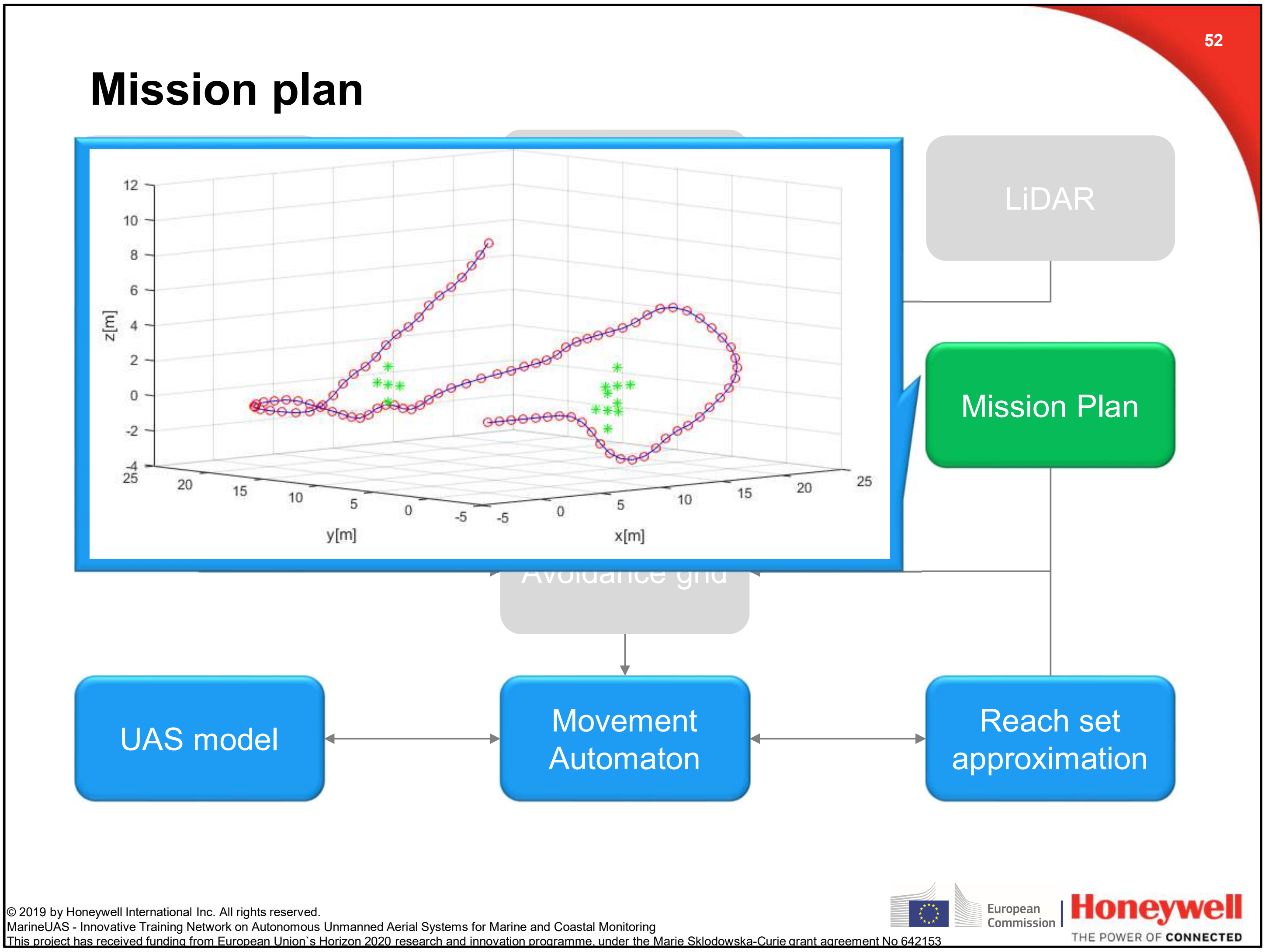
The idea behind combined RSA (6.4.7) is to have properties of both turn minimizing and coverage maximizing RSA.

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.

Note:

All reach sets are for 3D space

ACAS operational mode can be constrained.



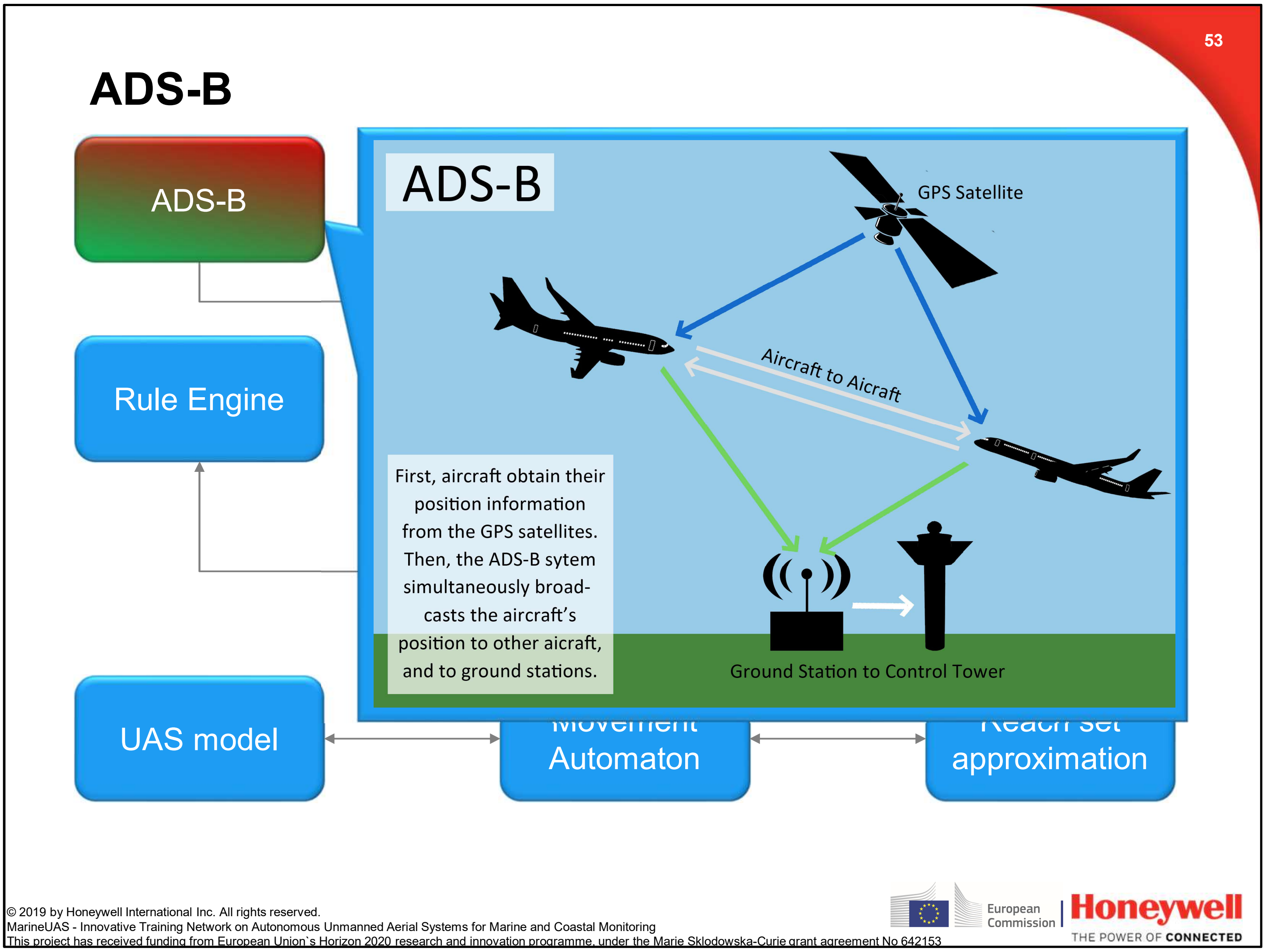
Speech:

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

Your Notes:



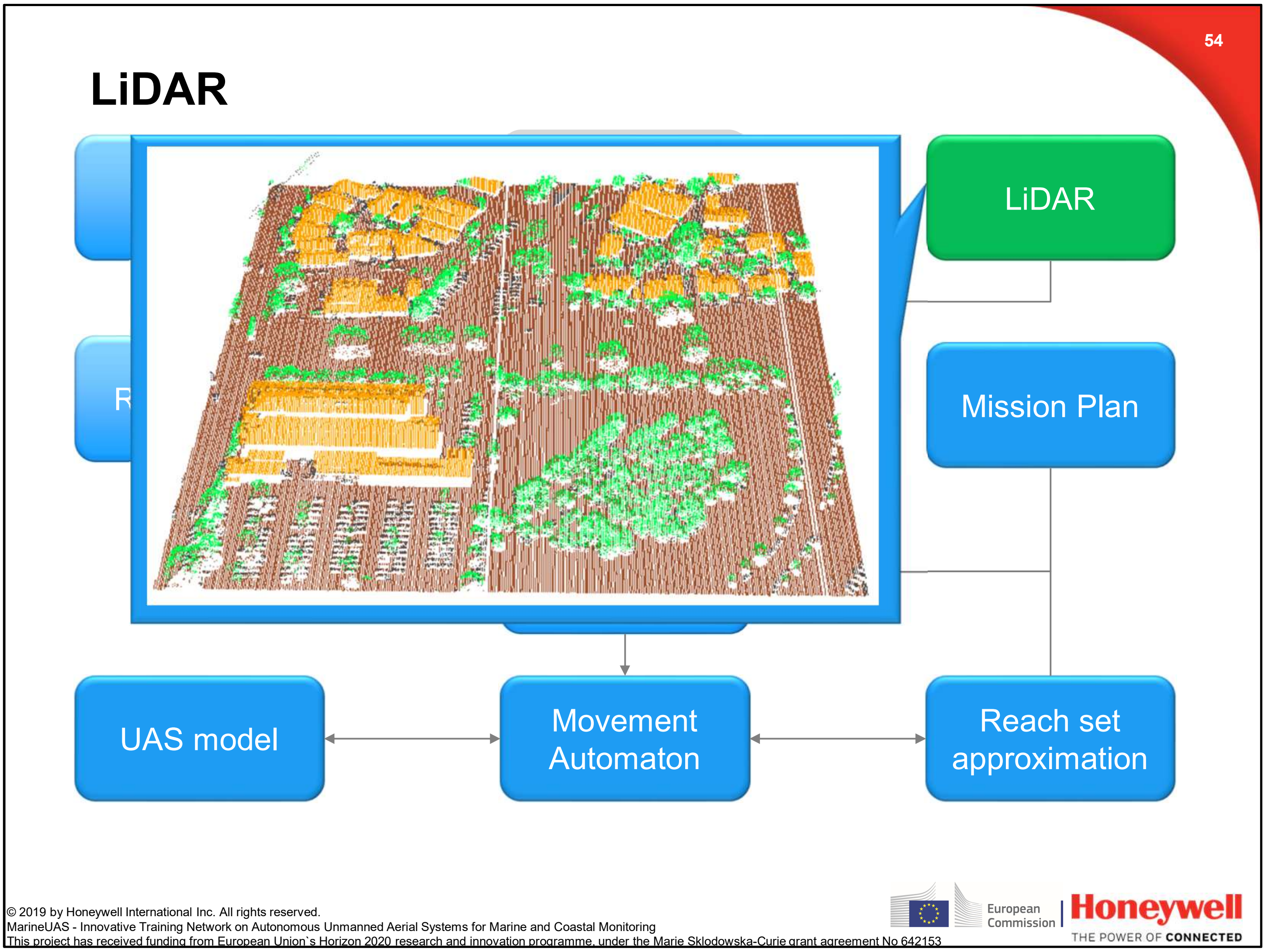
Speech:

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,

Your Notes:



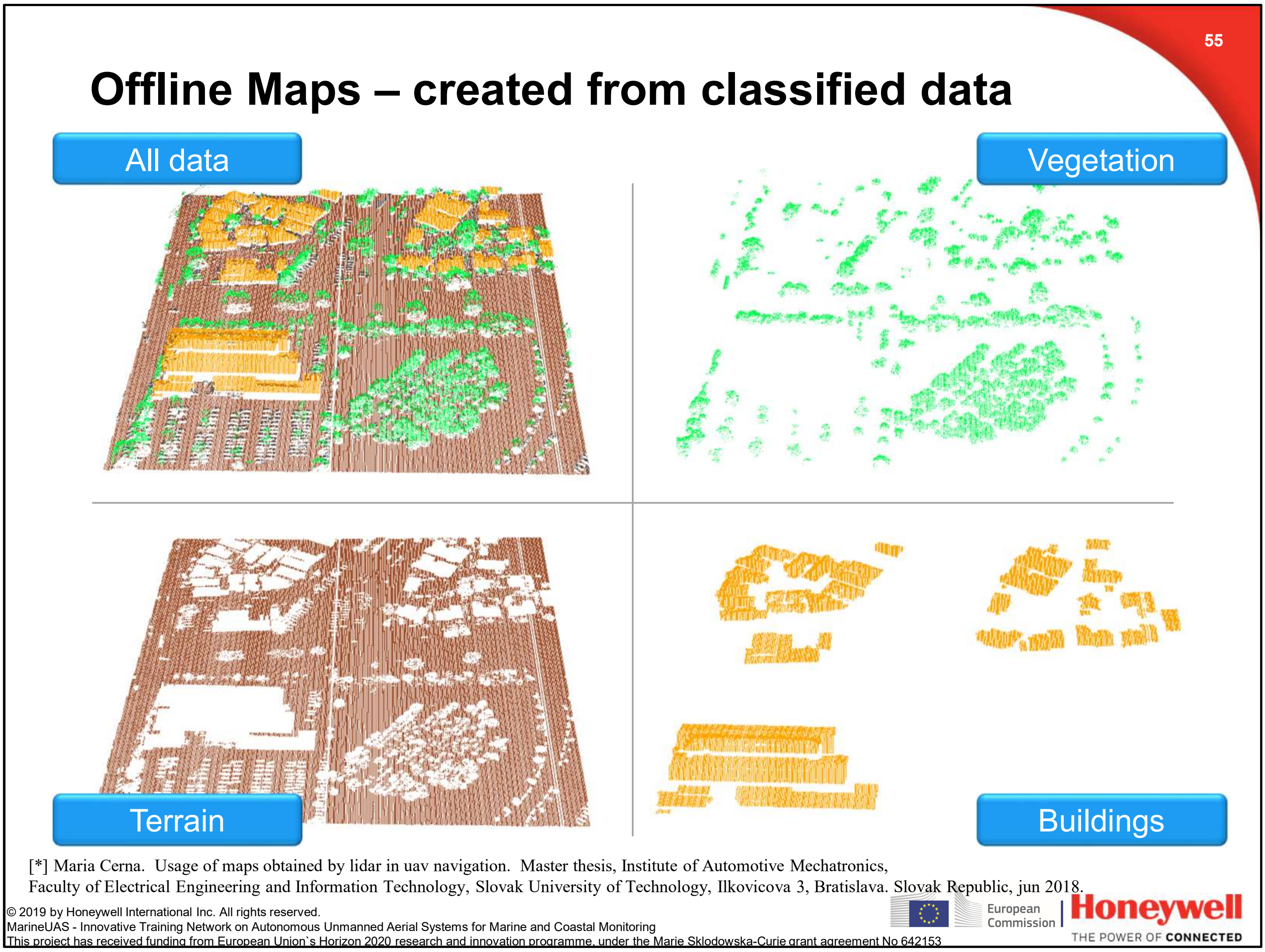
Speech:

LiDAR is a sensor of choice for static obstacles,

In the example data you can see a small farm,

Note:

Moving object filtering is neglected



Speech:

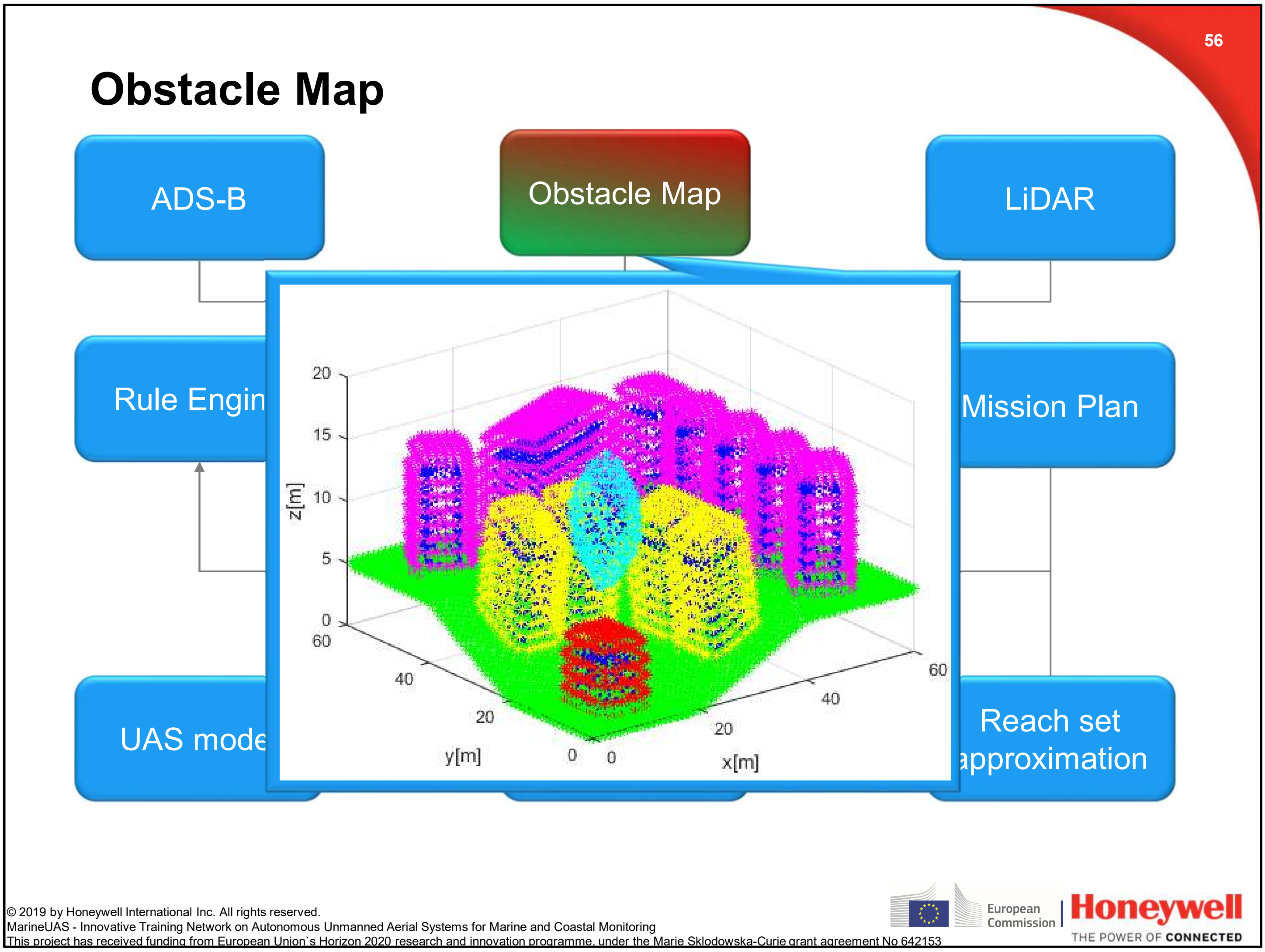
LiDAR classification algorithms can be used for the,

“Offline maps” creation,

In the example you can see farm data (NW) classification,

For vegetation (NE), Terrain (SW), Buildings (SE),

Your Notes:



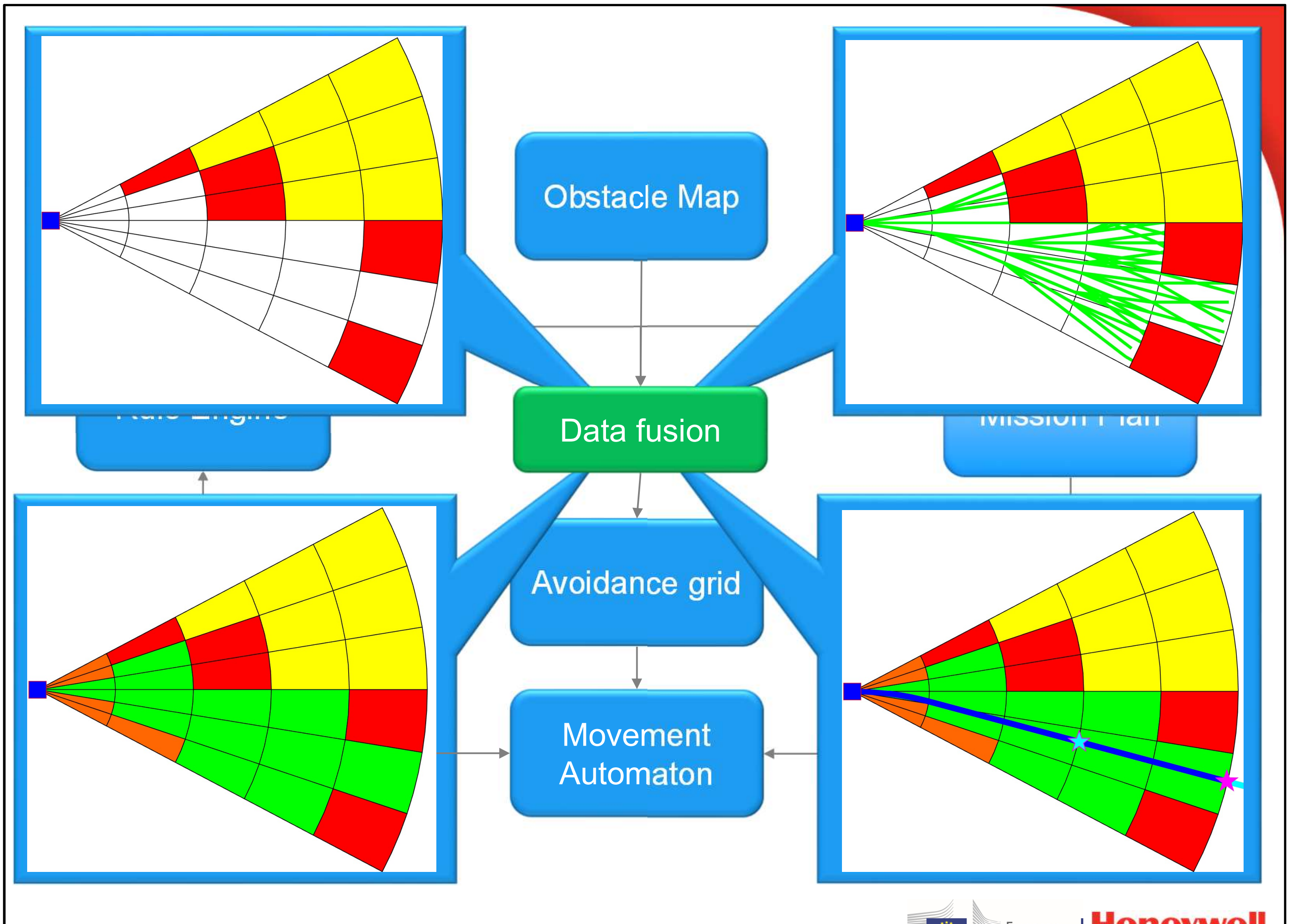
Speech:

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

Note:

Here is example of cuboid coatings (dark blue) with virtual convex coating (magenta, cyan, yellow, red)

Your Notes:



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Speech:

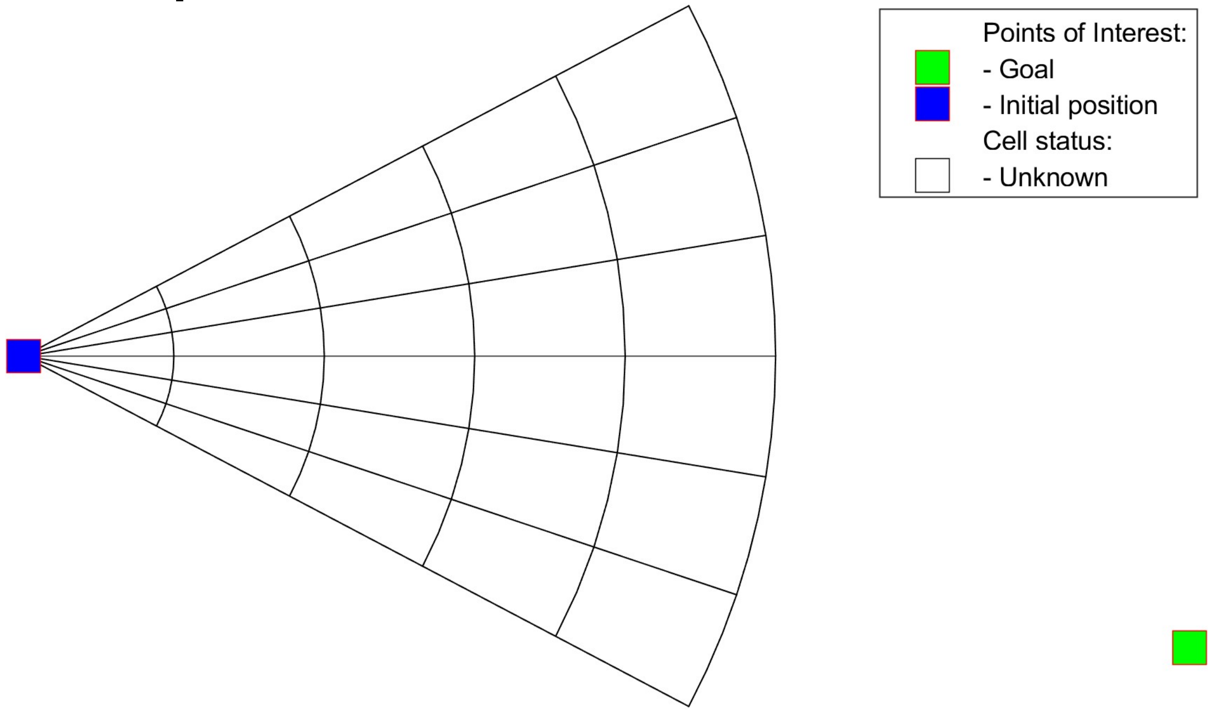
Now we have all the ingredients for Data fusion and Avoidance Run

The Avoidance Run is situation evaluation for one specific decision time point,

Your Notes:

58

Avoidance run (6.5.1)
Step 1/7 Initialization



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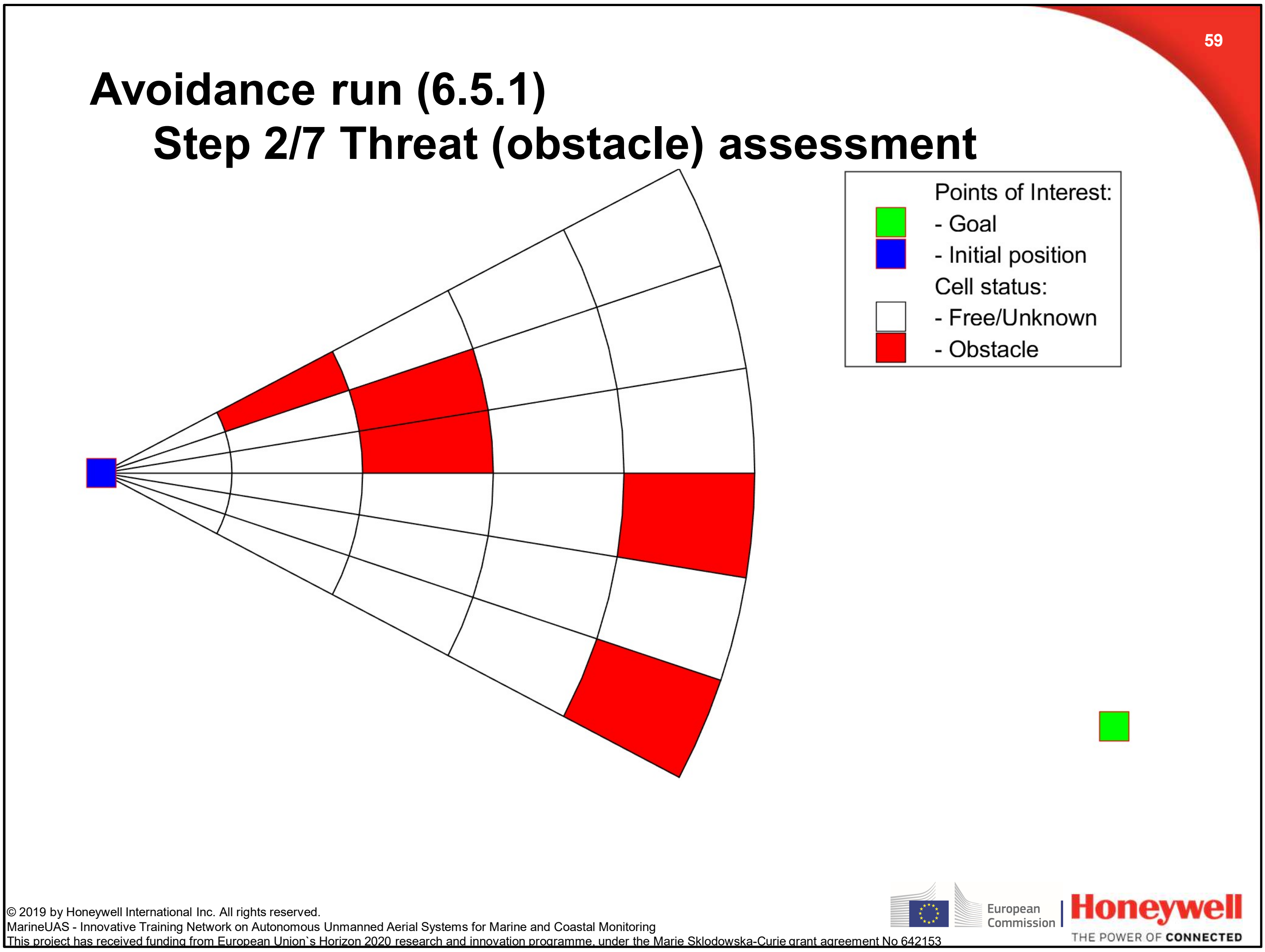
Speech:

First we start with empty avoidance grid,

The goal is green square,

The UAS position is blue square,

Your Notes:



Speech:

The “Data fusion” provides threat rating (obstacle rating) each cell in avoidance grid

Red cells are occupied,

Note:

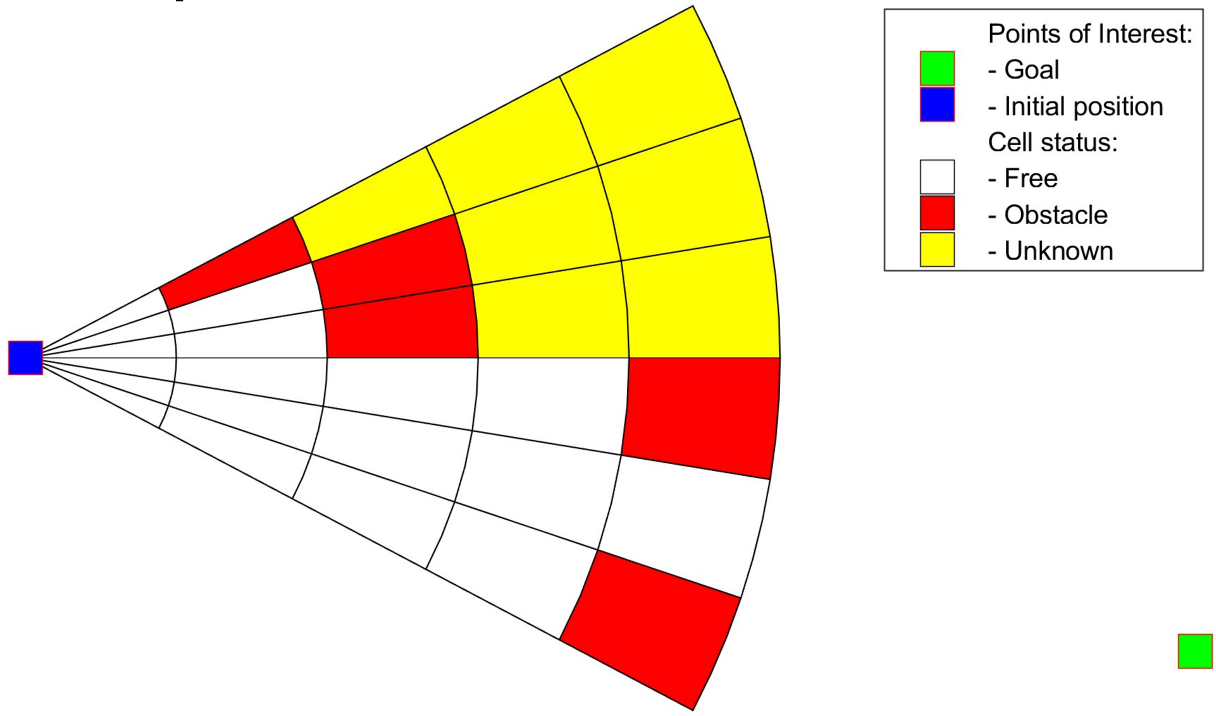
Red cells belongs to occupied space

Red cells can belong alsto to restricted space

Your Notes:

60

Avoidance run (6.5.1)
Step 3/7 Unknown state of the cells



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Speech:

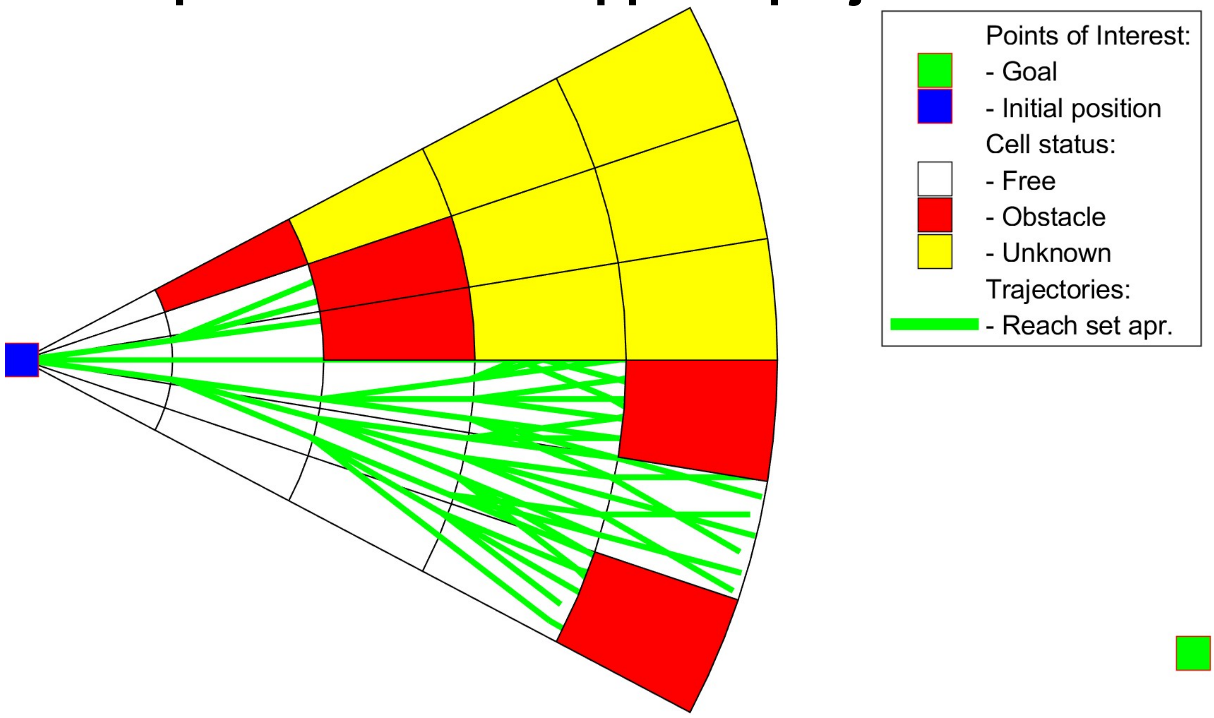
Then we evaluate the unknown as yellow cells,

Note:

The unknow portion of operation space belongs to Uncertain set,

61

Avoidance run (6.5.1)
Step 4/7 Reach set approx. projection



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Speech:

Then then we project reach set approximation into avoidance grid,

The result is trimmed reach set with only safe green trajectories,

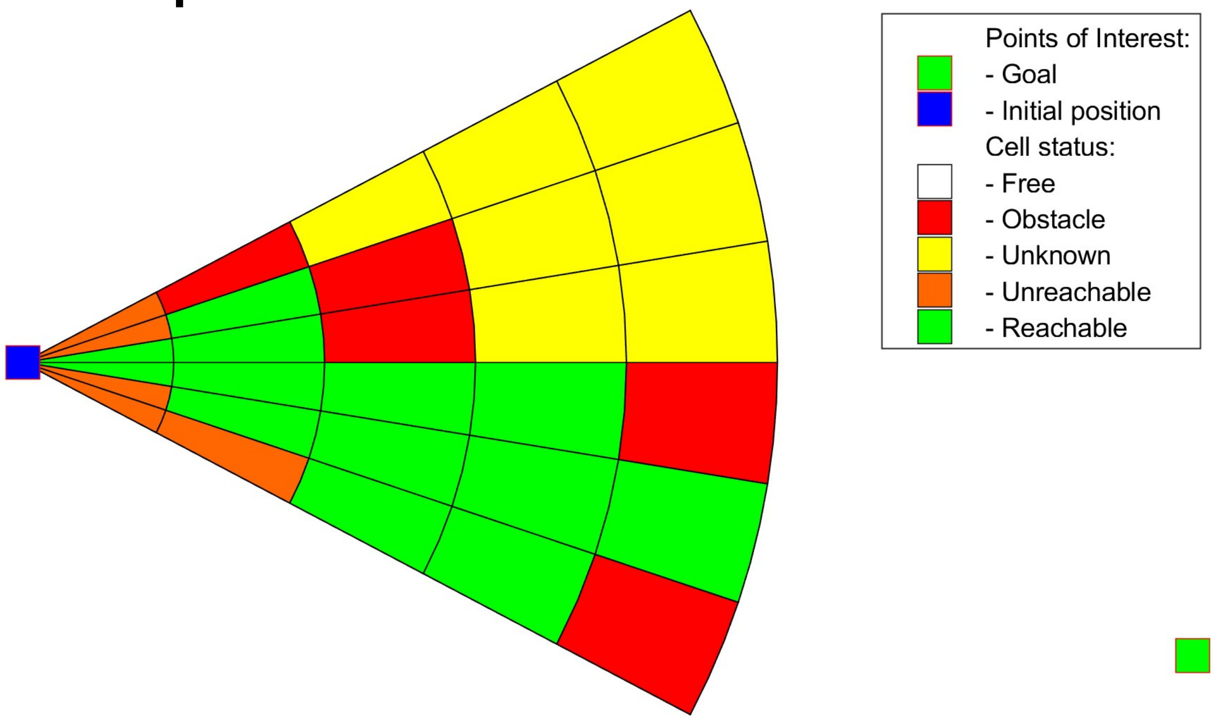
Note:

The safe trajectory is a trajectory going over Free space (white)

Your Notes:

62

Avoidance run (6.5.1)
Step 6/7 Reachable/Unreachable



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Speech:

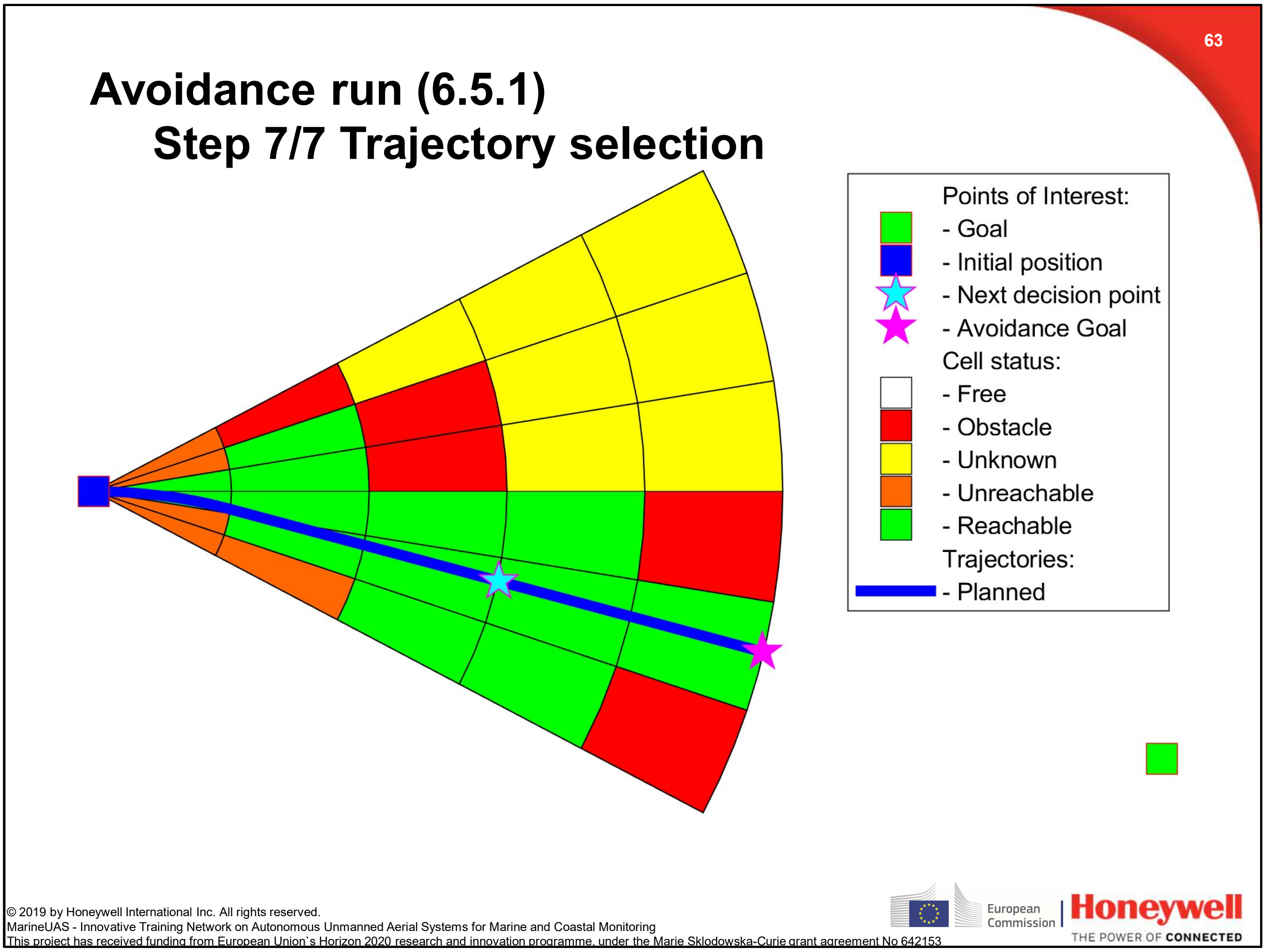
The green cells which are penetrated by at least one safe trajectory are considered reachable,

The orange unreachable cells do not have any.

Note:

Reachable + Unreachable = Free operational space

Your Notes:



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,

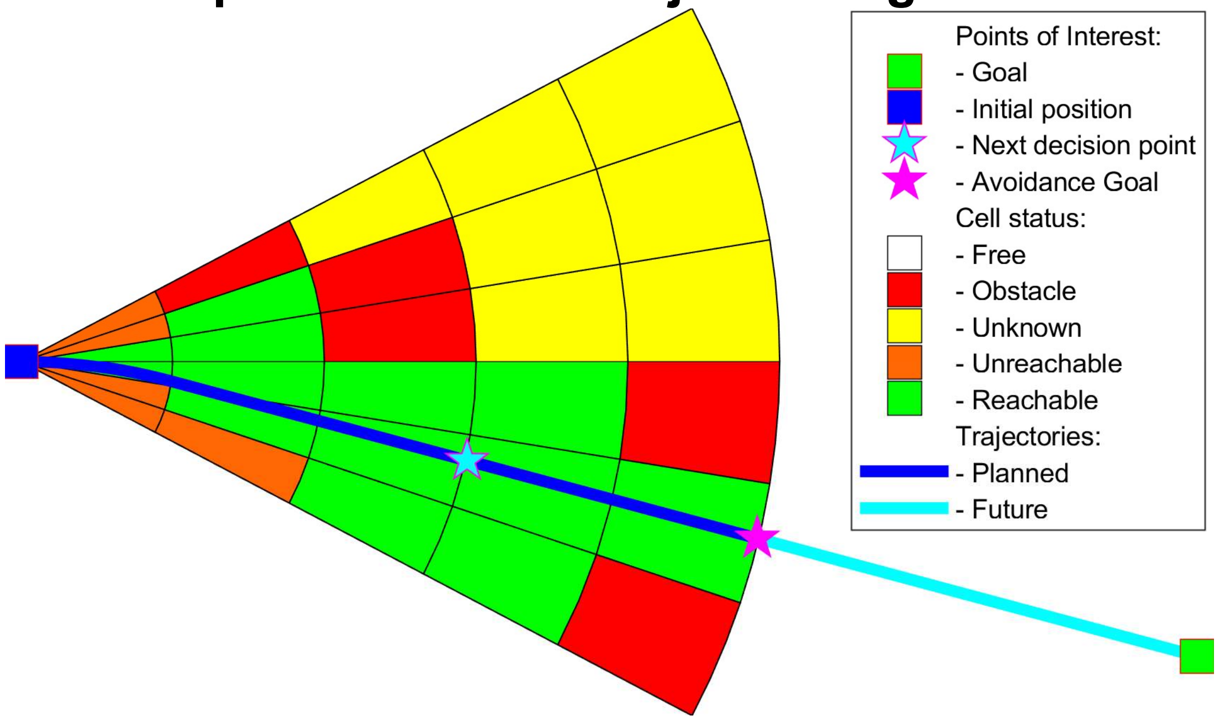
We fire up Avoidance Run again there

Note:

The path is selected according to the cost function and safety rules

Your Notes:

Mission control run (6.5.2)
Multiple avoidance run joined together



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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,

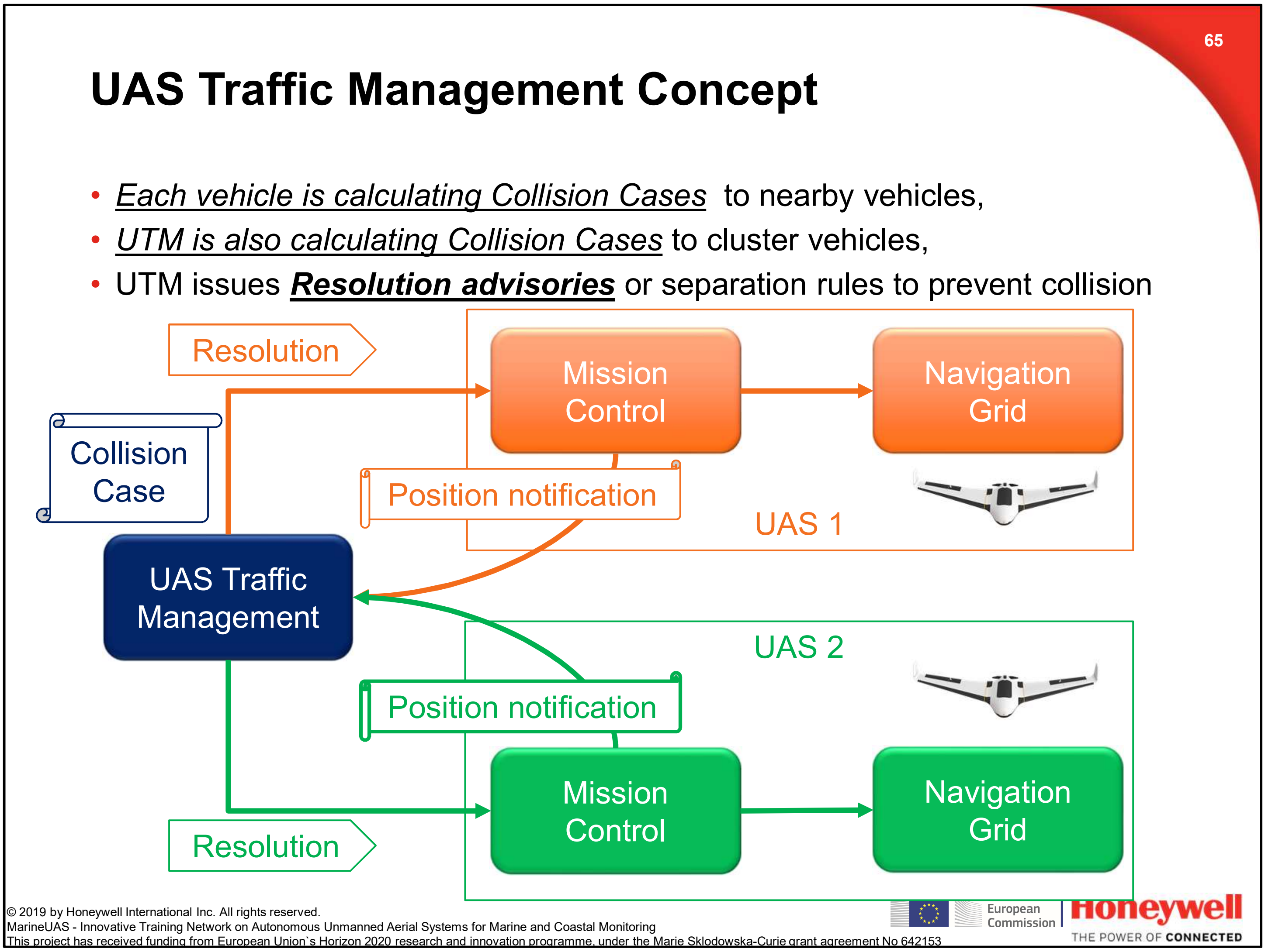
The cyan trajectory is planned from next decision point,

Note:

Mission control run is far more complex with magnitude of rules and other mechanisms,

It has been neglected in this presentation for simplicity purpose,

Your Notes:



Speech:

That was all for framework,

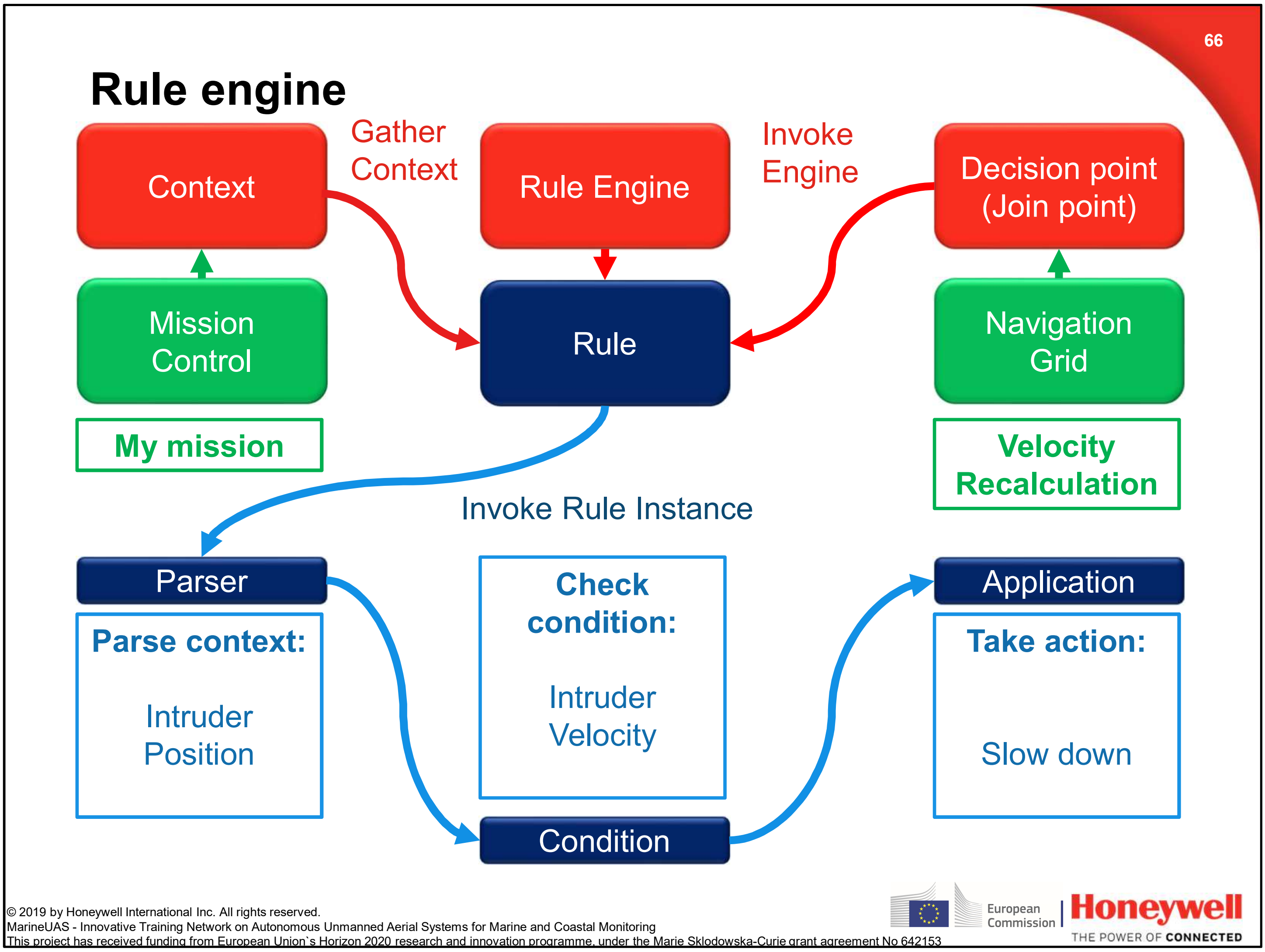
We need to make multiple instances to cooperates, for UAS to be airworthy,

This schematic shows a concept of centralized UTM,

UTM is receiving position updates from aircrafts,

If UTM detects collision its sends “Collision Resolutions”,

Your Notes:



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,

Your Notes:

67

Simulations:

Test plan

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Speech:

That's all for the framework,

Now lets get to the testing scenarios

Your Notes:

68

Test plan (7.1)

Test Case Name	*Operational Environment*	*Air Traffic Attendants*	*Weather*	*UTM*	*Navigation*	*Scenario*
Building Avoidance	Non-controlled (Rural) $4 \times buildings$	-	-	-	Open space	Fly mission around four buildings
Slalom	Non-controlled (Rural) $14 \times buildings$	-	-	-	Hidden waypoint	Navigate to hidden waypoint
Maze	Non-controlled (Urban) $30 \times buildings$	-	-	-	Maze structure	Solve maze with multiple curves
Storm	Non-controlled (Rural) $0 \times buildings$	-	Storm	-	Open Space	Avoid approaching storm
Emergency Converging	Non-controlled (Open air)	Non-cooperative UAS (1x)	-	-	Open Space	Converging situation resolution w. o. UTM
Emergency Head on	Non-controlled (Open air)	Non-cooperative UAS (1x)	-	-	Open Space	Head on situation resolution w. o. UTM
Emergency Multiple	Non-controlled (Open air)	Non-cooperative UAS (3x)	-	-	Open Space	Multi-collision case resolution w. o. UTM
Rule-based Converging	Controlled (Open air)	Cooperative UAS(1x)	-	Full	Follow Rules	Converging situation resolution with UTM
Rule-based Head on	Controlled (Open air)	Cooperative UAS(1x)	-	Full	Follow Rules	Head on situation resolution with UTM
Rule-based Multiple	Controlled (Open air)	Cooperative UAS(3x)	-	Full	Follow Rules	Multi-collision case resolution with UTM
Rule-based Overtake	Controlled (Open air)	Cooperative UAS (1x)	-	Full	Follow Rules	Overtake by UAS different speed ratio

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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,

Your Notes:

69

Simulations

Maze Solver

Storm Avoidance

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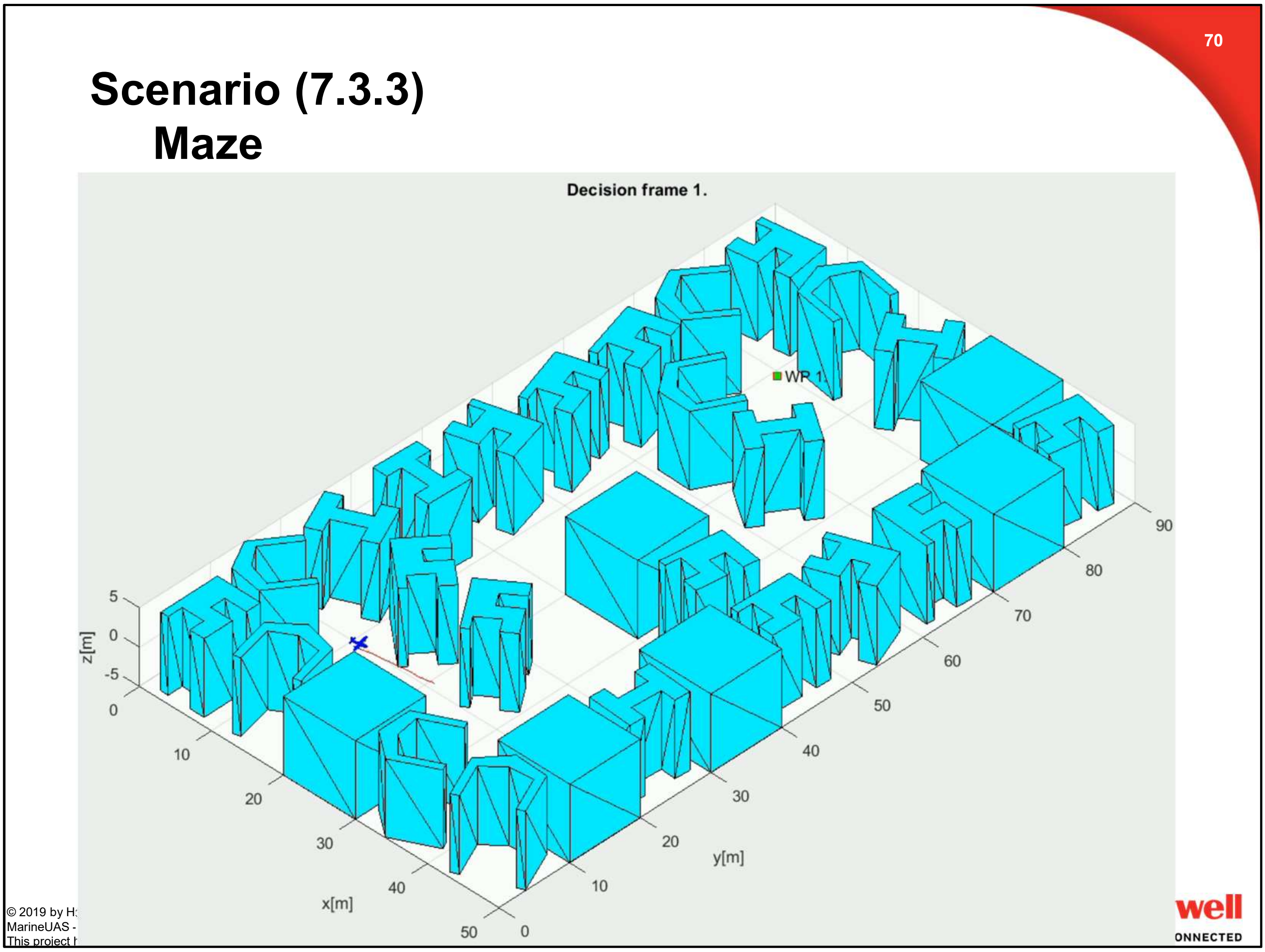
Speech:

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

Your Notes:



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

Note:

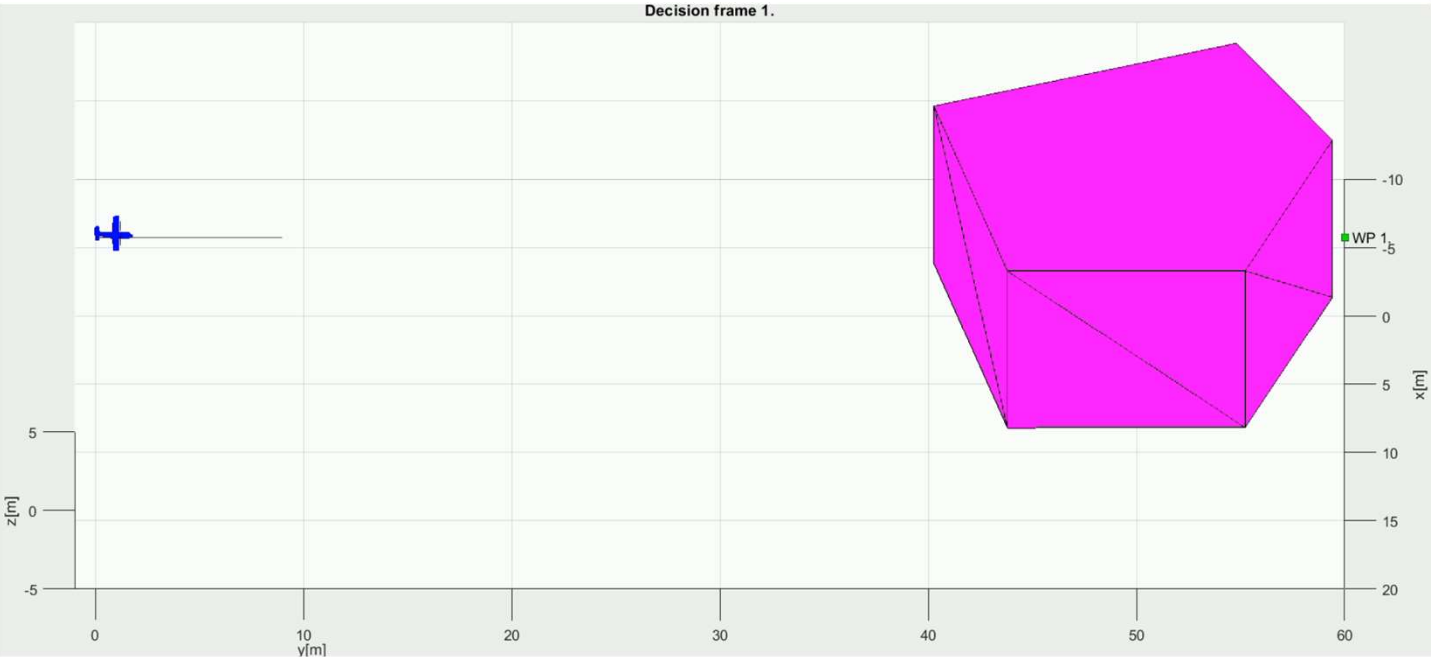
The UAS is capable to fly over buildings, The framework and reach sets are primarily 3D

The UAS is fed only over Sensor simulation, it does not know the mission plan or obstacle layout

Your Notes:

71

Scenario (7.3.4): Storm



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Speech:

The blue plane is approaching magenta storm,

The storm is considered as moving constraint

The plane avoids storm

Your Notes:

Rules of the Air Simulations:

Converging Maneuver

Head On Approach

Overtake

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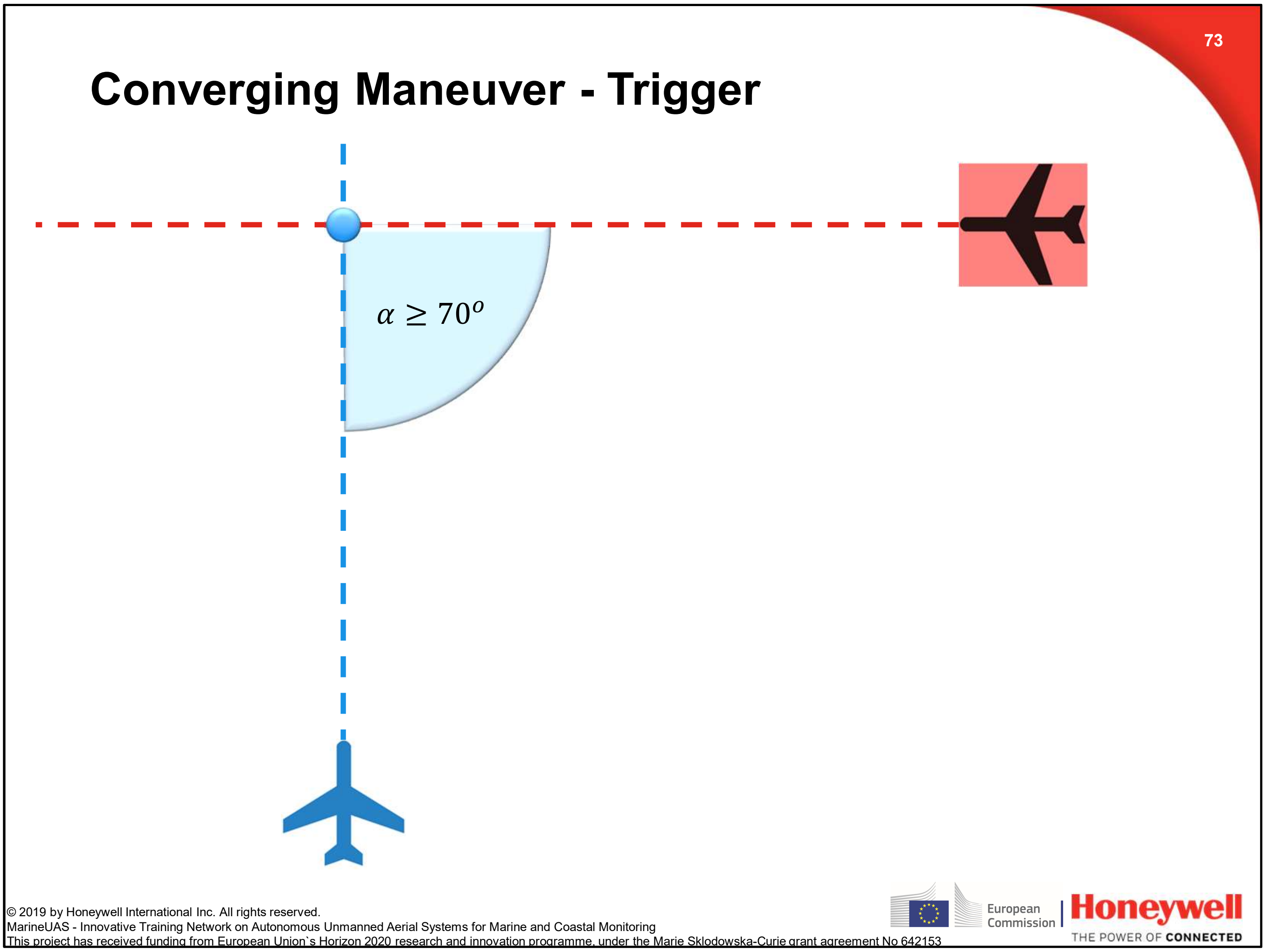
Speech:

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"

Note:

Class C, A, airspaces, B are airports, they have more complex and intricate rules,

Your Notes:



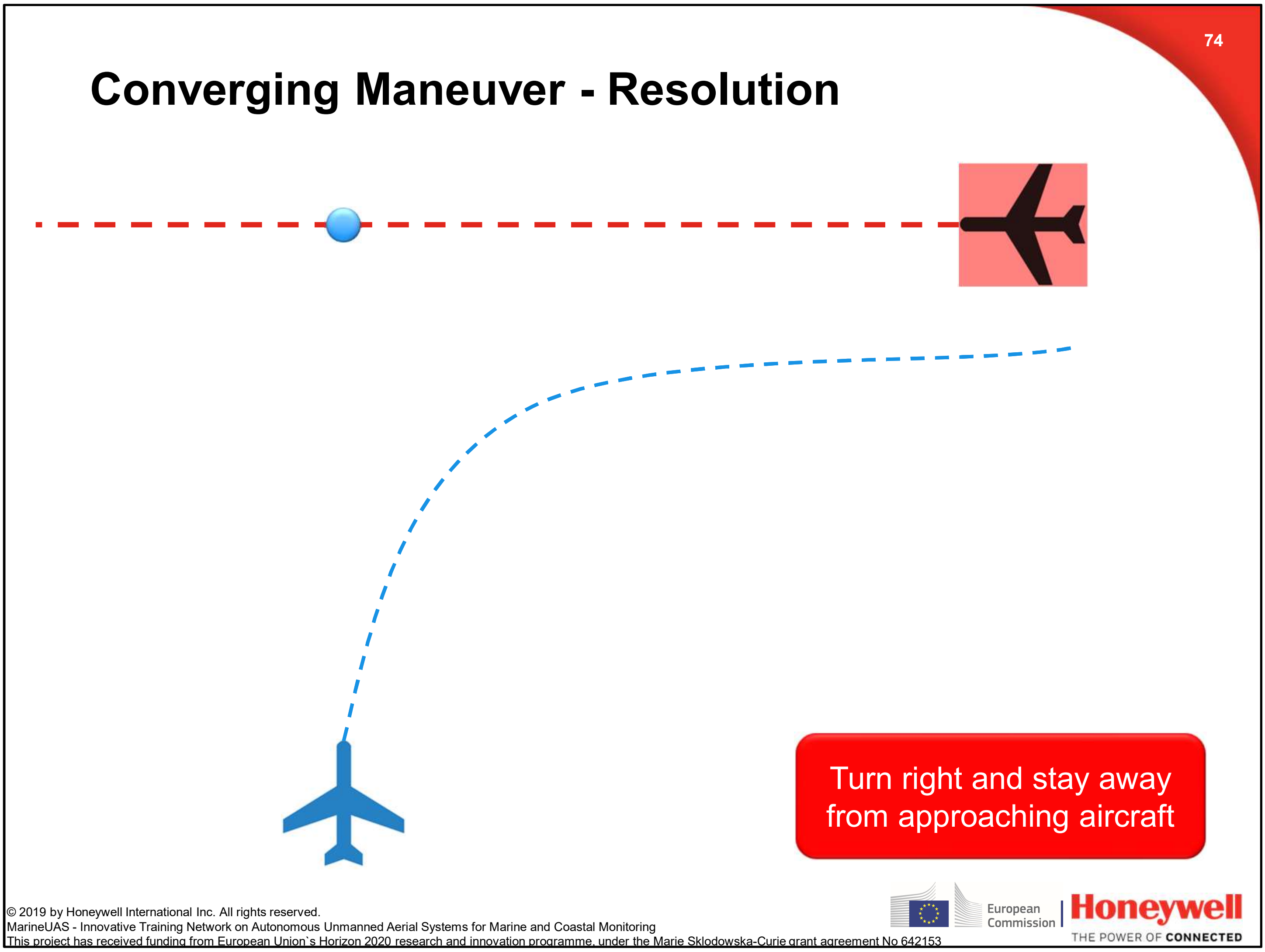
Speech:

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,

Your Notes:

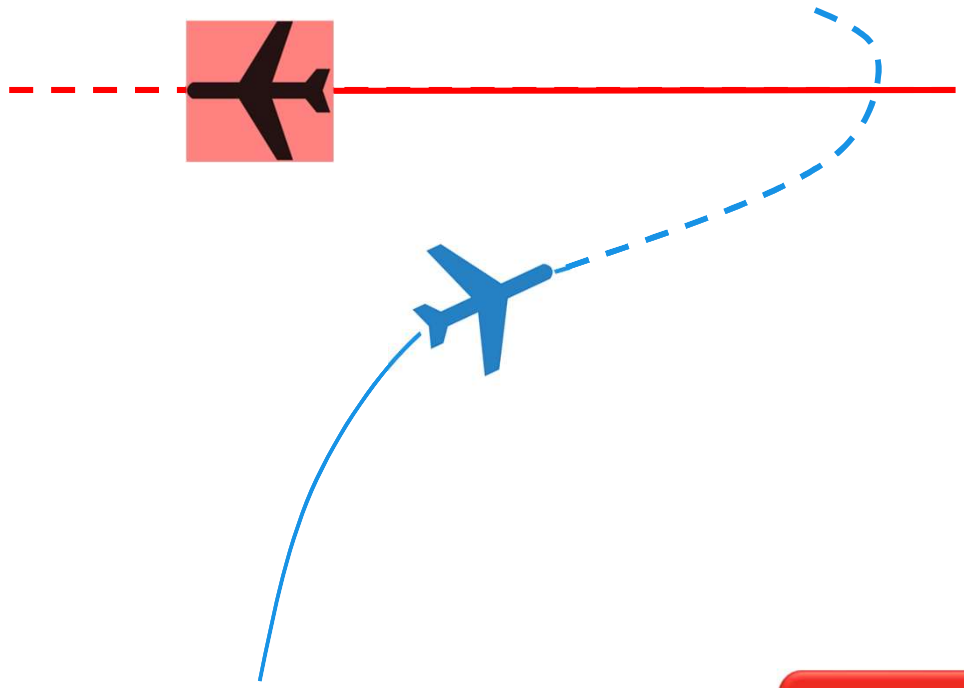


Speech:

The blue plane start avoidance keeping safe distance

Your Notes:

Converging Maneuver – Leave condition



Return to original path behind other aircraft

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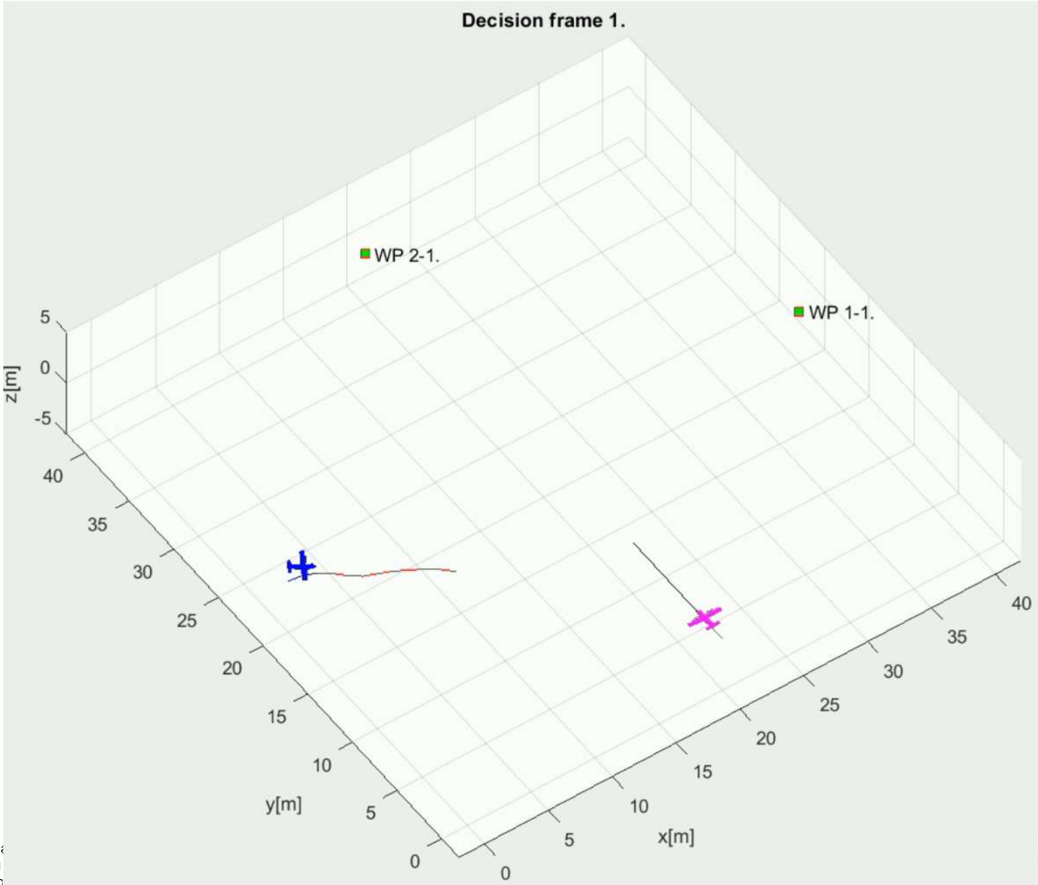
Speech:

The blue plane avoids wake turbulence and returns to original path

Scenario (7.4.1): Rule-based converging



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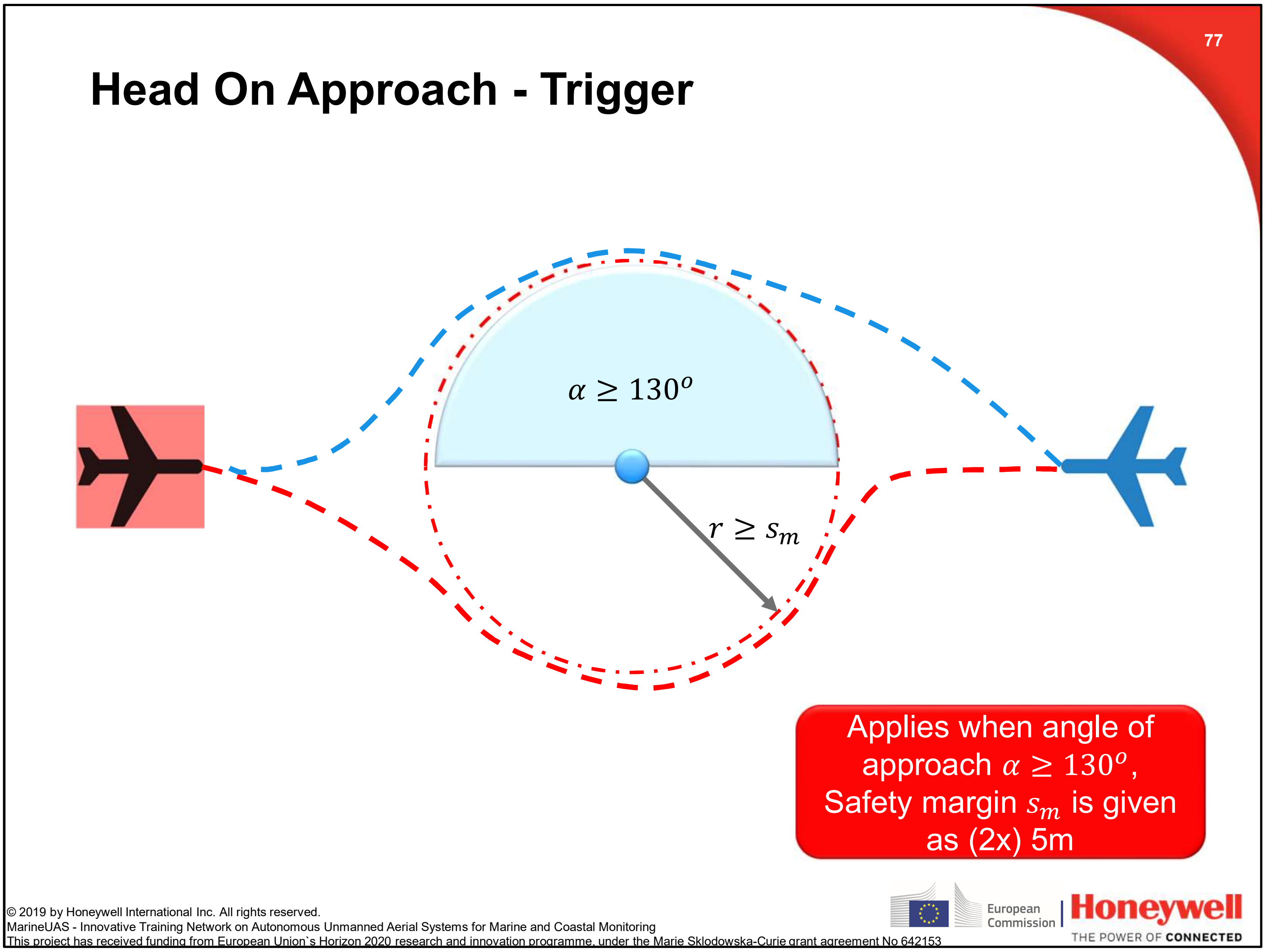
Speech:

Blue plane avoids magenta plane, which has "right of the way"

The rule engine has been deployed to tweak process,

Your Notes:



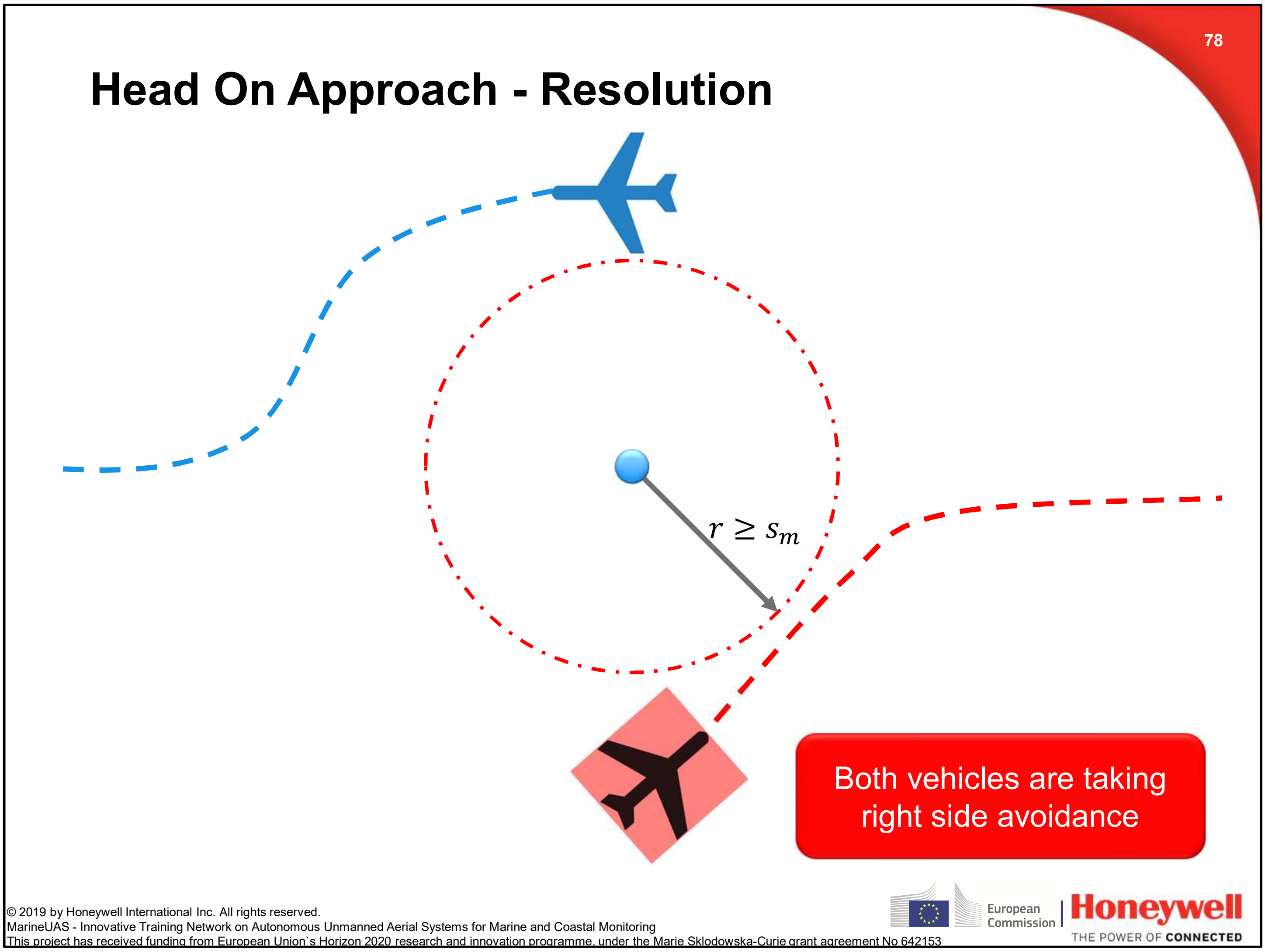
Speech:

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

Your Notes:



Speech:

Both planes keep safe distance from expected collision point to avoid wake and side turbulences

The maneuver ends when virtual roundabout is used

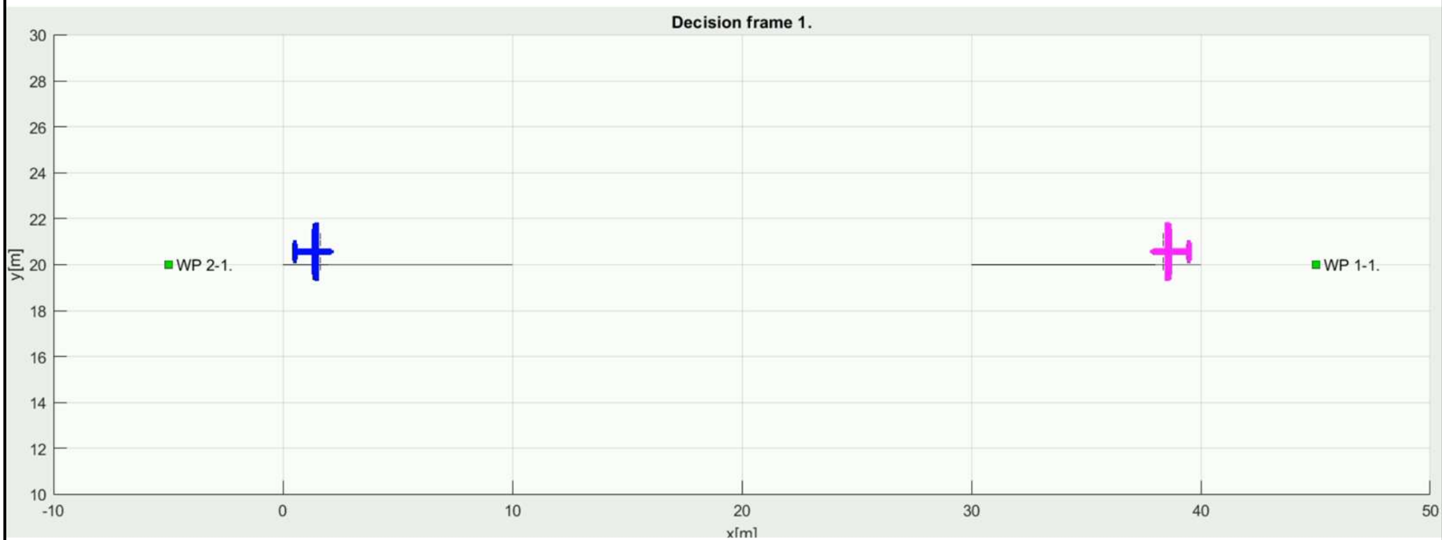
Note:

Every rule can fail, then its “Every man for himself” situation solved by “upper right corner” avoidance.

Your Notes:

79

Scenario (7.4.2): Rule-based head-on



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Speech:

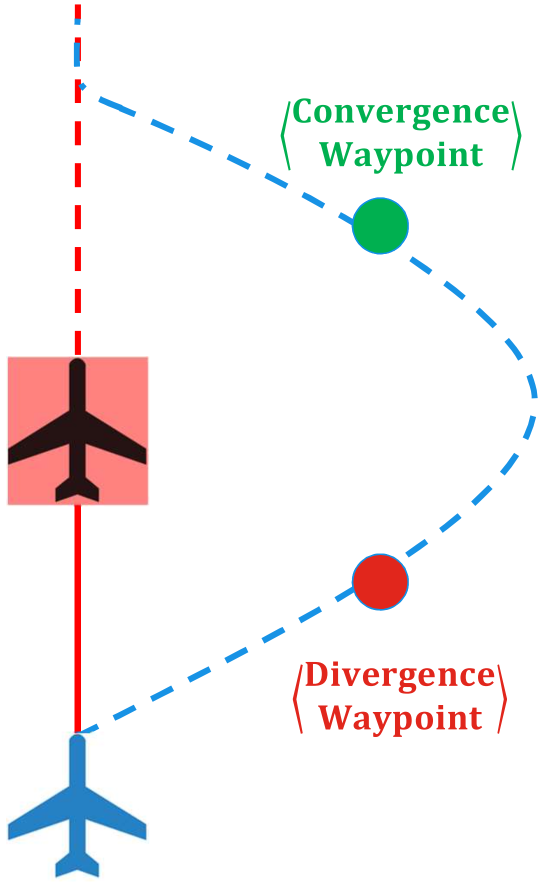
The collision point is used as a center of virtual roundabout

Both planes start to converge to original waypoint when the collision point is passed,

Your Notes:

80

Overtake Maneuver - Trigger



The aircraft being overtaken has the right of the way

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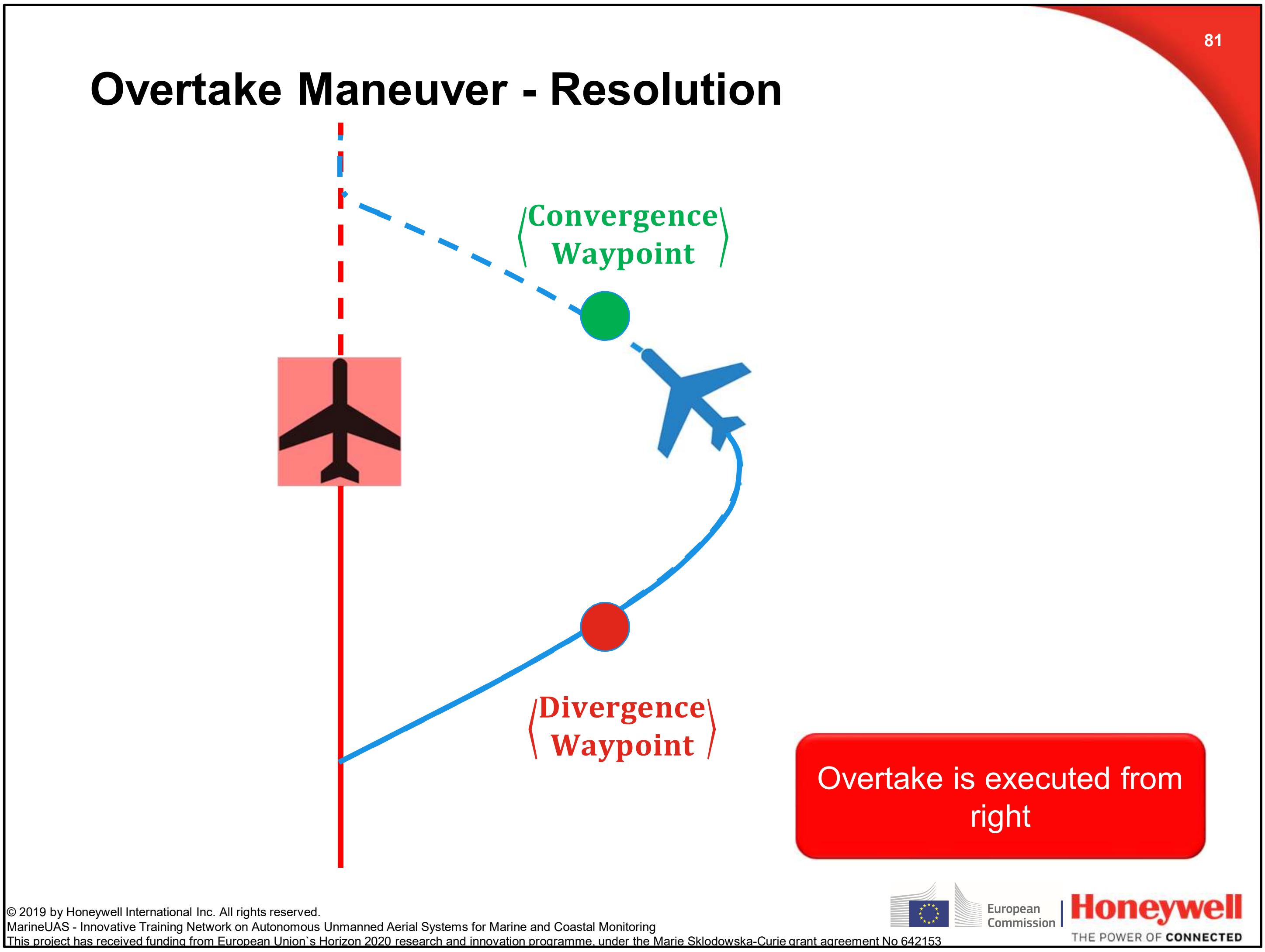
Speech:

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

Your Notes:



Speech:

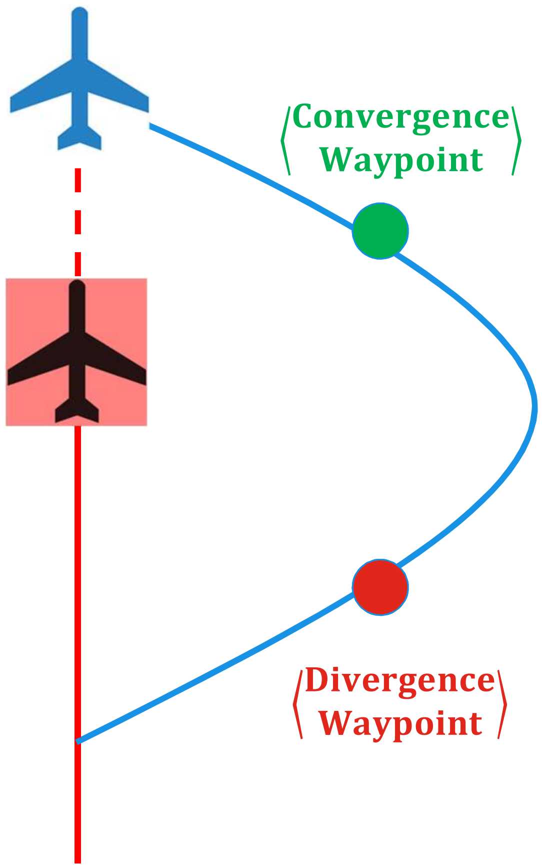
It's going like this,

During overtake both planes should keep constant speed

Your Notes:

82

Overtake Maneuver – Leave Condition



Overtake rule may apply only when well clear condition is guaranteed

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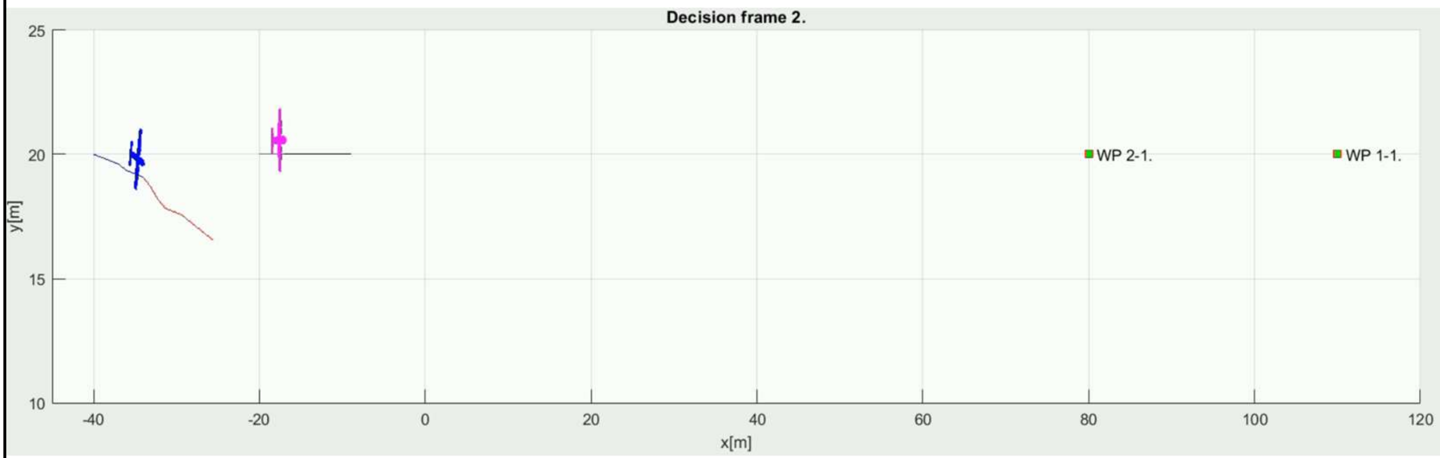
Speech:

Then it finishes like this

Your Notes:

83

Scenario (7.4.4):
Rule-based overtake



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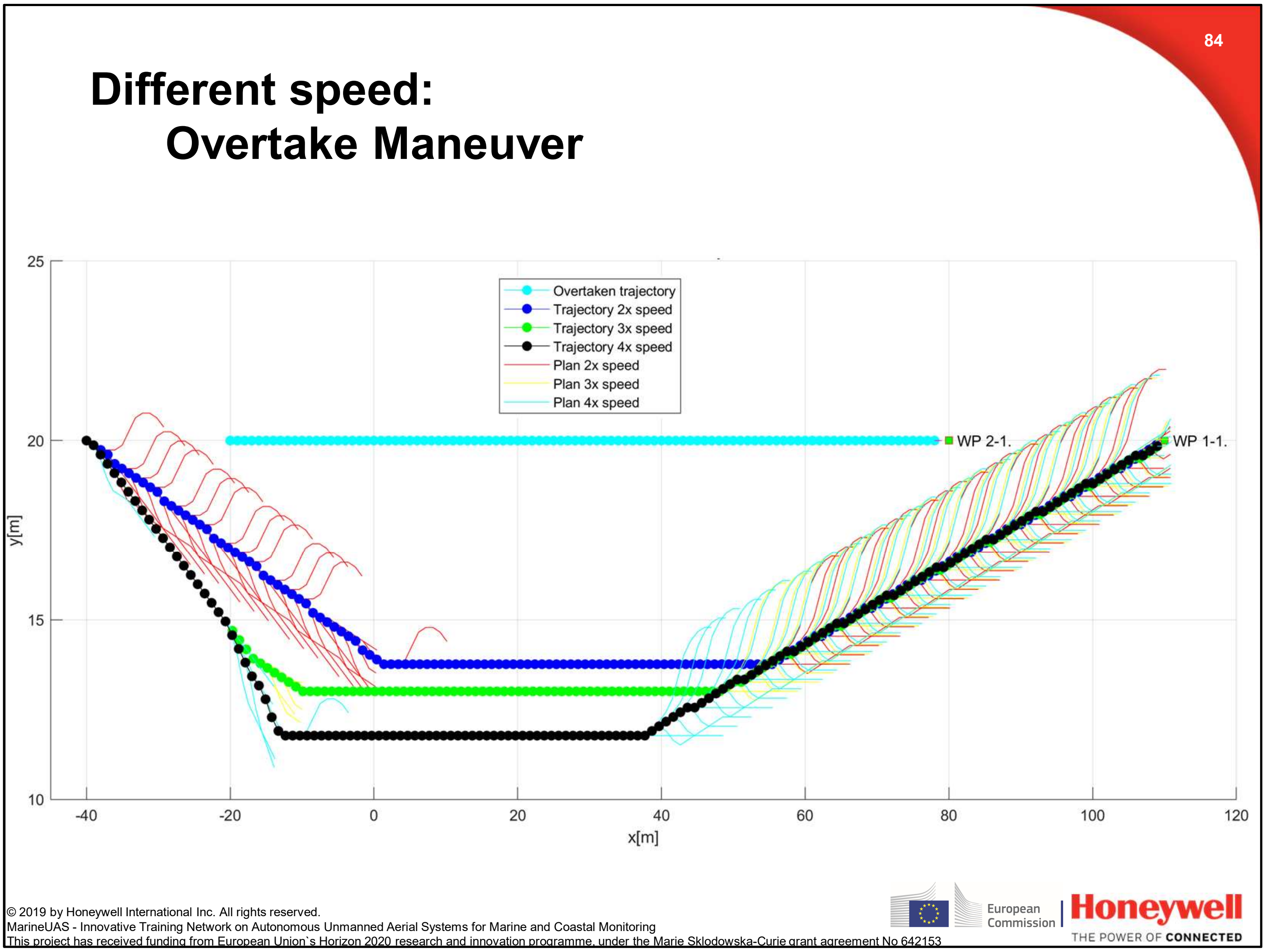
Speech:

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

Your Notes:



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

Note:

The speed difference changes the shape of overtake trajectory,

The turn angle and shape is getting more sharp

Blue trajectory shows overtake with 2x speed difference

Green trajectory shows overtake with 3x speed difference

Black trajectory shows overtake with 4x speed difference.

Simulations:

Cooperative vs. Noncooperative

Multi-Collision Situations

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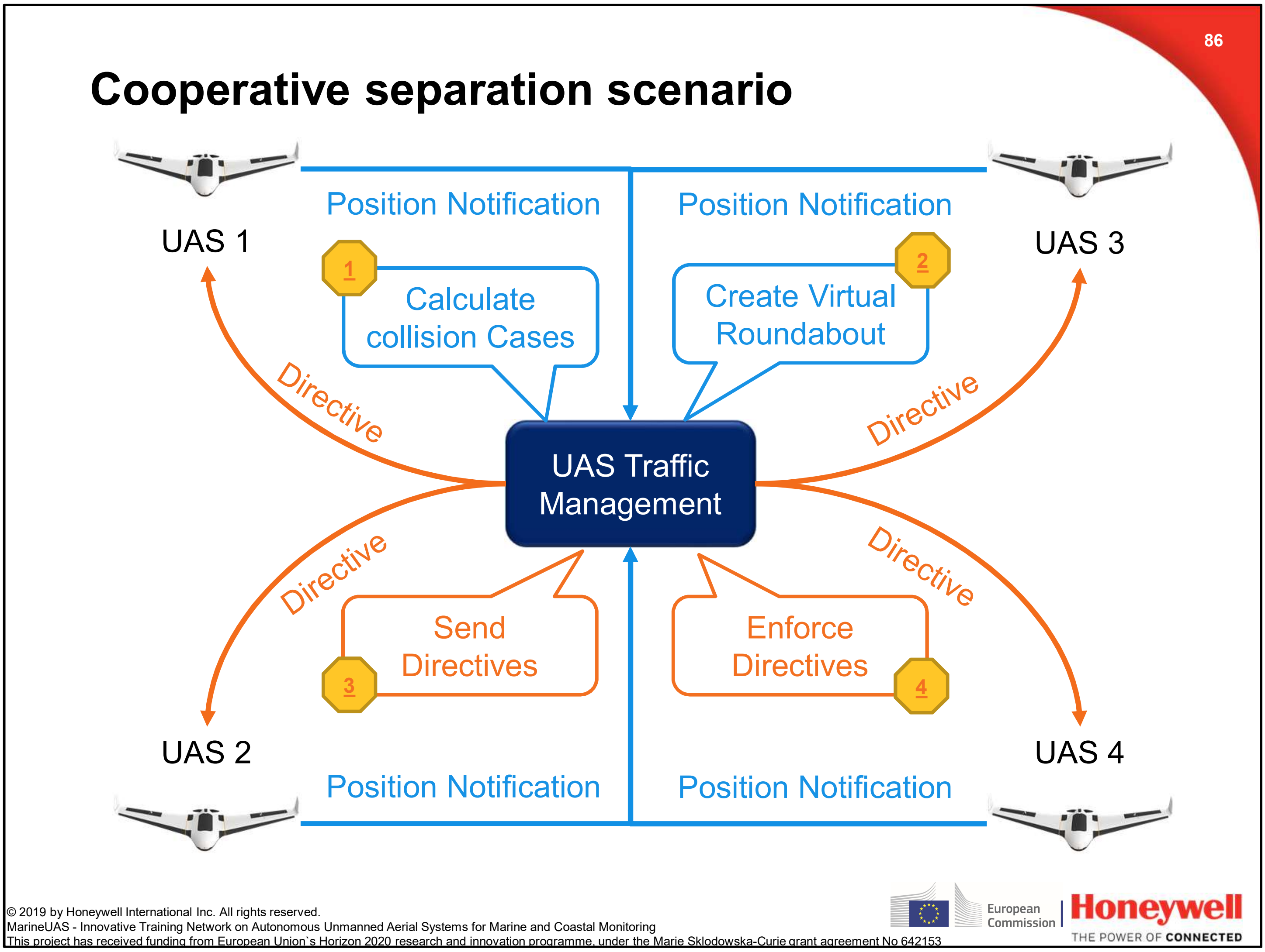
Speech:

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

Your Notes:



Speech:

There is a central UTM authority,

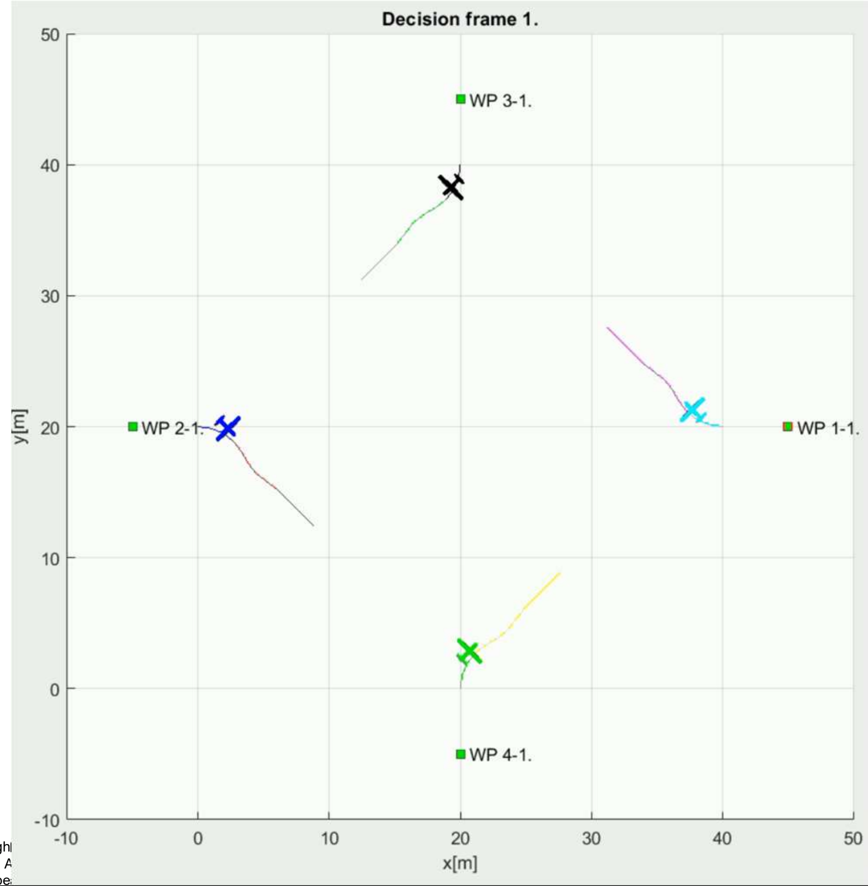
The UAS gives their “Position notification”,

The UAS is enforcing “Directives as a commands”,

Your Notes:

87

Scenario (7.4.3): Rule-based mixed head-on with converging



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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,

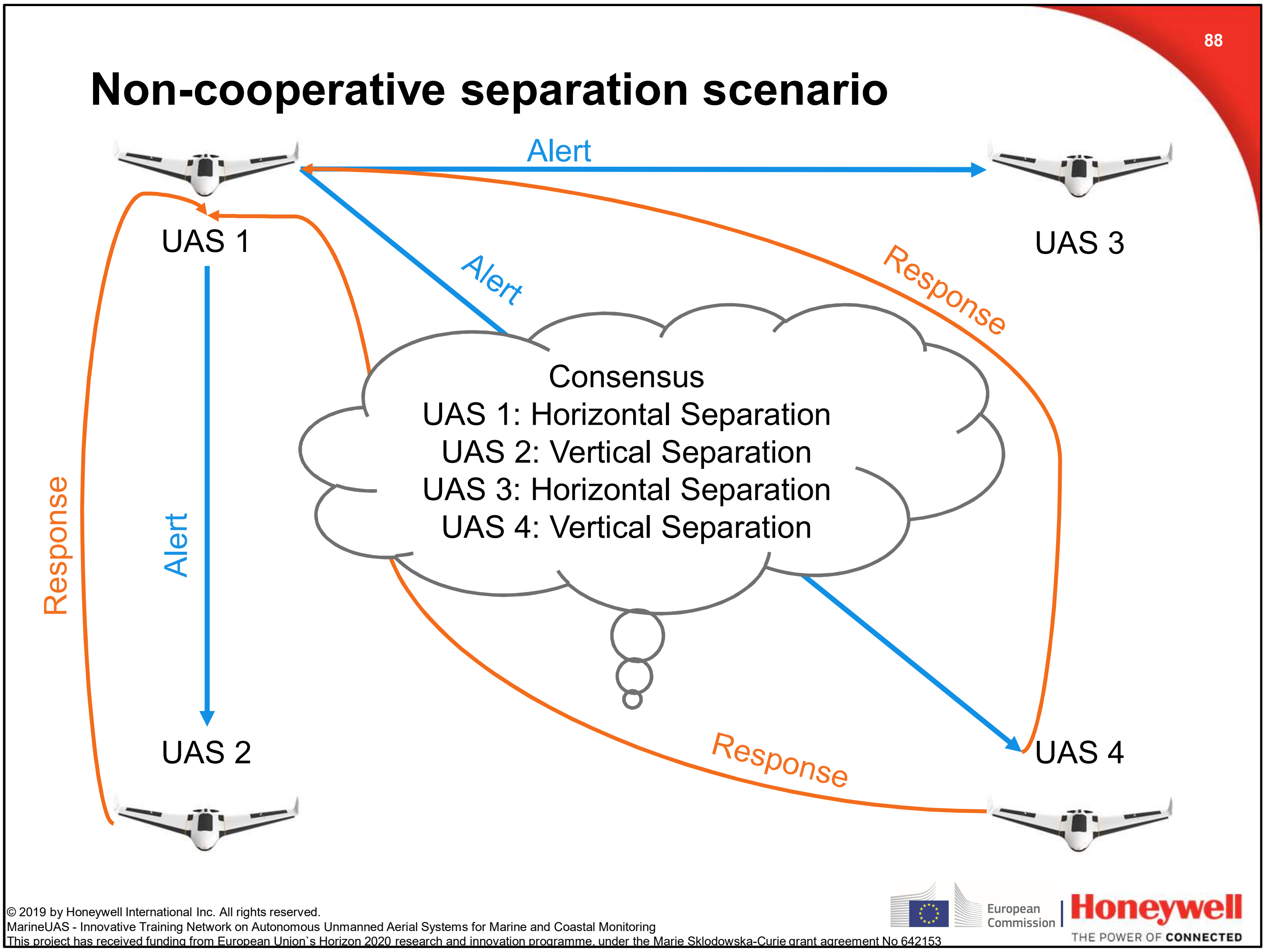
The capacity of virtual roundabout is depending on standard cruising speed,

All planes needs to use same speed while on roundabout

Note:

The algorithm to calculate roundabout and merge collision points is given by ICAO and its bounded to definition of airworthiness

Therefore any plane operating in controlled airspace is capable to adhere to ATM/UTM directives



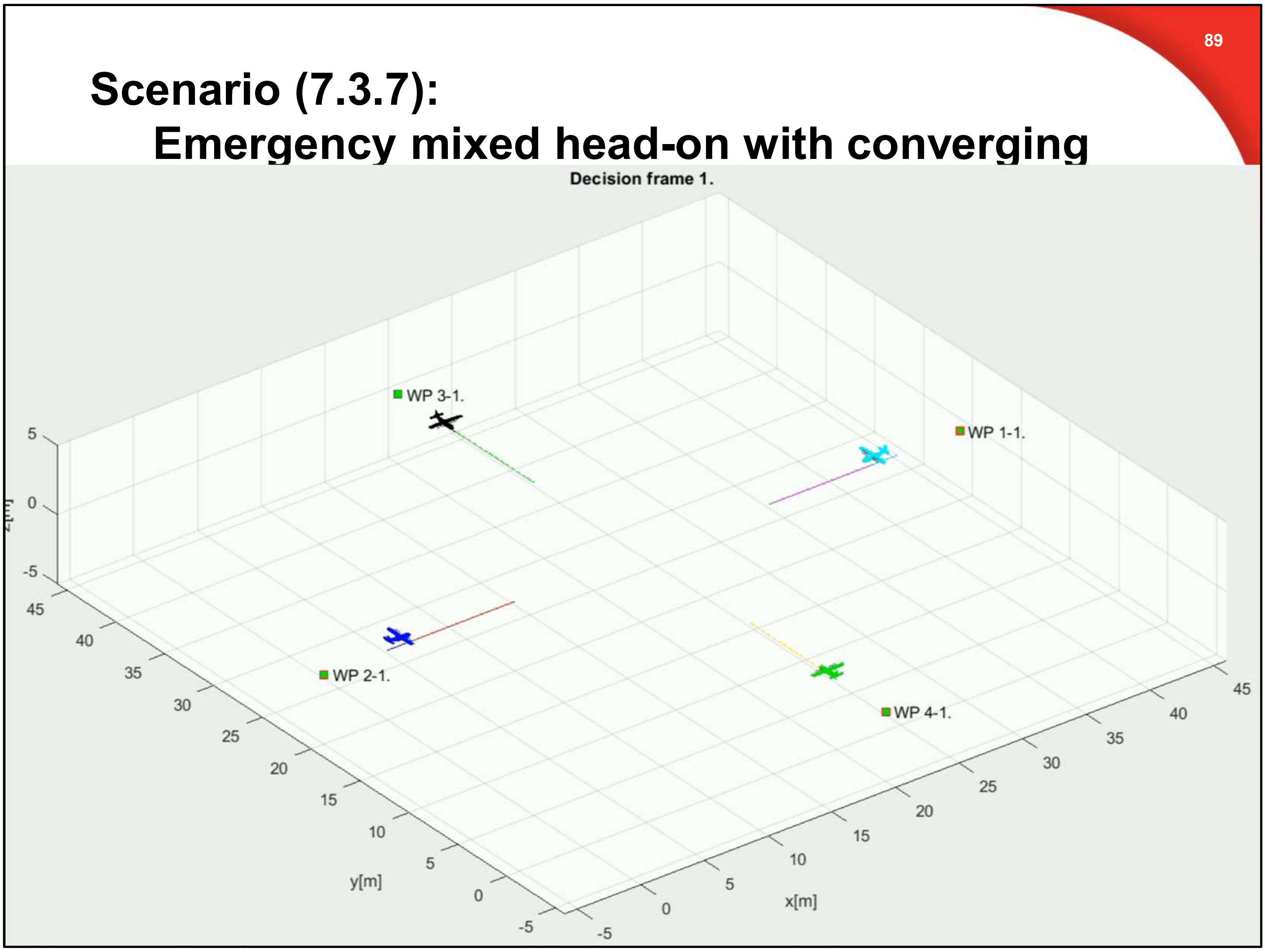
Speech:

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

Your Notes:



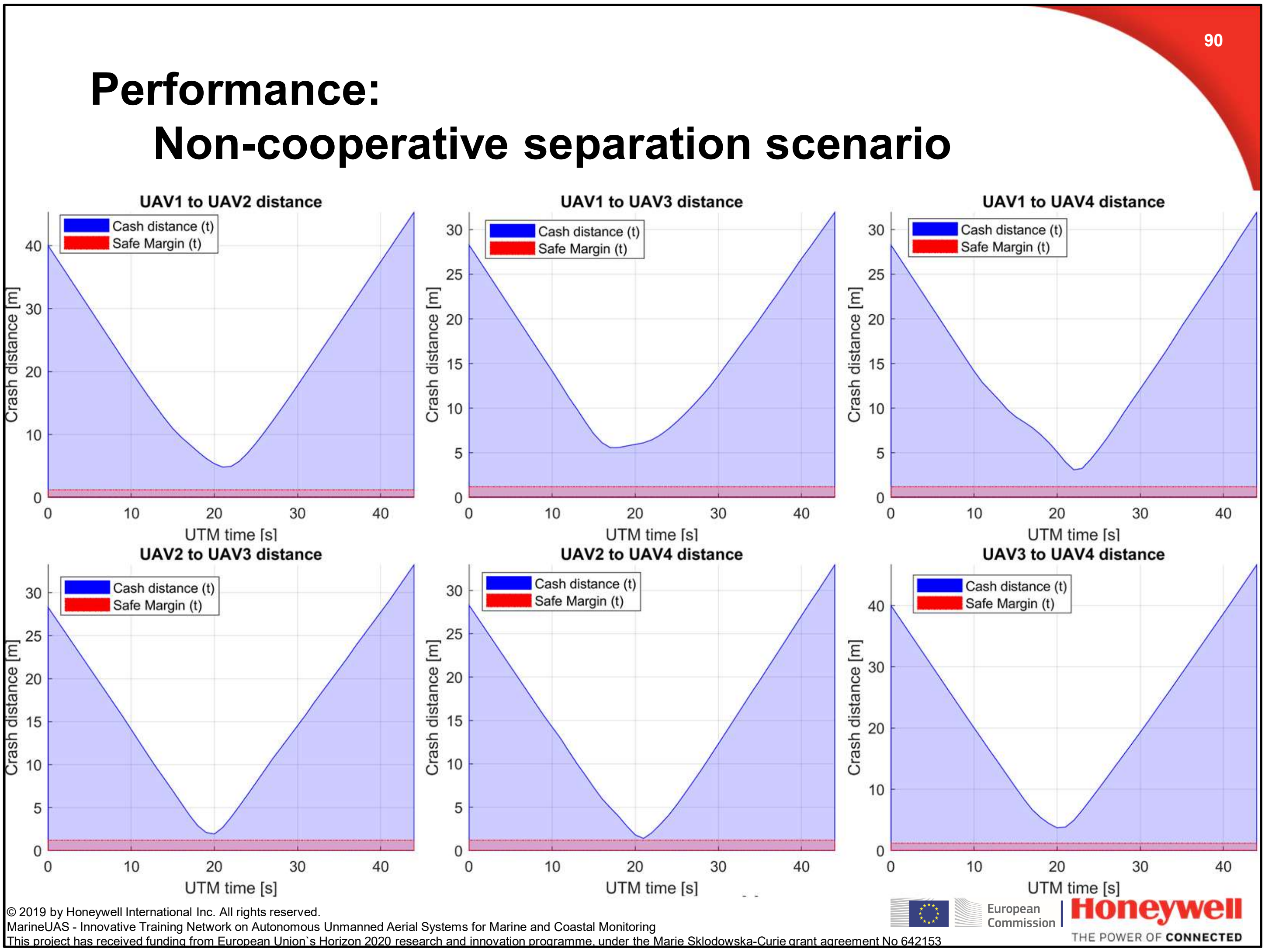
Speech:

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,

Your Notes:



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,

Note:

The usual safety margins are way greater, the safety margin was 4x diameter of UAS (30 cm)=> 1.2m

Your Notes:

Simulations results – non-cooperative

Scenario name	Safety Margin			Trajectory tracking			Pass / Fail
	Distance		Breach	Waypoint Reach	Reference Deviation	Acceptable Deviation	
	min	max					
Building avoidance (sim. 7.1)	0.69 m UAS 1	24.98 m UAS 1	No (7.2)	Yes/UAS 1/(7.3)	$\mathcal{WP}_1:$ 107.05m $\mathcal{WP}_2:$ 86.20m $\mathcal{WP}_3:$ 28.70m $\mathcal{WP}_4:$ 32.84m	Yes (7.10)	Pass
Slalom (sim. 7.5)	0.09 m UAS 1	3.74 m UAS 1	No (7.6)	Yes/UAS 1/(7.7)	$\mathcal{WP}_1:$ 20.06m	Yes (7.14)	Pass
Maze (sim 7.9)	0.01 m UAS 1	2.95 m UAS 1	No (7.10)	Yes/UAS 1/(7.11)	$\mathcal{WP}_1:$ 28.06m	Yes (7.18)	Pass
Storm (sim. 7.13)	0.04 m UAS 1	34.99 m UAS 1	No (7.14)	Yes/UAS 1/(7.15)	$\mathcal{WP}_1:$ 15.76m	Yes (7.22)	Pass
Emergency Converging (sim. 7.17)	1.67 m UAS 1-2	27.08 m UAS 1-1	No (7.18)	Yes/UAS 1/(7.19a) Yes/UAS 2/(7.19b)	$\mathcal{WP}_1:$ 3.25m $\mathcal{WP}_1:$ 0.00m	Yes (7.26)	Pass
Emergency Head On (sim. 7.21)	0.38 m UAS 1-2	38.00 m UAS 1-2	No (7.22)	Yes/UAS 1/(7.23a) Yes/UAS 2/(7.23b)	$\mathcal{WP}_1:$ 3.25m $\mathcal{WP}_1:$ 0.00m	Yes (7.30)	Pass
Emergency Multiple (sim. 7.25)	0.20 m UAS 2-4	45.46 m UAS 3-4	No (7.26)	Yes/UAS 1/(7.27a) Yes/UAS 2/(7.27b) Yes/UAS 3/(7.27c) Yes/UAS 4/(7.27d)	$\mathcal{WP}_1:$ 4.84m $\mathcal{WP}_1:$ 1.83m $\mathcal{WP}_1:$ 3.45m $\mathcal{WP}_1:$ 2.05m	Yes (7.34)	Pass

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Speech:

For all test cases we have tracked:

“Safety margin breach” which is primary performance criterion,

All simulations have passed

Note:

There are secondary criterions,

1. Path tracking performance: - deviations from expected trajectory
2. Computation load performance – maneuver feasibility by computational point of the view

Some of simulations has not been presented

Your Notes:

92

Simulations results – cooperative

Scenario name	Safety Margin: Distance min	Safety Margin: Distance max	Safety Margin: Breach	Trajectory tracking: Waypoint Reach	Trajectory tracking: Reference Deviation	Trajectory tracking: Acceptable Deviation	Pass / Fail
Rule-based Converging (sim. 7.29)	1.22 m UAS 1-2	20.28 m UAS 1-2	No (7.37)	Yes/UAS 1/(7.31a) Yes/UAS 2/(7.31b)	$\mathcal{WP}_1$: $10.22m$ $\mathcal{WP}_1$: $0.00m$	Yes (7.38)	Pass
Rule-based Head On (sim. 7.33)	0.21 m UAS 1-2	36.33 m UAS 1-2	No (7.34)	Yes/UAS 1/(7.35a) Yes/UAS 2/(7.35b)	$\mathcal{WP}_1$: $5.40m$ $\mathcal{WP}_1$: $5.40m$	Yes (7.42)	Pass
Rule-based Multiple (sim. 7.37)	0.54 m UAS 2-3	32.24 m UAS 1-2	No (7.38)	Yes/UAS 1/(7.39a) Yes/UAS 2/(7.39b) Yes/UAS 3/(7.39c) Yes/UAS 4/(7.39d)	$\mathcal{WP}_1$: $11.40m$ $\mathcal{WP}_1$: $11.40m$ $\mathcal{WP}_1$: $11.40m$ $\mathcal{WP}_1$: $11.40m$	Yes (7.46)	Pass
Rule-based Overtake (sim. 7.41)	0.80 m UAS 1-2	48.85 m UAS 1-2	No (7.43)	Yes/UAS 1/(7.44a) Yes/UAS 2/(7.44b)	$\mathcal{WP}_1$: $24.00m$ $\mathcal{WP}_2$: $0.00m$ $\mathcal{WP}_3$: $4.00m$ $\mathcal{WP}_4$: $5.00m$ $\mathcal{WP}_1$: $0.00m$	Yes (7.51)	Pass

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Speech:

The same goes for the cooperative test cases,

All simulations have passed,

Note:

You have seen all simulations from this test set during presentation

These test cases can be used for your approach evaluation

Your Notes:

93

Conclusion

Contributions:
- Reach Set Approximation methods
- Scalable navigation algorithm
- Portable D&A solution

- UTM services for phase II. & III.
- Set of test scenarios

Reach Set Approximation:
- Reach set approximated as *a set of discrete trajectories*
- Relationship between trajectories and operational space - *coverage*
- Minimal reach set representation
- Behavior encoded in Reach set

Approach avoidance capabilities:
- Static obstacles a
- (Non-)cooperative intruders
- Geo-fenced areas
- Weather threats

- UTM Resolutions (Rule engine)

Approach reusability/portability:
- Abstract data fusion procedure
- Control interface as discrete command chain (movements)

- Events & decision making
- UTM services definition

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Speech:

*TBD on the go

Note:

This slide is summary of chapter 8.,

Its starter of a discussion, it remains on the board

Your Notes:

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Q&A Session

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