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Alojz Gomola
4th April 2018

Rules of the Air within Reach Set SAA

Progress report on framework development

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Presentation Summary

Just read the ***Bold Text*** …

Rules of the Air Context

- Framework Elements
- UAS Traffic Management
- Collision Case and Resolution
- Rules of The Air

Rule Engine

- Rule Engine Concept
- Joint Point Definitions
- Test Rule Configurations
- Trajectory Disabling Rules
- Before Avoidance Rule
- After Avoidance Rule
- Collision Case Resolution Rule
- Maneuver Rules

ACAS-XU Reach Set Approximation

- ACAS-XU in context SAA for UAS
- DAA separations from ACAS-X
- DAA separations

Emergency and Planned Avoidance

- Concept of Emergency Avoidance
- Concept of Planned Avoidance
- Standard Scenarios simulations:
  - Converging Maneuver
  - Head On Approach
  - Multiple Collisions
  - Overtake at different speeds

Summary and Future Research

MarineUAS - Innovative Training Network on Autonomous Unmanned Aerial Systems for Marine and Coastal Monitoring
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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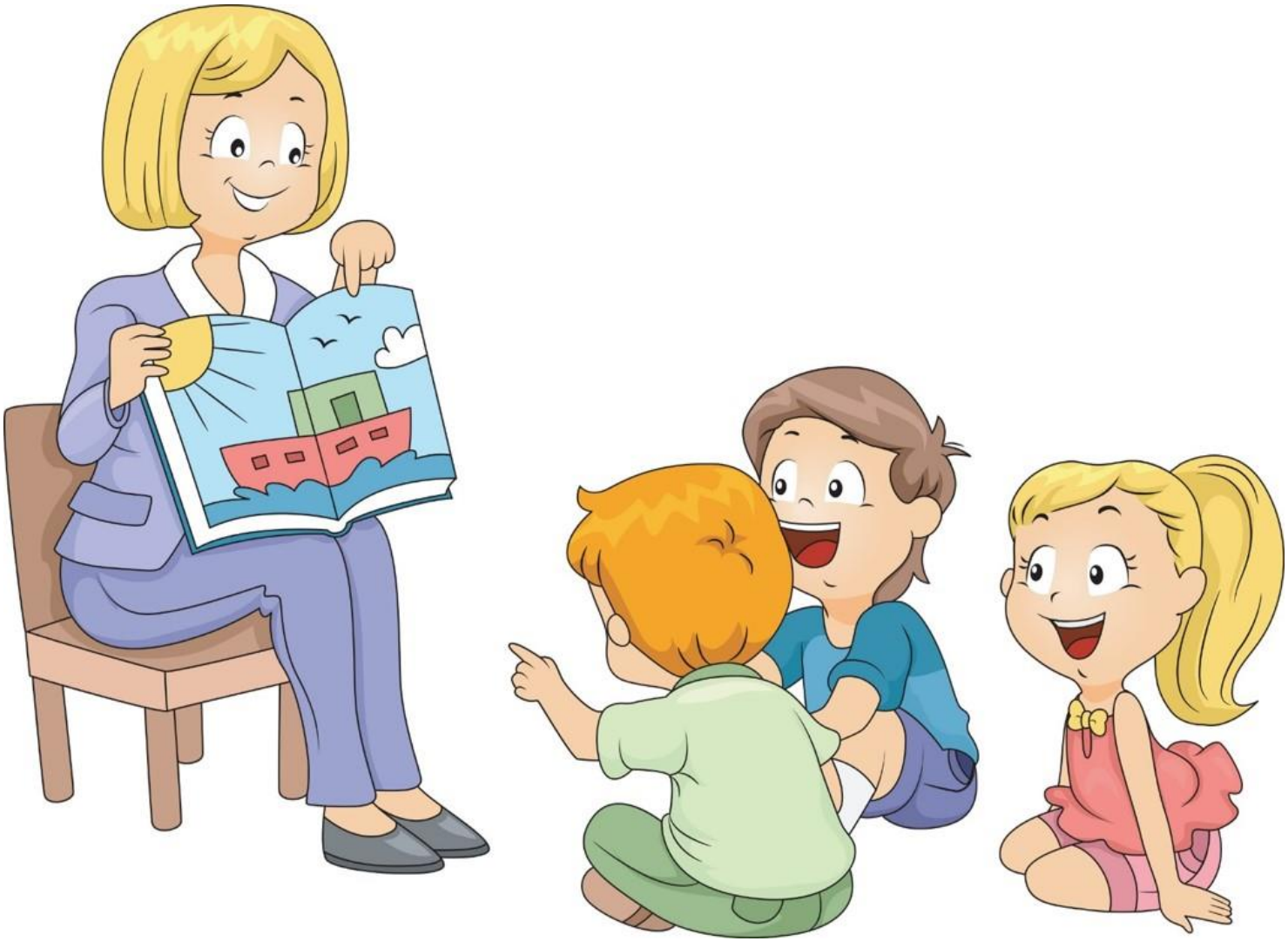
Rules of the Air Context Introduction



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Framework

We have this architecture:

ADS-B

Obstacle Map

LiDAR

Rule Engine

Data fusion

Mission Plan

Avoidance grid

Let us focus on Rules

Vehicle control

Movement Automaton

Reach set estimation

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Covered Functionality

ADS-B

Obstacle Map

Rule Engine

Data fusion

Avoidance grid

Vehicle control

Movement Automaton

Reach set estimation

Reach set based framework covering:

1. Path planning,
2. Evolving world,
3. Adversarial,
4. Data fusion,
5. Static restrictions,
6. Weather,
7. *Rules*

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Current Architecture in Nutshell

We have standard *noncooperative* framework based on *Reach Sets*

Mission Control responsible for:

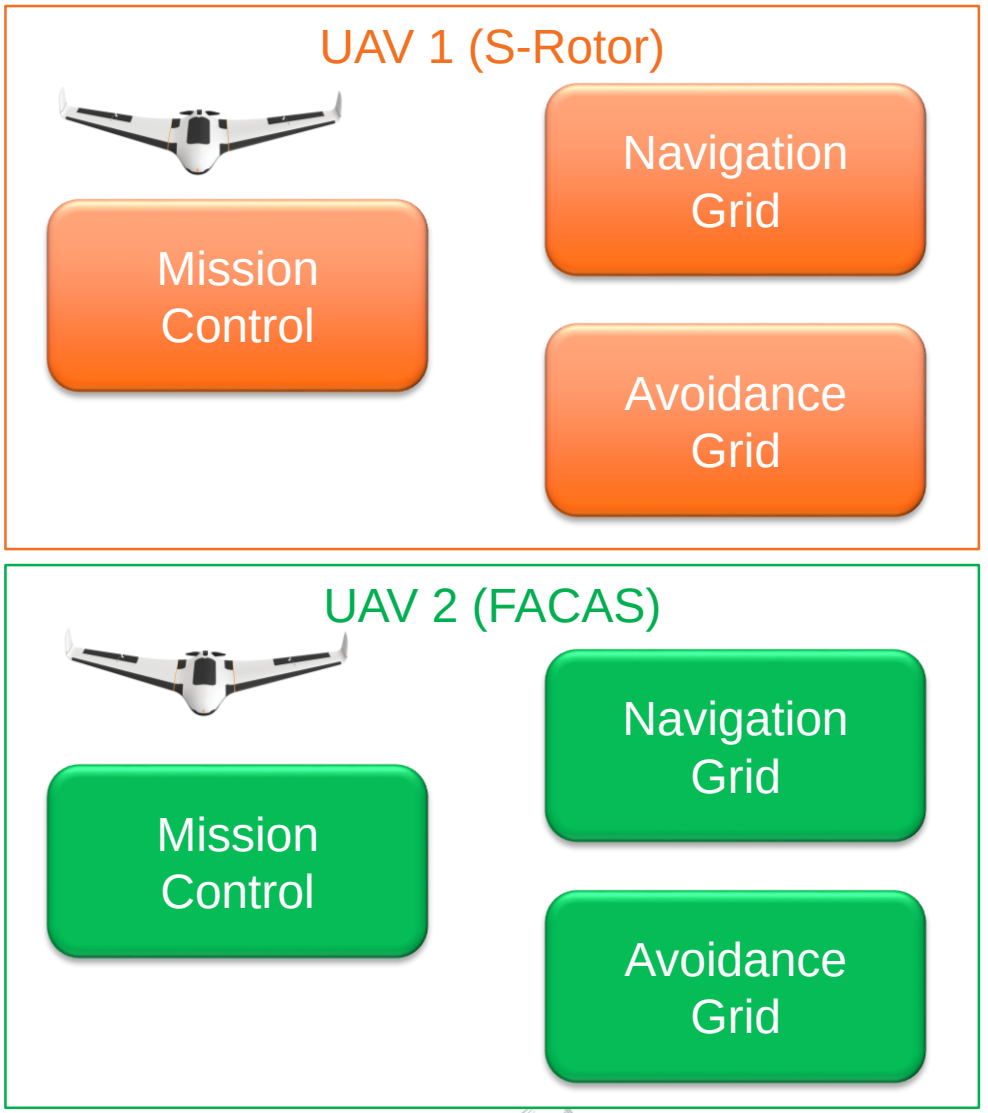
- Waypoint management,
- Priority checkup,
- Vehicle safety.

Navigation Grid responsible for:

- Navigation in open space.

Avoidance Grid responsible for:

- Intruder avoidance
- Obstacle avoidance



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Avoidance in the nutshell

What is a reason to have *two separate grids* ?

To separate:

- ***Event based avoidance***

When sky is clear we can consider to apply man made rules.

- ***Situation based avoidance***

When situation arises, we need to protect ourselves

Preemptive based	Event based	Situation based
• Well defined Waypoints • Free Space guarantee • Preflight preparation • Legal compliance	*Targets of avoidance*: • Cooperative intruders (Rules of the air) • Bad weather • Geofencing	*Targets of avoidance*: • Non-Cooperative intruders • Terrain • Other physical obstacles

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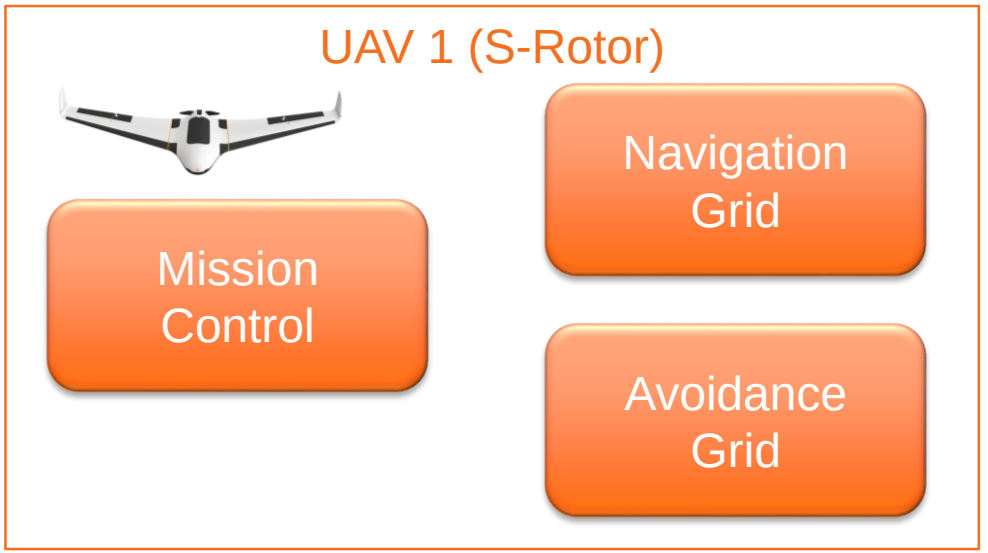
UTM Module Introduction

We have standard *noncooperative* framework based on *Reach Sets*

There is need for *UASTrafficManagement* (UTM)
- provide C2 link and
- cooperative functionality

UAS Traffic Management

One module to rule them all (USpace EU, UTM US)



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Which Functionality is Provided by UTM

Traffic management responsibilities (selected):

- *Separation* – keep all airspace users (manned/unmanned) *Well Clear.*
- *Collision prevention* – prevent collision and enforce rule compliance.
- *Conflict resolution* – the UTM decides request satisfaction based on rules.

Separation:

- *Controlled Airspace* is segregated into *Flight Levels* by 1000 feet's of Barometric Altitude (ASL).
- Each Flight Level is considered as *separated space with planar routing.*
- *UAS* can induce climb/descent maneuvers in *local level altitude 250-750 feet.*
- *UAS* must ask for a permission to change flight levels and reserve multiple levels during take of and landing.
- *UAS* must stay *"Well clear"* from any other traffic considering protection tube with given own radius (intruder radius).
- *ACAS-XU* defines such separations.

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Collision Prevention

Collision prevention is based on ***aircraft mode***:

1. *Descending* – aircraft is *changing flight levels from higher to lower* during landing maneuver or during required descent given by flight plan.

2. *Climbing* – aircraft is *changing flight levels from lower to higher* during take off maneuver or during required ascend given by geographical features.

3. *Horizontal Flight* – aircraft is *moving in same flight level* (We will focus on this part), aircraft is required to keep:
   1. Horizontal separation – avoid protection range of other aircrafts on same level
   2. Vertical separation – avoid entering to protected zones of flight level (0-250 feet, 750-1000 feet) of local altitude in flight level.

Note: *EuroContol/EASA separates flight levels based on barometric pressure in controlled region,* therefore aircraft needs to have barometric altitude measurement equipment to fly in *Controlled Airspace*.

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Conflict resolution

Conflict resolution is *Event-based* depending on proclaimed aircraft *position, heading and velocity, and classification*.

Collision Case is created for two conflict participants (for both):

- *Position* (Latitude, Longitude, Flight level).
- *Velocity* (Vectorizer, Planar),
- *Vehicle Category* (Size/Maneuverability)
- *Trajectory Prediction* (Planned/Predicted)
- *Collision point* (Based on possible trajectory intersection)
- *Angle of Approach* (to adversarial vehicle)
- *Collision type* (Based on Angle of approach)
- *Avoidance role* (Based on previous data and decision algorithm)

Note: This work is focused on *resolution of Loitering incidents* in same flight level. The *UTM have final decision on Collision case opening/closing.*

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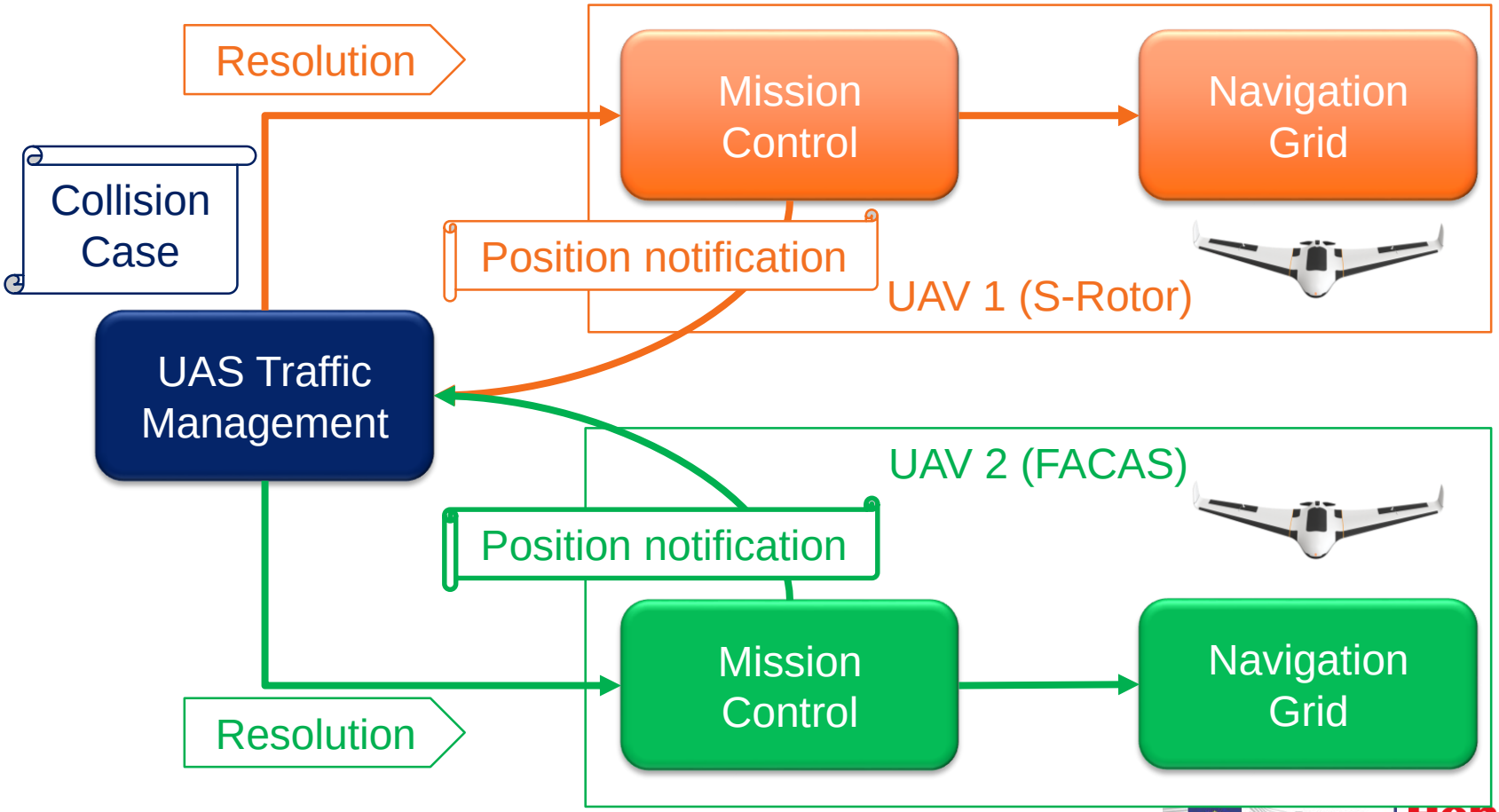
How is Collision Case resolved by UTM

- *Each vehicle is calculating Collision Cases* to nearby vehicles,
- *UTM is also calculating Collision Cases* to nearby vehicles,
- UTM issues ***Resolution advisories*** or separation rules to prevent collision



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What is Considered in UTM Resolution

What is considered in ***UTM Resolution*** processing:

1. *Vehicle category* (higher category is always favored)
2. *Vehicle maneuverability* (higher maneuverability is forced to avoidance)
3. *Collision Point surroundings* (other collision points in proximity)
4. *Other Collision Cases* related to aircrafts in current *collision case* or *collision point*.

The *expected behavior of UAV platform* is given by following table:

Intruder	Our vehicle	Priority
Manned aircraft	Any UAV	Manned aircraft
VLOS piloted UAV	VLOS piloted UAV	Coordinated avoidance
VLOS piloted UAV	Autonomous UAV	Autonomous UAV
Autonomous UAV	Autonomous UAV	Coordinated avoidance

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Vehicle Category/Maneuverability

From highest to lowest:

1. Manned aviation in distress,
2. Balloon (manned),
3. Glider (manned),
4. Aerial towing (manned)
5. Airship (manned)
6. Other manned aviation
7. UAS Autonomous
8. RPAS

Note: This categorization reflects only Pilot community statement, *the general priority rule is broken*, because maneuverability and vulnerability should be always considered as ked decision factor.

From highest to lowest:

1. Altitude control
   (Balloon, Hovering aircraft)
2. Full control – no propulsion
   (Gliders of any sort)
3. Full control – gliding
   (Any aircraft of plane type)
4. Full control – VTOL
   (Any aircraft with VTOL)

Note: This categorization with vehicle cruising/maximal velocity should be main decision matter.

Original categorization is based on maneuverability (extended not)

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Right of the Way Rules

Right of the way rules aid pilots in *avoiding each other visually*

- The rules are found:
  - Part 91 Federal Aviation Regulation (USA)
  - ICAO Annex 2 -> Chapter 3 - General Rules -> 3.2 Avoidance of collisions -> 3.2.2 Right of way (International)

- When *aircrafts are converging*, the *right of way* is generally given to the *least maneuverable aircraft* (higher class).
- The *aircraft now having the right of the way is to pass well clear of the aircraft* ***not having*** *the right of the way.*

- *Application for rules of the air* in case of UAV seems *to be reduced to immediate avoidance* in case of manned aviation adversary
- The avoidance ***rules can be applied between the same class of UAV.***

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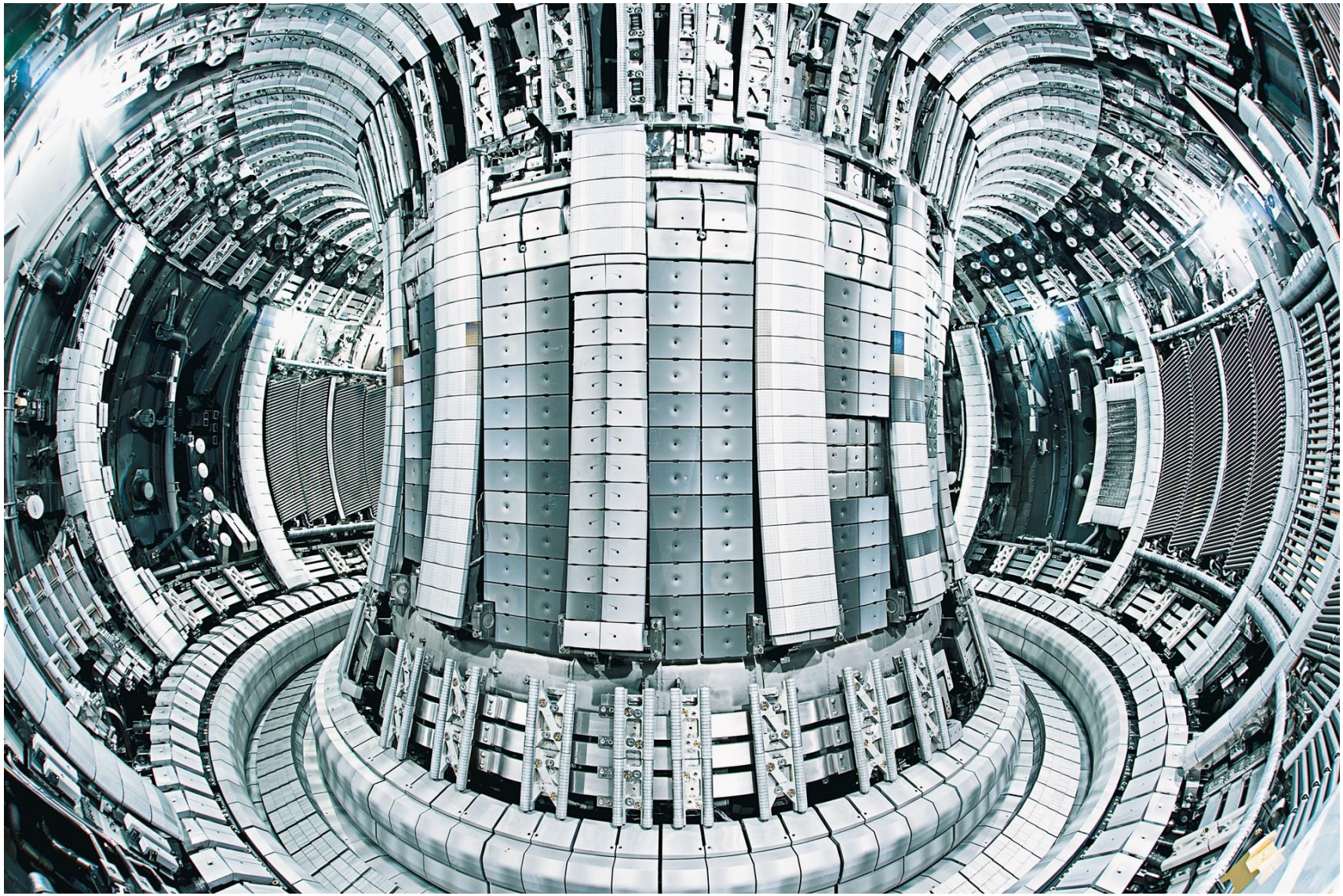
Rule Engine



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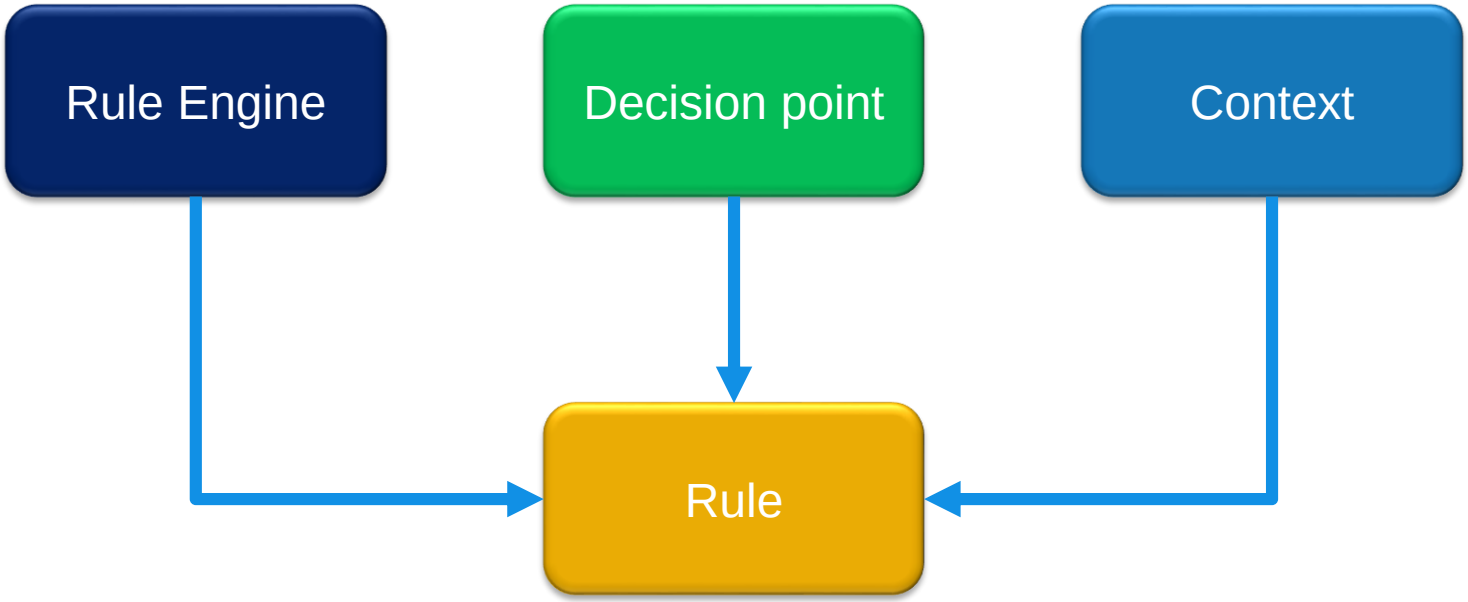
Rule Engine Introduction

Rule Engine – configurable engine weaved into *UTM, Mission Control, Avoidance Grid, Reach Set* classes to enrich existing functionality.

Joint Point – point in process where rule engine is invoked,
Context – context passed to rule body
Rule – small piece of functionality



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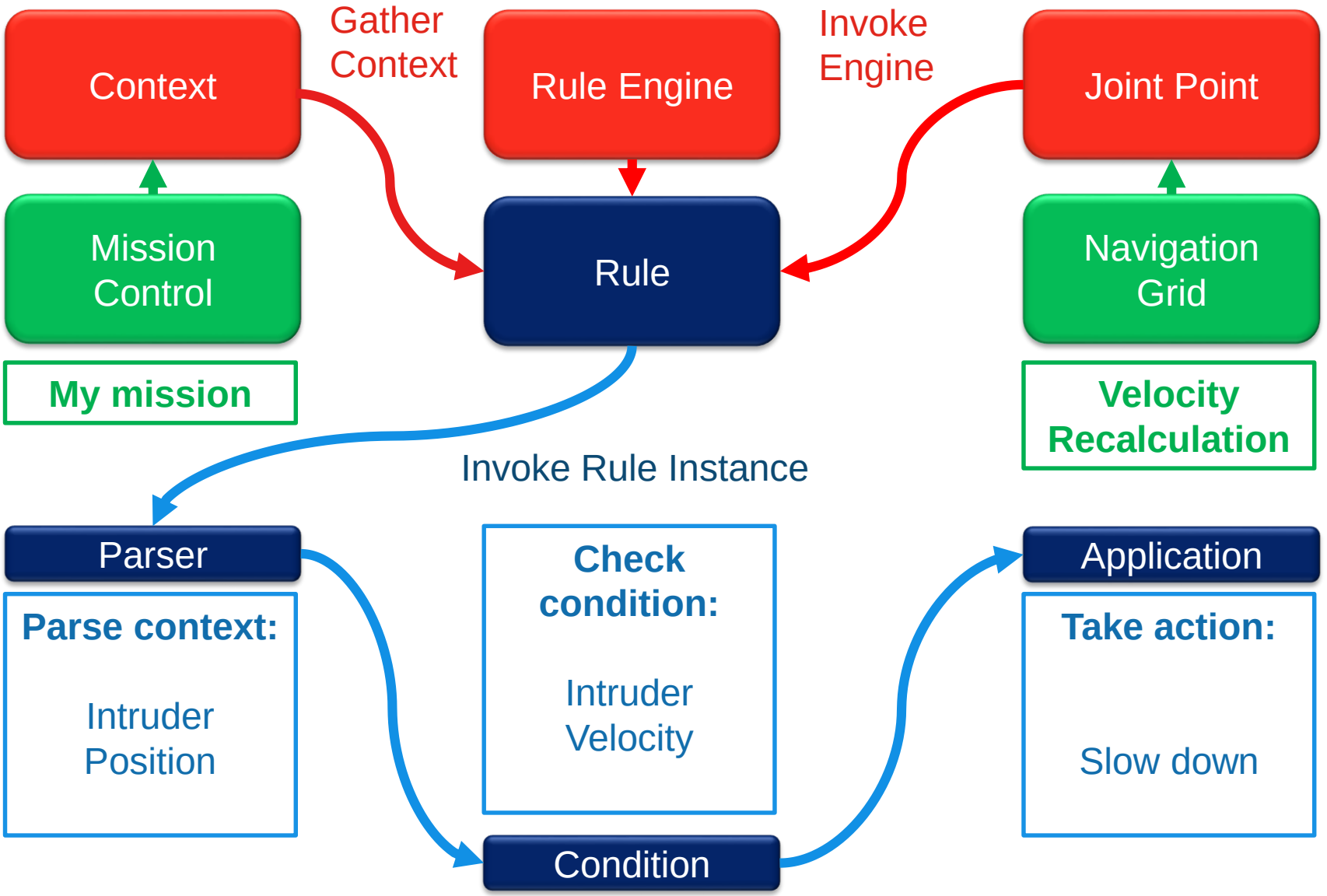
Rule Engine Architecture



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Rule Engine in Nutshell

Benefits:

- ***Modularity*** – keep rule specific *code separated in one class* with given *condition and impact application*, maintain separate functionality .

- ***Scalability*** – use *piece wise code* in navigation/avoidance/control frameworks, *activate/deactivate aspects* and specific behaviors.

- ***Rule chaining*** – rule can be *invoked from Joint Point*, or from *other rule body*, for example specific maneuver rule can be invoked from resolution rule, this becomes especially handy when aspects of logical programing are necessary.

Shortcomings:

- ***Border Case Testing*** – needs to be implemented to verify rule functionality as intended, *the test conditions are hard to assume*.
- ***Configurability Bias*** – is induced at change of *configuration*.

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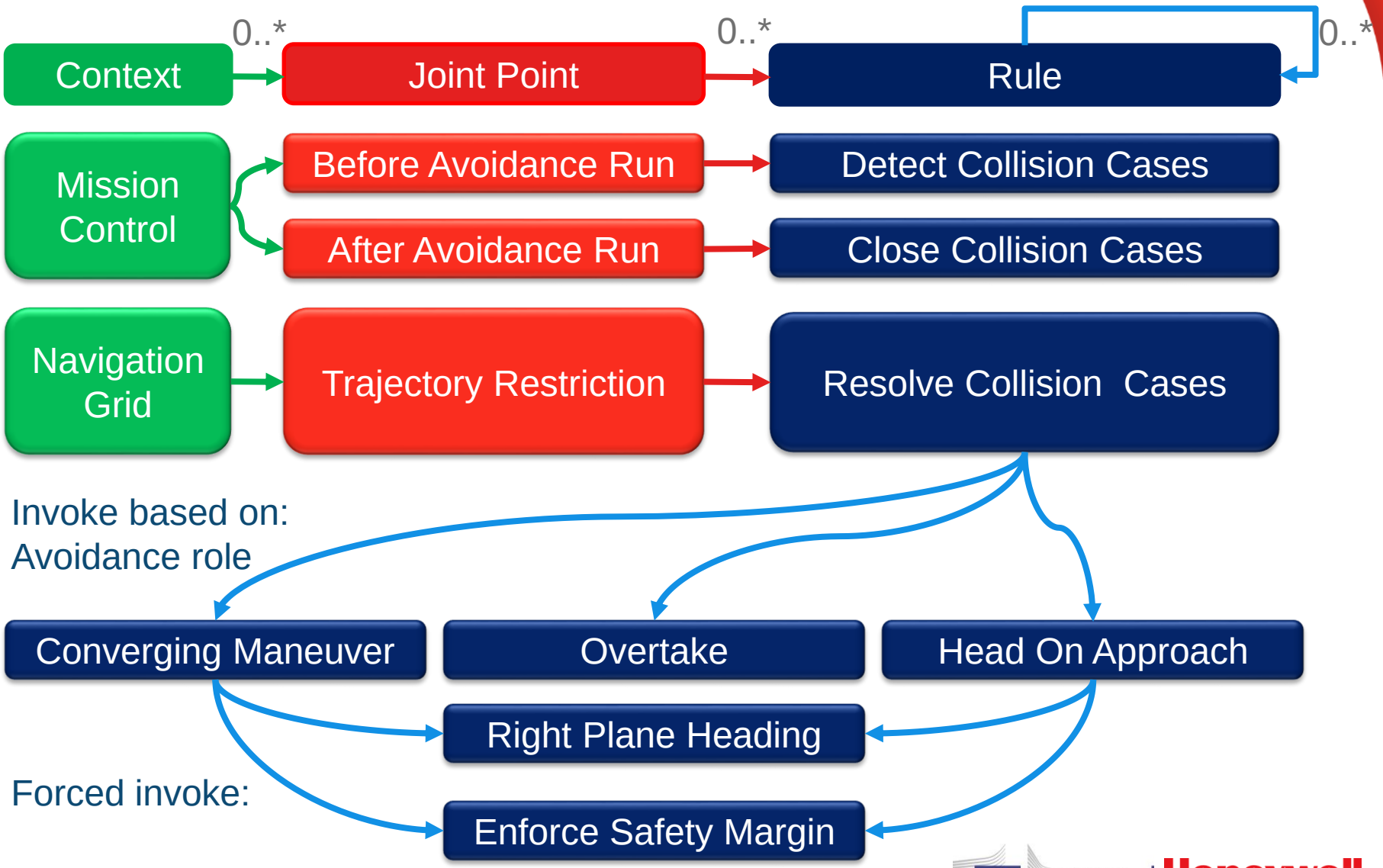
Rule Engine Setup



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Rule: Right Plane Heading

Collision Zone: For given *vehicle position* and *collision point* there exist a space division by plane defined between points parallel with Z axis. The separation divides operation space into:

- *Collision zone* – all points on left from vehicle viewpoint,
- *Free zone* – all points on the right form vehicle viewpoint.

Objective: Disable trajectories which are:

1. Heading into Collision zone,
2. Leading into Collision zone.

[o] Collision Point
[-] Separation Line
[-] Enabled Trajectories
[-] Disabled trajectories
[] Reachable cells
[] Unreachable cells

Context	Condition	Application
UAS Navigation Grid Collision Point (LOC)	There are feasible trajectories	Disable trajectories of Navigation grid

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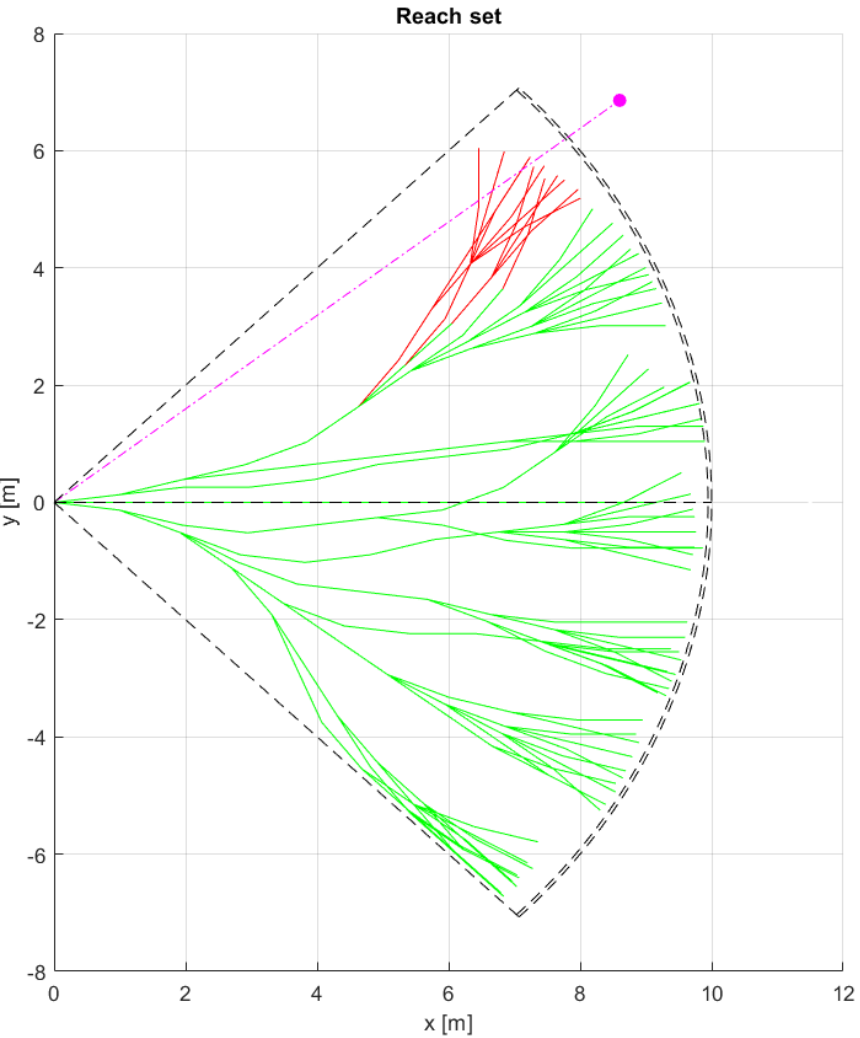
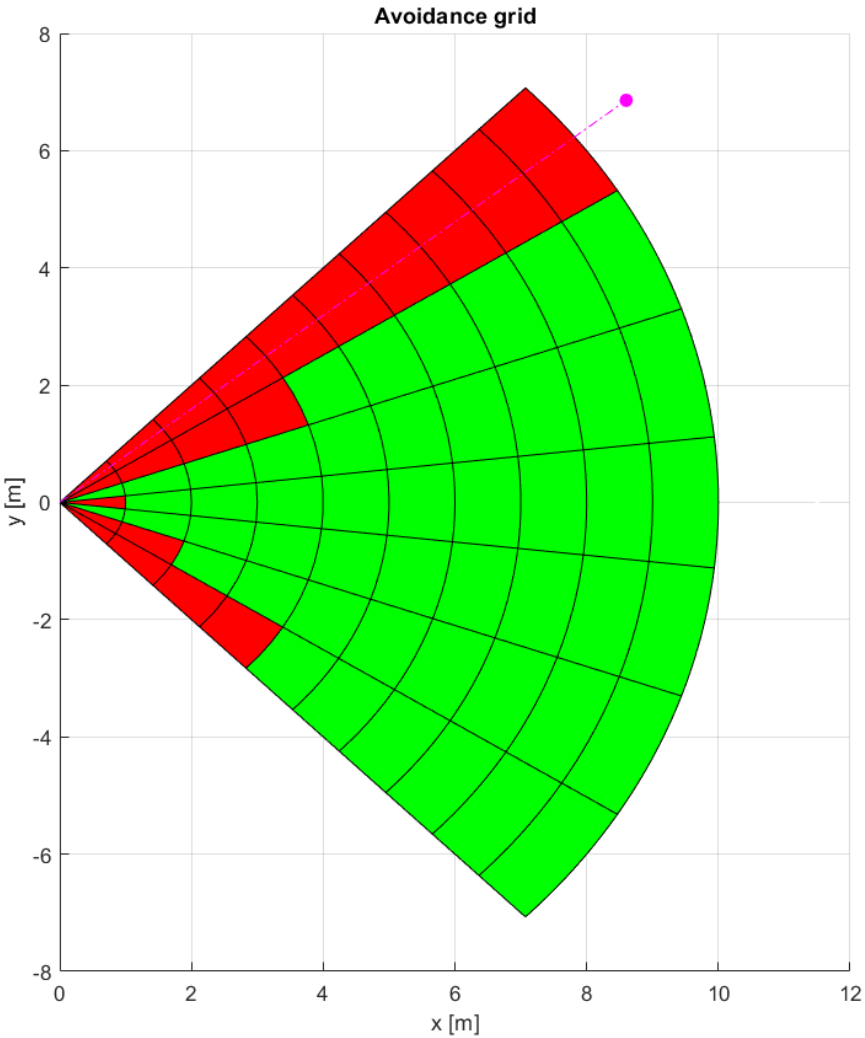
Right Plane Heading (1)





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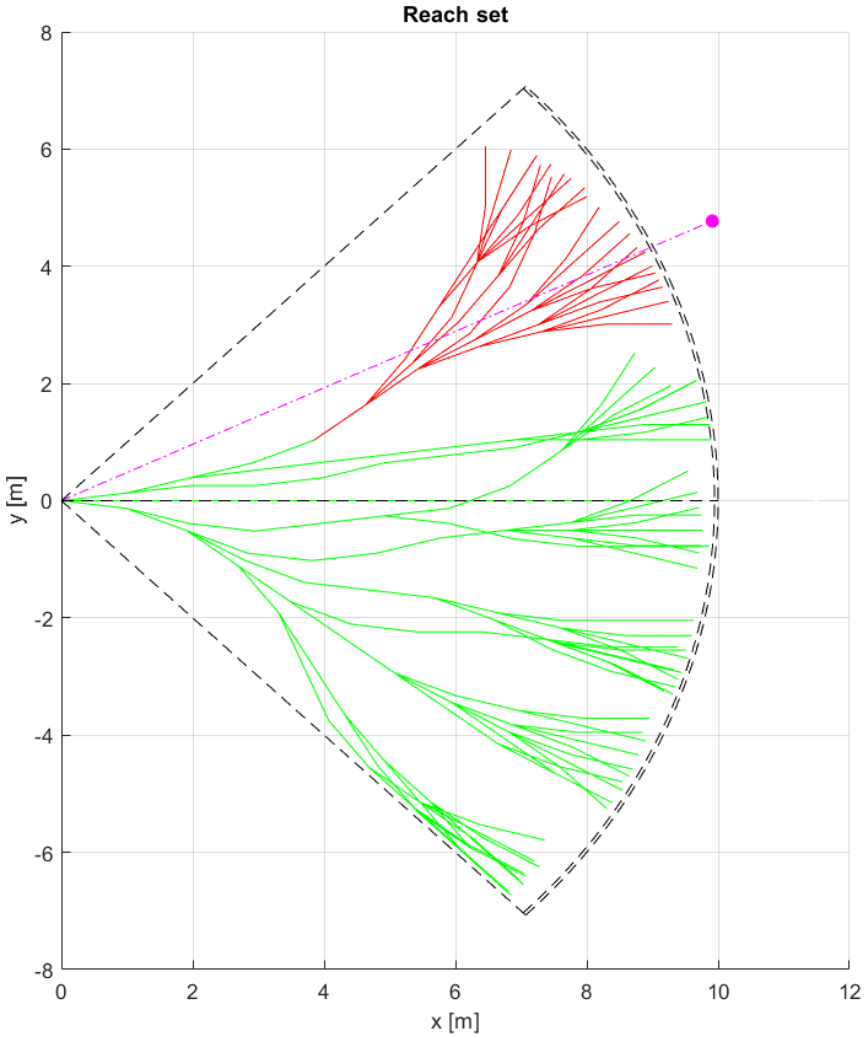
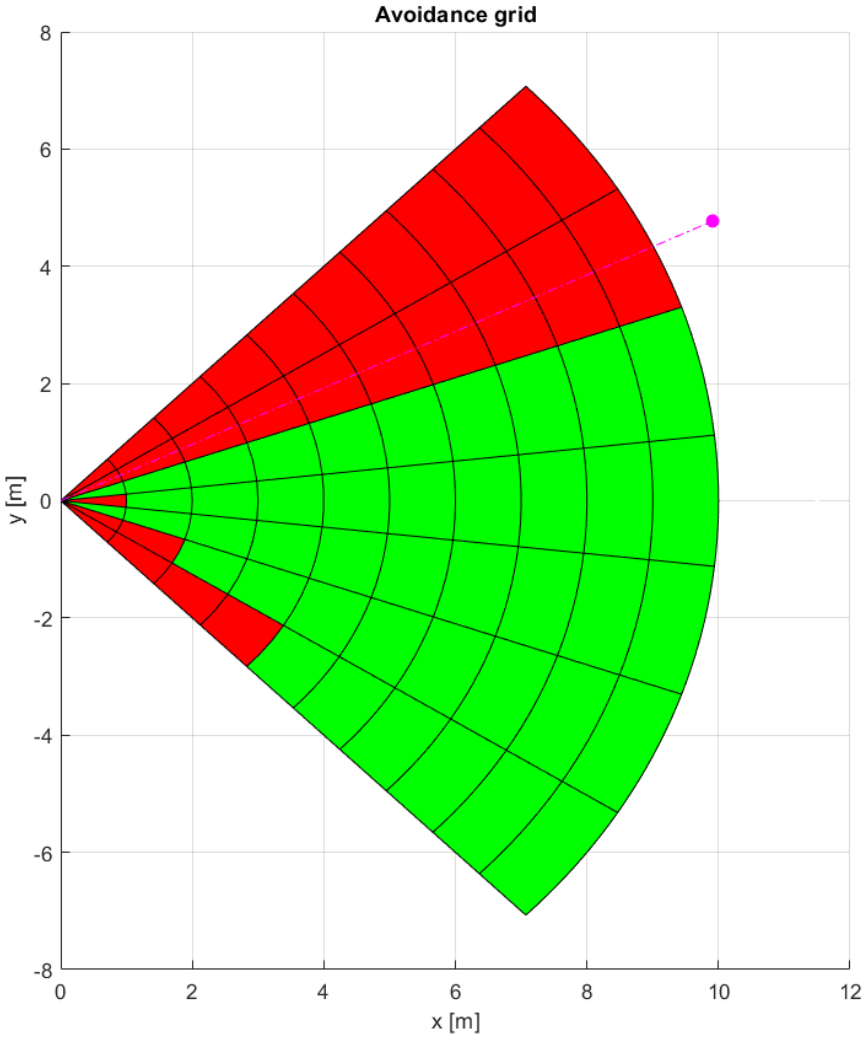
Right Plane Heading (2)





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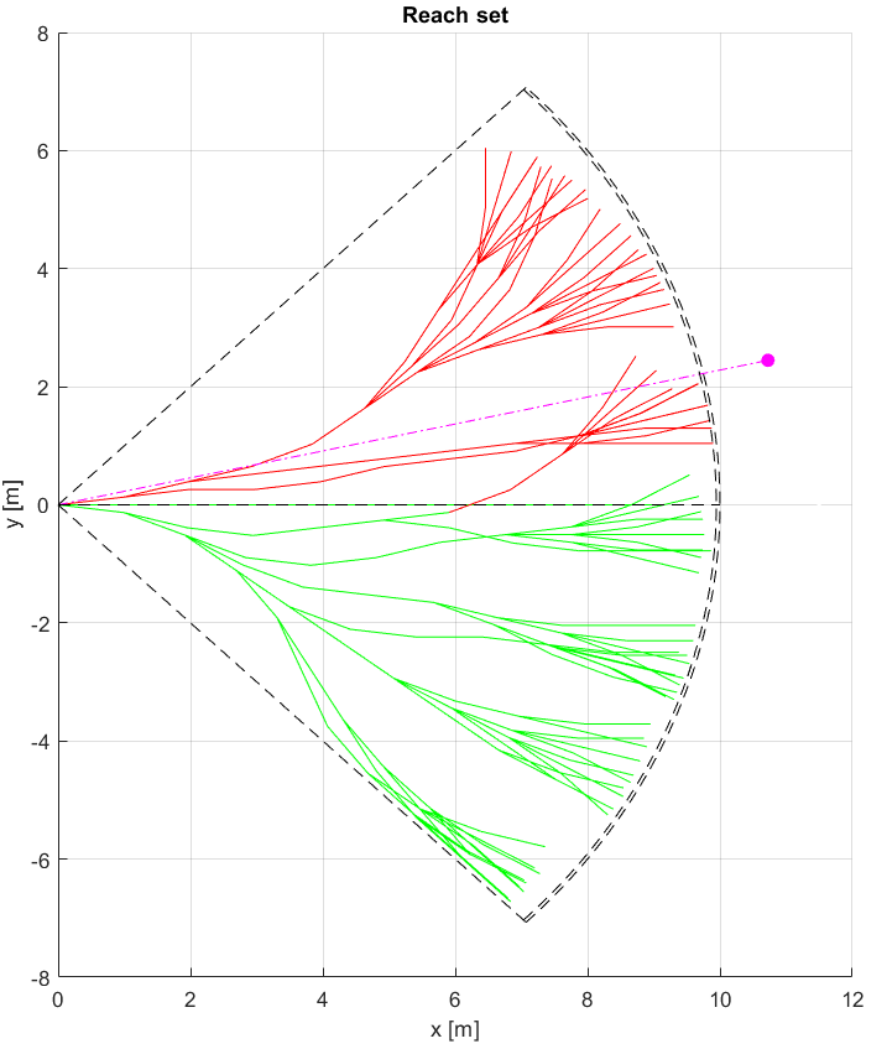
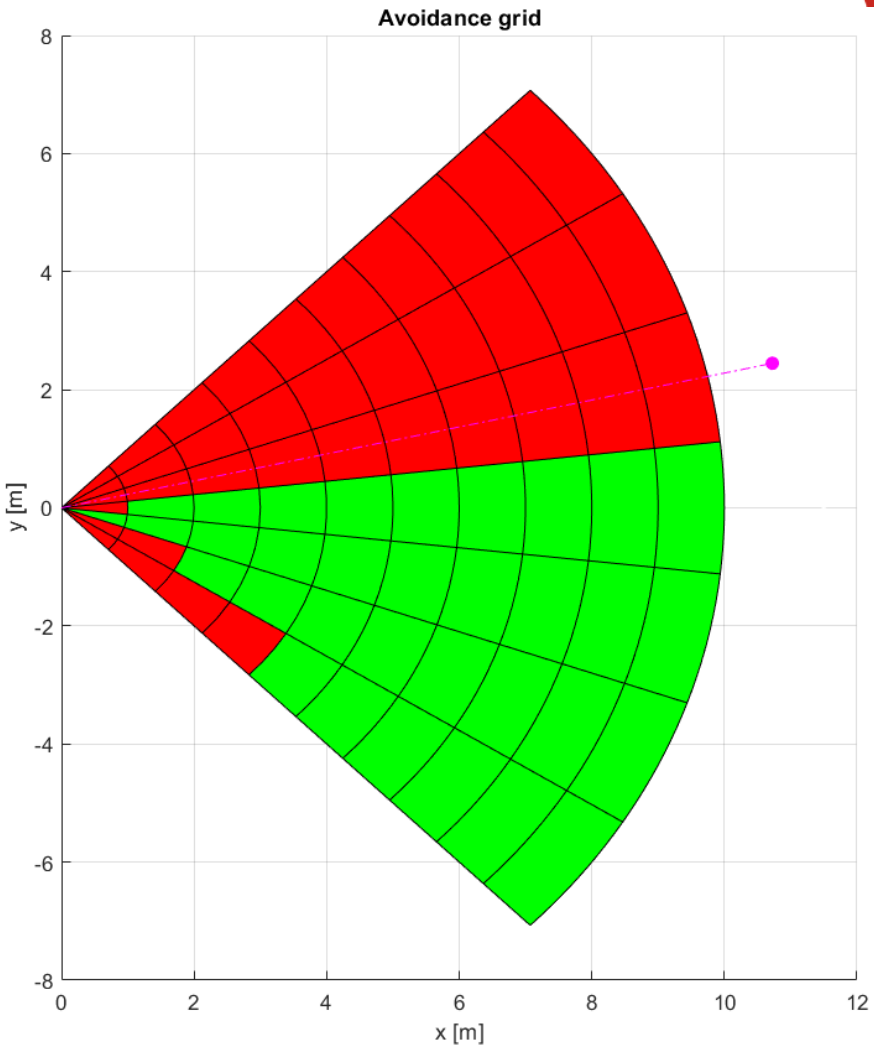
Right Plane Heading (3)





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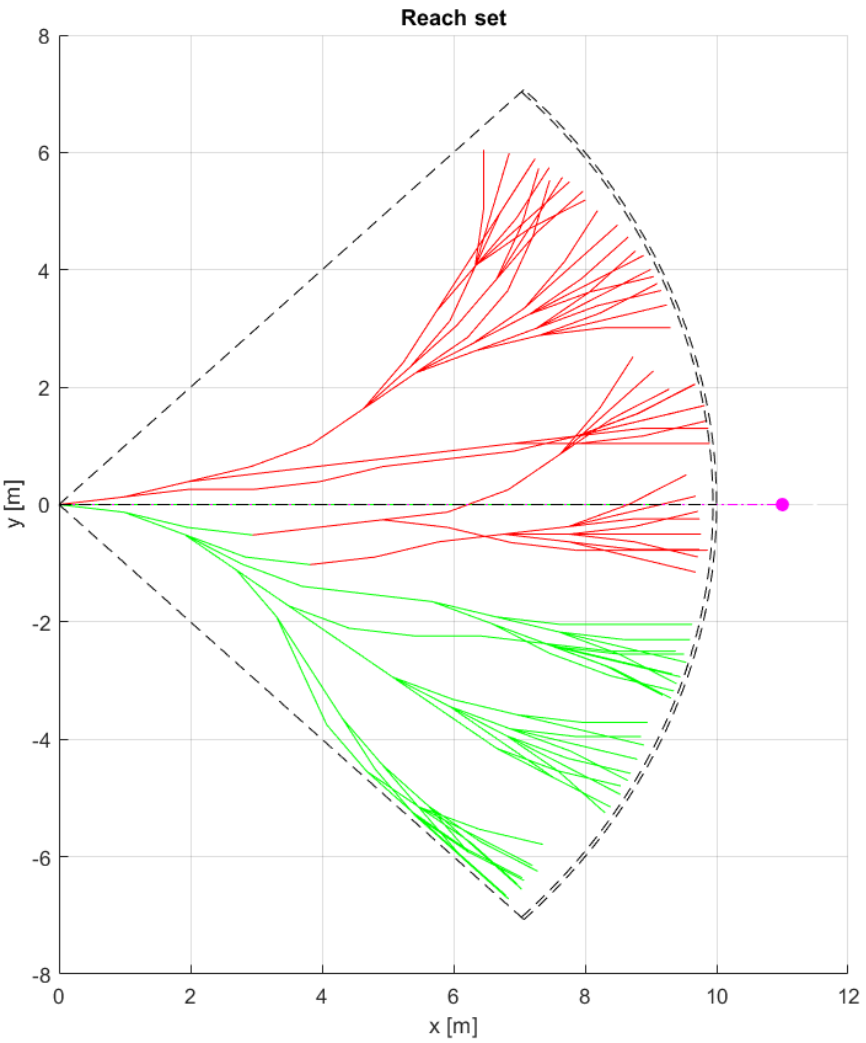
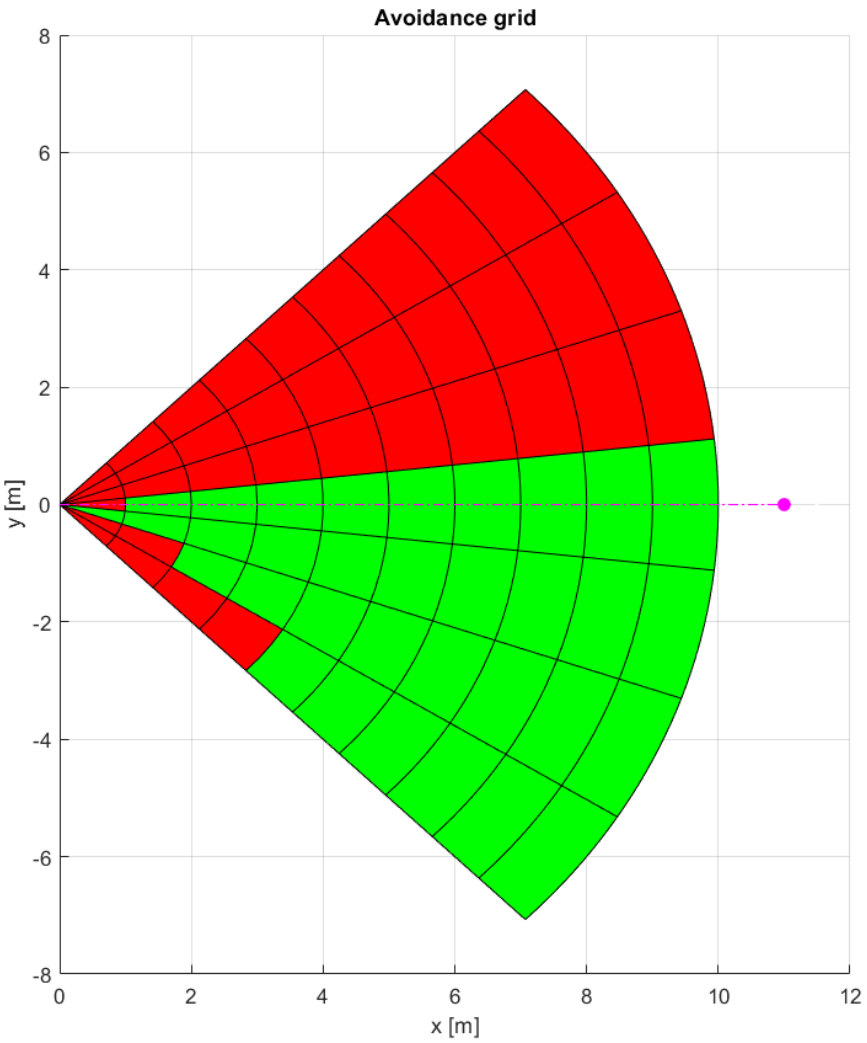
Right Plane Heading (4)





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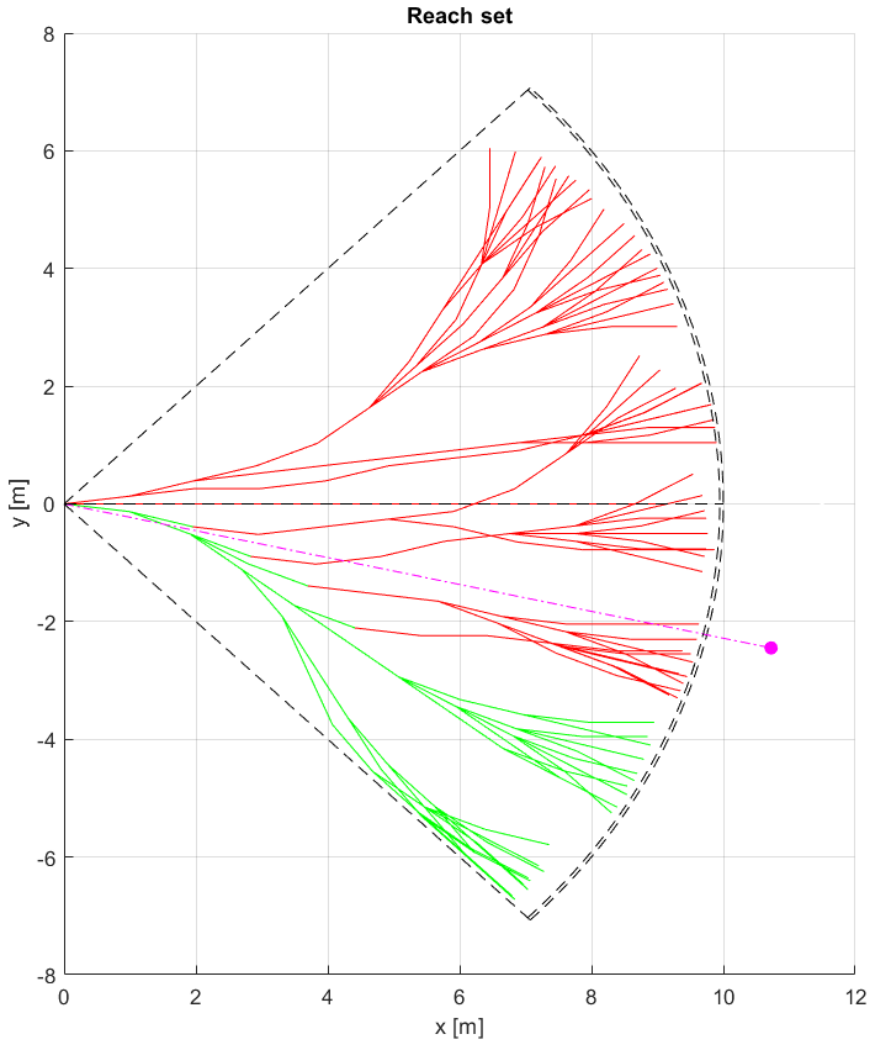
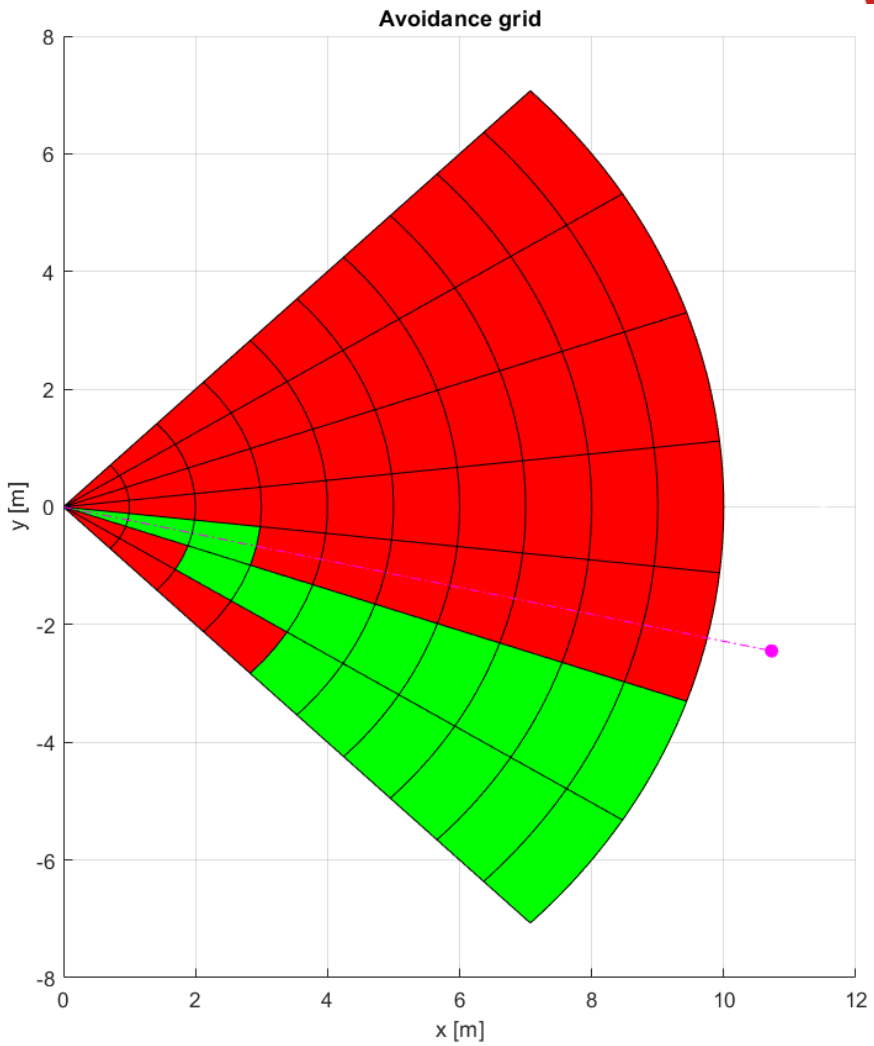
Right Plane Heading (5)





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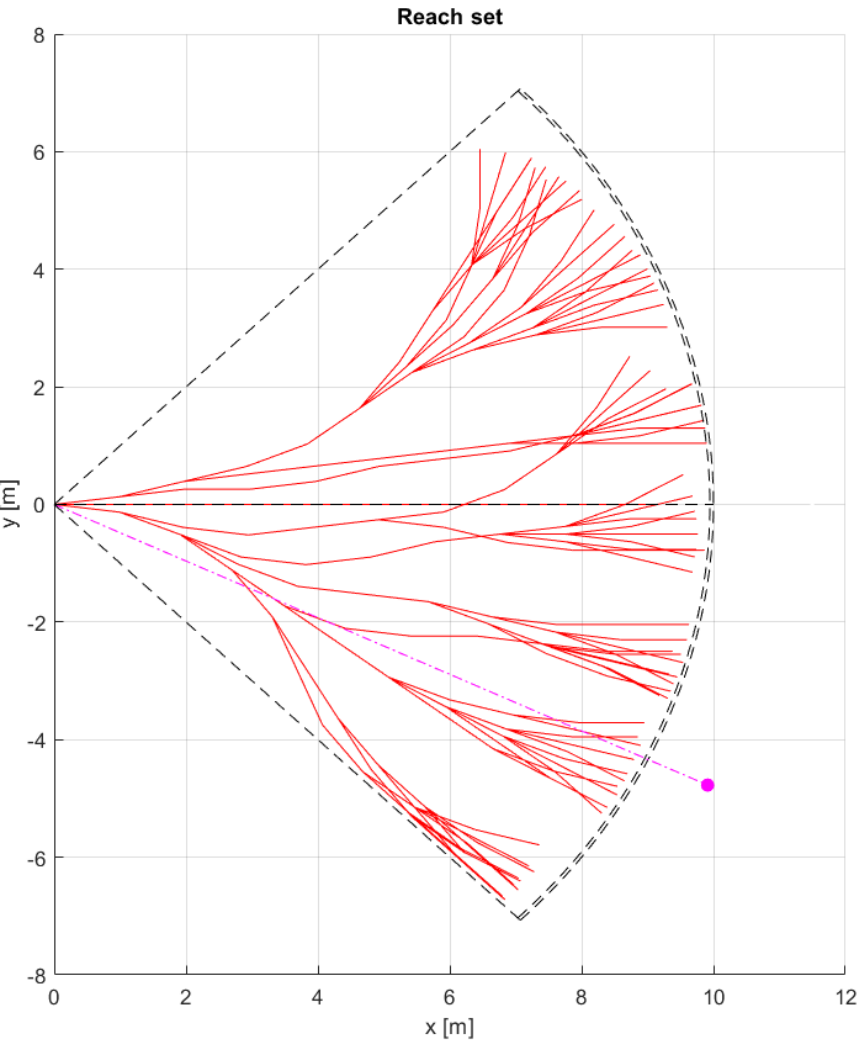
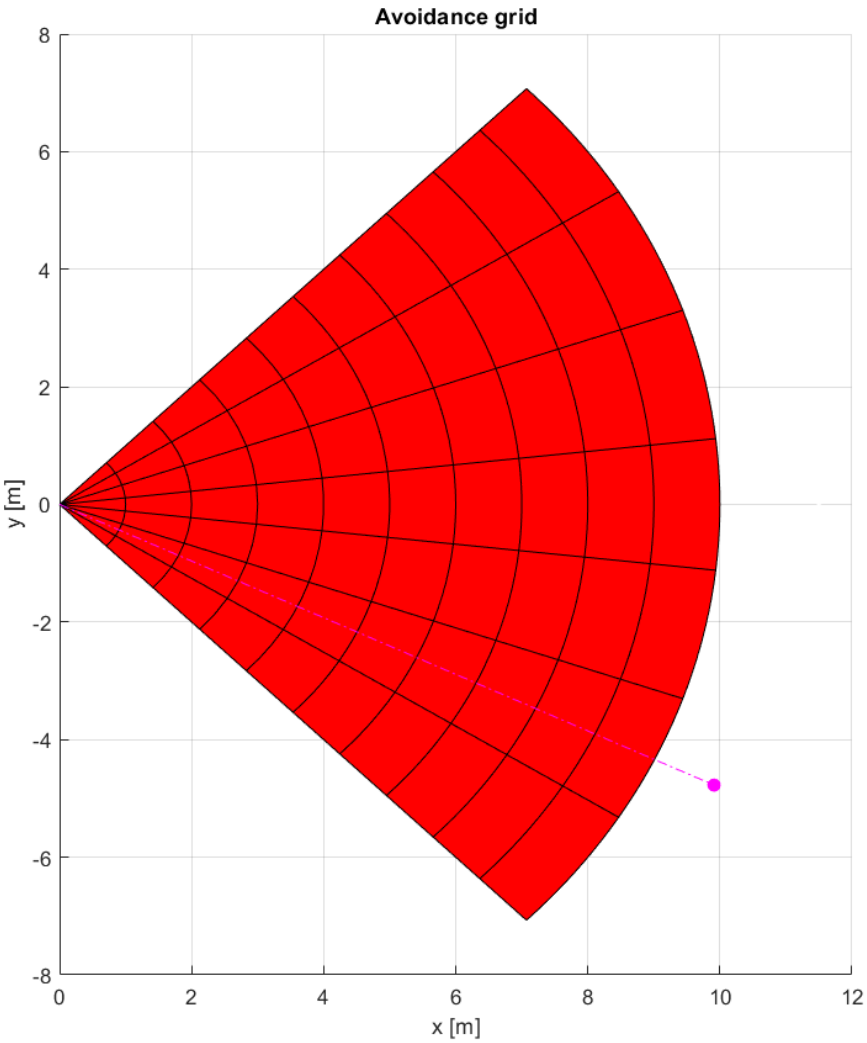
Right Plane Heading (6)





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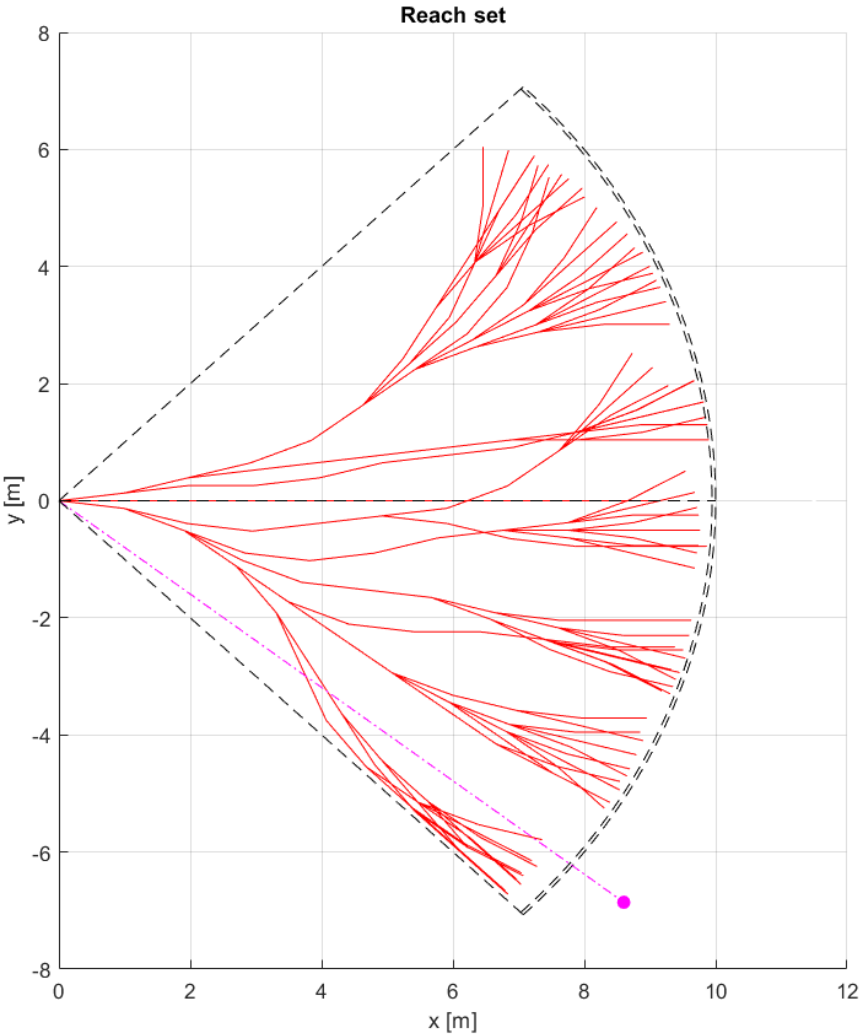
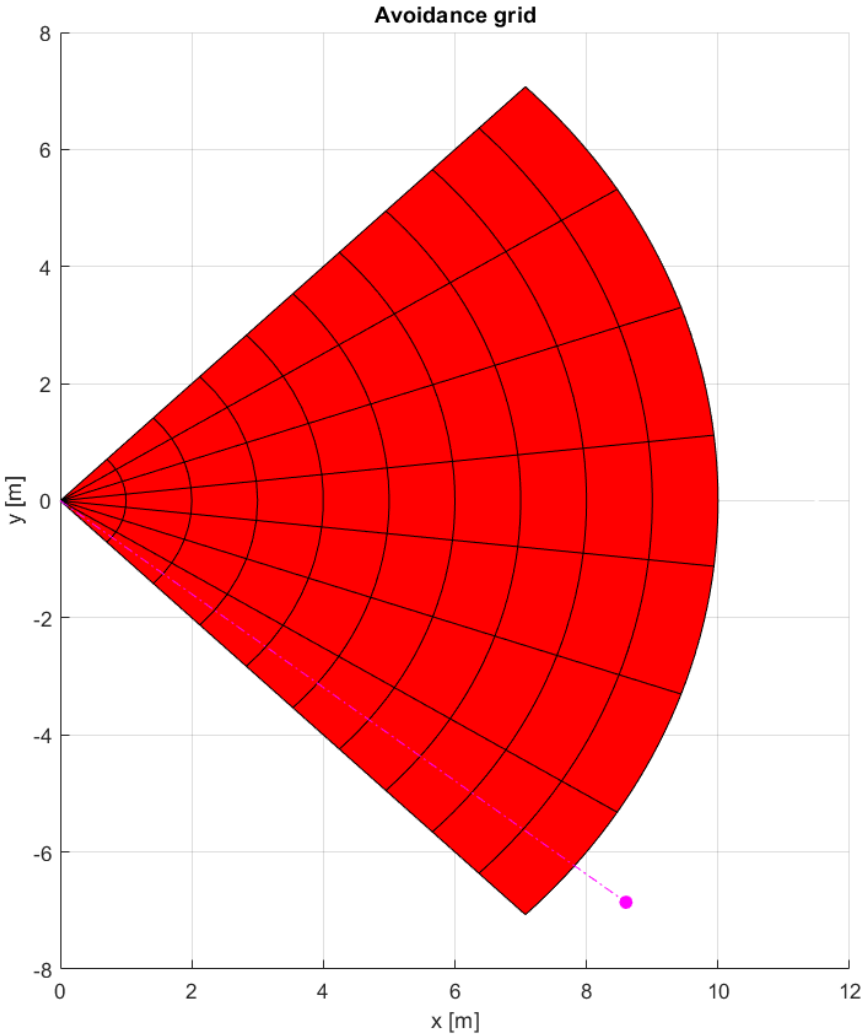
Disable Left Plane Heading (7)





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Rule: Enforce Safety Margin

Collision zone: Well clear zone defined as:

$$XY\ distance(Collision\ point, Airspace\ point) \leq Safety\ margin$$
$$Flight\ Level\ Start \leq \mathrm{Z}(\text{Airspace point}) \leq Flight\ Level\ End$$

Note: *Collision zone Safety Margin is greater than Emergency Collision Safety Margin*, Collision zone Safety Margin is enforced by Aviation Authority.

Objective: Disable trajectories which are:

1. *Leading into Collision zone.*
2. *Heading is not considered*, Collision point can change in timeframes.

[o] Collision Point
[--] Separation Line
[.-] Safety Margin Boundary (Collision zone boundary)
[--] Enabled Trajectories
[--] Disabled trajectories
[ ] Reachable cells
[ ] Unreachable cells

Context	Condition	Application
UAS Navigation Grid Collision Point (LOC)	There are feasible trajectories	Disable trajectories of Navigation grid

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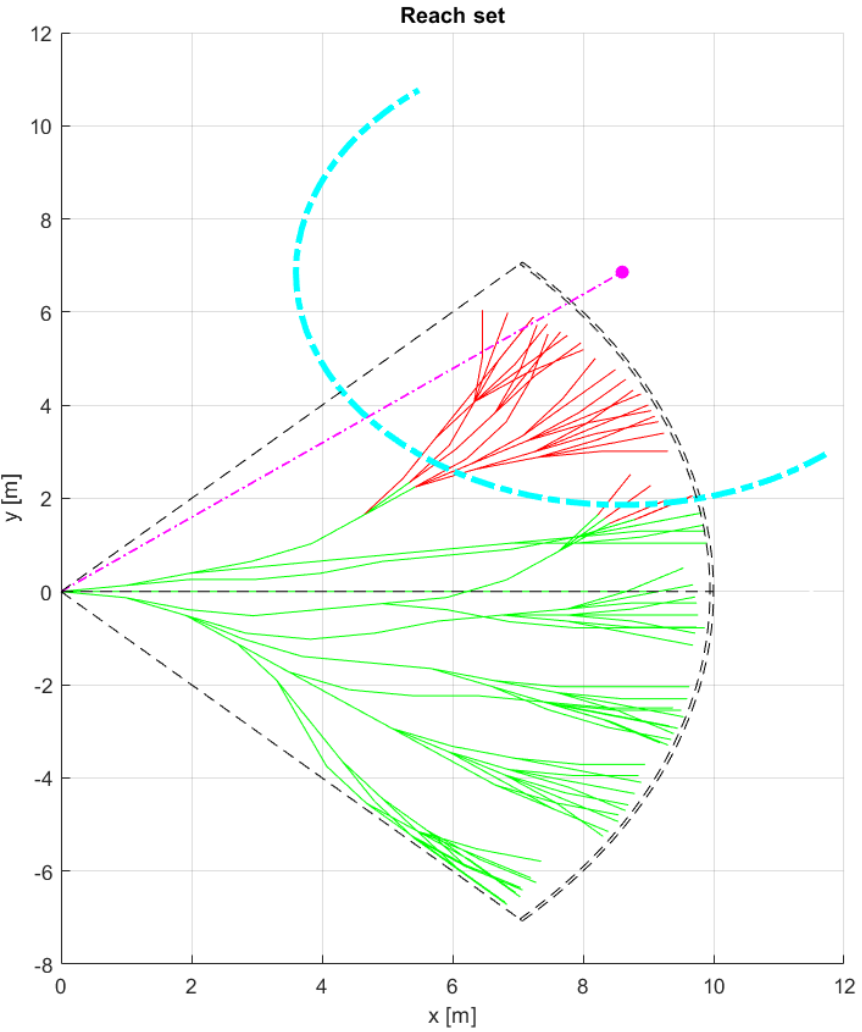
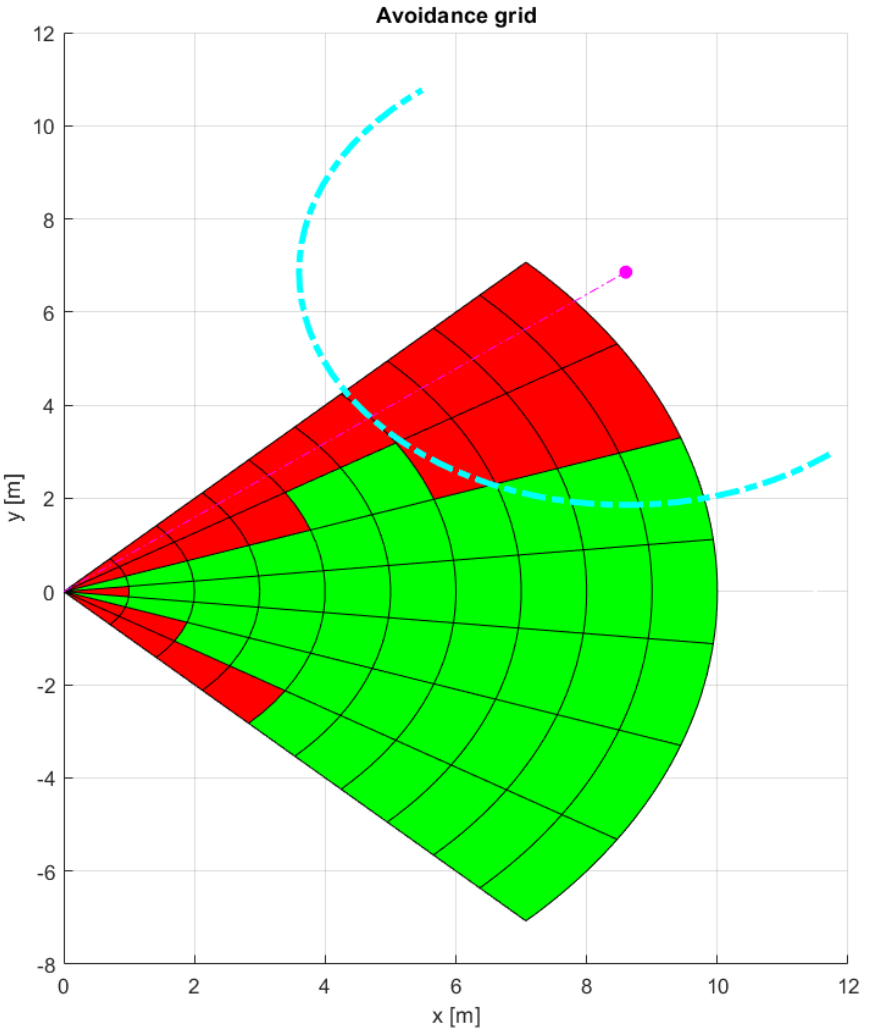
Enforce Safety Margin (1)





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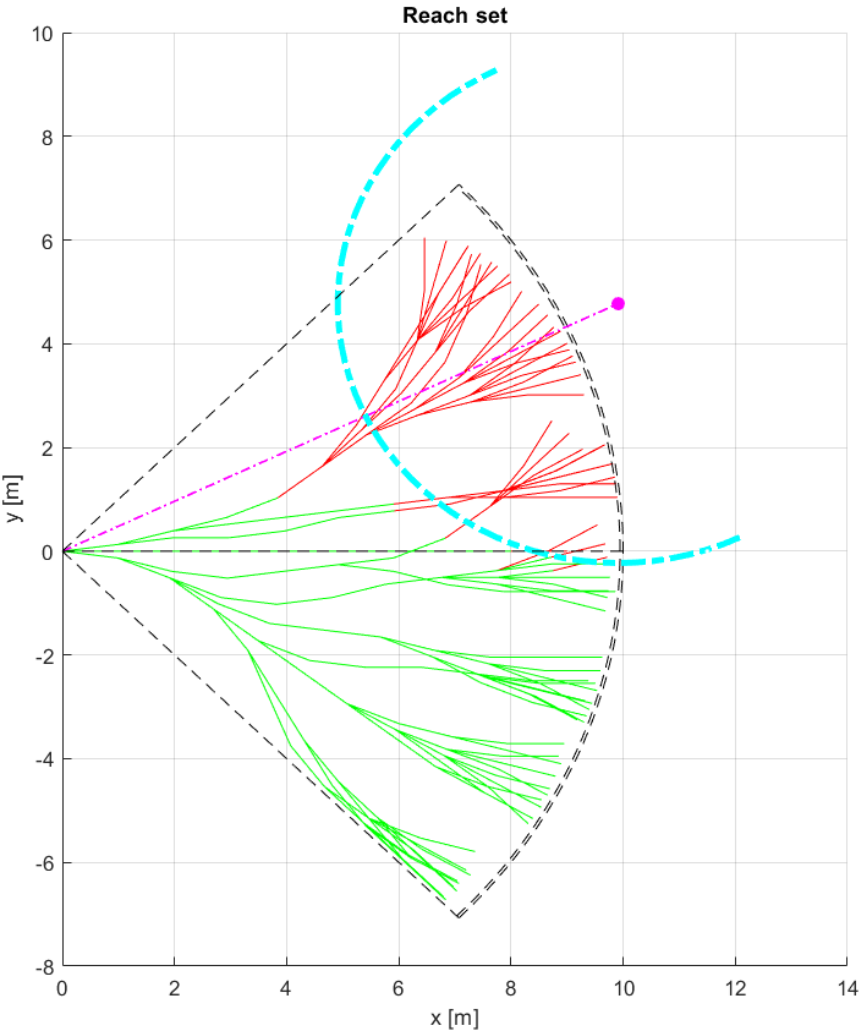
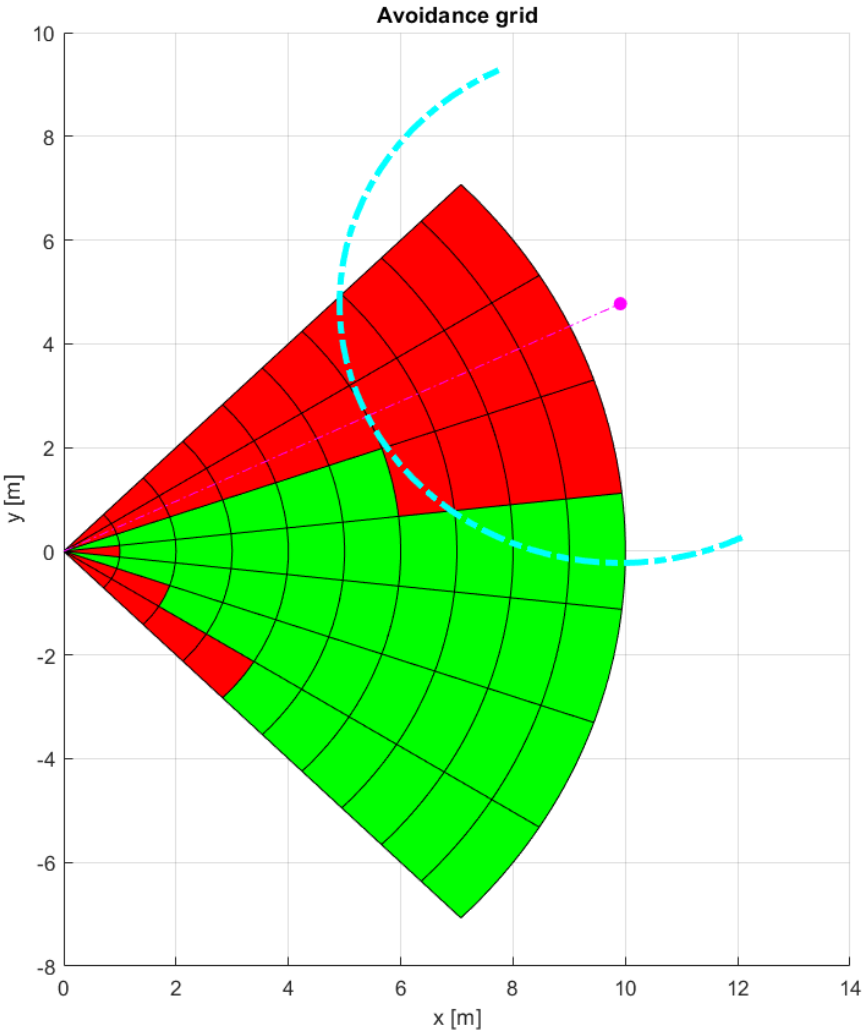
Enforce Safety Margin (2)





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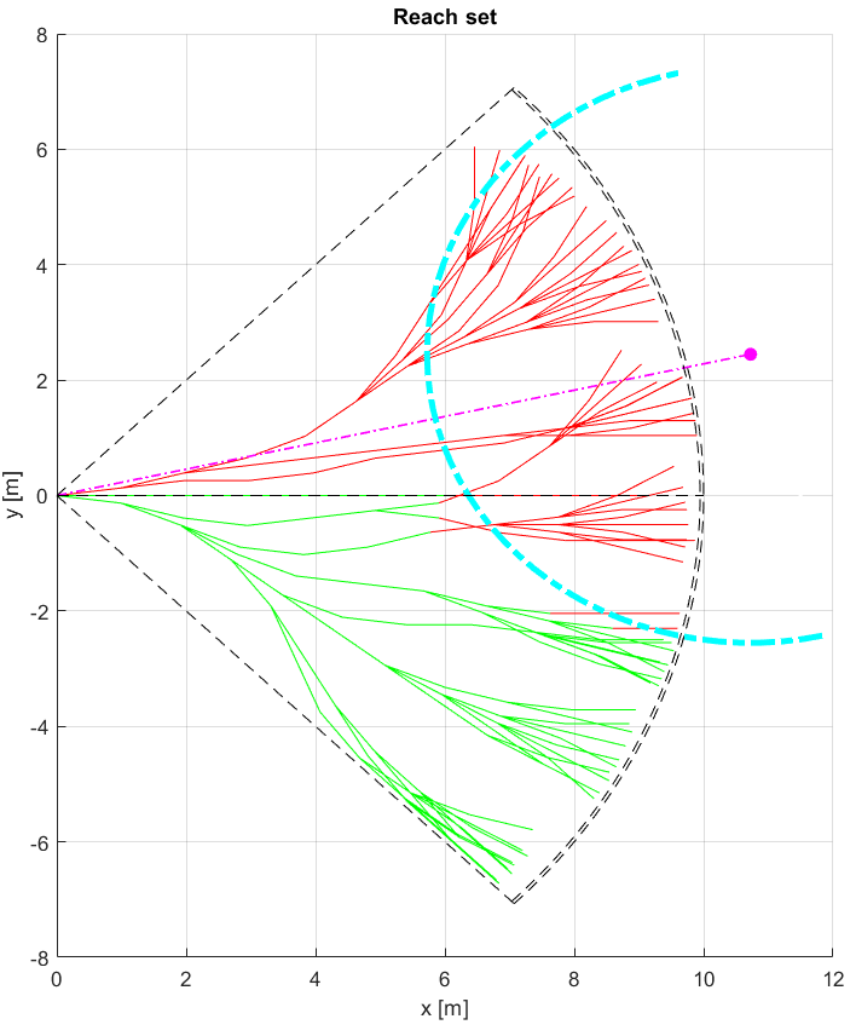
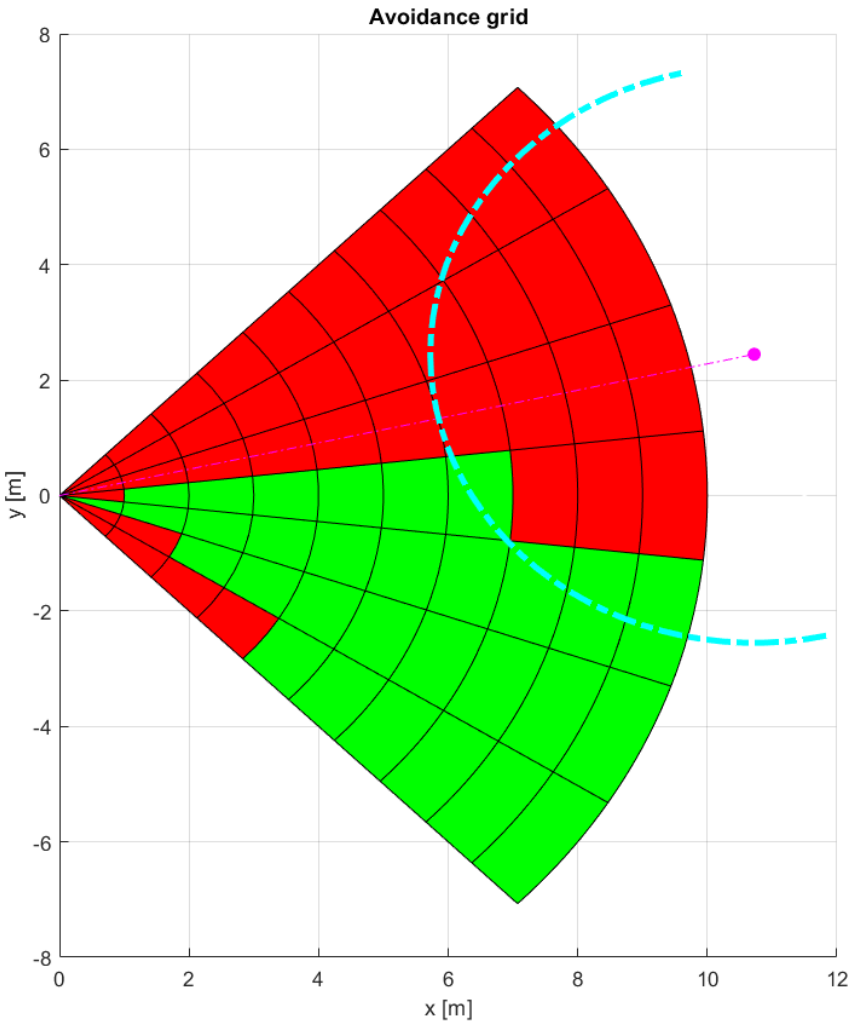
Enforce Safety Margin (3)





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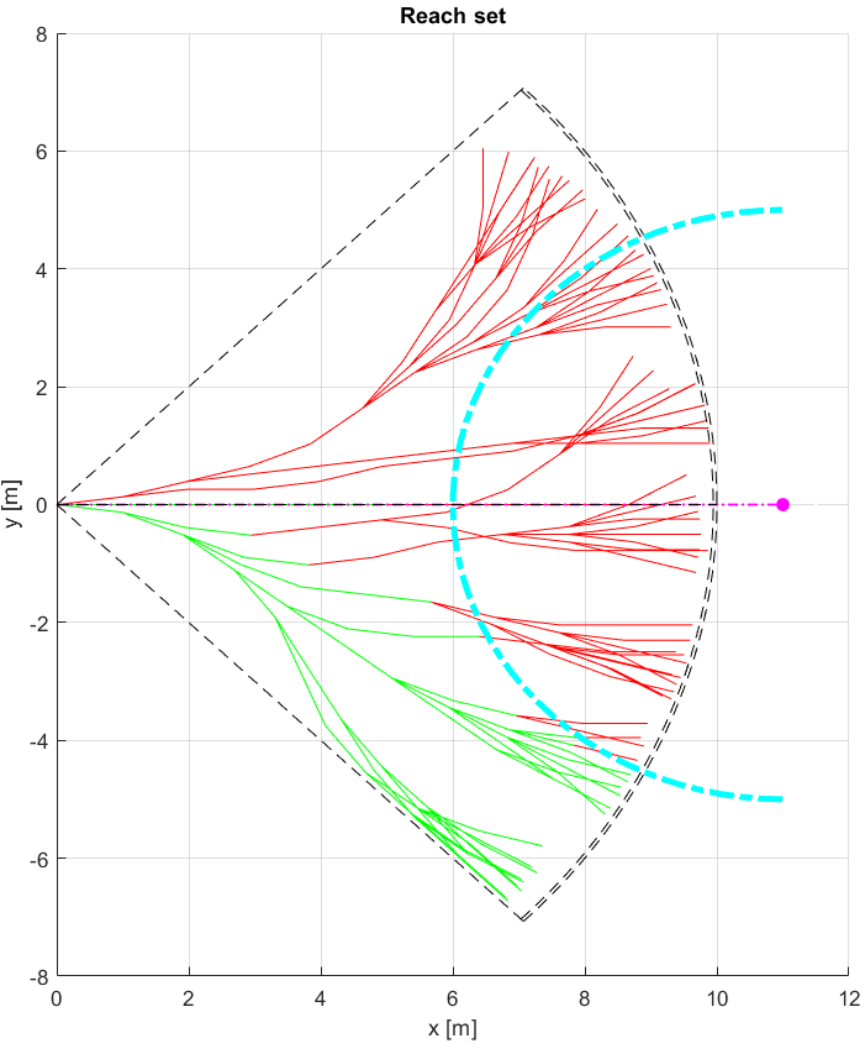
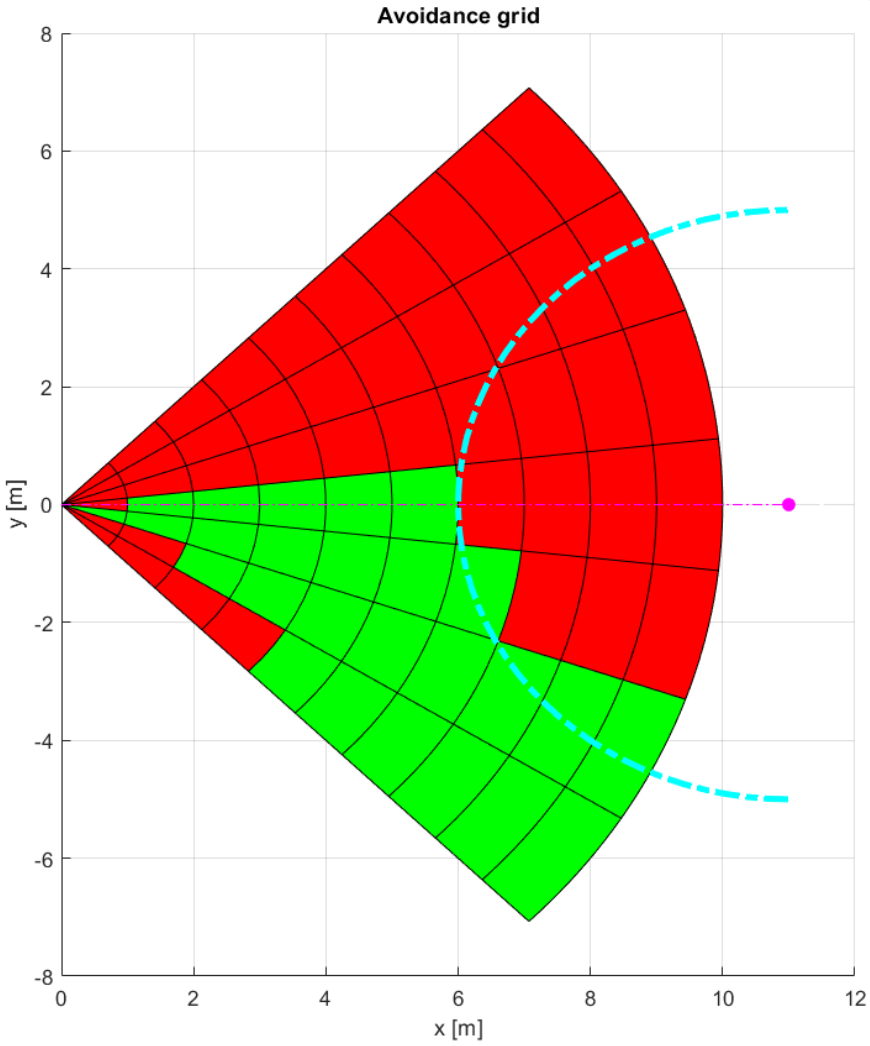
Enforce Safety Margin (4)





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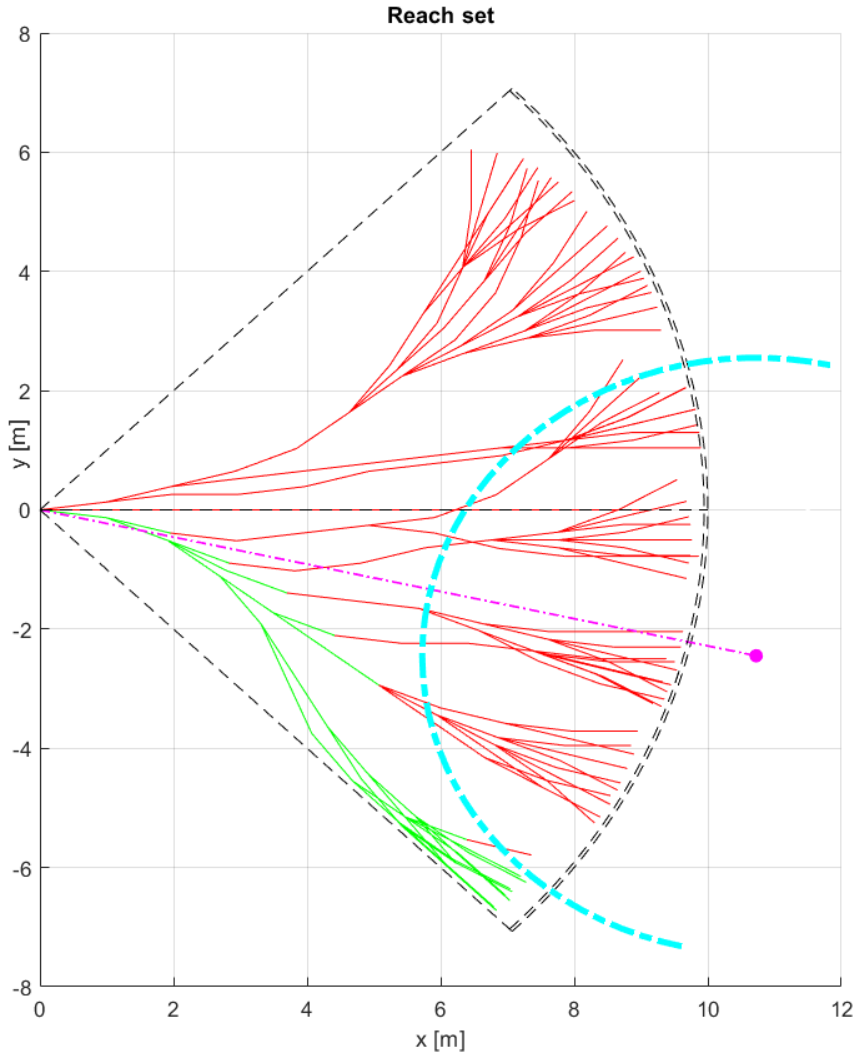
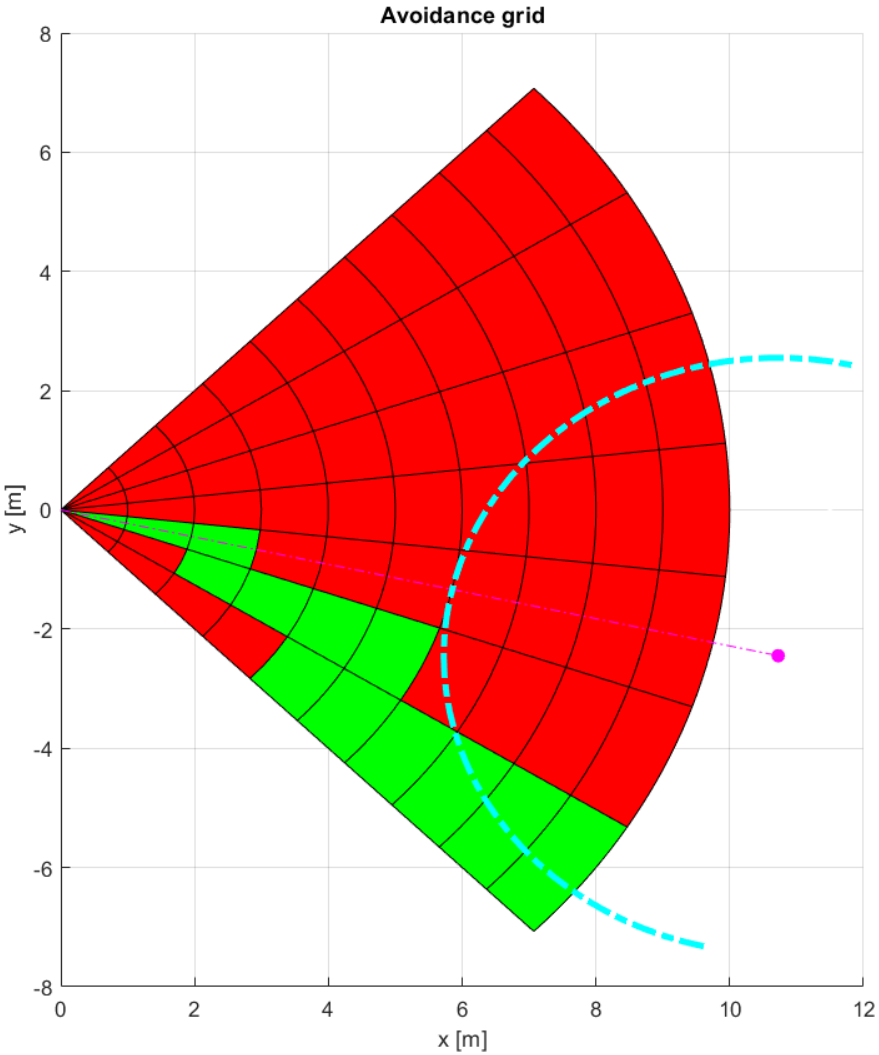
Enforce Safety Margin (5)





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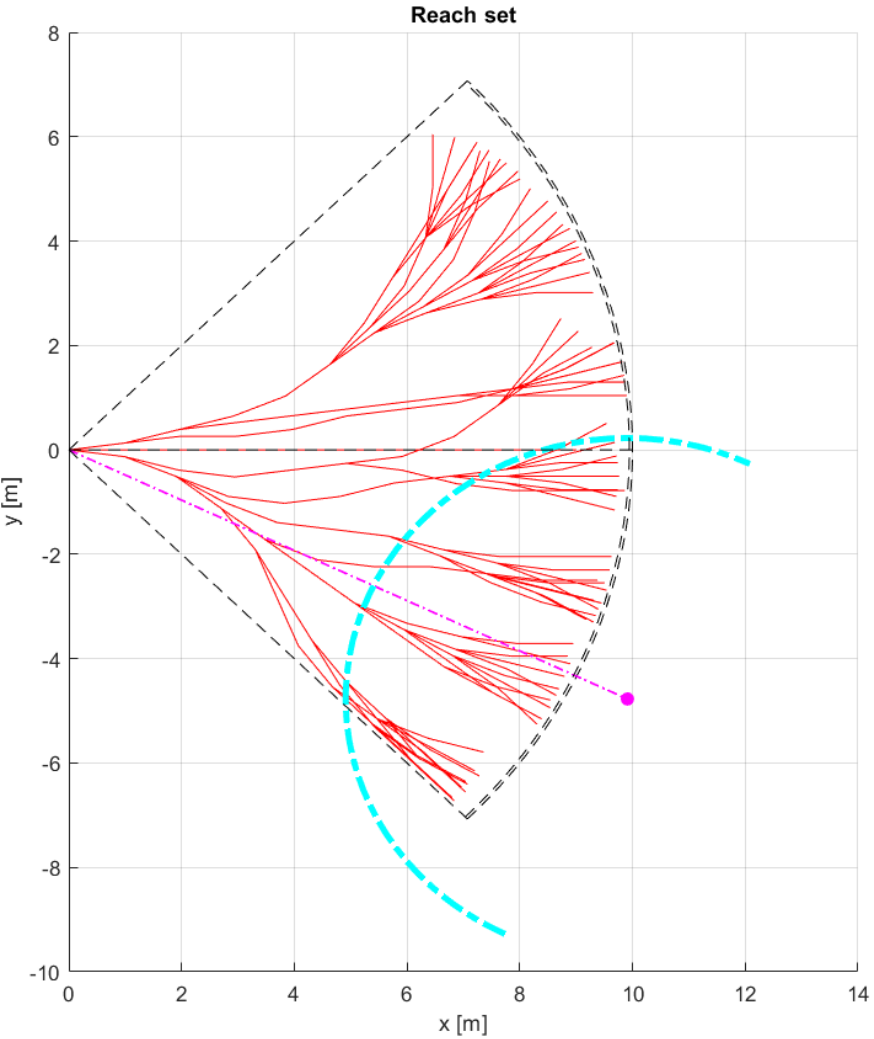
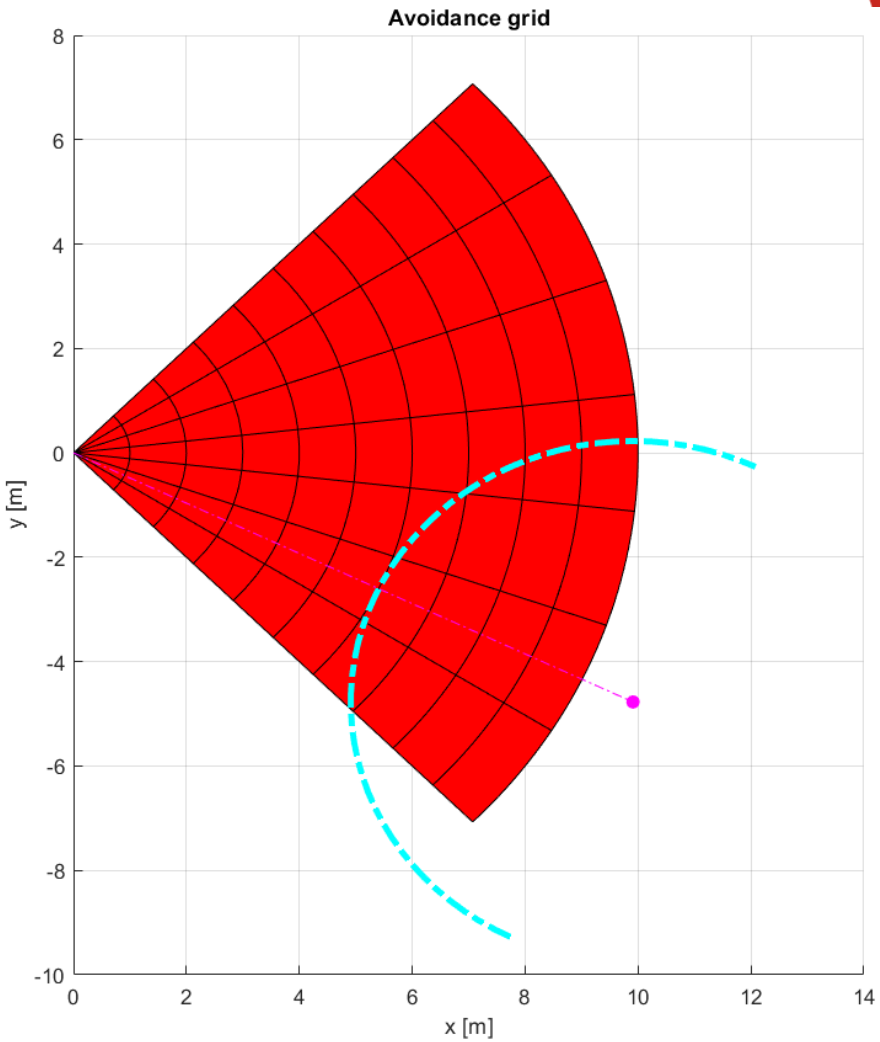
Enforce Safety Margin (6)





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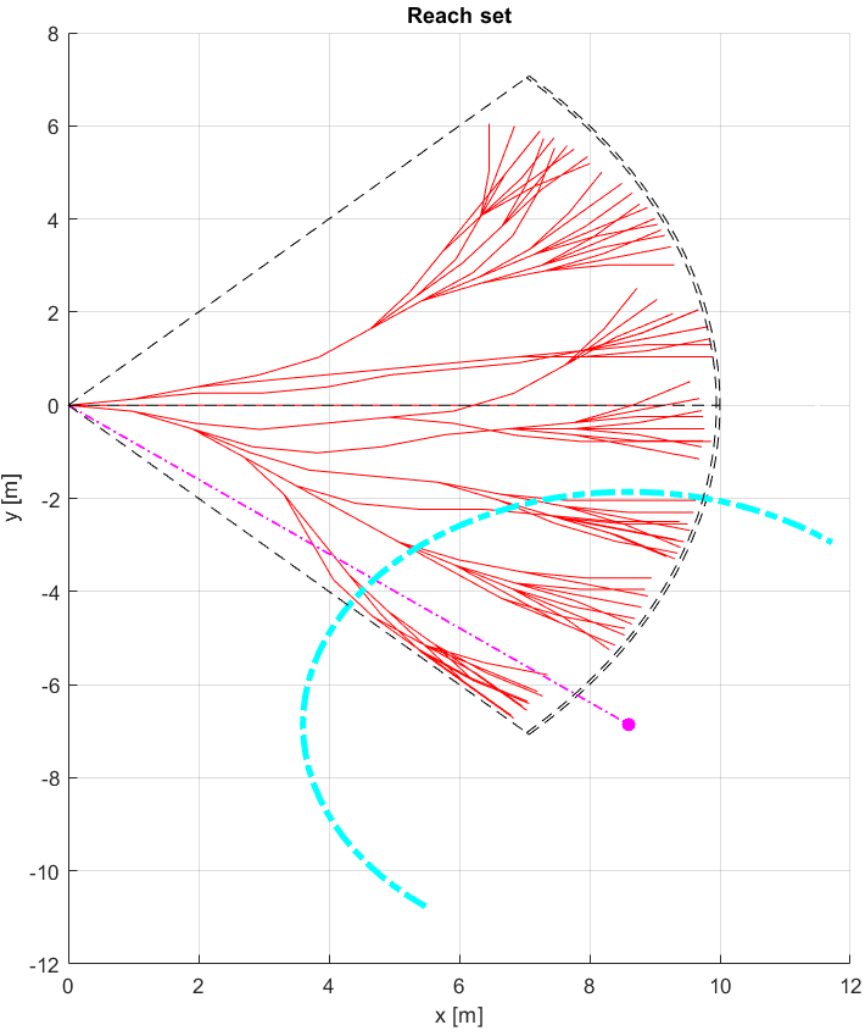
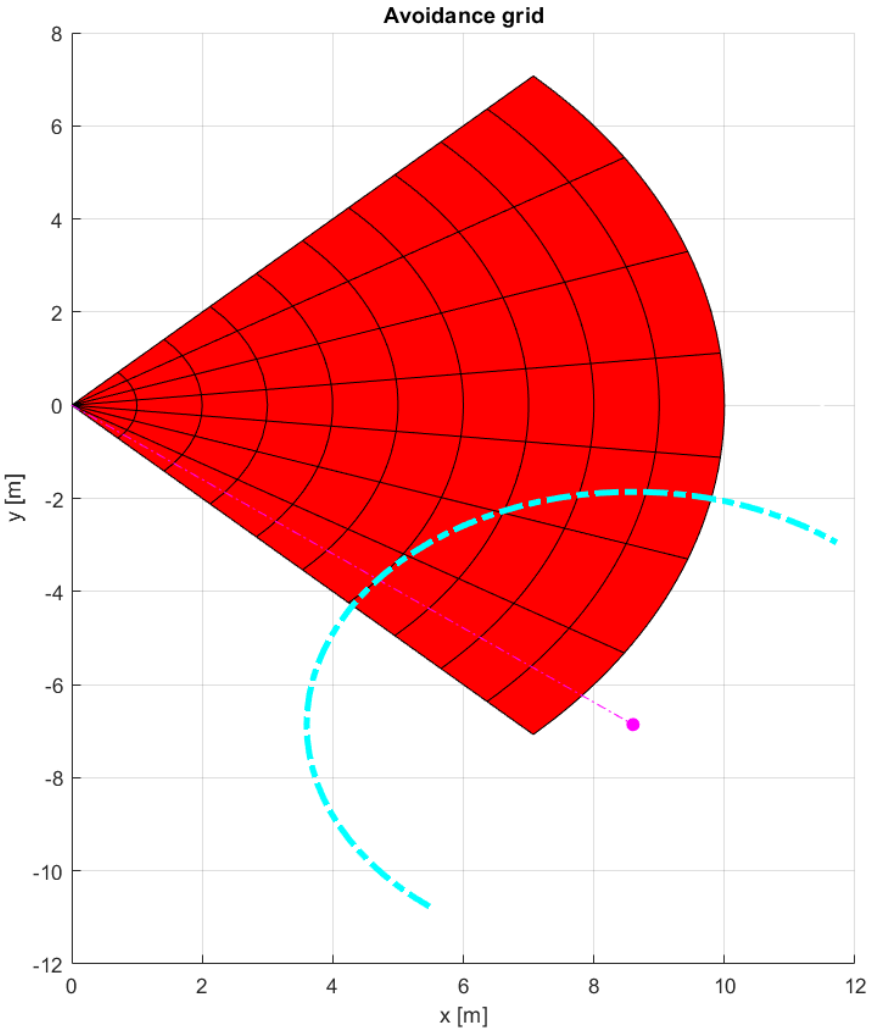
Enforce Safety Margin (7)





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Rule: Detect Collision Cases

Invocation: Every *Decision Point* in UAS main *navigation loop*.

Objective: Prepare Collision Cases for evasive maneuvers application

1. Fetch UTM Collision Cases for given timeframe,
2. Create/Update own Collision Cases for given timeframe,
3. Merge Collision cases based on source priority order,
4. Select Active Collision Cases based on following conditions:
   1. *Active participation* in collision *case => avoidanceRole ~= Right of the Way,*
   2. Collision Point is in front of vehicle,
   3. *Emergency mode* of all Collision Case participants is ***INACTIVE.***
5. Order Collision Cases *based on **SEVERENITY*** (descending),
6. If there is at *least one active collision case enforce inner Avoidance Run.*

Context	Condition	Application
UAS Mission Control Before Avoidance Run, UTM/UAS Col. Cases	Clean Avoidance Grid, No higher Avoidance priority,	Active Collision Cases selection, Prioritization

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Rule: Resolve Collision Case

Invocation: This rule is invoked only if there is any active Collision Case in given Navigation Grid timeframe, moreover Avoidance Grid should be empty.

Objective: Based on own calculated collision cases and UTM directives (has higher priority):

1. Fetch Active Collision Cases(Avoidance Role, Collision Point)
2. Enforce Rules *based on Avoidance Role and Collision Point* as:
    1. Converging Maneuver – invoke Rule: Converging Maneuver
    2. Head On approach – invoke Rule: Head On Approach
    3. Overtake – invoke Rule: Overtake
    4. Emergency Maneuver – register intruder object into UAS Mission Control

Context	Condition	Application
UAS Mission Control, Trajectory restriction, Collision Cases	Active UTM collision Case, Resolution mandate for UAV	Enforce Rules of Air OR Enforce Emergency

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Rule: Close Collision Case

Invocation: There *exists at least one Active Collision Case.*

Objective: Ensure that *multiple Avoidance Rules application gives feasible Avoidance Strategy*, otherwise enter ***EMERGENCY MODE,***

1. *Collect rules* applied on *Navigation Grid* from *Active Collision Cases*,
2. *Calculate* possible *routes for Avoidance* (there may be none),
3. ***If there is no Active Route***: *For each Intruder*:
    1. Issue warning message to containing expected *Collision Point*, and, *Preferred Separation Type*,
    2. Create *Intruder* objects for *Avoidance Grid*
    3. Calculate *Evasive Maneuver* based on *Expected Separation*.
4. Notify UTM about Collision Case *Resolutions*.
5. Notify UTM with ***Planned Trajectory*** and ***Avoidance Mode***

Context	Condition	Application
UAS Mission Control, After Avoidance Run, Collision Resolutions	At least one route in Navigation Grid, Emergency check	Force Emergency Mode OR Close Collision Cases

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Rule: Converging Maneuver

Invocation: When role of UAS is Converging and Avoidance Grid is Empty

Objective: Ensure that UAS will not enter into Intruder “Well clear” barell.

1. Prevent Left-Side Maneuvers
2. Prevent Converging Safety Margin Breach
3. Return to original Path
4. Prevent Wake turbulence.

Context	Condition	Application
UAS Navigation Grid Collision Point, Avoidance Role	None	RunRules: • Right Plane Heading • Enforce S. Margin

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Rule: Head On Approach

Invocation: When role of UAS is Converging and Avoidance Grid is Empty

Objective: Ensure that UAS will not enter into Intruder “Well clear” barbell.

1. Prevent Left-Side Maneuvers,
2. Prevent Converging Safety Margin Breach,
3. Return to original Path,
4. Prevent Wake turbulence,
5. Enforce Round-about behavior,

Context	Condition	Application
UAS Navigation Grid Collision Point, Avoidance Role	None	Run rules: • Right Plane Heading • Enforce S. Margin

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Rule: Overtake

Invocation: Invoked by rule *Collision Case Resolution.*

Divergence Waypoint: waypoint to diverge from original UAS path to ensure Intruder safety, within unchanged intruder velocity and heading.

Convergence Waypoint: waypoint when convergence to original UAS path is enabled, within unchanged intruder velocity and heading.

Objective:

1. Calculate Divergence Waypoint
2. Calculate Convergence Waypoint
3. Enforce Divergence/Convergence waypoint

Context	Condition	Application
UAS Navigation Grid Collision Point, Avoidance Role,	UAS Velocity >>>> Intruder Velocity	Calculate: • Divergence WP • Convergence WP

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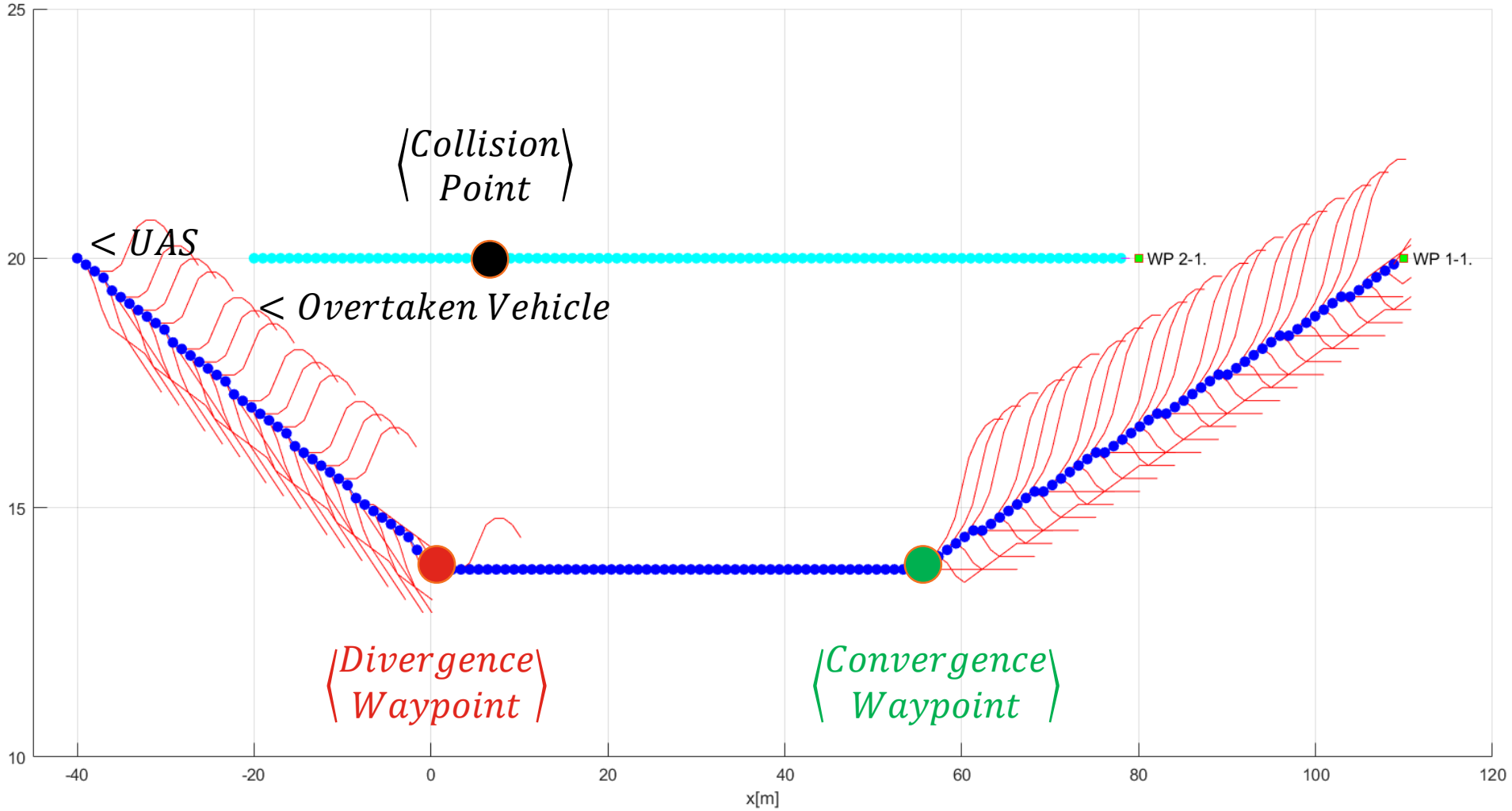
Divergence/Convergence Waypoint Example



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Divergence/Convergence Waypoint Calculation

Main idea is to calculate ***Safe Offset for Overtake Maneuver***, we have:

$$velocityDifference = uasVelocity - overtakenVelocity, \left[\frac{m}{s}, \frac{m}{s}, \frac{m}{s}\right]$$

Decision distance is distance until next framework decision is made:

$$decisionDistance = velocityDifference\ x\ uasDecision\ frame, \left[m, \frac{m}{s}, s\right]$$

Overtake middle distance is length of hypotenuse for triangle where positional difference and safety margin are cathetuses:

$$overtakeMiddle = \sqrt{\|uasPosition - collisionPoint\|_2 + safetyMargin^2}, [m, m^3, m^3, m]$$

Safe offset is then considered as combination of:

$$safeOffset = overtakeMiddle + decisionDistance + waypointReachMargin, [m, m, m, m]$$

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Divergence/Convergence Waypoint Calculation

Simplification: UAS and Overtaken are in Local coordinate frame heading in X+ axis direction (X+ front of vehicles, X- back of vehicles, Y- right side, Y+ left side), *Collision Point* is considered as [0;0;0],

Divergence point in local coordinates is given as right offset of safety margin and decision distance:

$$divergence = \begin{bmatrix} 0 \\ -decisionDistance - safetyMargin \\ 0 \end{bmatrix}, [m^3, m, m]$$

Convergence point in local coordinates is given frontal safeOffset and right offset of safety margin and decision distance:

$$convergence = \begin{bmatrix} safeOffset \\ -decisionDistance - safetyMargin \\ 0 \end{bmatrix}, [m^3, m, m, m]$$

Convergence and Divergence waypoint in global coordinate frame:

$$divergenceWaypoint = collisionPoint + R_{XYZ}(overtakenOrientation)x \ldots \ldots x\ divergence$$

$$convergenceWaypoint = collisionPoint + R_{XYZ}(overtakenOrientation)x \ldots \ldots x\ convergence$$

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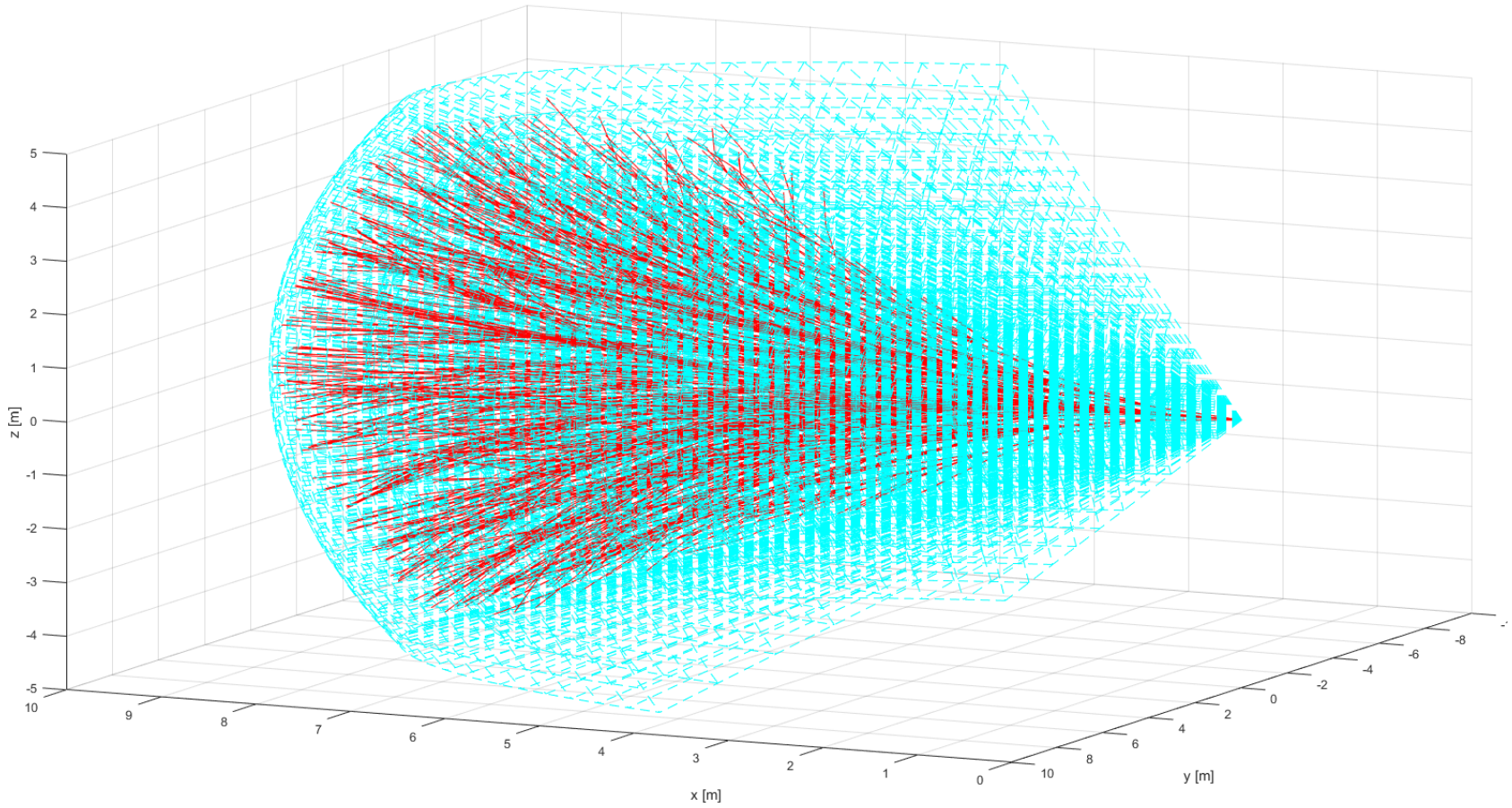
ACAS-XU Reach Set



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ACAS-XU functionality as Reach Set

The Standard Controlled Airspace provides *horizontal and vertical separation* functionality, the separation in *manned aviation is secured* by ***TCAS I/II*** systems which issues *Traffic Alerts* and recommends *Directional Changes Advices*.

Next generation separation system family ACAS-X (in development) can issue *Traffic Commands*, taking *Unmanned Aviation* into account, the special framework ***ACAS-XU is dedicated for UAS systems*** (autonomous drones).

The ACAS-XU provides following separations:

- Standard Separations – inherited from TCAS II and Other ACAS-X systems.
- Combined Separations – native for ACAS-XU systems.

Restricted Reach Set estimation method is presented for following reasons:

- Increase Framework variability and provide functionality for ACAS-XU
- Prove that framework is independent of the used Reach Set Estimation method

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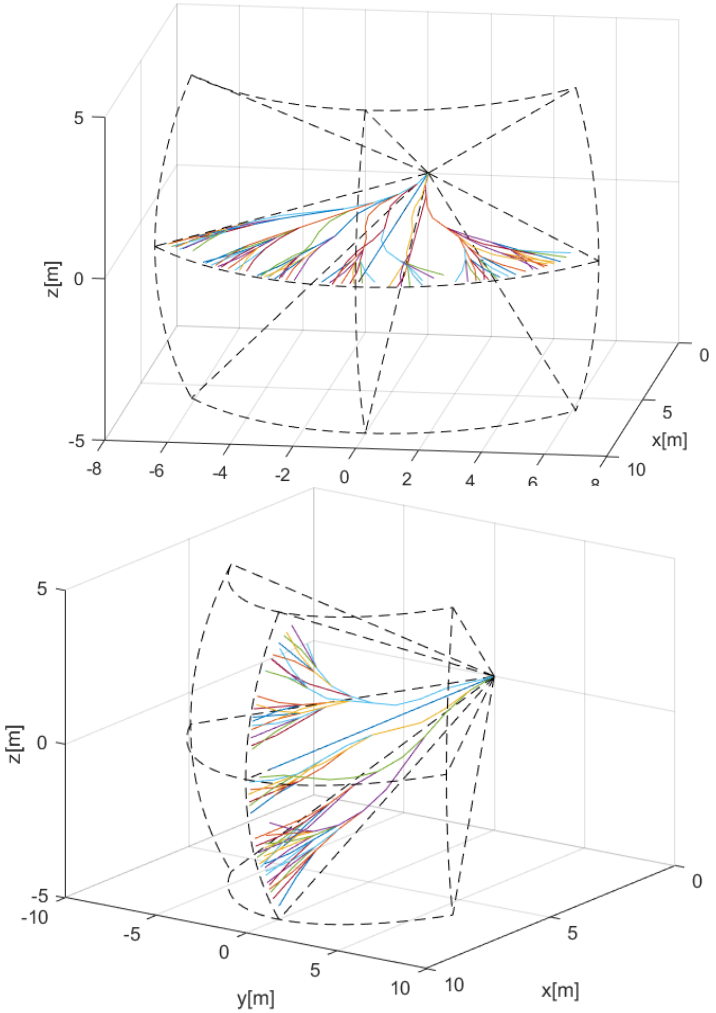
Standard Separations

Standard Separations are supported in other *ACAS-X implementations* as *maneuver look-up tables*, the trajectories are slightly diverged right (horizontal) and down (vertical) for support of *standard TCAS II behavior* and *Rules of the Air implementation.*

Horizontal Separation – standard separation in *Flight Level area regardless of the altitude*, horizontal separation *would not break flight level* therefore is preferred for conflict resolution.

Vertical separation – separation for aircrafts with *better horizontal maneuverability*.



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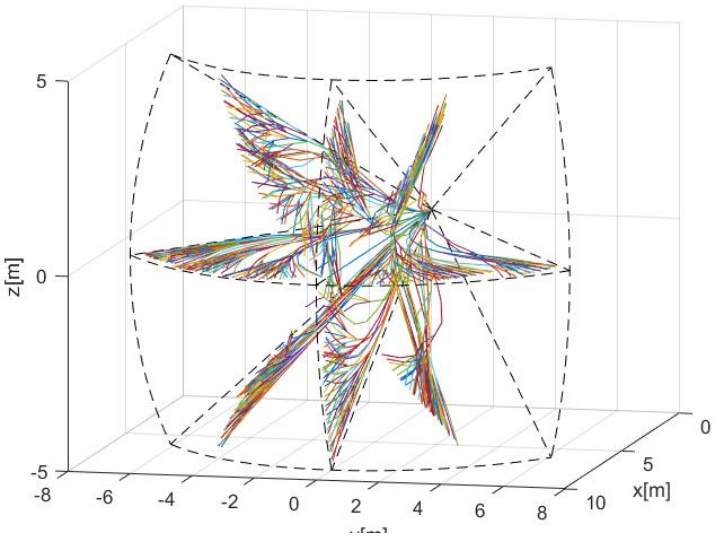
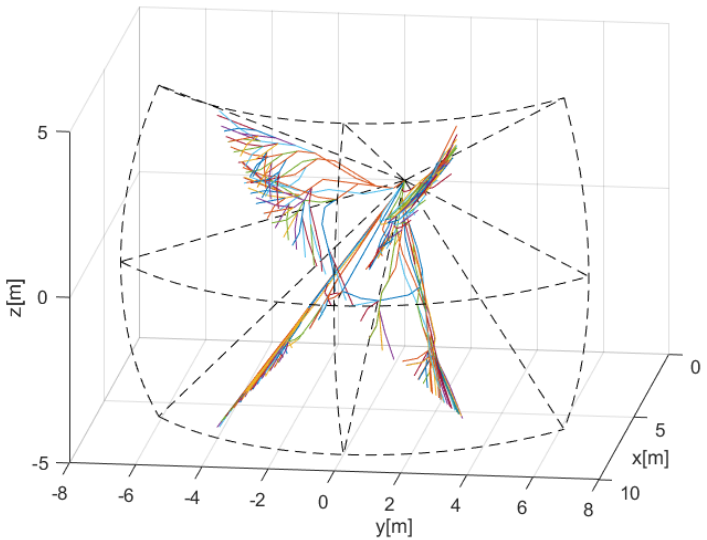
Combined Separations

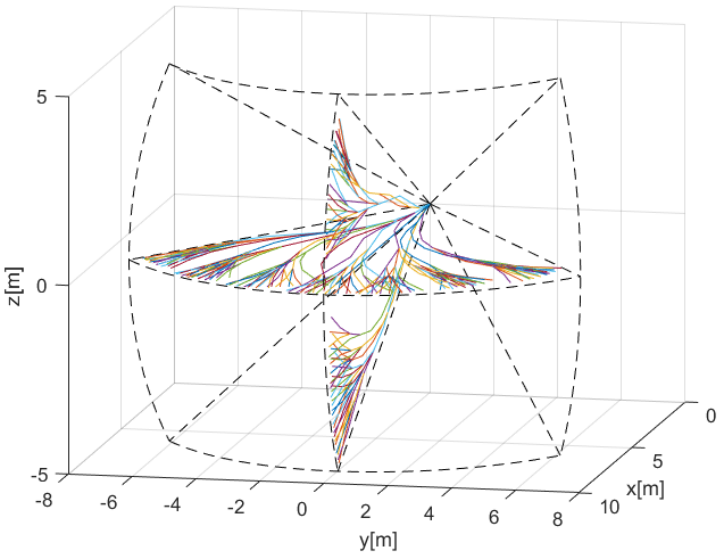
Complete separations – containing horizontal vertical and tilted separations, closest to original *Harmonic Reach set.*

Horizontal/Vertical – containing horizontal and vertical separations, close to original *TCAS II.*

Tilted Left/Tilted Right – ACAS-XU







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Emergency and Planned Avoidance

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What is Going to be Tested

Time to do some testing

Innocent UAS systems

Yay!

We are going to test:
- Event Based Avoidance
- Situation Based Avoidance

On standard ACAS/ICAO scenarios:
- Converging Maneuver
- Head On Approach
- Multiple Collision Cases
- Overtake (Multiple speeds)

Reminder on Collision Avoidance Types

Preemptive based	Event based	Situation based
• Well defined Waypoints • Free Space guarantee • Preflight preparation • Legal compliance	*Targets of avoidance*: • Cooperative intruders (Rules of the air) • Bad weather • Geofencing	*Targets of avoidance*: • Non-Cooperative intruders • Terrain • Other physical obstacles

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Standard Scenarios

Converging Maneuver

- *Event Based:*
  - 2x UAS system
  - ADS-B I/O
- *Situation Based:*
  - 2x UAS system
  - ADS-B I/O
  - UTM Advisory

Head-On Approach

- *Event Based:*
  - 2x UAS system
  - ADS-B I/O
- *Situation Based:*
  - 2x UAS system
  - ADS-B I/O
  - UTM Advisory

Multiple Collision Cases

- *Event Based:*
  - 4x UAS system
  - ADS-B I/O
- *Situation Based:*
  - 4x UAS system
  - ADS-B I/O
  - UTM Advisory

Overtake

- *Situation Based*
  - 2x UAS system
  - ADS-B I/O
  - UTM Advisory
  - 2x Overtaking/Overtaken velocity
  - 3x Overtaking/Overtaken velocity
  - 4x Overtaking/Overtaken velocity

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Converging Maneuver

Situation:

- *Two UAS systems* equipped with ADS-B are *approaching* Collision Point
- Both systems are using *ACAS-XU Horizontal Separation*
- Angle of Approach is equal to 90 degrees

Resolution (Emergency)

- Both *UAS receive ADS-B message* with intruder *heading and position*
- Safety margin: 1.2 m (30 cm body radius, 30 cm protection margin)
- Intruder model: Time-Based, Body mass intersection (r=60 cm)

Resolution (Rule Based)

- Both UAS broadcasts ADS-B message to UTM system
- *UTM creates Collision Case* and Mandates UAS with *Avoidance Roles*
- Safety margin: 8 m (Enforced in Navigation Grid)

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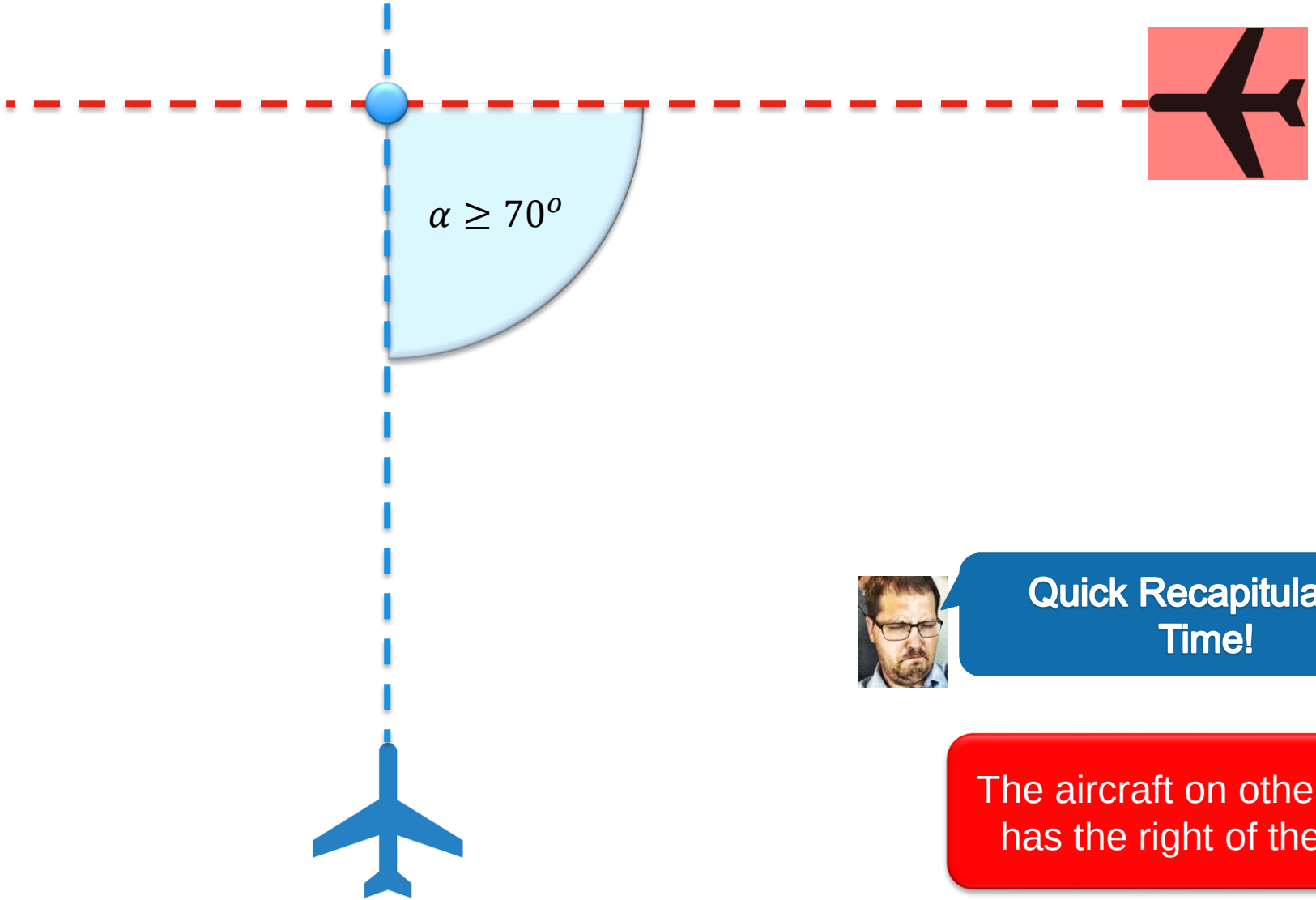
Converging Maneuver - Trigger



Quick Recapitulation Time!

The aircraft on other right, has the right of the way

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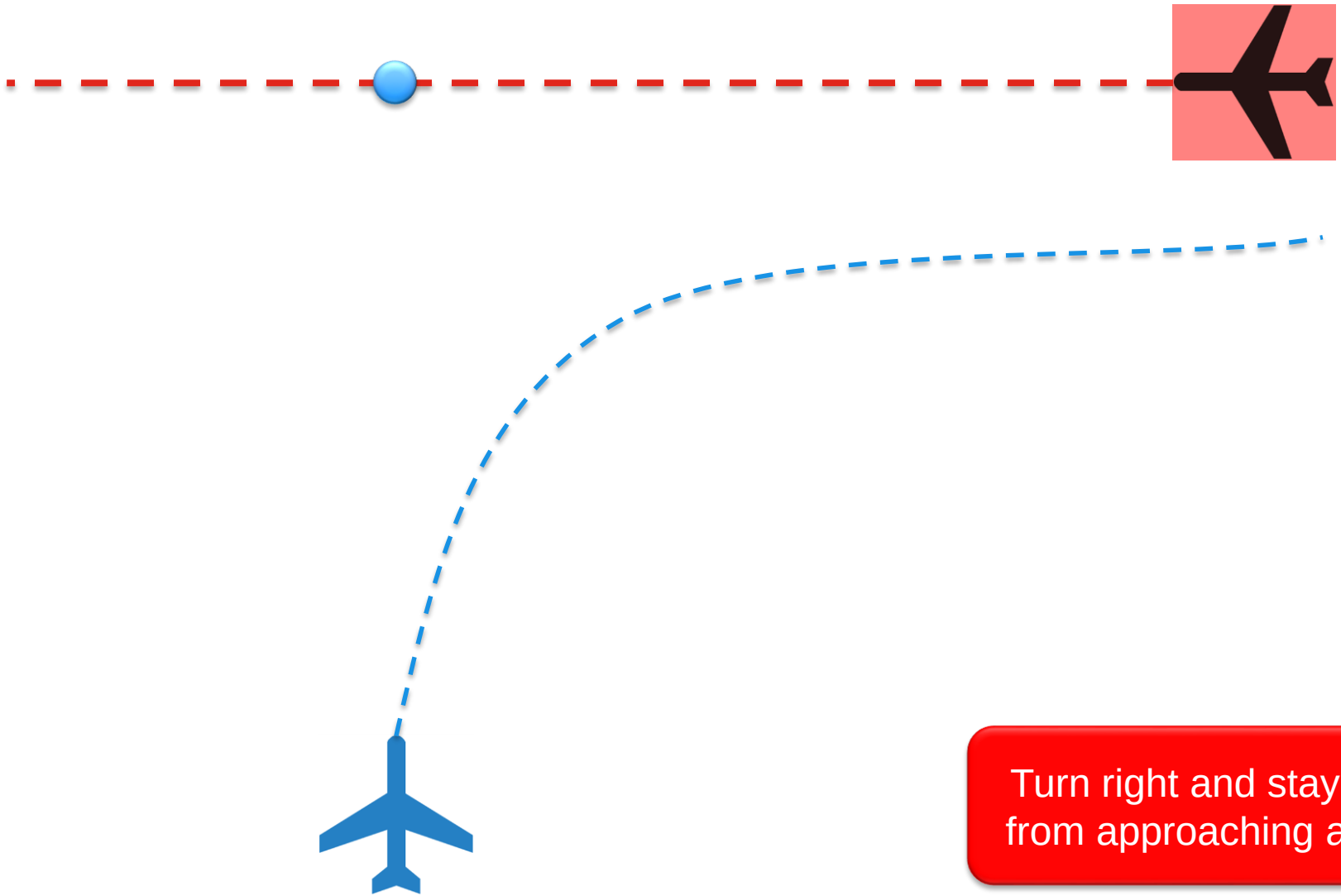
Converging Maneuver - Resolution



Turn right and stay away from approaching aircraft

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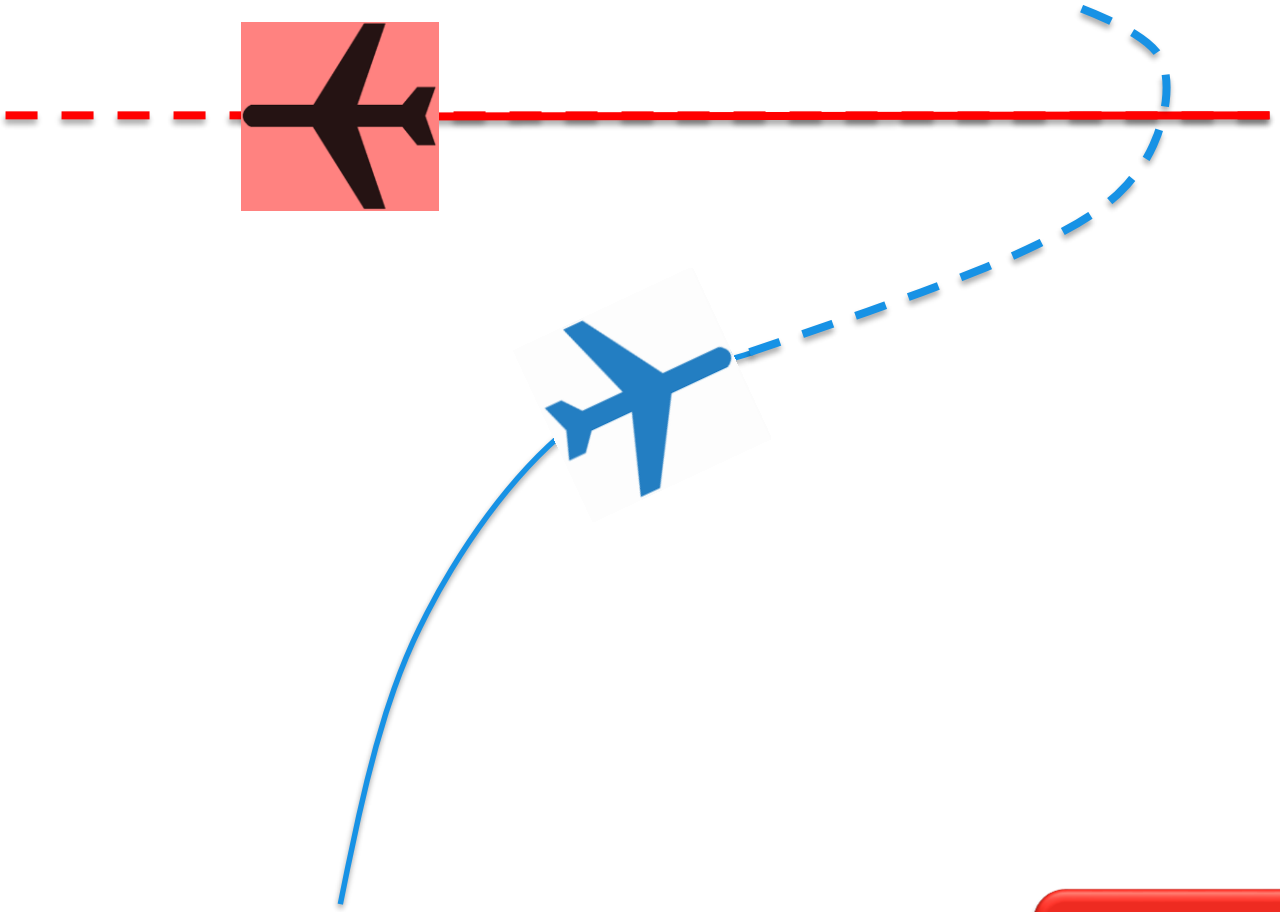
Converging Maneuver – Leave condition



Return to original path behind other aircraft

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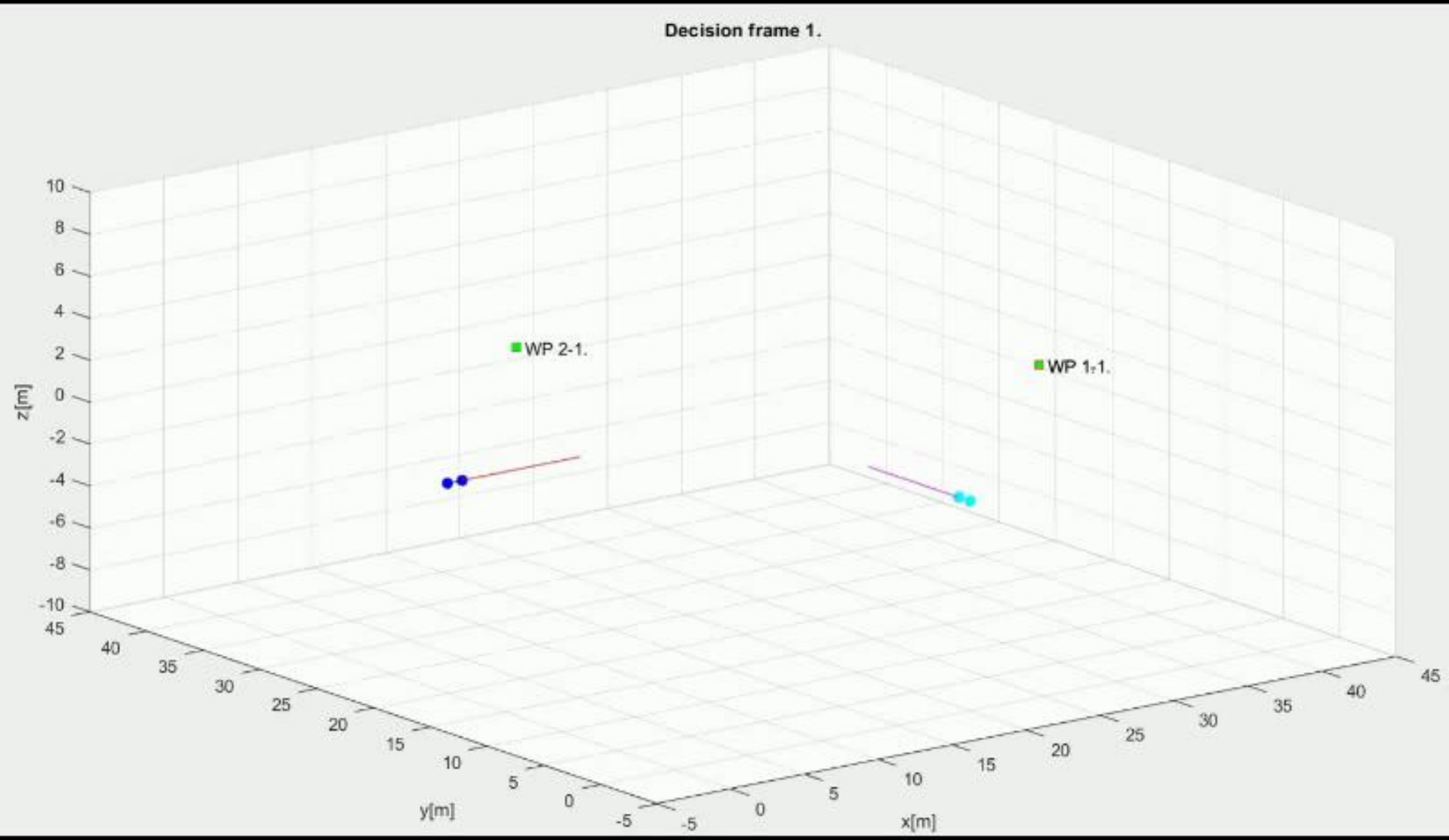
Emergency: Converging Maneuver



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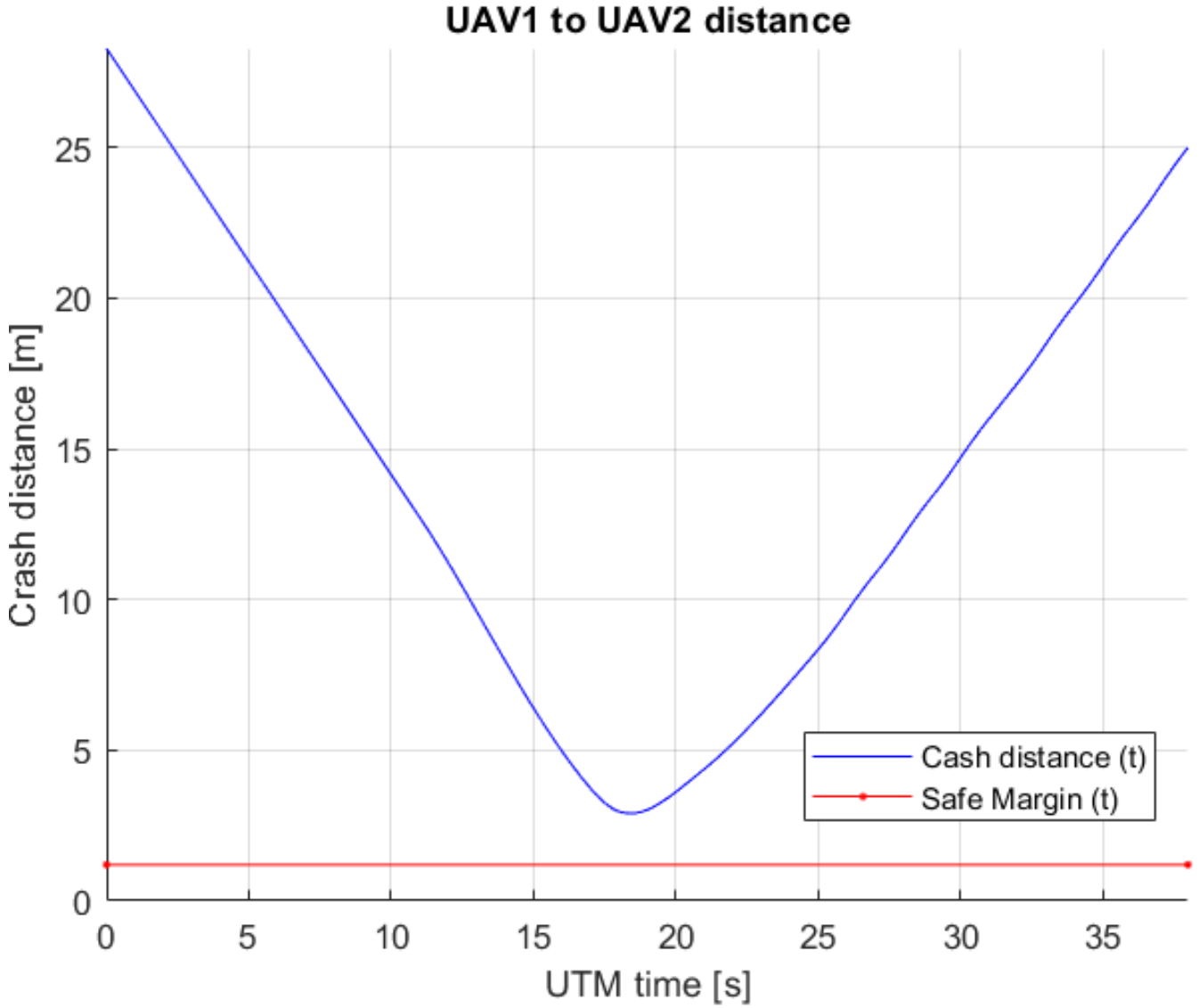
Emergency: Converging Maneuver

No Collision!



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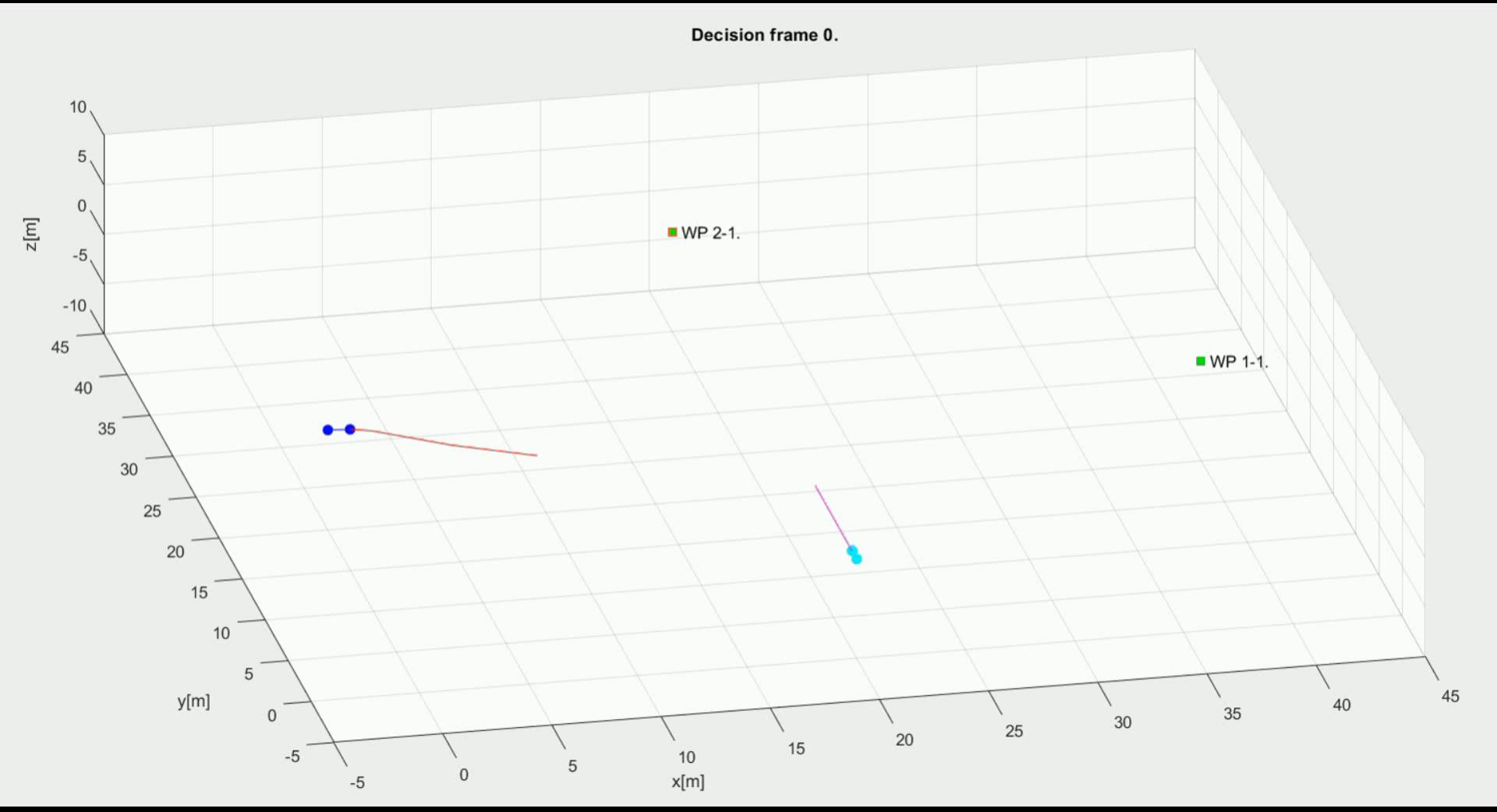
Rule-Based: Converging Maneuver



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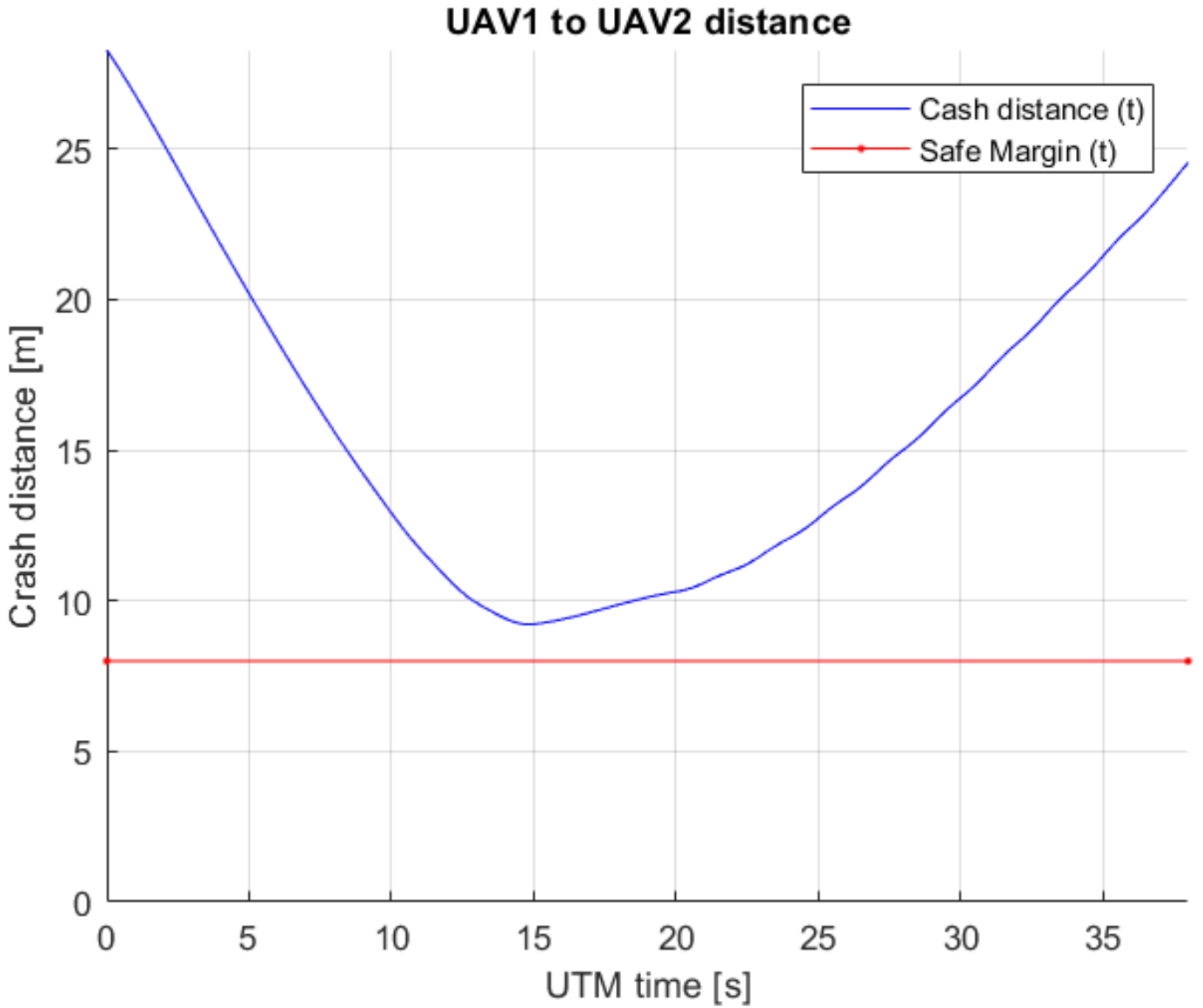
Rule-Based: Converging Maneuver

No Collision!



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Head On Approach

Situation:

- *Two UAS systems* equipped with ADS-B are *approaching* Collision Point
- Both systems are using *ACAS-XU Horizontal Separation*
- Angle of Approach is equal to 180 degrees

Resolution (Emergency)

- Both *UAS receive ADS-B message* with intruder *heading and position*
- Safety margin: 1.2 m (30 cm body radius, 30 cm protection margin)
- Intruder model: Time-Based, Body mass intersection (r=60 cm)

Resolution (Rule Based)

- Both UAS broadcasts ADS-B message to UTM system
- UTM creates Collision Case and Mandates UAS with avoidance roles
- Safety margin: 15-20 m (Enforced in navigation grids)

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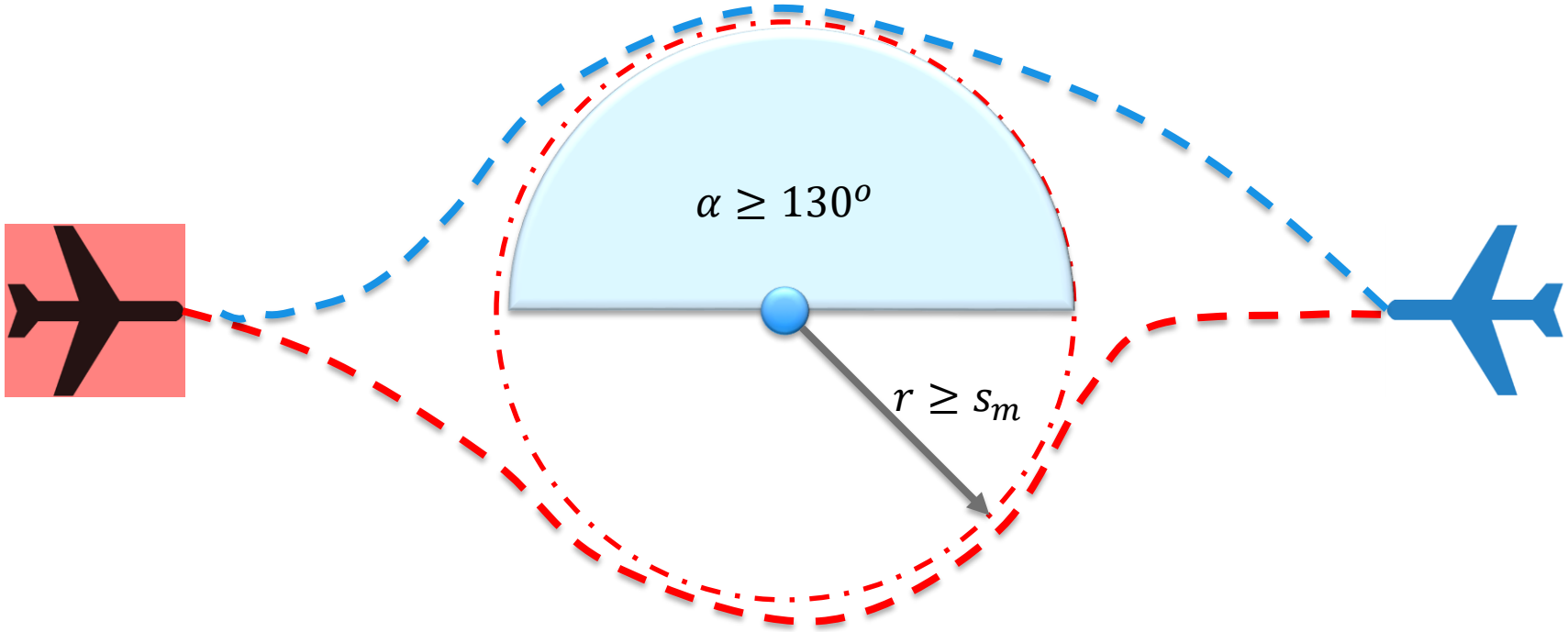
Head On Approach - Trigger

Quick Recapitulation Time!



Applies when angle of approach $\alpha \geq 130^o$, Safety margin s_m must be defined

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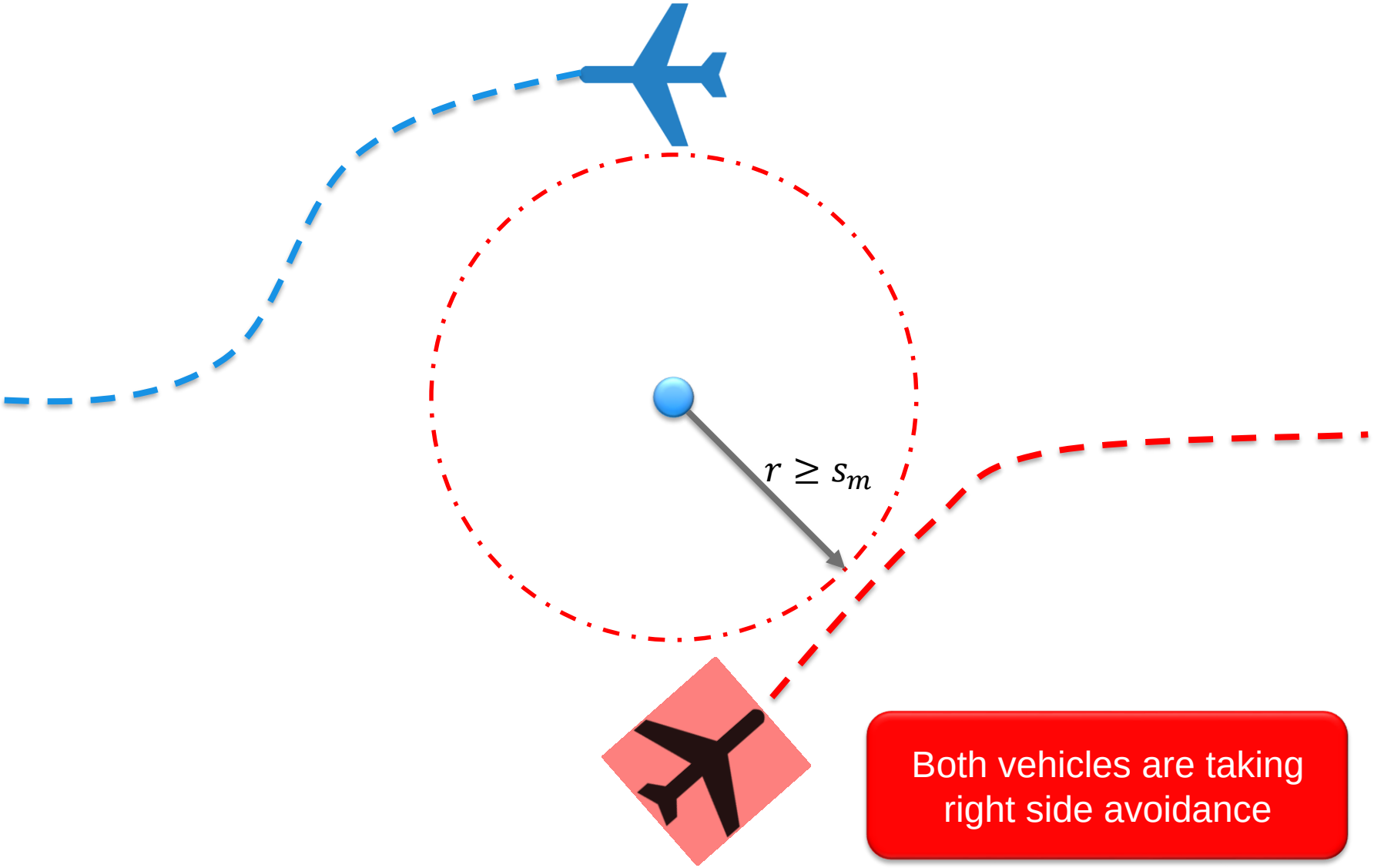
Head On Approach - Resolution



Both vehicles are taking right side avoidance

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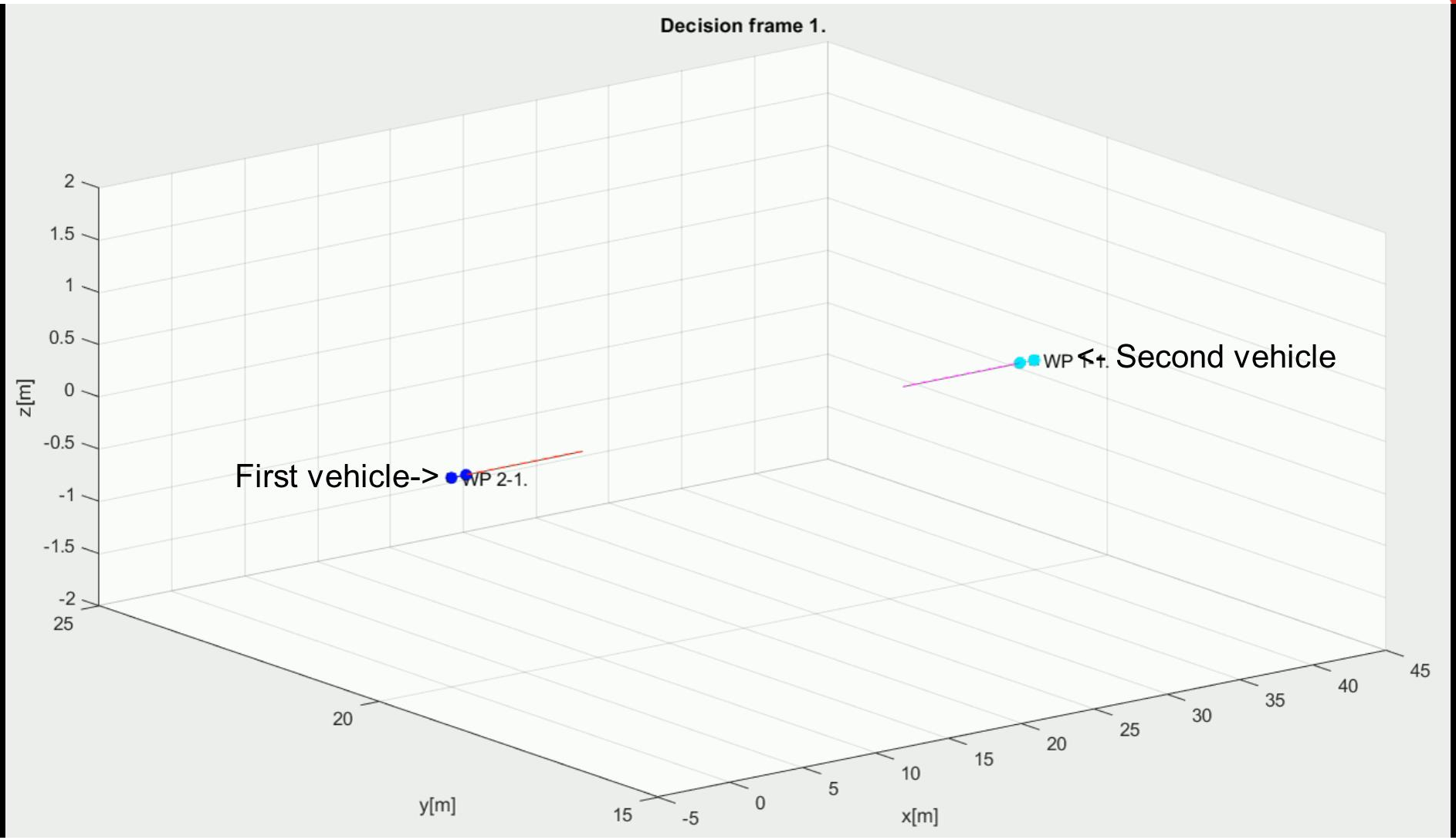
Emergency: Head On Approach



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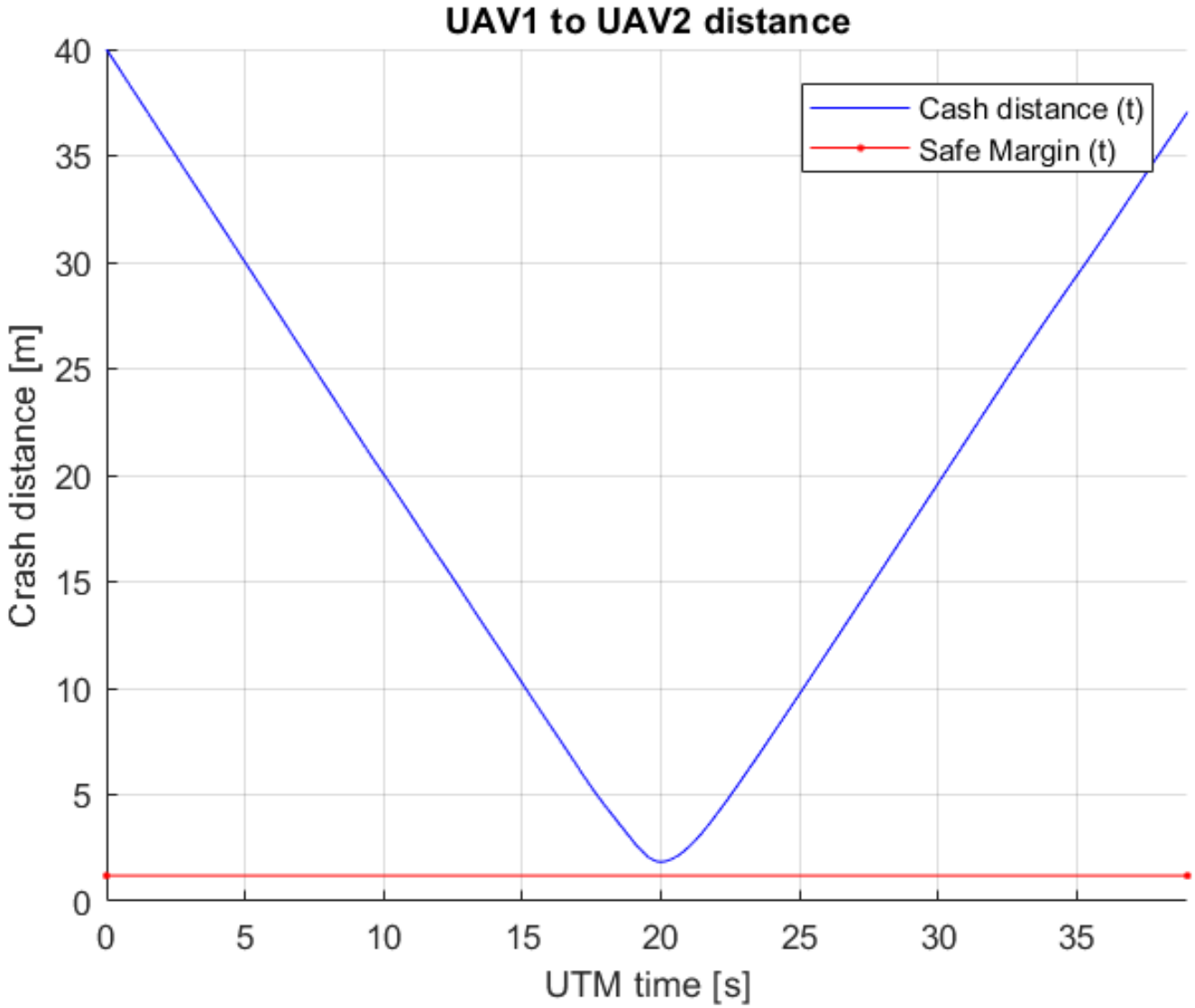
Emergency: Head On Approach

No Collision!



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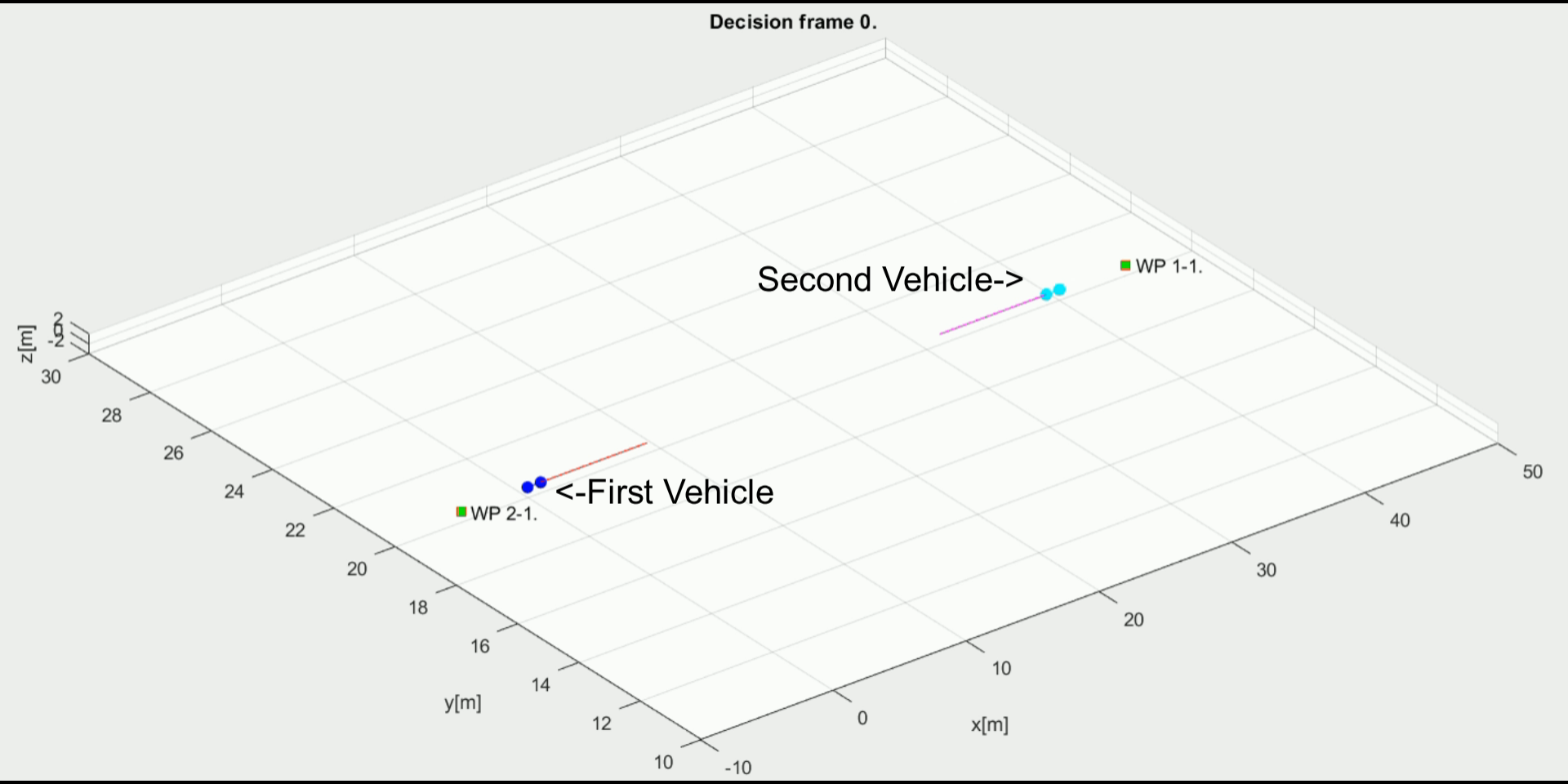
Rule-Based: Head On Approach



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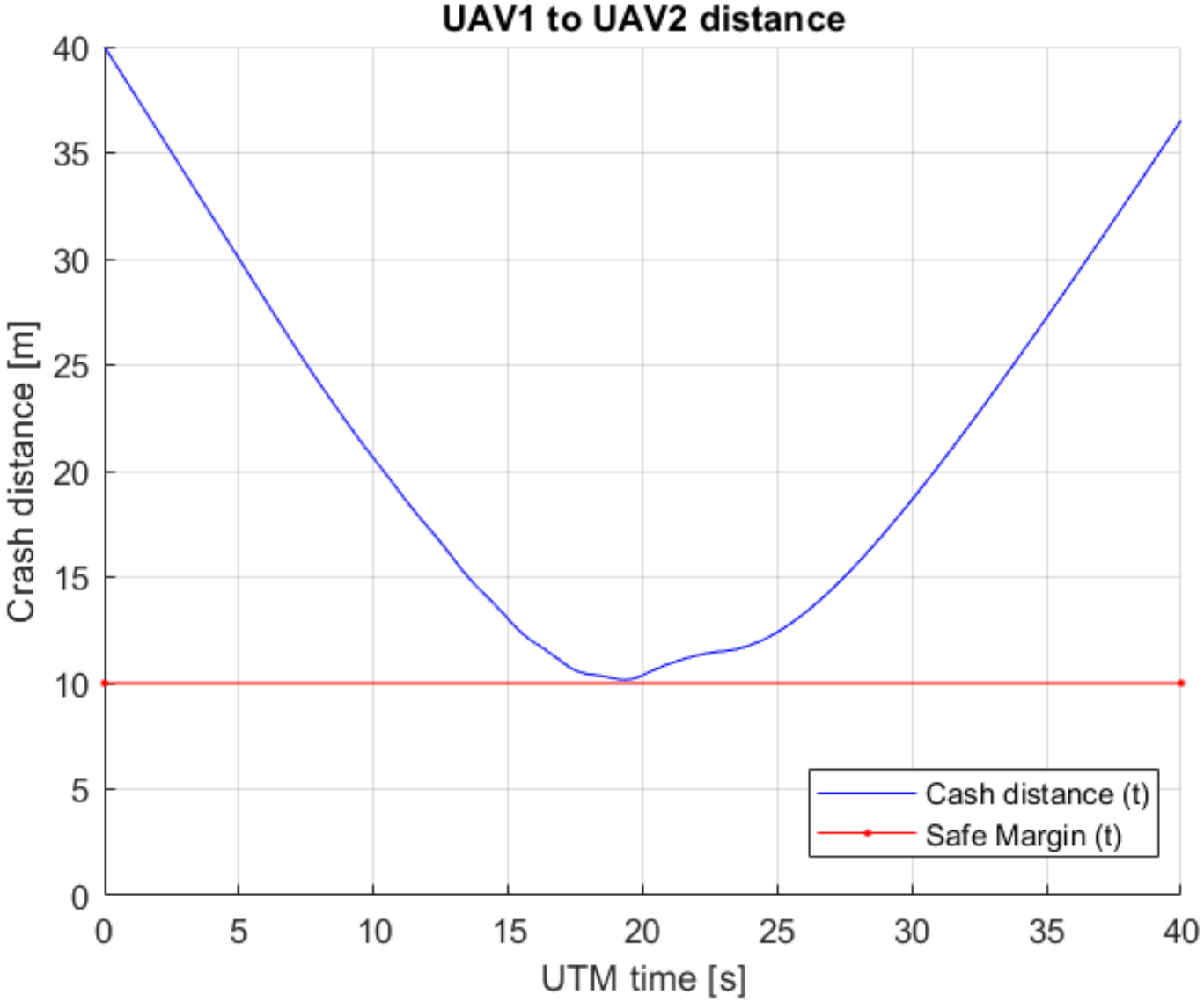
Rule-Based: Head On Approach

No Collision!



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Multiple Collision Cases

Situation:

- *Four UAS systems* equipped with ADS-B are *approaching* Collision Point
- Both systems are using *ACAS-XU Horizontal Separation*
- Angle of Approach is equal to 90-180 degrees (Multiple cases)

Resolution (Emergency)

- All *UAS receive ADS-B message* with intruder *heading and position*
- Safety margin: 1.2 m (30 cm body radius, 30 cm protection margin)
- Intruder model: Time-Based, Body mass intersection (r=60 cm)

Resolution (Rule Based)

- All UAS broadcasts ADS-B message to UTM system
- *UTM creates Collision Case* and Mandates UAS with *Avoidance Roles*
- Safety margin: 8 m (Enforced in Navigation Grid)

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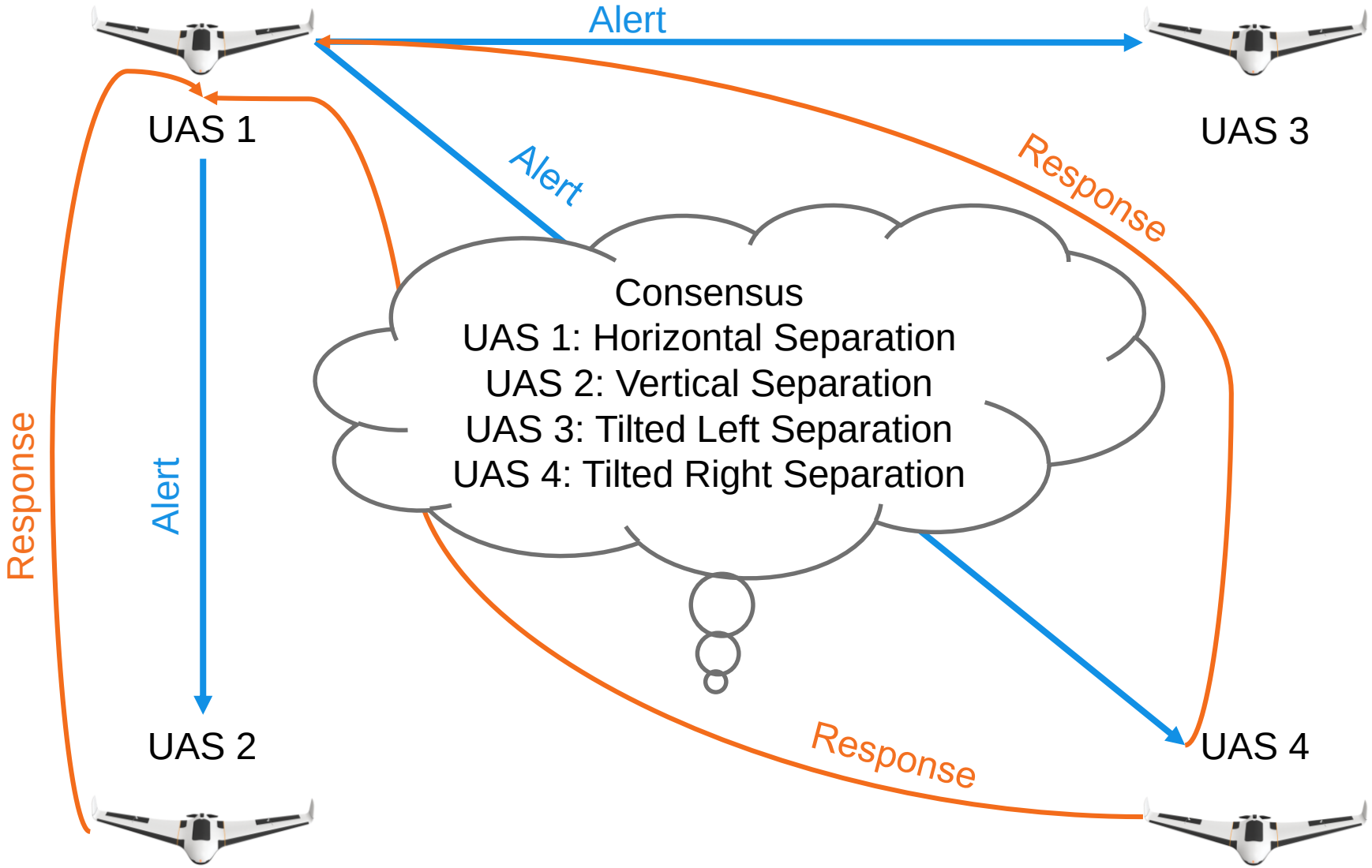
ACAS-XU Separation (Emergency Based)



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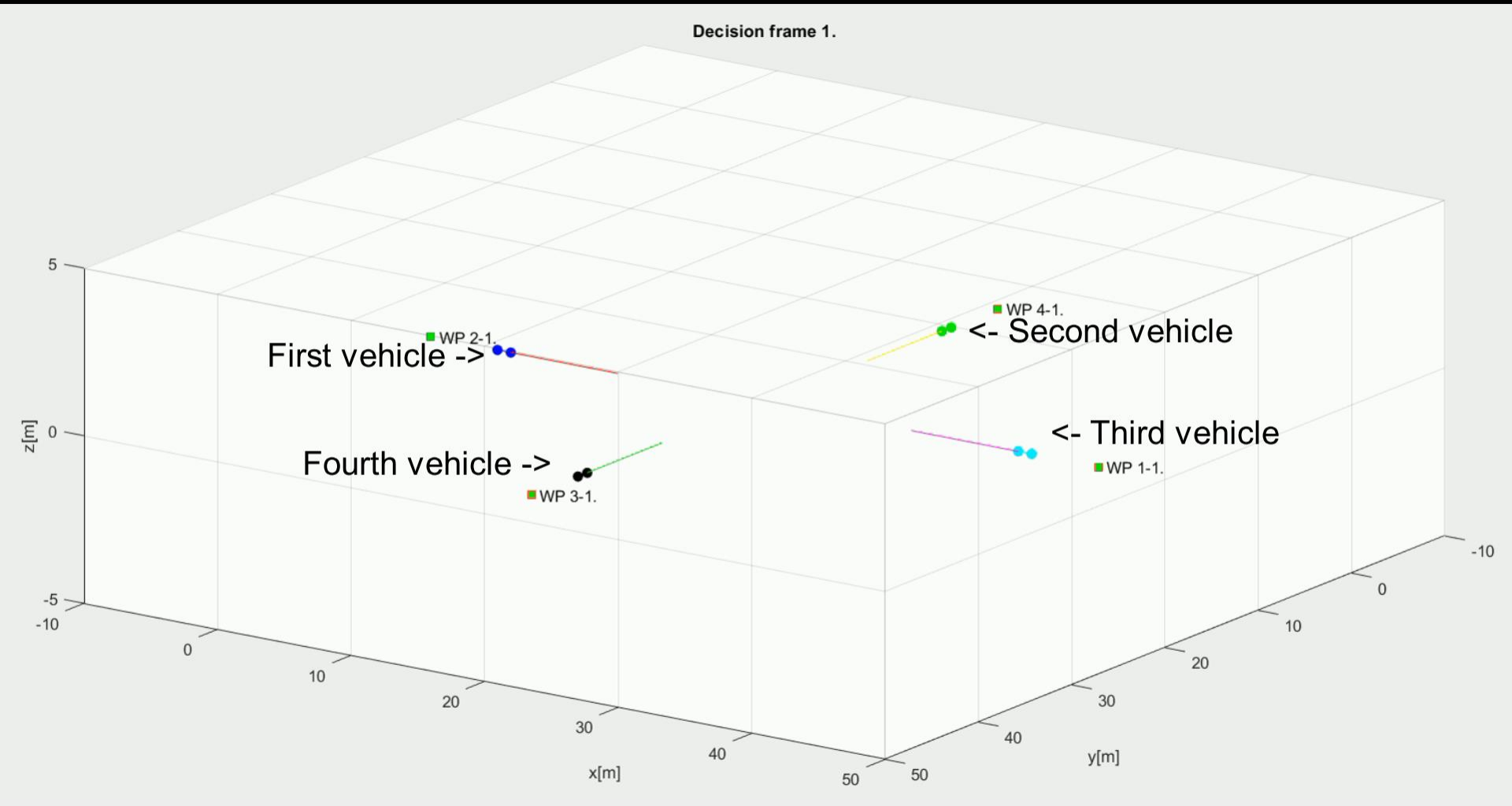
Emergency: Multiple Collision Cases



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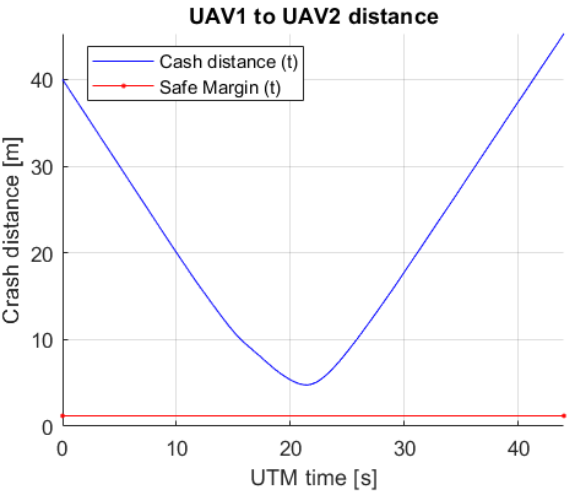
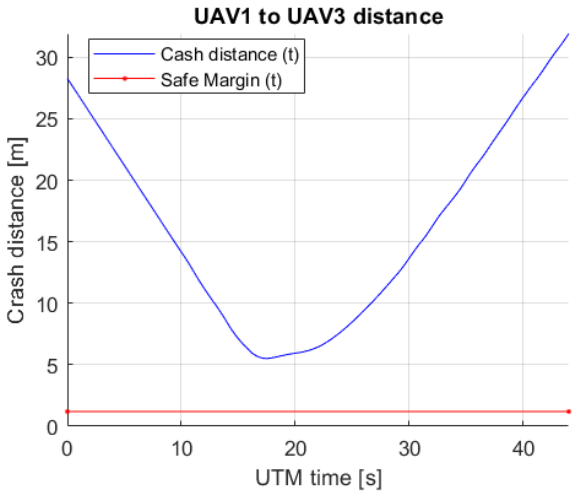
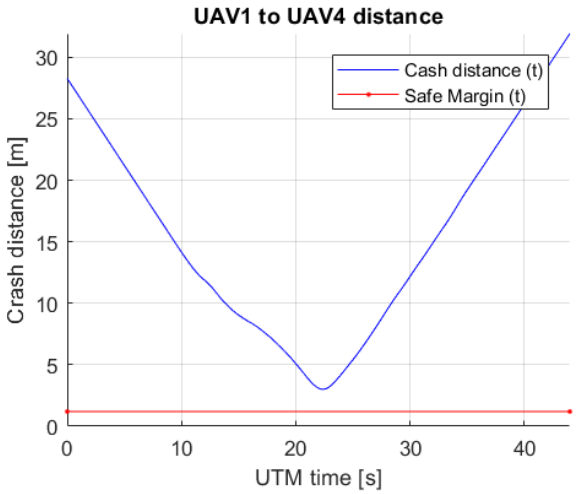
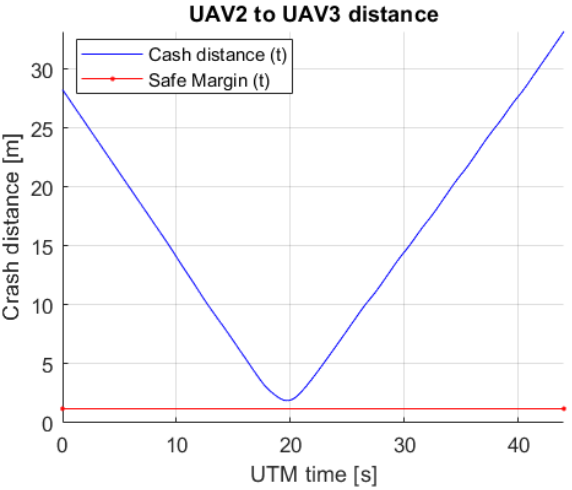
Emergency: Multiple Collision Cases

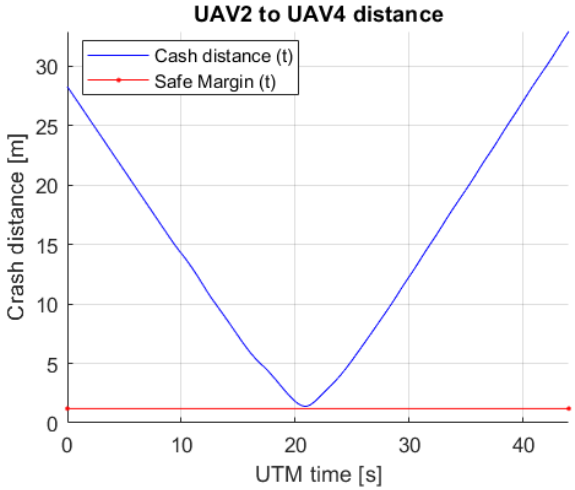
No Collision!

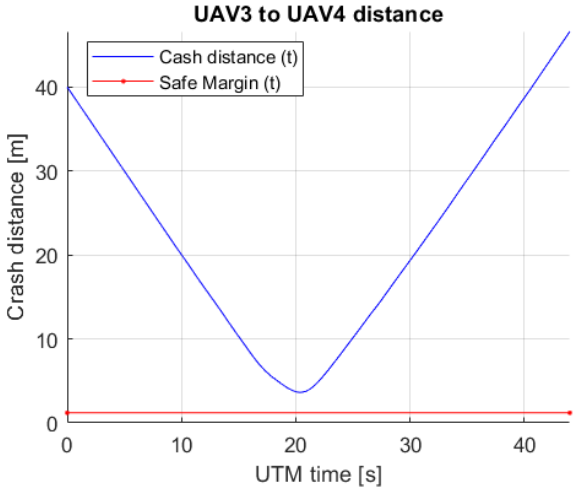












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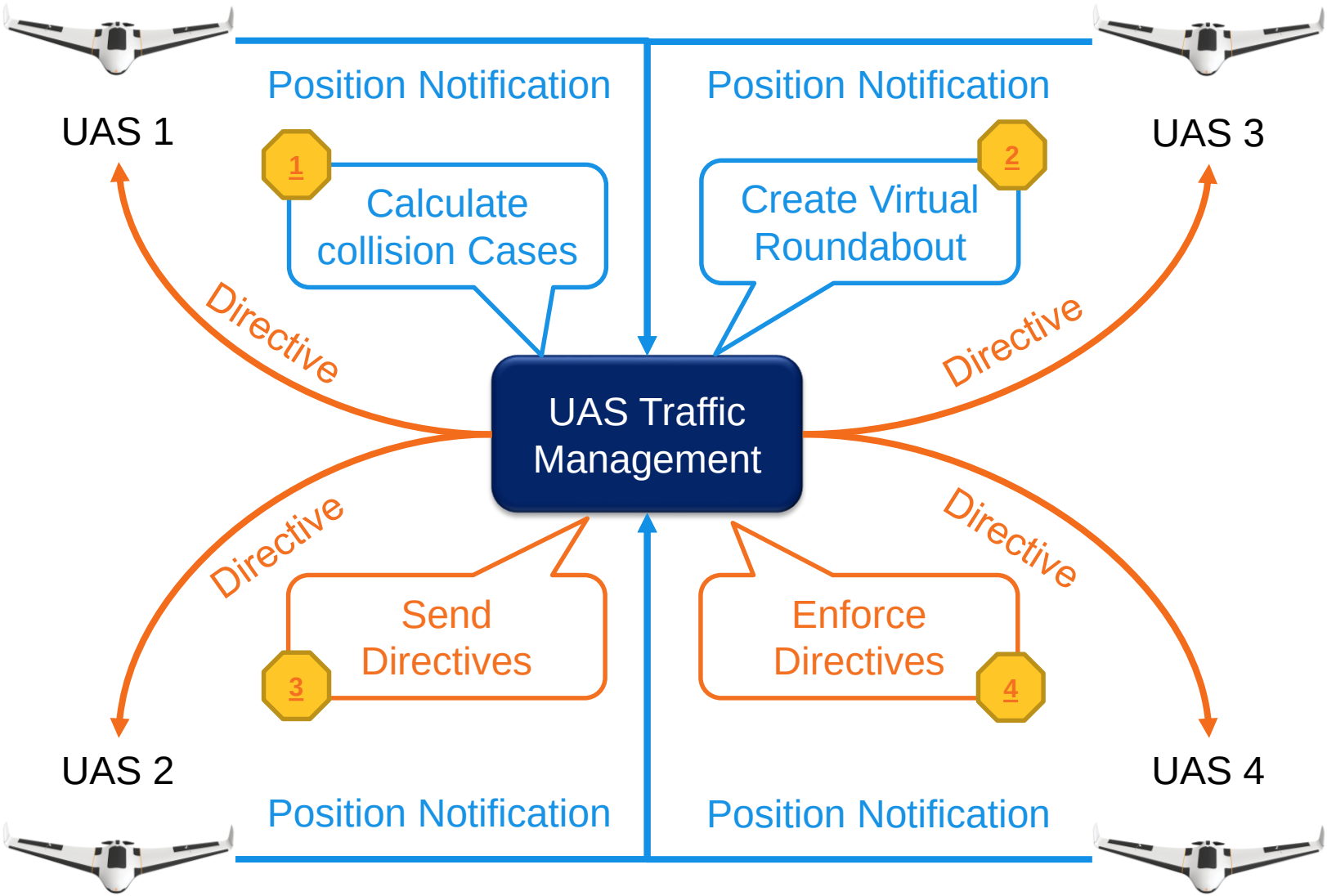
Enforced Virtual Roundabout (Rule-Based)



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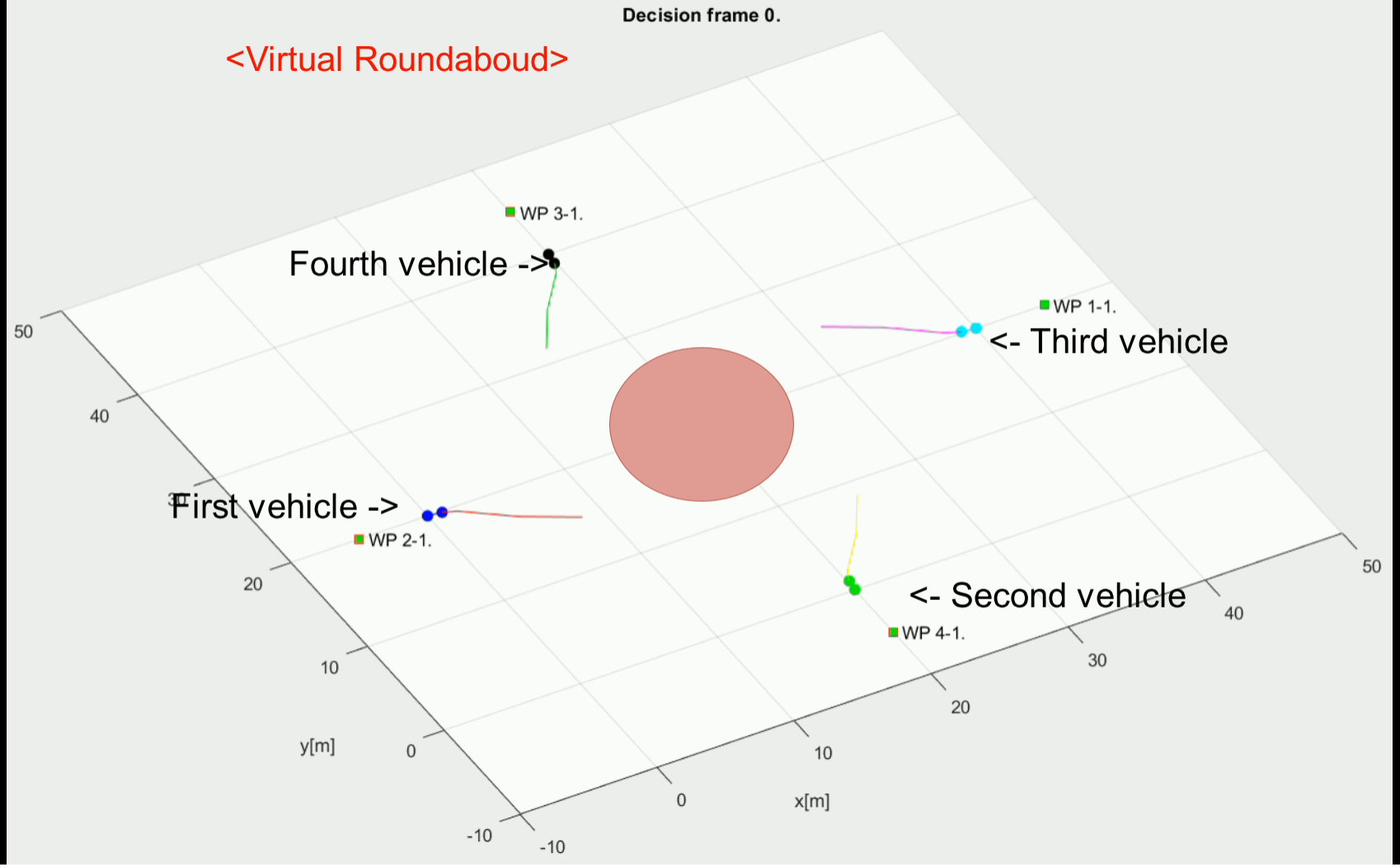
Rule-Based: Multiple Collision Cases



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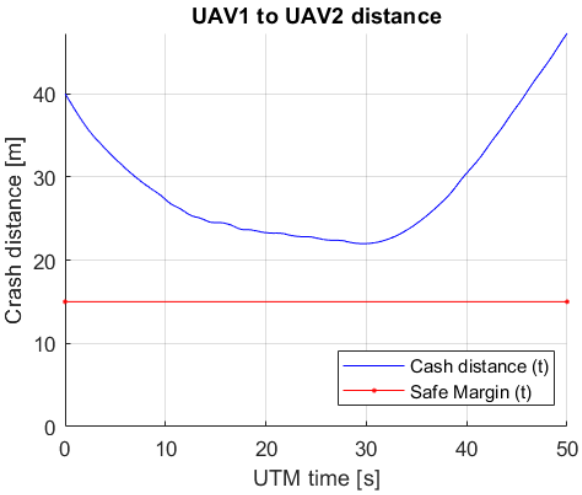
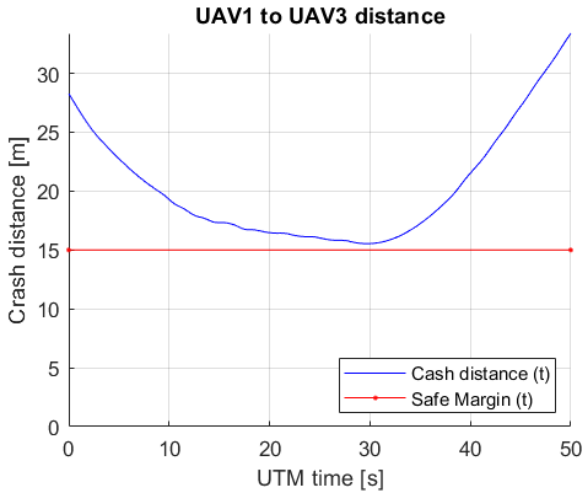
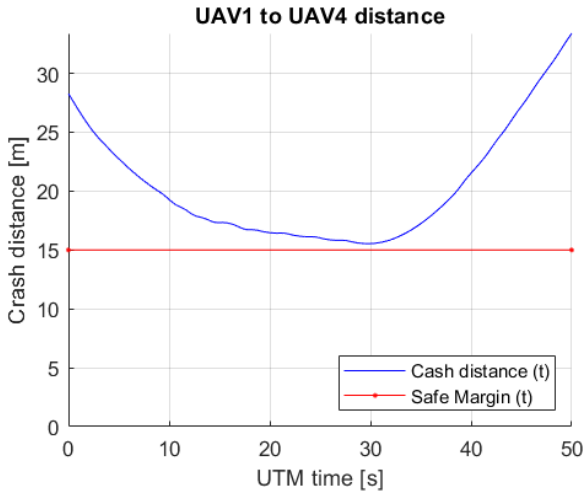
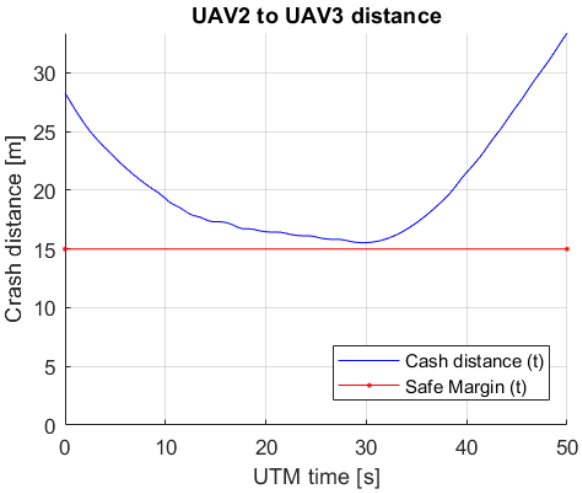
Rule-Based: Multiple Collision Cases

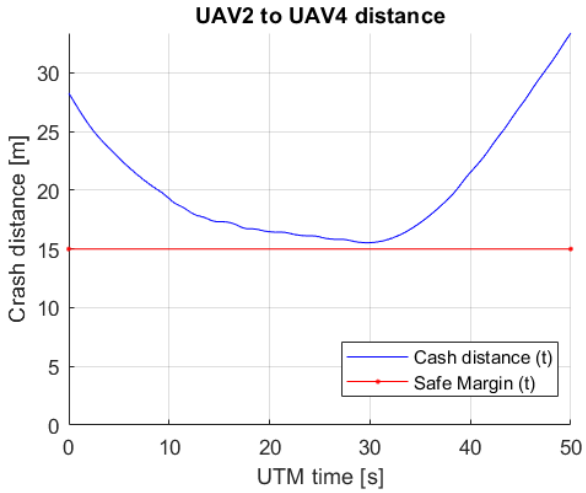
No Collision!

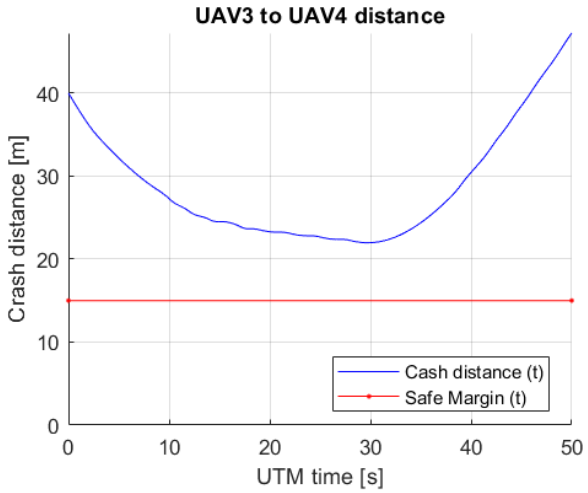












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Overtake Maneuver

Situation:

- *Two UAS systems* equipped with ADS-B are *flying* in same direction
- Both systems are using *ACAS-XU Horizontal Separation*
- Angle of Approach is equal to 0 degrees
- Overtaken UAS is slower than Overtaking UAS

Resolution (Rule Based)

- All UAS broadcasts ADS-B message to UTM system
- *UTM creates Collision Case* and Mandates UAS with *Avoidance Roles*
- Safety margin: 5 m (Enforced in Navigation Grid)

Simulation Scenarios:

1. Speed of Overtaking UAS is ***2x higher*** than speed of Overtaken UAS
2. Speed of Overtaking UAS is ***3x higher*** than speed of Overtaken UAS
3. Speed of Overtaking UAS is ***4x higher*** than speed of Overtaken UAS

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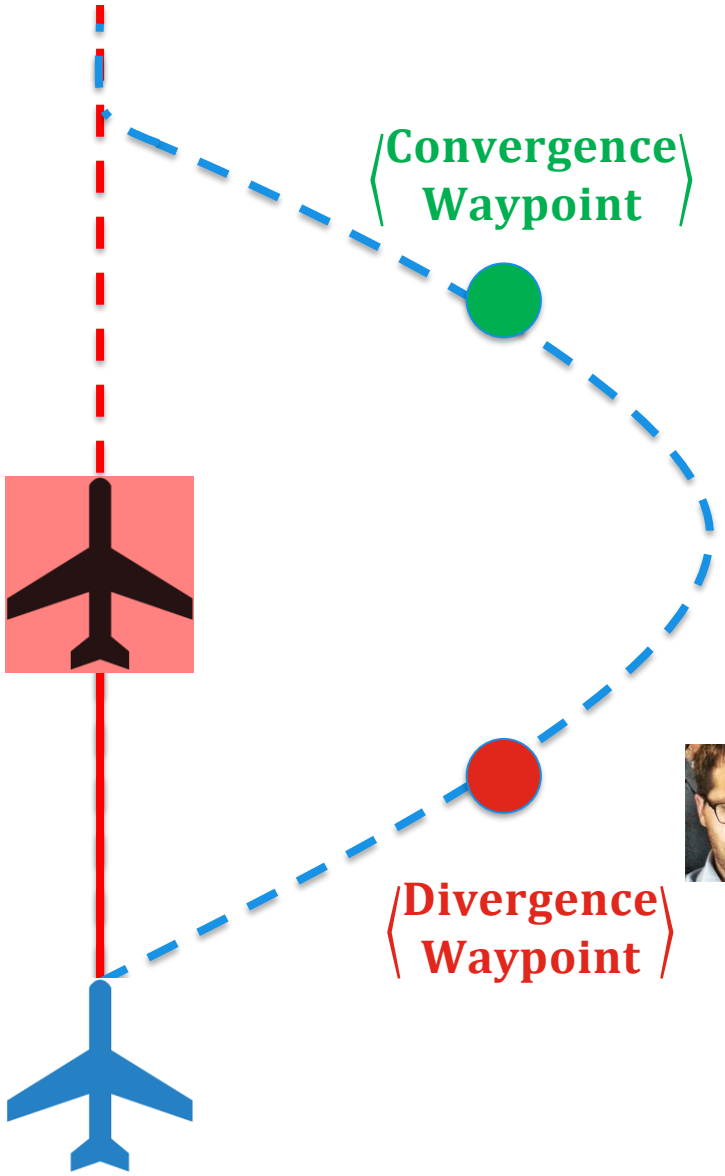
Overtake Maneuver - Trigger



Quick Recapitulation Time!

The aircraft being overtaken has the right of the way

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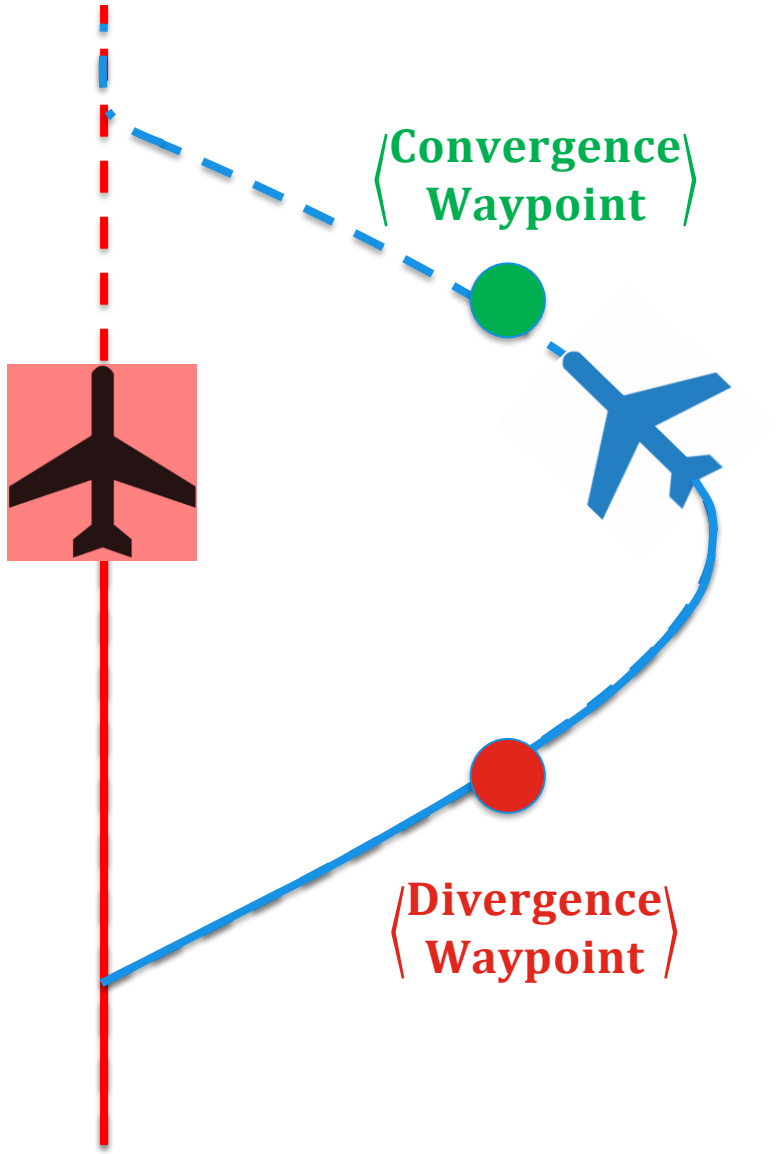
Overtake Maneuver - Resolution



Overtake is executed from right

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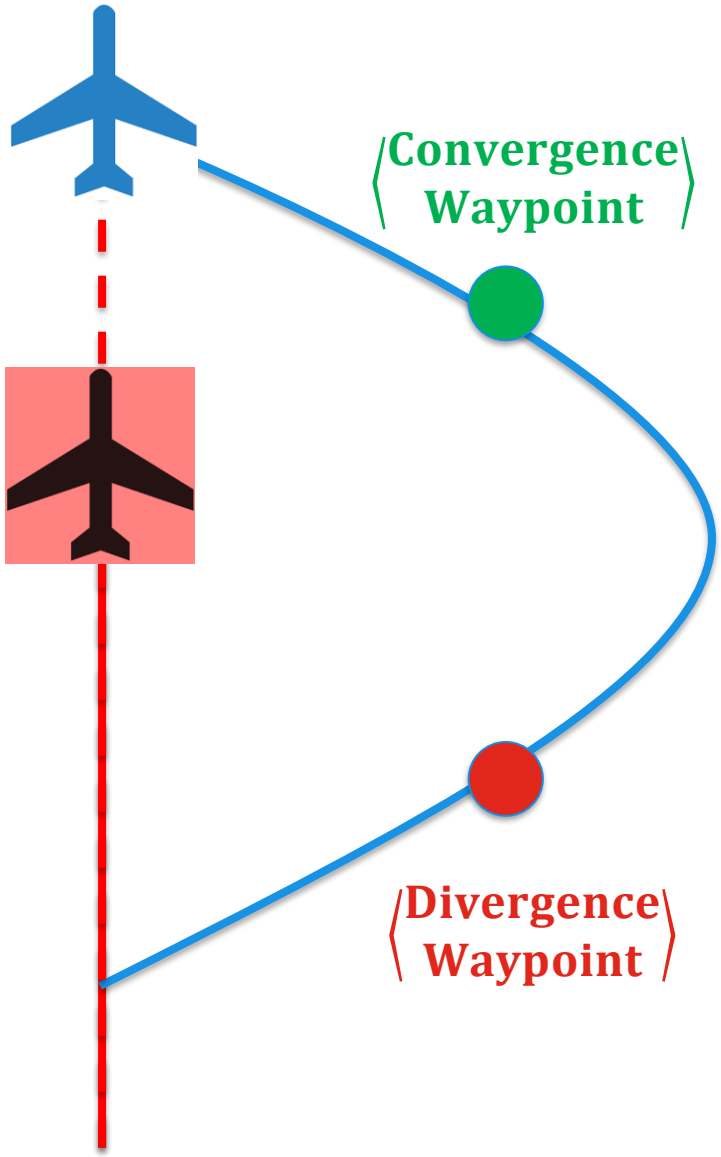
Overtake Maneuver – Leave Condition



Overtake rule may apply only when well clear condition is guaranteed

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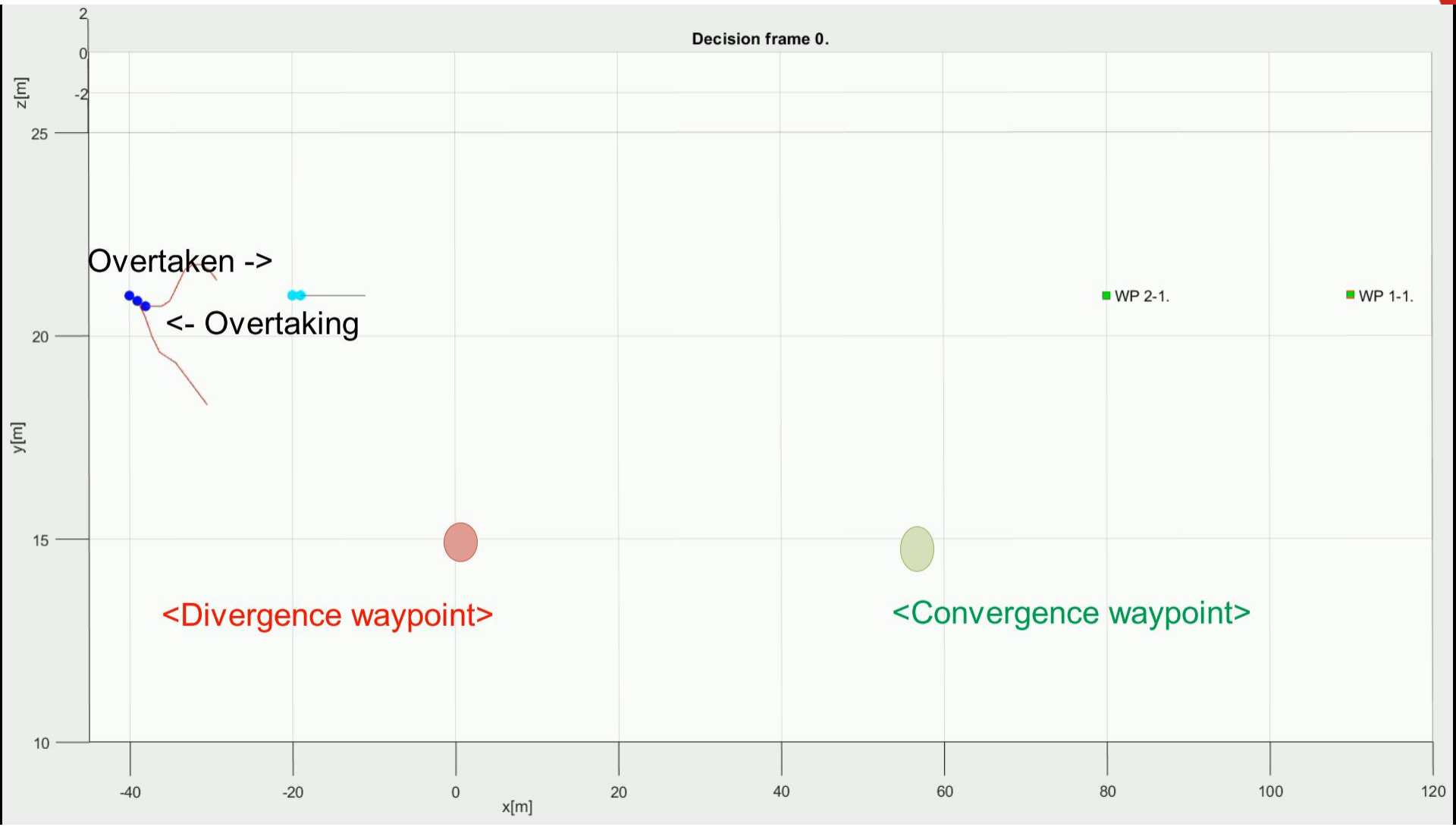
Rule-Based: Overtake Maneuver (3x speed)



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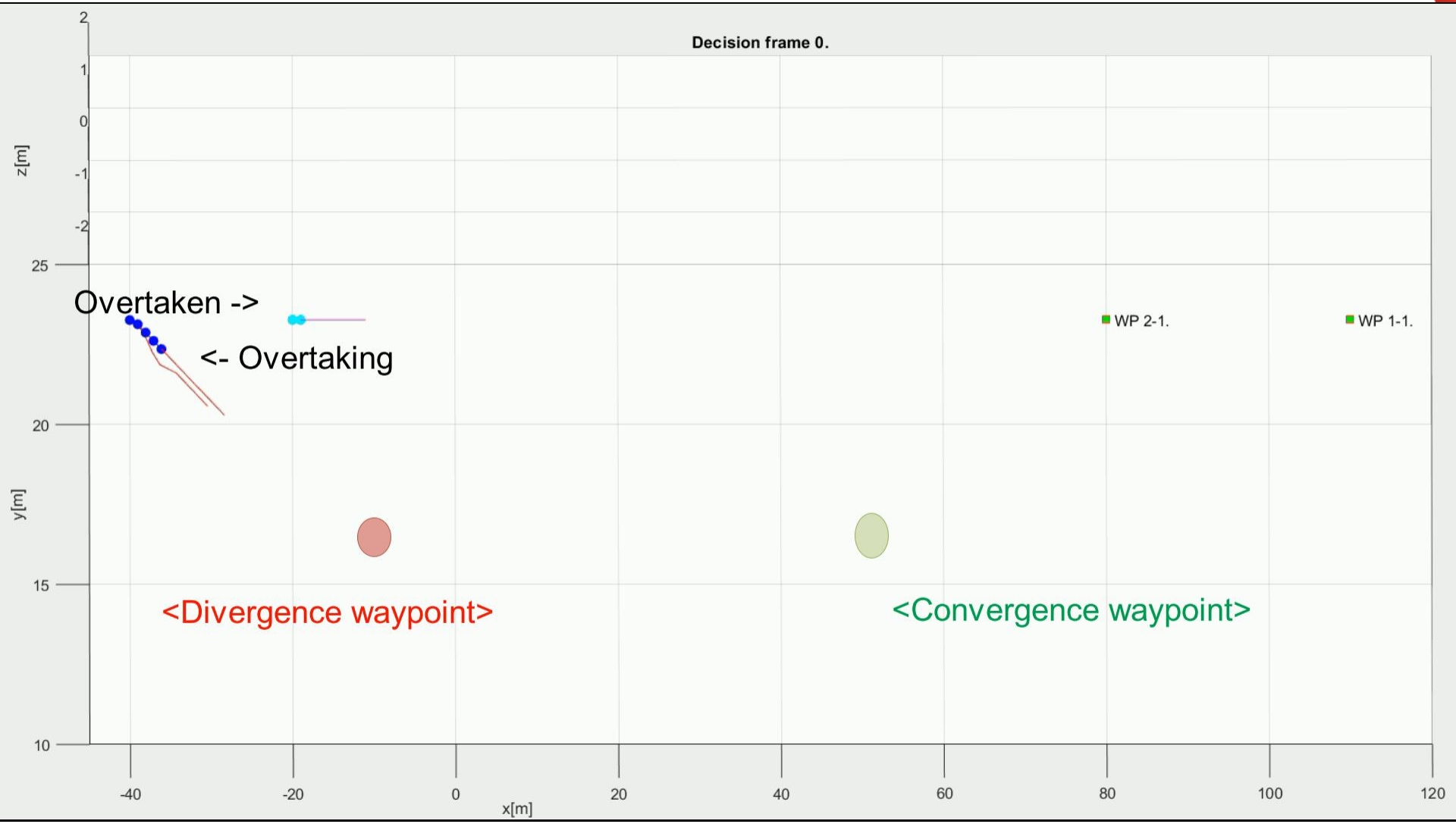
Rule-Based: Overtake Maneuver (3x Speed)



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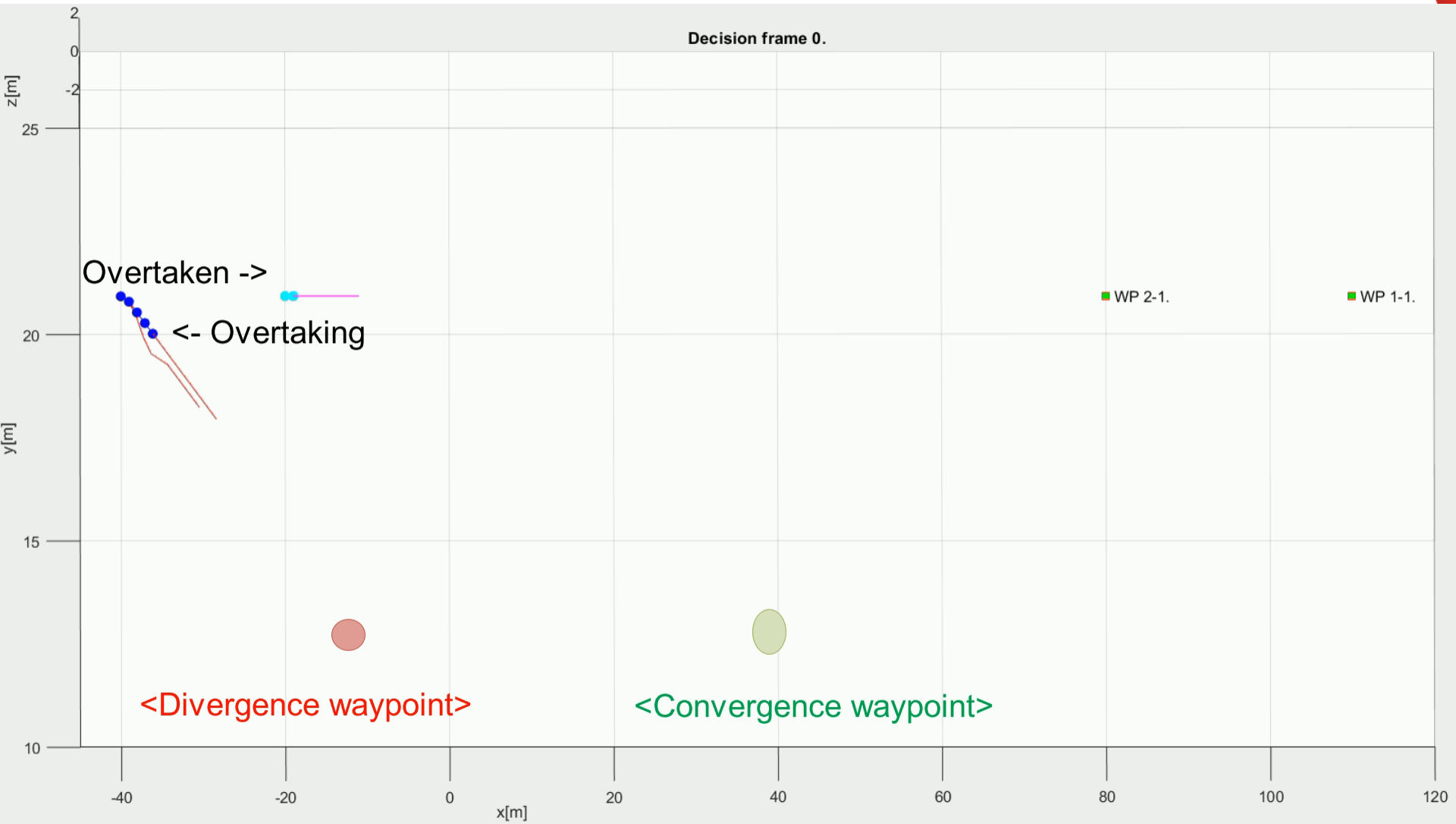
Rule-Based: Overtake Maneuver (4x Speed)



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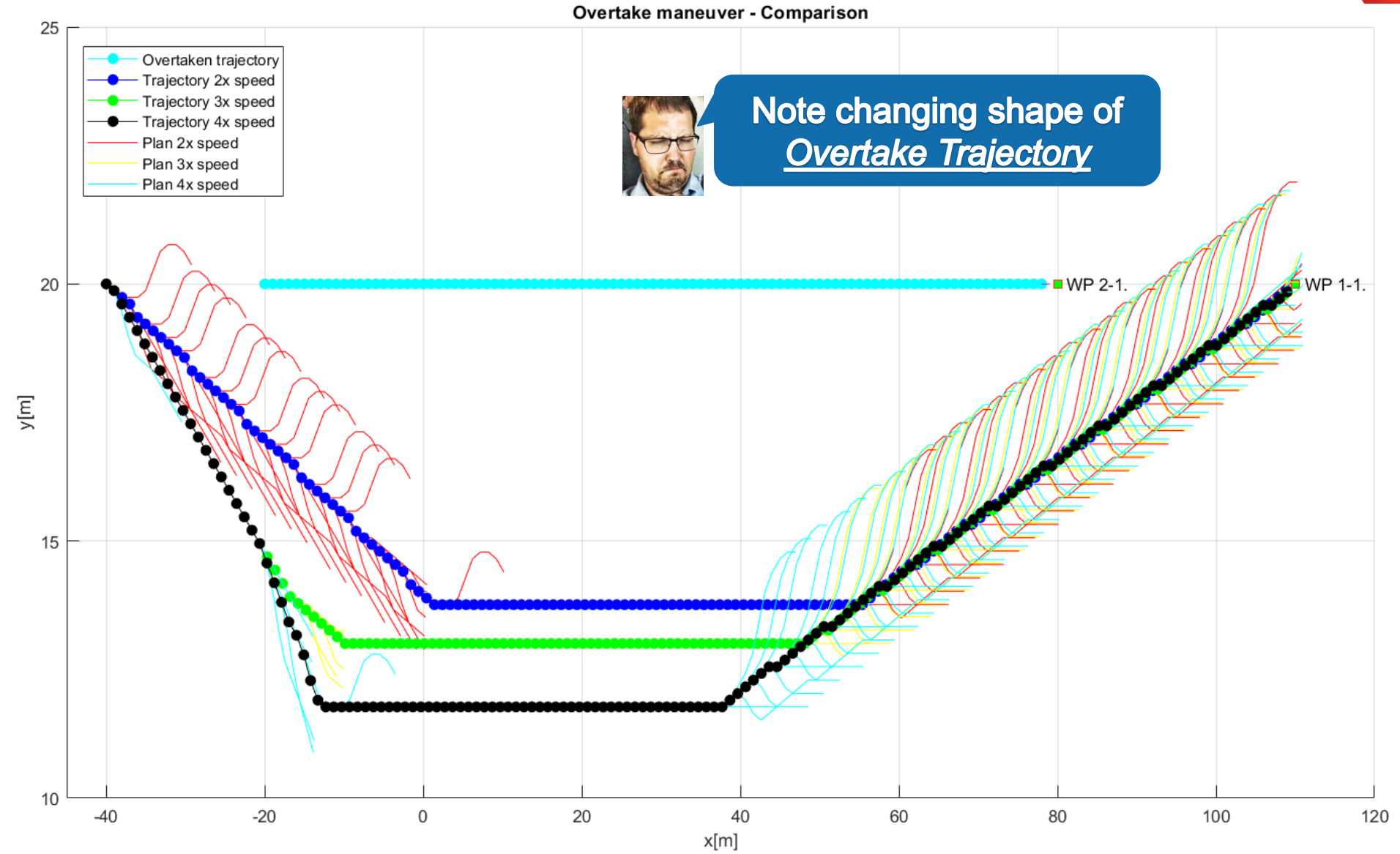
Rule-Based: Overtake Maneuver (Comparison)



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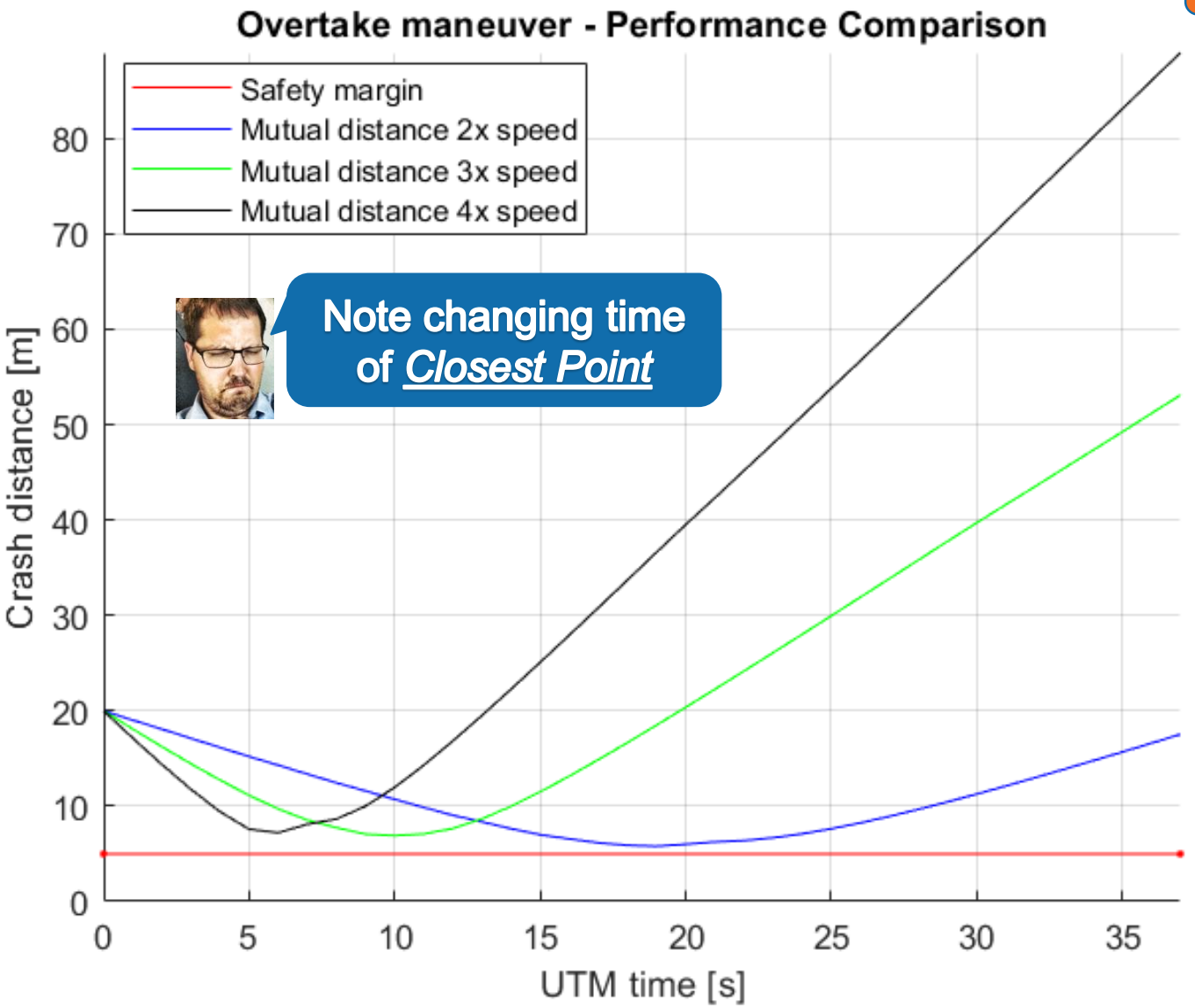
Rule-Based: Overtake Maneuver (Margins)

No Collision!



Note changing time of *Closest Point*

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Conclusion and Future Work

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Conclusion and Future Work

UAS Traffic Management Module provides following functionality:

- *Separation* – keep Airspace traffic separated
- *Collision Prevention* – prevent two or more airspace attendants collision
- *Conflict Resolution* – give Directives when conflict arises.

Rule Engine is key enabler for:

- *Rules of the Air implementation*, change behavior during avoidance,
- *Well Clear guarantee* during *Avoidance Maneuvers*,
- *Advanced Functionality* and *Code Enhancement*,
- Mission plan enhancement by forcing *Divergence/Convergence Waypoints*

Future work:

- Publish results with focus on current “Rules of Air shortcomings”
- Propose ***Avoidance Priority*** based on:
  - *Vehicle Maneuverability Class*
  - *Velocity/Acceleration/Deceleration Capabilities*

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Q&A Session

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