7.0.1 Rule based Overtake

Scenario: Two UAS are flying in the *controlled airspace* (over 500 feet Above Ground Level) on the *airway* (in same direction). *Slower UAS* is in front of *Faster UAS*. There is possibility of a *collision* or a *near miss incident* or a *well clear breach*. The *Faster UAS* (Overtaking) must contact *UTM* service and ask for *overtake permission*. Scenario steps:

1. *Faster UAS* (Overtaking) notices *UTM* service about *Slower UAS* (Overtaken). (This step is Optional.)
2. *UTM* service issues *Directives* to all *UAS* in area.
3. *Overtake Directive* is received by *Faster UAS* (Overtaking) and *Slower UAS* (Overtaken).
4. *Faster UAS* (Overtaking) mission plan is altered to reflect *Overtake directive*, *Divergence Waypoint* and *Convergence Waypoint* are added.
5. *Faster UAS* (Overtaking) safely overtakes *Slower UAS* (Overtaken) without breaking *Well clear* condition.

Mission parameters for both *UAS* systems are defined in (tab. 7.1).

UAS	Position		$\mathcal{WP}_1$
	$[x, y, z]$	$[\theta, \varpi, \psi]$	
1	$[-40, 20, 0]^T$	$[0°, 0°, 0°]^T$	$[110, 20, 0]^T$
2	$[-20, 20, 0]^T$	$[0°, 0°, 0°]^T$	$[80, 20, 0]^T$

Table 7.1: Mission setup for all *Rule based overtake* scenarios.

Assumptions: Following assumptions are valid for this test:

1. *Controlled Airspace Airworthiness* - UAS system is equipped with necessary controlled airspace equipment like ADS-B In/Out, Radar, Transponder, etc. Moreover airworthy *UAS* has capability to precisely follow *UTM directives* (max. 5 % deviation).
2. *C2 (Command & control) Link Established* - necessary for (UAS $\leftrightarrow$ UAS) and (UAS $\leftrightarrow$ UTM) communication. If *C2* link is lost the *UAS* will enter into *Emergency avoidance mode*.
3. *Decision frame synchronization with UTM* - necessary in discrete C2 environment otherwise *safety margins* needs to be *bloated*.

Main Goal: Show possibility of *Overtake Maneuver* invoked by the *UTM Directive* (event based flight constraint).

Acceptance Criteria: Following criteria must be met:

1. *Proper passing of Divergence/Convergence Waypoint* - minimal distance of *UAS trajectory* to *Divergence/Convergence waypoint* must be below passing threshold. Waypoints needs to be passed in given order (Divergence 1^{st}, Convergence 2^{nd}).

2. *Slower UAS (Overtaken) keeps Right of the Way* - the UAS with lesser maneuverability does not stand a chance in avoidance situation, it needs to keep its *Right of the Way.*

3. *Both UAS does not breach Well Clear (safety) Margin* - mutual distance does not get trough *calculated Safety Margin.*

Testing Setup: The *standard test setup* for each UAS defined in (tab. **??**, **??**, **??**, **??**, **??**) is used with following parameter override:

1. *Navigation grid - type - ACAS-like* with enabled *Horizontal maneuvers*

This *configuration* is based on assumption that every UAS is in *controlled airspace* in *FL450* (flight level 45000 feet Above Sea Level), without permission for *climb or descent maneuver*. *Rule engine* is initialized in standard *Rules of the air* configuration (fig. **??**).

There is *UTM* service for given *airspace cluster* calculating *collision cases* (tab. **??**) based on incoming *UAS position notifications* (tab. **??**).

Simulation Run: Notable moments from the *simulation run* (fig. 7.5) are following:

1. *Collision case creation* (fig.7.1) - *Faster UAS* (blue) receives *UTM Directive* to invoke *Overtake Rule* (tab. **??**). *Slower UAS* (magenta) receives *UTM Directive* to keep *Right of the Way* and warning that is going to be *Overtaken*. *Faster UAS* (blue) creates two *virtual waypoints*:

   a. *Divergence waypoint* at position $[0, 14, 0]^T$.

   b. *Convergence waypoint* at position $[24, 14, 0]^T$.

   Faster UAS then sets *Divergence waypoint* as *Goal waypoint* and It starts overtake maneuver while checking mutual distance.

2. *Divergence waypoint reach* (fig. 7.2) - *Faster UAS* (blue) successfully reached *Divergence Waypoint*, setting *Convergence Waypoint* as new *Goal waypoint.*

3. *Convergence waypoint reach* (fig. 7.3) - *Faster UAS* (blue) successfully reached *Convergence Waypoint*, setting *Original Goal Waypoint* as new *Goal waypoint*. The *UTM* service is notified from *Faster UAS* (blue) that *Overtaken Maneuver* have been completed. UTM *acknowledges* maneuver competition and It sends notification to *Slower UAS* (magenta) that *Overtake Maneuver* is finished. *Slower UAS* (magenta) was successfully overtaken.

4. *Original waypoint reach* (fig. 7.4) - *Faster UAS* (blue) successfully reached *Original Waypoint*, Starting landing Sequence.

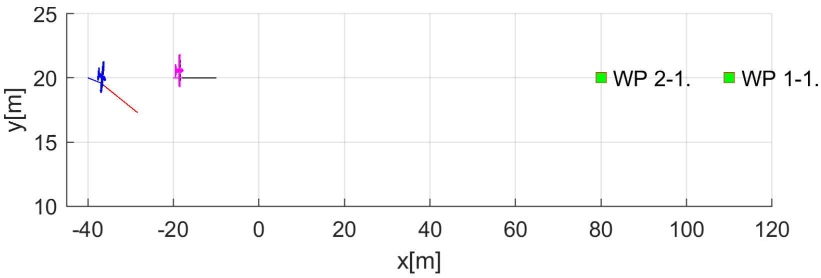

Figure 7.1: Collision case creation.

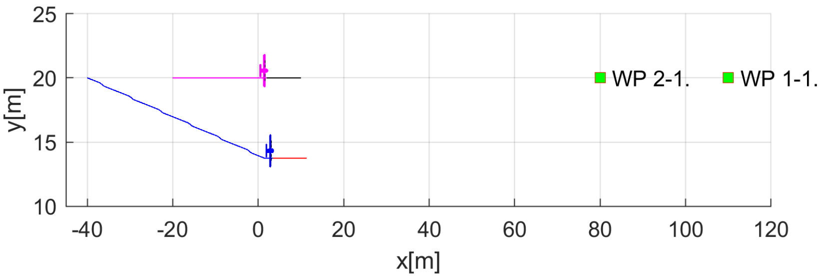

Figure 7.2: Divergence waypoint reach.

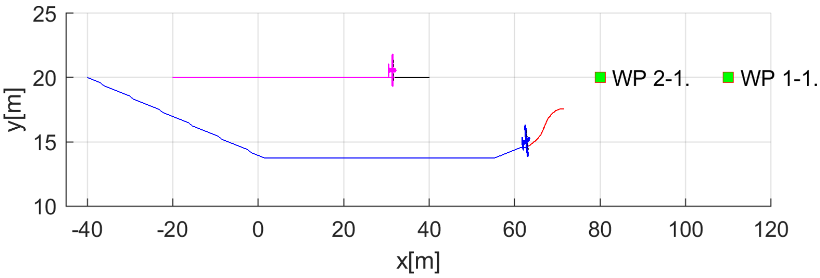

Figure 7.3: Convergence waypoint reach.

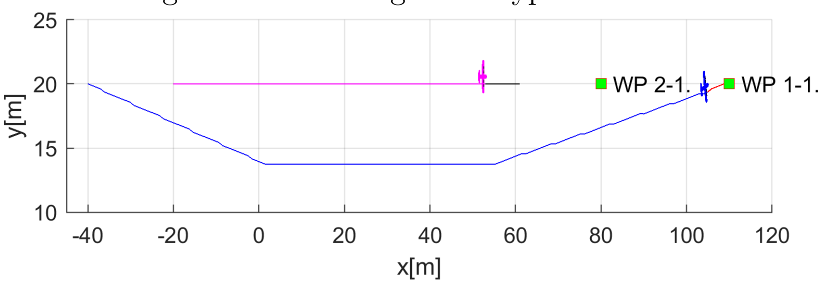

Figure 7.4: Original waypoint reach.

Figure 7.5: Test scenario for *Rule based Overtake* (double speed of overtaking aircraft).

Collision Case Calculation: The *Collision Case* (tab. 7.2) was calculated according to *Collision Calculation process* (sec. **??**). *Faster UAS* (1) has *Overtaking* role and *Slower UAS* has *Right of the Way*. *Collision Point* is direct type at $[0.20.0]^T$. *Collision case type* was set based on *angle of approach* 0° as *Overtake*. The *Safety Margin* was set as *5 m*.

Collision Case						Margins	
id	UAS	role	collision point	angle of approach	type	safety	case
1-2	1	Overtaking	$[0, 20, 0]^T$	$0°$	Overtake	5	5
	2	Right o.W.				5	

Table 7.2: Collision case for *Rule-based Overtake* scenario 2x speed.

Overtake Speed: Divergence/Convergence Waypoints *Divergence waypoints* have been calculated according to (eq. **??**), and, *Convergence Waypoints* have been calculated according to (eq. **??**). Following *Speed Differences* were taken into account (Faster/Slower UAS speed ratio): *2x, 3x, 4x*. Following observations can be made:

1. *Distance between Divergence and Convergence waypoint* is decreasing with increasing *speed difference*.
2. *Divergence waypoint* is moving *back/right* in *UAS Local Coordinate Frame* with Increasing *speed difference*.
3. *Convergence waypoint* is moving like *Divergence waypoint* but little bit faster.

<table>
<tr><th rowspan="2">Speed diff.</th><th colspan="2">Divergence</th><th colspan="2">Convergence</th><th rowspan="2">Final waypoint</th></tr>
<tr><th>waypoint</th><th>difference</th><th>waypoint</th><th>difference</th></tr>
<tr><td rowspan="2">2x</td><td rowspan="2">$[0, 14, 0]^T$</td><td></td><td rowspan="2">$[24, 14, 0]^T$</td><td></td><td rowspan="2">$[110, 20, 0]^T$</td></tr>
<tr><td rowspan="2">$[-10, -1, 0]^T$</td><td rowspan="2">$[-8, -1, 0]^T$</td></tr>
<tr><td rowspan="2">3x</td><td rowspan="2">$[-10, 13, 0]^T$</td><td rowspan="2">$[16, 13, 0]^T$</td><td rowspan="2">$[110, 20, 0]^T$</td></tr>
<tr><td rowspan="2">$[-3.4, -1, 0]^T$</td><td rowspan="2">$[-1.3, -1, 0]^T$</td></tr>
<tr><td rowspan="2">4x</td><td rowspan="2">$[-13.4, 12, 0]^T$</td><td rowspan="2">$[14.7, 12, 0]^T$</td><td rowspan="2">$[110, 20, 0]^T$</td></tr>
<tr><td></td><td></td></tr>
</table>

Table 7.3: Convergence and divergence waypoints for various speed differences.

Overtake Speed: Impact on Trajectory Overtake *speed difference* is visible in (fig. 7.6). The *Slower vehicle trajectory*(cyan) is following *standard mission waypoints*. The *Faster vehicle trajectory* for 2x (blue), 3x (green), 4x (black) are following *Divergence/Convergence* waypoints from (tab. 7.3).

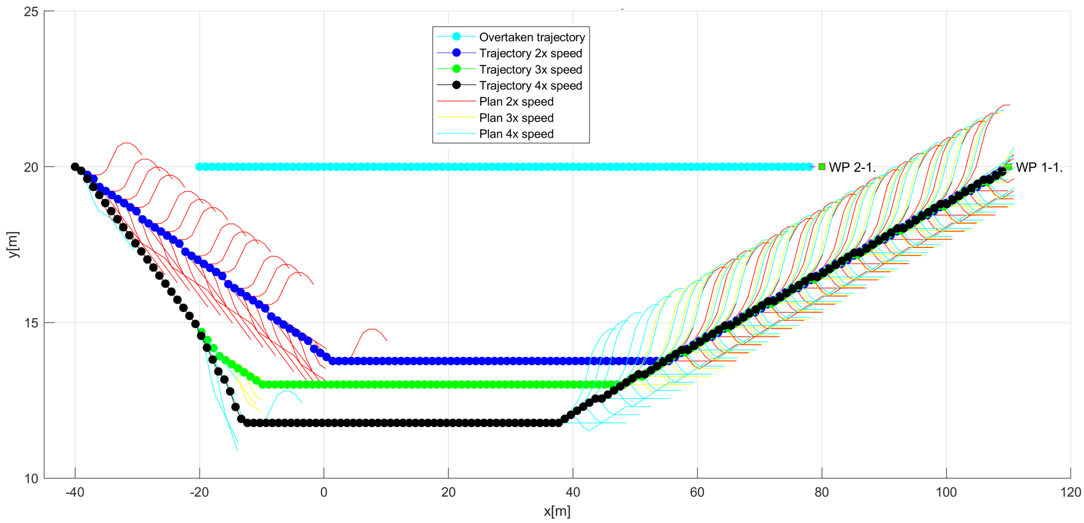

Figure 7.6: *Rule based overtake* trajectories for different speed.

Overtake Speed: Impact on Safety Margin Performance *Safety margin* (red line) is set to *5 m*. It is obvious that *Faster UAS* will take down *Slower UAS* if there was not for an *Overtake maneuver*. The distance of *Faster UAS* to *Slower UAS* evolution is depending on *Speed difference*. *Inflection point* (closest point of two UAS) is reached sooner with *Higher speed*. *Safety margin performance* was measured for the *UTM performance time* in interval $[0, 35]$ s and *Speed difference* of 2x (blue), 3x (green), 4x (black).

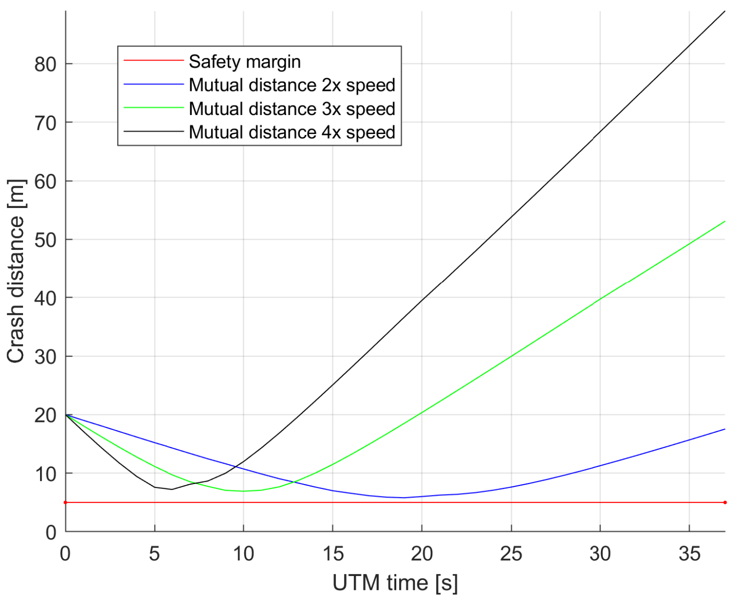

Figure 7.7: *Rule based overtake* safety margin performance for different speed.

Overtake Speed: Impact on Safety Margin Distance There is summary table (tab. 7.4) for measurement of minimal and maximal values for *Safety Margin Performance* over *UTM time* (fig.7.7). The minimal *Overtake Distance to Safety Margin* in 0.7991 m for 2x *Speed Difference*. The minimal *Overtake closest point reach time* is 7 s for 4x *Speed Difference*.

For each *Speed difference* (2x, 3x, 4x), the *Well Clear Margin* (Safety Margin) was not reached by the *Faster UAS Body boundary*.

Speed diff.	Minimal		Maximal		Breach
	distance	time	distance	time	
2x	0.7991	20	48.8508	76	false
3x	1.9180	11	73.5336	51	false
4x	2.2154	7	84.0721	38	false

Table 7.4: *Rule based overtake* safety margin distances and times.

Path Tracking Performance: 2x Speed Performance was only evaluated for case when *Faster/Slower UAS speed ratio* is $2x$. All waypoints are marked as green numbered *squares* with number. Initial waypoint is marked as green square with *S*. Reference trajectory is annotated as *green dashed line*. *Executed trajectory is annotated* as *blue solid line*.

Following observations can be made from path tracking (fig. 7.10):

1. *UAS 2 has the Right of the Way* (fig. 7.9) - *reference trajectory* and *executed trajectory* are identical.

2. *UAS 1 is Overtaking* (fig. 7.8) - the following waypoins are marked on reference trajectory:

    a. *Collision Point* ($\mathcal{WP}$ 1.) - this is not used for navigation, its marking of *Collision Point*.

    b. *Divergence waypoint* ($\mathcal{WP}$ 2.) - there will *Faster UAS* navigate to avoid *Collision*.

    c. *Convergence waypoint* ($\mathcal{WP}$ 3.) - there will *Faster UAS* navigate to gain *Safe Return Distance*.

    d. *Original Goal Waypoint* ($\mathcal{WP}$ 4.) - there will *Faster UAS* continue until *original goal* is reached.

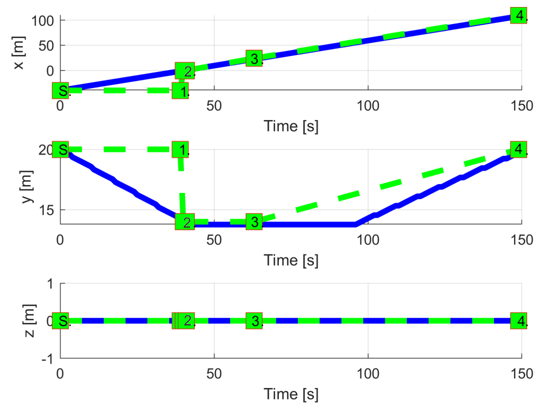

Figure 7.8: UAS 1.

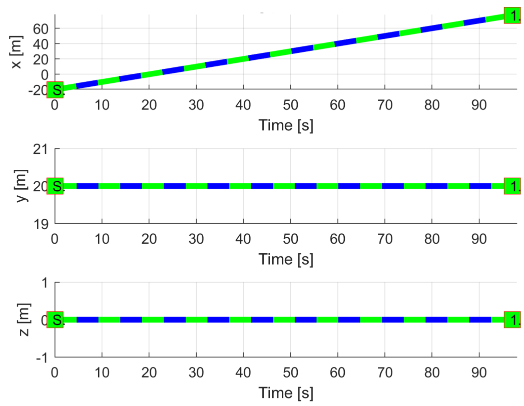

Figure 7.9: UAS 2.

Figure 7.10: Trajectory tracking for *Rule based overtake double speed* situation test case.

Path Tracking Deviations: 2x Speed Path tracking deviations (tab. 7.5) are interesting for an *Overtake Maneuver* performance.

Maximal deviation distance is for important waypoints: Divergence ($\mathcal{WP}$ 2.), Convergence ($\mathcal{WP}$ 3.) and Original Goal Waypoint ($\mathcal{WP}$ 4.), equal to 0 m. This is *desired effect* for *Overtake maneuver*.

Collision point ($\mathcal{WP}$ 1.) is avoided at minimal distance 5.7991 m (tab. 7.4) and maximal distance 24.5 m (tab. 7.5).

Other *Speed Difference Ratios* yields similar results.

Param.	UAS 1				UAS 2
	$\mathcal{WP}_1$	$\mathcal{WP}_2$	$\mathcal{WP}_3$	$\mathcal{WP}_4$	$\mathcal{WP}_1$
	col.	div.	conv.	orig.	nav.
$\max\|x\|$	20	0	0	0	0
$\max\|y\|$	6	0	4	5	0
$\max\|z\|$	0	0	0	0	0
$\max dist.$	24.5	0	4	5	0

Table 7.5: Path tracking properties for *Rule overtake 2x speed* scenario.