7.5 Test Cases Conclusion

This section contains summary of performance evaluation (sec. **??**), adversary behavior impact on our approach (sec. 7.5.2), *calculation load* in (sec. 7.5.3).

7.5.1 Performance Evaluation

Performance of test cases was evaluated according to criteria given by (sec. **??**). The performance for *test cases* from test plan (tab. **??**) has been summarized in (tab. 7.1).

Scenario name	Safety Margin			Trajectory tracking			Pass / Fail
	Distance		Breach	Waypoint Reach	Reference Deviation	Acceptable Deviation	
	min	max					
Building avoidance (sim. **??**)	0.69 m UAS 1	24.98 m UAS 1	No (**??**)	Yes/UAS 1/(**??**)	$\mathcal{WP}_1$: 107.05m $\mathcal{WP}_2$: 86.20m $\mathcal{WP}_3$: 28.70m $\mathcal{WP}_4$: 32.84m	Yes (**??**)	Pass
Slalom (sim. **??**)	0.09 m UAS 1	3.74 m UAS 1	No (**??**)	Yes/UAS 1/(**??**)	$\mathcal{WP}_1$: 20.06m	Yes (**??**)	Pass
Maze (sim **??**)	0.01 m UAS 1	2.95 m UAS 1	No (**??**)	Yes/UAS 1/(**??**)	$\mathcal{WP}_1$: 28.06m	Yes (**??**)	Pass
Storm (sim. **??**)	0.04 m UAS 1	34.99 m UAS 1	No (**??**)	Yes/UAS 1/(**??**)	$\mathcal{WP}_1$: 15.76m	Yes (**??**)	Pass
Emergency Converging (sim. **??**)	1.67 m UAS 1-2	27.08 m UAS 1-1	No (**??**)	Yes/UAS 1/(**??**) Yes/UAS 2/(**??**)	$\mathcal{WP}_1$: 3.25m $\mathcal{WP}_1$: 0.00m	Yes (**??**)	Pass
Emergency Head On (sim. **??**)	0.38 m UAS 1-2	38.00 m UAS 1-2	No (**??**)	Yes/UAS 1/(**??**) Yes/UAS 2/(**??**)	$\mathcal{WP}_1$: 3.25m $\mathcal{WP}_1$: 0.00m	Yes (**??**)	Pass
Emergency Multiple (sim. **??**)	0.20 m UAS 2-4	45.46 m UAS 3-4	No (**??**)	Yes/UAS 1/(**??**) Yes/UAS 2/(**??**) Yes/UAS 3/(**??**) Yes/UAS 4/(**??**)	$\mathcal{WP}_1$: 4.84m $\mathcal{WP}_1$: 1.83m $\mathcal{WP}_1$: 3.45m $\mathcal{WP}_1$: 2.05m	Yes (**??**)	Pass
Rule-based Converging (sim. **??**)	1.22 m UAS 1-2	20.28 m UAS 1-2	No (**??**)	Yes/UAS 1/(**??**) Yes/UAS 2/(**??**)	$\mathcal{WP}_1$: 10.22m $\mathcal{WP}_1$: 0.00m	Yes (**??**)	Pass
Rule-based Head On (sim. **??**)	0.21 m UAS 1-2	36.33 m UAS 1-2	No (**??**)	Yes/UAS 1/(**??**) Yes/UAS 2/(**??**)	$\mathcal{WP}_1$: 5.40m $\mathcal{WP}_1$: 5.40m	Yes (**??**)	Pass
Rule-based Multiple (sim. **??**)	0.54 m UAS 2-3	32.24 m UAS 1-2	No (**??**)	Yes/UAS 1/(**??**) Yes/UAS 2/(**??**) Yes/UAS 3/(**??**) Yes/UAS 4/(**??**)	$\mathcal{WP}_1$: 11.40m $\mathcal{WP}_1$: 11.40m $\mathcal{WP}_1$: 11.40m $\mathcal{WP}_1$: 11.40m	Yes (**??**)	Pass
Rule-based Overtake (sim. **??**)	0.80 m UAS 1-2	48.85 m UAS 1-2	No (**??**)	Yes/UAS 1/(**??**) Yes/UAS 2/(**??**)	$\mathcal{WP}_1$: 24.00m $\mathcal{WP}_2$: 0.00m $\mathcal{WP}_3$: 4.00m $\mathcal{WP}_4$: 5.00m $\mathcal{WP}_1$: 0.00m	Yes (**??**)	Pass

Table 7.1: Test cases *performance evaluation*.

Highlights: Each *scenario* contains the reference to notable simulation moments and results. The scenarios were grouped according to the *Operational Space* category, and each category is separated by strike line.

Non-cooperative test cases for the Rural/Urban environment:

1. *Static obstacle avoidance* (Building/Slalom/Maze) - the buildings were correctly avoided without security breach; navigation algorithm was sufficient for given scenarios and obstacle density.

2. *Weather avoidance* (Storm) - the moving *storm* have been avoided in both *soft constraint* and *hard constraint* state. The assumption of *early detection/notification* is key in successful weather avoidance.

Non-cooperative test cases for Intruder Avoidance - the key assumptions are early intruder detection in *Avoidance Grid* and *non-adversarial* behavior. Each UAS was running own instance of *Navigation loop* (fig. **??**). The summary of test cases is going like follow:

1. *Emergency converging* - both UAS identified correct roles according to the rules of the air. The UAS 2 kept *right of the way.*

2. *Emergency head on* - both UAS identified correct roles according rules of the air, both of them uses full separation with *Combined Reach Set Approximation* (sec. **??**).

3. *Emergency mixed* - all four UAS enters into emergency avoidance mode intermediately after intruders detection. The *non-cooperative* consensus of separation is reached (fig. **??**)

Cooperative test cases with UTM supervision are working according to *UTM architecture* (fig. **??**), where the *UTM* is considered as main authority. The key assumptions are UTM Resolution fulfillment and *non-adversary behavior.* Each UAS was running own instance of *Navigation loop* (fig. **??**) with enabled *Rule Engine* (sec. **??**). The summary of test cases is going like follow:

1. *Rule-based converging* - correct handling of *converging maneuver* (fig. **??**), proper rule invocation (rule **??**) on UAS side.

2. *Rule-based head on* - correct handling of *head on maneuver* (fig. **??**), proper rule invocation (rule **??**) on UAS side.

3. *Rule-based multiple* - proper *Collision case Merge* (tab. **??**) with new collision point (eq. **??**) and *safety margin calculation* (eq. **??**).

4. *Rule-based overtake* - correct handling of *overtaking maneuver* (fig. **??**), proper rule invocation (rule **??**). Divergence/Convergence (eq. **??**,**??**) for multiple waypoints calculation works for various speed difference (fig. **??**).

7.5.2 Adversary Behaviour Impact

The *abuse* of UAS for *ill intentions* realization is expected. The *UAS* is cheap, disposable and does not have ethic boundaries.

One of the *assumptions* was that there are only intruders who do not actively look to harm our *UAS*. Breaking this assumption can be lethal for our system and also for other systems.

Let us take *Rule-based Head on* test case (sec. **??**), changing only following aspects:

1. *UAS 2 position spoofing* - the adversarial vehicle is *faking its position* according to expected behavior.

2. *UAS 2 Navigation goal* - set as *UAS 1 position* from intercepted *position notifications* (tab. **??**).

Simulation: The *simulation* (fig. 7.1) have been run with defined condition. UAS 2 (magenta) has been chosen as the *adversary*. UTM sees the expected trajectory of UAS 2 (grey plane/trajectory) based on spoofed *position notifications*. The *navigation/avoidance grid* range (black dashed line boundary) is shown. The notable moment of the simulation are:

1. *Deviation detection* ($UAS2 \leftrightarrow UTM$) (fig. 7.1a) - the *collision case* (tab. **??**) is active and *enforced* by UTM. The *adversary* UAS 2 (magenta) starts deviating from expected trajectory (grey). UAS 1 (blue) does not register any foreign object in *avoidance grid range* (black dashed line).

2. *Adversary attacking* ($UAS2 \rightarrow UAS1$) (fig. 7.1b) - the adversary UAS 2 (magenta) starts actively pursuing UAS 1 (blue) by changing the original heading. This can be considered as the beginning of *active pursuit*. UAS 1 (blue) does not detect any foreign object in *avoidance grid* (black dashed line boundary). *UTM* is receiving expected UAS position (grey plane/line).

3. *Emergency avoidance* ($UAS1 \rightarrow UAS2$) (fig. 7.1c) following happens:

    a. *Adversary UAS 2* (magenta) is spotted by *UAS 1*(blue), it entered into UAS 1 avoidance grid (black dashed line boundary).

    b. *UAS 1* (blue) enters into *Emergency Avoidance Mode* because there is a *foreign object* in *avoidance grid*.

    c. *UTM* notices a warning to *UAS 1* (blue) because it entered into *Emergency Avoidance Mode*. UTM is not aware of any breach, because of expected UAS 2 position (grey plane/line)

    d. *Adversary UAS 2* (magenta) has UAS 1 (blue) locked in *navigation grid* as thegoal (which guarantees optimal pursuit).

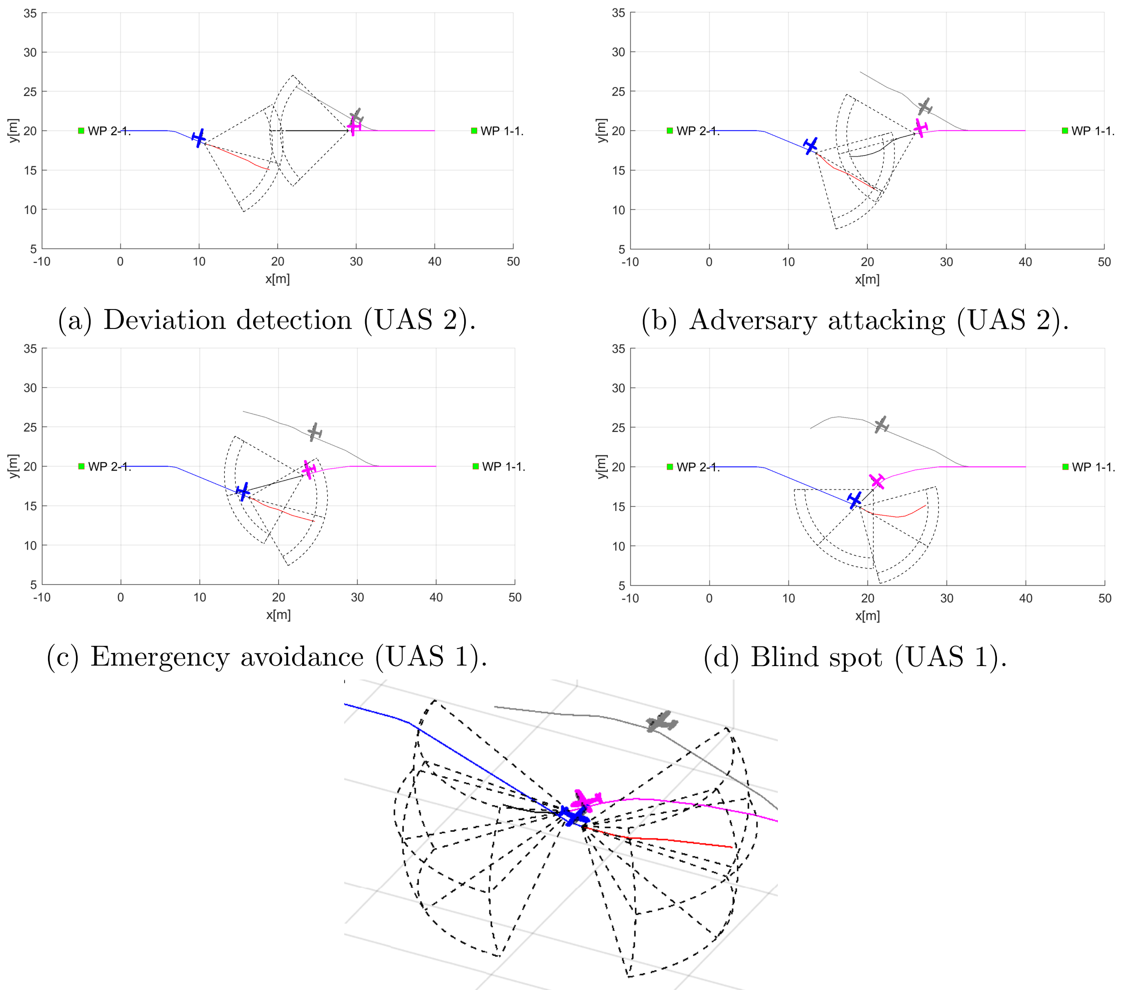
4. *Blind spot ($\circlearrowright UAS1$)* (fig. 7.1d) following happens:

   a. *UAS 1* (blue) returns to *Navigation Mode* because there is no *foreign object* in *avoidance grid* (black dashed line boundary).

   b. *UTM* receives the mode change, and it starts enforcing *resolutions* for *collision case*, Adversary *UAS 2* is considered clear due to *expected position* (grey plane/line) compliance with the resolution.

   c. *Adversary UAS 2* (magenta) is on UAS 1 blind spot. The target UAS 1 (blue) is locked in the UAS 2 navigation grid (black dashed line boundary).

5. *Collision detail ($UAS1 \leftrightarrow UAS2$)*(fig. 7.1e) - Target *UAS 1* (blue) is hit by *Adversary UAS 2* (magenta) on left wing tip. Both UAS are going down. UTM will detect sudden loss of both UAS systems.



(a) Deviation detection (UAS 2).

(b) Adversary attacking (UAS 2).

(c) Emergency avoidance (UAS 1).

(d) Blind spot (UAS 1).

(e) Collision detail.

Figure 7.1: Adversarial behaviour of *UAS 2* (magenta) to compliant *UAS 1* (blue)

Performance Parameters Evaluation: Performance parameters (y-axis) are tracked over *UTM time* (x-axis). The evolution of *performance* (fig. 7.2) is tracking following parameters:

1. *Expected crash distance* (gray line) - defined as (eq . ??) between UAS 1 (blue)and expected UAS 2 position (grey plane/line) over mission time $t \in [0, 22]$.

2. *Crash distance* (blue line) - defined as (eq . ??) between UAS 1 (blue) and real UAS 2 position (magenta plane/line) over mission time $t \in [0, 22]$.

3. *Safety margin* (yellow line) - constant value according to *collision case* (tab. ??) as the value of *10 m*. The safety margin is considered as a *soft constraint*.

4. *Body margin* (red line) - constant value according to (tab. ??) as value of *1.2 m*. The body margin is considered as a *hard constraint*. The breaking of *body* margin means an effective *collision* UAS 1 and UAS 2.

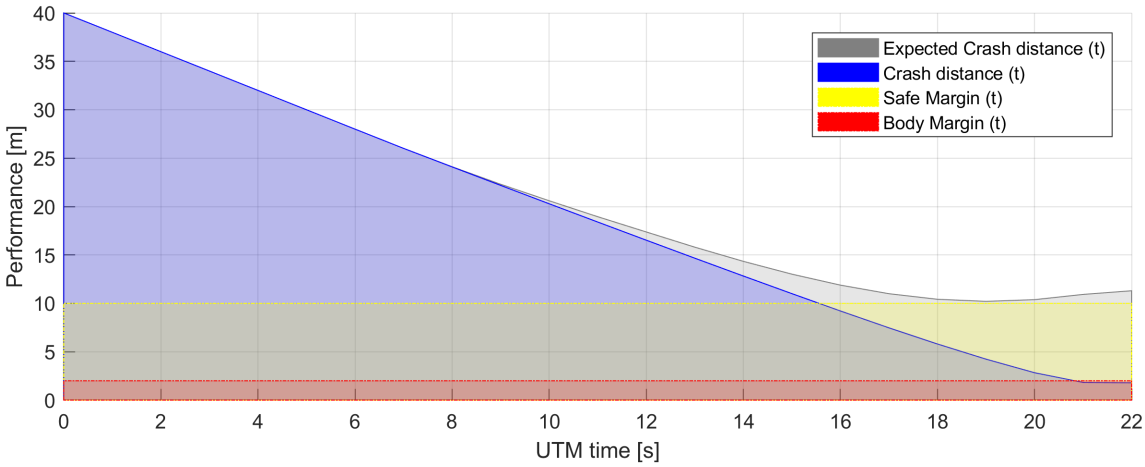


Figure 7.2: Expected/Real Distance to body/safety margin evolution for *adversarial behavior* of UAS 2.

Safety criteria for both *body* and *safety margins* in case of *expected behavior* are satisfied (eq. 7.1). This means that *UAS 1* fulfilled the *UTM directive* even though it entered *Emergency Avoidance Mode* (fig. 7.1c).

$$\begin{aligned} expectedDistanceToSafetyMargin(t) \geq 0, \qquad \forall t \in [0, 22] \\ expectedDistanceToBodyMargin(t) \geq 0 \qquad \forall t \in [0, 22] \end{aligned} \tag{7.1}$$

Safety Margin is broken at UTM time *15 s*, *body margin* is broken at UTM time *21 s*, the collision happens at UTM time *22 s*. This is summarized in *Distance Condition Breach* (eq. 7.2).

$$\begin{aligned} distanceToSafetyMargin(t) < 0, \qquad \forall t \in [21, 22] \\ distanceToBodyMargin(t) < 0 \qquad \forall t \in [15, 22] \end{aligned} \tag{7.2}$$

Note. An *adversary behavior* needs to be addressed on:

1. *UAS Traffic Management Level* - our UTM implementation failed to detect *deviation* (fig. 7.1a) and *start of attack* (fig. 7.1b). UAS 2 (magenta) had clean

intention from the beginning and did not change pursuit even when *safety margin* was breached.

2. *Emergency Avoidance Level* - our *navigation loop implementation* does not consider the *ill-intentions*. The UAS 1 (blue) properly switched to *Emergency avoidance mode* (fig. 7.1c) after detection of UAS2 (magenta). UAS 2 (magenta) then used the blind spot to exploit UAS 1 vulnerability.

7.5.3 Computation Footprint

The *computation footprint* is summarized in computation load (tab. 7.2). The *computation load* (eq. ??) was calculated for each *time-frame* in scenarios. There is the summary of *minimal, maximal, average* and *median* values.

The *computational load* never exceed more than 55.95% in case of *emergency Head On* (eq. ??), which means that *every path* was calculated on time.

Scenario	Computation load			
	min.	max.	avg.	med.
Building avoidance (fig. ??)	2.20%	27.40%	12.11%	13.20%
Slalom (fig. ??)	12.20%	30.50%	21.42%	21.50%
Maze (fig. ??)	24.90%	46.10%	31.51%	30.80%
Storm (fig. ??)	2.60%	26.90%	11.57%	13.90%
Emergency Converging (fig. ??)	2.75%	16.50%	5.84%	4.95%
Emergency Head On (fig. ??)	3.90%	55.95%	13.19%	6.90%
Emergency Multiple (fig. ??)	5.90%	52.35%	12.77%	8.56%
Rule-based Converging (fig. ??)	3.60%	13.50%	7.32%	5.97%
Rule-based Head on (fig. ??)	4.65%	41.60%	13.64%	9.30%
Rule-based Multiple (fig. ??)	4.37%	23.30%	11.96%	10.93%
Rule-based Overtake (fig. ??)	3.85%	13.40%	7.62%	6.70%

Table 7.2: *Computation load statistics* for all test cases.

Following observations can be made:

1. *Building avoidance*, *Slalom*, and *Maze* scenarios - the computation load is increasing with the *number of static obstacles*. The *average load* for *Emergency avoidance mode* in *clustered environment* is 31.51% (Maze).

2. *Storm scenario* - the overall *computation load* is very low due to the *moving constraint implementation* (sec. ??).

3. *Emergency Converging/Head On/Multiple* scenarios - the *overall computation load* is quite high due to the ineffective *body volume intersection* (sec. ??) implementation.

4. *Rule-based Converging/Head On/Multiple* scenarios - the *median computational* load is low, because of the linear *rule implementation* (sec. **??**)

5. *Rule-based Overtake* - the *average computation load* is very low because only *divergence/convergence* (rule. **??**) waypoints are calculated and UAS stays in *navigation mode*.

Bibliography