

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/(??)	WP ₁ : 107.05m WP ₂ : 86.20m WP ₃ : 28.70m WP ₄ : 32.84m	Yes (??)	Pass
Slalom (sim. ??)	0.09 m UAS 1	3.74 m UAS 1	No (??)	Yes/UAS 1/(??)	WP ₁ : 20.06m	Yes (??)	Pass
Maze (sim ??)	0.01 m UAS 1	2.95 m UAS 1	No (??)	Yes/UAS 1/(??)	WP ₁ : 28.06m	Yes (??)	Pass
Storm (sim. ??)	0.04 m UAS 1	34.99 m UAS 1	No (??)	Yes/UAS 1/(??)	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/(??)	WP ₁ : 3.25m 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/(??)	WP ₁ : 3.25m 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/(??)	WP ₁ : 4.84m WP ₁ : 1.83m WP ₁ : 3.45m 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/(??)	WP ₁ : 10.22m 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/(??)	WP ₁ : 5.40m 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/(??)	WP ₁ : 11.40m WP ₁ : 11.40m WP ₁ : 11.40m 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/(??)	WP ₁ : 24.00m WP ₂ : 0.00m WP ₃ : 4.00m WP ₄ : 5.00m 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 immediately 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 the goal (which guarantees optimal pursuit).

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

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

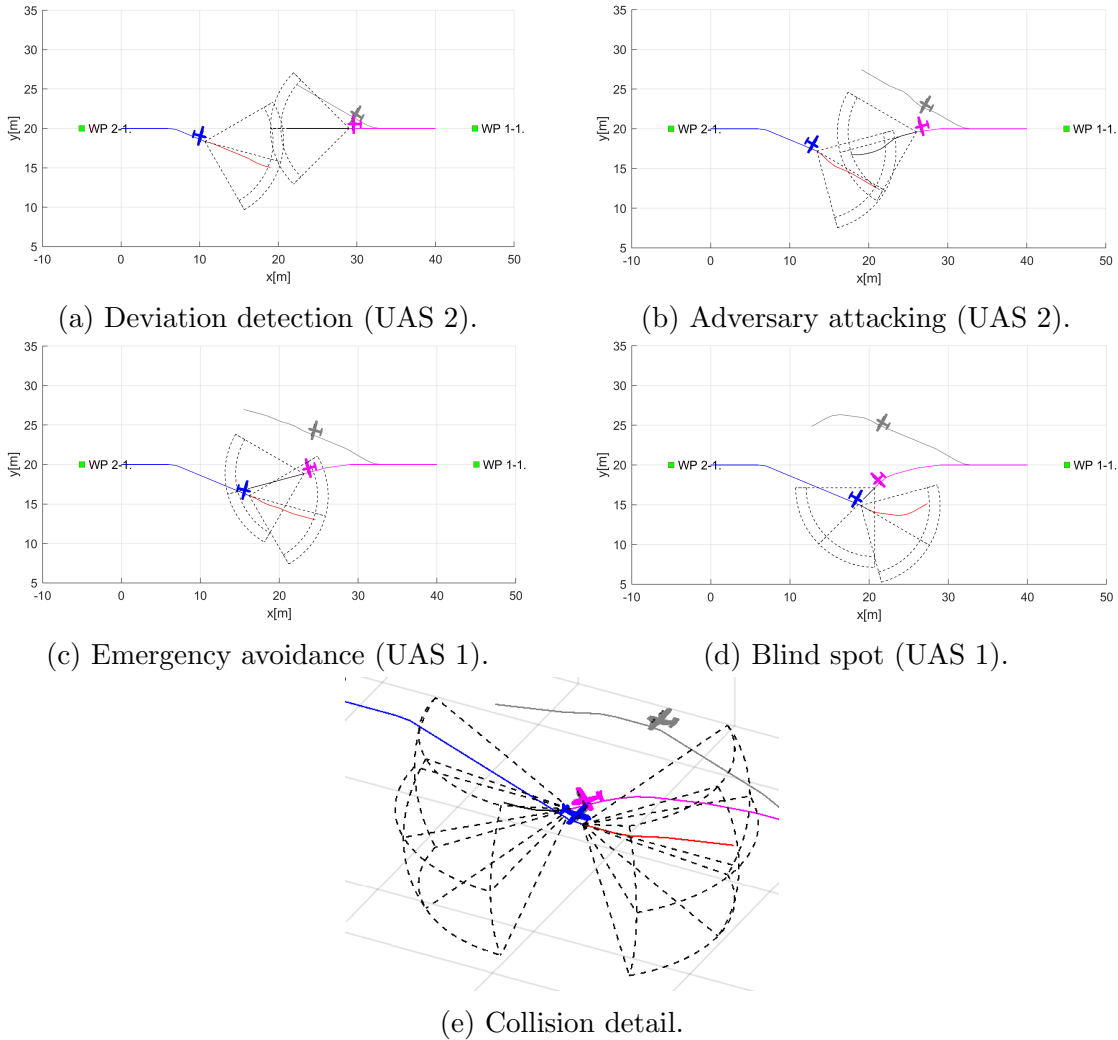


Figure 7.1: Adversarial behaviour of *UAS 2* (magenta) to compliant *UAS 1* (blue)

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.

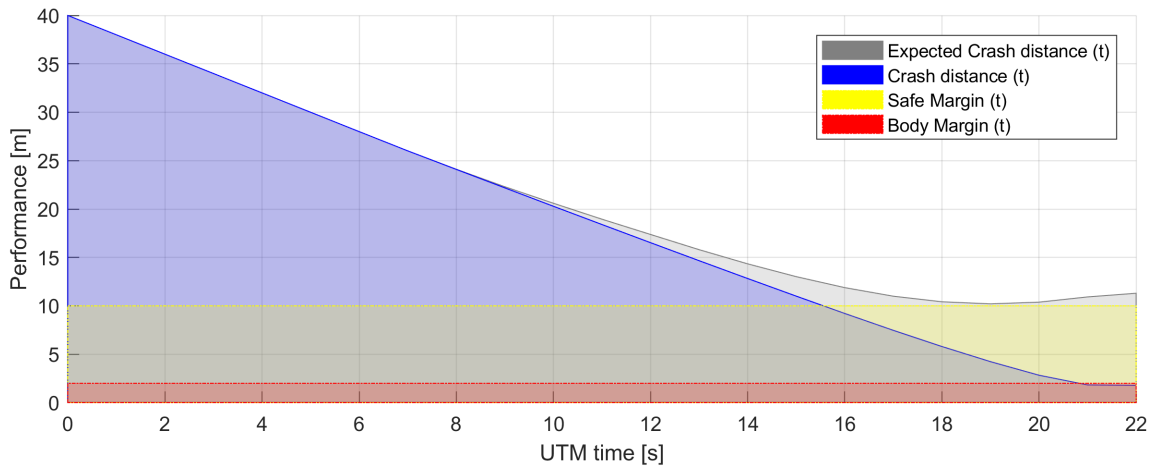


Figure 7.2: Expected/Real Distance to body/safety margin evolution for *adversarial behavior* of UAS 2.

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).

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

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).

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

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