Chapter 7

Simulations

The chapter presents the set of simulations developed according to a test plan (sec. 7.1). Test configuration (sec. ??) targets at exercising and evaluating proposed framework. The test cases are grouped in the following sections:

1. *Non-cooperative test cases* (sec. ??).
2. *Cooperative test cases* (sec. ??).
3. *Test cases conclusion* (sec. ??).
4. *Reach set approximation performance tests* (sec. ??).

7.1 Test Plan

The *Avoidance requirements* are given in (sec. ??), namely:

1. *Safety Margin Enforcement* (sec. ??) - keep UAS safe depending on situation.
2. *Path Tracking* (sec. ??) - track mission is given by a set of *waypoints* in the manner of *Energy Efficiency* (sec. ??).

These are given as nominal behavior (sec. ??), further enhanced by rule-based behavior (sec. ??).

The *Navigation requirements*, out of this scope, are given in (sec. ??). These are satisfied by *Mission Control Run* (sec. ??).

7.1.1 Testing approach

The purpose of this section is to show complex scenarios, not unit testing of framework functionality. The focus is on *borderline* cases for typical situations in an *expected environment*. The *mode switch* between *Navigation* and *Emergency Avoidance*.
The *Tests* are designed to focus on particular functionality in specific *operational environment* with main *obstacle/weather/intruder feature* with environment induced *constraints*. There is also *UTM* factor and *Navigation penalty*.

Operational Environment is classified according to:

1. *Operation space* - important for *Low Altitude Operations*, the difficulty of *Avoidance Maneuvers* is proportionally increasing with *Obstacle density.* There are following main categories

   a. *Rural environment* - the relief and man-made structures are sparsely spread around the *operation space*; the UAS is operating on *very low altitude* ($\leq$ 50 feet).

   b. *Urban environment* - the concentration of the man-made structures are much higher, and they are more incorporated info land relief pattern, the UAS is operating on *very low altitude.*

   c. *Open air* - the concentration of ground structures is very low, the concentration of *cooperative* and *non-cooperative intruders* is increased, the UAS is operating in altitude ranging from *50 feet* to *space border.* This brings us to:

2. *Airspace category* - when *Operation Space* pattern is categorized as *Open air* and depending on *altitude above mean sea level.* The UTM is *designed authority* for controlled airspace in current *F/G class airspace.*

   a. *Controlled* - Open air where authority is present. The cases when *Authority* is not enforced due to the UTM malfunction, $C2$ link loss or other cause are not considered.

   b. *Non-Controlled* - Open air operation space where is no central arbiter to determine or enforce traffic attendants behavior.

Static obstacles: Static obstacles with various features detectable by main *LiDAR* sensor. The main purpose is to show avoidance capabilities combined with heavy restrictions imposed by *soft* and *hard* constraints. The original purpose of our approach was to provide robust framework for static obstacle avoidance. Three tests with increasing obstacle density and navigation complexity are delivered.

Operational Space Constraints depends mainly on the *operational environment.* The standard set of constraints were taken into account for our test cases:

1. *Rural, Urban environment (low altitude)* are geo-fencing zones, ground (hard constraints), non-controlled airspace altitudes (soft constraints).

2. *Non-controlled airspace constraints (open air)* are geo-fencing zones (hard constraints), restricted airspace (hard constraint), weather (soft/hard constraint), controlled airspace (hard constraint), very low altitude border (soft constraints).

3. *Controlled airspace constraints (open air)* are restricted airspace (hard constraint), weather (soft/hard constraint), non-controlled airspace boundary (hard constraints), UTM Directives (hard constraints).

Air Traffic Attendants:

1. *Non-cooperative UAS* (Intruder) - there are some intruders with some degree of authority, size and *severity*. There were three test cases for non-cooperative intrudes. Non-cooperative Intruders can be categorized as following based on behavior:

   a. *Chaotic* intruders usually tend to behave unpredictable, for example, bird or *UAS in distress*, for this type of intruders *Maneuver Uncertainty Intersection Model* is used (app. **??**).

   b. *Harmonic* intruder usually follows long straight paths, for example, UAS converging to waypoint, for this type of intruder *Body Volume Intersection Model* is used. (app. **??**).

   Cooperative UAS (Intruder) - there are cooperative intruders who are obeying authority (UTM) or follow *common consensus*. The work focus on *UTM* authority implementation in four test cases. These test cases are reflecting the traffic management situations essential for successful UTM collision management

Weather impose *soft* and *hard* space constraint, which can be moving or static. The *soft constraint avoidance* is covered by *hard constraint avoidance*. The *static constrained area* is covered by *static obstacle avoidance* capability due to the *data fusion procedure* [1]. The only case which is not covered is *Moving constrained area*; small constraints can be covered by intruder models. The ideal candidate is a *storm*, because it covers quite a large area, the clouds are constantly moving, and severity is changing with time.

UTM: The *UAS Traffic Management* service should be implemented in *controlled airspace* by 2035. It is necessary to study impact of UTM services on the *Detect and Avoid* systems like ours.

The most basic service is *Identity provider* which should be implemented by 2020.

Then there are *location services*, which are necessary for coordinated collision avoidance, these were implemented in our solution up to necessary level for *Rules Of the Air* implementation.

Mission tracking is service tracking deviations from *declared mission plan* and *actual execution*. These statistics were used in all tests to track deviations from the reference trajectory.

Directives for *Traffic management* and *Collision prevention* are implemented as the functional life cycle of *Position notification* (sec. **??**), *Collision Case* (sec. **??**) for UTM. The directive handling is implemented as *Rule engine* (sec. **??**) on UAS side.

Navigation: Navigation algorithm is depending on *Navigation mode*. UAS is usually in *Navigation mode* most of the time, despite this fact, UAS was forced into *Emergency Avoidance Mode* most of the time in test cases. The navigation complexity has been divined into following categories:

1. *Open space* - UAS has visibility to goal waypoint most of the time; there are no traps.

2. *Hidden waypoint* - UAS does not have visibility to goal waypoint, most of the time; there are irregular traps sometimes.

3. *Maze solving* - UAS line of sight for goal waypoint is hindered by multiple obstacles, there are irregular traps often.

4. *Rule following* - UAS navigation capabilities are constrained by rule enforcement.

7.1.2 Test Cases Summary

Test cases are summarized in (tab. 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

Table 7.1: Test Cases Summary.

7.1.3 Performance Evaluation

Evaluation method: *Test cases* were evaluated according to performance requirements defined in (sec. ??). The method was tracking critical parameter for *Safety* (sec . ??) (primary) and *Trajectory Tracking* (sec. ??) (secondary) including *Energy Efficiency* (sec. ??).

Safety Margin Performance Evaluation: The *safety of UAS* is main concern of *DAA system*. The common concept of *safety margin* is evaluated.

The *threat* is multidimensional; there are often multiple *static obstacles, intruders* or *weather constraints*. To reduce the multidimensional threats to one-dimensional value *crash distance* concept is used:

$$crashDistance(t) = distance(UAScenter(t), threat)$$
where *selection the criterion* is:
$$\min\left\{\begin{array}{c}\begin{pmatrix}distance(UAScenter(t), threat) - \dots\\ \dots - threat.SafetyMargin\end{pmatrix}\\ : \forall threat \in KnownWorld(t)\end{array}\right\} \quad (7.1)$$

The *crash distance* (eq. 7.1) for given time is evaluated as shortest distance between UAS center and threat. The threat origins from the known world (sec. **??**). The *threat* has safety margin. The distance to safety margin is used as a prioritization criterion in our test cases (tab. 7.1).

The *safety margin* evolution over time (eq. 7.2) is calculated similarly to *crash distance*. The most dangerous threat is selected based on *distance to the safety margin* criterion. The value of *safety margin* property is then used.

$$safetyMargin(t) = threat.SafetyMargin$$
where *the selection criterion* is:
$$\min\left\{\begin{array}{c}\begin{pmatrix}distance(UAScenter(t), threat) - \dots\\ \dots - threat.SafetyMargin\end{pmatrix}\\ : \forall threat \in KnownWorld(t)\end{array}\right\} \quad (7.2)$$

The *distance to safety margin* (eq. 7.3) is calculated as a difference between the *crash distance* (eq. 7.1) and *safety margin* (eq. 7.2). The *acceptance criteria* for safety is the *distance to safety margin* ≥ 0.

$$distanceToSafetyMargin(t) = crashDistance(t) - safetyMargin(t) \geq 0 \quad (7.3)$$

Note. On Signed Distance: The most works are using *unsigned distance.* This work considers the *signed distance* with the following intervals:

1. + (away from the safety margin).
2. 0 (touching margin with UAS edge).
3. - (inside margin - crash/collision/broken boundary).

Distance to Safety Margin peaks are measured:

1. *Minimal* distance to safety margin indicates if *acceptance criterion* (eq. 7.3 is met).

2. *Maximal* distance to safety margin indicates the future *minimal detection range*. All scenarios were considered as borderline cases.

Trajectory Tracking Evaluation is a secondary priority after safety, following parameters were checked:

1. *Waypoint reach* - the *Mission* (**??**) is considered as completed if and only if $\forall$ waypoints are reached and in the given order (check the output of **??**). Moreover, if there is multiple UAS, each must meet the condition.

2. *Acceptable deviation* - for *tracking problem* (eq. **??**) is a trajectory which in addition to *basic obstacle problem* (sec. **??**) keeps deviation from the *reference trajectory* under a certain threshold (eq. **??**).

Trajectory tracking deviation threshold (eq. 7.4) is defined as double of maximal distance between *goal waypoint* and *previous waypoint*.

$$trackingDeviationTreshold = 2 \times distance(goalWaypoint, previousWaypoint) \quad (7.4)$$

Note. If *goal waypoint* is first in the *mission*, the *UAS initial condition* is considered as a *previous waypoint*.

Computation Load: There is a theoretical definition of *intersection models* for *static obstacles and constraints* (sec. **??**), *moving obstacles and constraints* (sec. **??**), *avoidance run* (sec. **??**), *mission control* (sec. **??**) computational complexity.

The practical application requires to measure *computation load* in constrained environment. Let say that *avoidance framework* is running on stand alone embedded computer with 1.2 GHz processor and 1GB of dedicated RAM. This is simulated by *virtual machine*.

The *simulations* were executed in *Matlab/Simulink* environment[1] using: *UTM*[2], *Navigation loop* [3], *Avoidance grid*[4] and *Reach set*[5] implementations.

The *decision frame* length is set to 1s which gives *computation load* (eq. 7.5). The *computation load* represents the portion of the *previous decision frame* used to current decision frame calculation.

$$computationLoad = \frac{computationTime(frame)}{decisionFrameDuration} \times 100, \quad [\%; s, s] \quad (7.5)$$

[1]Prototype framework implementation: `https://github.com/logomo/Feature-based-ACAS/`
[2]UTM class: `.../UavTraficManagement/UTMControl.m`
[3]Navigation Loop main class: `.../MissionControl/MissionControl.m`
[4]Avoidance Grid class: `.../AvoidanceGrid/AvoidanceGrid.m`
[5]Reach set tree class: `.../AvoidanceGrid/PredictorNode.m`

Note. Computation load is depending on the actual situation; when the UAS is in *navigation mode*, it should be low, when the UAS is in a *clustered environment* it should be high.

Matlab implementation is quite ineffective; the Python/C++ implementation can give better results.

For *computational feasibility* there is *implicit* acceptance criterion (eq. 7.6): the computation of a feasible path for *this time-frame* must end in the *previous time-frame.*

$$\forall time \in Mission : \quad computationLoad < 100\% \tag{7.6}$$

Bibliography

[1] Alojz Gomola, Pavel Klang, and Jan Ludvik. Probabilistic approach in data fusion for obstacle avoidance framework based on reach sets. In *Internal publication collection*, pages 1–93. Honeywell, 2017.