New Sections - Structure check + Intro

# 6.4 Reach Set Approximation

There is a need to have a tool with a finite count of trajectories, which has enough variability to support avoidance task. The reach set covers all possible trajectories , but it is not countable. Trajectories represented as tree originating in the same initial state can be considered as a skeleton of the reach set. There is a need to compare trajectories regarding avoidance capability. To achieve this, it is necessary to distinguish them based on measurable criteria. Different approximation based on the measurable criteria is introduced to cover different avoidance behaviors.

## 6.4.1 Trajectory Set Approximation of Reach Set

To achieve finite representation, it is necessary to establish a general relationship between the reach sets and trajectory trees, built from a set of prototypical movements.

## 6.4.2 Distinctive Properties of the Trajectories

A characterization of trajectories is provided to support the selection of feasible representatives to build a skeleton of the reach set.

## 6.4.3 Heuristic Trajectory Tree Building

There is a need for building tool to create trajectory set based reach set approximation iteratively. The iterative procedure is based on wave-front expansion algorithm. The node selection criteria for trajectory construction is used to build performance-based reach set approximations.

## 6.4.4 Coverage-Maximizing Reach Set Approximation

This procedure will produce trajectories maximizing aggressive maneuvering, ideal for avoidance tasks.

## 6.4.5 Turn-Minimizing Reach Set Approximation

This procedure will produce trajectories minimizing aggressive maneuvering, ideal for navigation tasks.

## 6.4.6 ACAS-X like Reach Set Approximation

This procedure will produce trajectories encoding ACAS-X separation modes, ideal for controlled airspace navigation

## 6.4.7 Combined Reach Set Approximation - Tree Merge

If there is a need to improve the reach set approximation with additional trajectories, it is possible to merge it with another reach set approximation under certain conditions.

# 6.5 Situation Representation in the Avoidance Grid

There is a need to have a safety assessment of the operational space in the form of the Avoidance Grid. Each type of threat coming from different sources (sensors, maps) like obstacles, intruders, and constraints is handled separately. The data fusion procedure provides a unified representation of sourced threats.

## 6.5.1 Obstacles

There is a need to asses filtered LiDAR readings into detected obstacle rating associated to each cell. There are known obstacles in the form of a map which are verified taking into the account visibility constraints.

## 6.5.2 Intruders

The intruder information coming from ADS-B needs to be assessed in relationship to the Avoidance Grid. The final assessment consists of time encounter and space encounter ratings. The space encounter rating describes the probability of UAS meeting intruder in the same space. The time encounter rating is reflecting simulations time in the same cell.

## 6.5.3 Constraints

There are different constraints from various sources with different impacts. There is a need for constraint impact assessment on the cells in the Avoidance Grid.

## 6.5.4 Data fusion

There is a need for the final threat assessment in the Avoidance Grid. The data fusion provides mechanisms to represent, process, and assess threat in the cell including the safety of trajectories in the RSA. The output of the data fusion procedure is used further in Avoidance run (6.6.1).

# 6.6 Avoidance Concept

There is a need for a functional orchestration of previous concepts to achieve avoidance and navigation capabilities. The avoidance grid threat assessment done in (sec. 6.5.4) needs to be applied on the RSA of choice to produce a safe trajectory for one fixed time. This procedure is described in the avoidance grid run. There is a need to join output multiple avoidances runs over the time to achieve the required avoidance/navigation capabilities. This procedure is described in the navigation run. There is a need to assess the computational complexity of the approach to show implementation feasibility.

## 6.6.1 Avoidance Grid Run

Based on the provided threat assessment find the optimal trajectory in compliance with safety and given navigation goal.

## 6.6.2 Mission Control Run

Event-based navigation algorithm connecting results of the multiple Avoidance Grid Runs over time to generate a trajectory satisfying the mission. The concept of discrete future events is introduced to support the processing of various threats and commands. The overview of process description and thread orchestration is provided.

## 6.6.3 Computational Complexity

Brief approach computational complexity analysis considering navigation/control/data fusion in support of real-time application feasibility.

# 6.7 UTM Prototype Implementation

The UAS system is already equipped to fend the treat itself. The practical applications require some degree of cooperation with authority (UTM). The requirements for UTM supervised operations are outlined in (sec 2.5). First, the interaction architecture is established. The notable maneuvers and situations are analyzed under VFR/IFR conditions. The position notification message and handling are proposed to support collision case calculations and life-cycle management.

## 6.7.1 UTM Architecture

The UTM authority needs to communicate with the UAS attendants. The communication scheme is asynchronous notification(UAS)-directive(UTM).

## 6.7.2 Handling Head-on Approach

Two UAS are facing each other head-on. There is a need to define triggers for detection and resolution approach for autonomous UAS. Rules for VFR/IFR modes in manned aviation are the base for the autonomous collision resolution. The concept of the virtual roundabout is introduced.

## 6.7.3 Handling Converging Maneuver

Two planned trajectories of the UAS are perpendicular, thus resulting in a protentional collision. There is a need to define triggers for detection and resolution approach for autonomous UAS. Rules for VFR/IFR modes in manned aviation are the base for the autonomous collision resolution.

## 6.7.4 Handling Overtake Maneuver

Summary: Two UAS are on the same airway, flying in the same direction. The slower UAS is in front of the faster UAS. The slower UAS has the right of way, and the faster UAS needs to make an overtake. There is a need to define triggers for detection and resolution approach for autonomous UAS. Rules for VFR/IFR modes in manned aviation are the base for the autonomous collision resolution.

## 6.7.5 Position Notification Implementation

There is a need to define a “minimal “data-set for UAS position notification. The base of such notification is the ADS-B message.

## 6.7.6 Collision Case Implementation

The UTM needs to detect and prevent possible collisions. The collision case is a record of such event detection, processing, and closure. Two detection methods are defined, one using linear intersection and other using planned trajectories intersection. The angle of approach and UAS relative speed determines the maneuver to be used in situation handling.

# 6.8 UTM Directives Framework Implementation on UAS

The standard framework implementation (sec. 6.5) needs to be enhanced for UTM directives following. The rule engine software architecture supports the addition and removal of rules and regulations.

## 6.8.1 Rule Engine Architecture

The implementation of the rule engine architecture in our framework environment.

## 6.8.2 Rule Engine Setup

The setup to cover collision case resolution according to (sec. 6.7.6).

Appendixes – structure check + Intro ??

# A Complementary Definitions

# B Simplified Framework Conceptual Scheme

# C Movement Automaton Theory

## C.1 Specialization of Hybrid Automaton

## C.2 Formal Movement Automaton Definition

## C.3 Segmented Movement Automaton

## C.4 Reference Trajectory Generator

# D Intruder Probabilistic Models

## D.1 Small body direct movement Intruder intersection

## D.2 Notable body direct movement intruder intersection

## D.3 Maneuvering Intruder Intersection

# E Conflict Resolution Schemes

## E.1 Cooperative Conflict Resolution

## E.2 Non-Cooperative Conflict Resolution

# F Additional UTM functionality

## F.1 Weather Case Implementation

## F.2 Rule: Detect Collision Cases

## F.3 Rule: Resolve Collision Case

## F.4 Rule: Close Collision Cases

## F.5 Rule: Head on Approach

## F.6 Rule: Converging Maneuver

## F.7 Rule: Overtake

## F.8 Rule: Right Plane Heading

## F.9 Rule: Enforce safety margin

# G Approach Guidelines

## G.1 Guideline - Grid Size Calculation

## G.2 Guideline - Safety Margin Calculation