RTA UxV Challenge Problem

# Overview

In order to further utilize advanced control technologies in autonomous systems the Air Force needs to develop methodologies to properly bound and manage systems that are increasingly difficult to V&V utilizing traditional methods. A technique to mitigate this limitation is building a system that will bound advanced controllers with a number of certifiable controllers that are validated using current standard methods.

# CONOPS

This system utilizes an UxV (ground vehicle or air vehicle with a set altitude) in order to conduct complex autonomous tasking allocation. The UxV will proceed from an origin location (Homebase), proceed to the given objective locations in whatever order it chooses, and return to the origin to complete the mission. While conducting the mission objectives, the UxV will have to have to avoid Restricted Operating Zones (known before deployment) and also intruder UxVs that are proceeding in straight lines across the area of operations. The dynamics of the UxVs in the system will initially be a Dubin’s model to develop the autonomous planning algorithms within the allowable constraint space.

# Vehicle Highest Level Requirements

* The vehicle will be designed properly
  + The vehicle shall remain safe
  + The vehicle shall complete its mission

# Detailed Requirements Derivation

1. The vehicle shall remain safe
   1. Vehicle Hazard Level Definition:
      1. Measure of risk to the vehicle and the flight safety. An abstract way to measure the level of hazard to the vehicle at any given time.
      2. Range from 0 to 60
         1. 0 : no hazard to the vehicle
         2. 20+ : loss of vehicle
      3. Calculation
   2. The vehicle shall avoid Restricted Operating Zones (ROZs) with certain specific exceptions
      1. A vehicle is considered inside a ROZ if the point-mass of the vehicle is within the boundary of the ROZ.
      2. Threat Levels
         1. Measure of risk to the mission and to the vehicle safety as related to the ROZ
         2. Range from 0 to 9 or 20
            1. 0 : no threat to the vehicle
            2. 1-4 : Threat to mission

Example: Vehicle detected by enemy sensors

* + - * 1. 5-9 : Threat to safety

Example: Probable incoming fire (5-7)

Example: Physical obstructions (8-9)

* + - * 1. 20 : Loss of vehicle

Example: Collision with building/ridge

* + 1. Safe Now: the current state of the vehicle is within the safety bounds (1.2.5)
    2. Safe on the Horizon: the predicted state of the vehicle is within the safety bounds for a horizon of 5 seconds (arbitrary assigned – could be changed) (1.2.5)
    3. If the vehicle is detected to be unsafe (now or on the horizon), revert to reversionary control
    4. Safety bounds
       1. The vehicle’s threat due to ROZ () shall be 0 in non-exception cases.
       2. The vehicle’s threat due to ROZ () shall be less than 20 if a specific exception case occurs.
    5. List of exceptions
       1. Flight path causes the lowest hazard level to the vehicle
       2. Avoidance of intruder
       3. Time constraints for mission
       4. Fuel constraints
  1. The vehicle shall not violate the structural G-Limits
     1. The current G-limit on the vehicle is calculated according to the following force equation.
     2. Load limits of the vehicle are:
        1. Safety Load Limit: 3G for the aircraft
           1. Exceeding the safety load sets the Threat G-Load to 1
        2. Maximum Load Limit: 5G
           1. Exceeding the maximum load sets the Threat G-Load to 20 (loss of vehicle)
     3. Safe Now: The current g-load of the vehicle is within the safety bounds (1.3.6)
     4. Safe on the Horizon: the predicted g-load is within the safety bounds for a horizon of 5 seconds (arbitrary assigned – could be changed) (1.3.6)
     5. If the vehicle is detected to be unsafe (now or on the horizon), revert to reversionary control
     6. Safety bounds
        1. The vehicle’s threat due to G-Load () shall be 0 in non-exception cases.
        2. The vehicle’s threat due to G-Load () shall be less than 20 if a specific exception case occurs.
     7. List of exceptions
        1. The maneuver causes the lowest hazard level to the vehicle
        2. Avoidance of intruder
        3. Time constraints for mission
        4. Fuel constraints
  2. The vehicle shall not collide with Intruders
     1. Threat Levels
        1. Identifies the risk of collision with the vehicle based on proximity and Vehicle (non-intruder) speed.
        2. Range from 0, 5 or 20
           1. 0 : no threat to the vehicle

Intruder outside of Caution Halo

* + - * 1. 5 : Potential threat to collide

Intruder inside Caution Halo and outside the Safety Halo

* + - * 1. 20 : loss of vehicle

Intruder is inside the Safety Halo and a collision is unavoidable

* + 1. Safe Now: the current Intruder position is not within the safety halo of the vehicle and not inside the caution halo unless there is an exception case (1.4.6).
       1. The UxV shall maintain a safety halo separation from Intruders by maneuvering as required to ensure the relative position to the Intruder is always greater than the safety halo radius.
          1. The UxV system shall always ensure the following safety equation

* + - 1. The intruder can enter the caution halo under certain exceptions but it will increase the overall threat to the vehicle.
         1. The UxV system shall ensure the following equation unless an exception exists

Where:

* + 1. Safe on the Horizon: the projected Intruder position is not within the safety halo of the projected vehicle position and not inside the caution halo unless there is an exception case (1.4.6).
       1. The UxV CMA (Command Navigation Algorithm) inertial point shall maintain a safety halo separation from Intruders by commanding a flightpath that will not violate the safety constraints of the vehicle over time.
       2. Forward Flightpath Propagation (FFP)
          1. The propagation of the vehicle’s flightpath forward in time assuming that there is no change to the trajectory plan during that time
          2. The Intruder shall not violate the safety halo of the UxV’s FFP at any future time t.
       3. Reference section 1.4.2 for halo equations.
    2. If the vehicle is detected to be unsafe (now or on the horizon), revert to reversionary control
    3. Safety bounds
       1. The vehicle’s threat due to the Intruder () shall be 0 in non-exception cases.
       2. The vehicle’s threat due to the Intruder () shall be less than 20 if a specific exception case occurs.
    4. List of exceptions
       1. The maneuver causes the lowest hazard level to the vehicle
       2. Avoidance of intruder
       3. Time constraints for mission
       4. Fuel constraints
  1. The vehicle shall prioritize the safest decisions in the event of a conflict between multiple hazards.
     1. The autonomy on the vehicle shall command the minimal cost decision in the event of a conflict according the hazard level as defined in section 1.1.

1. The vehicle shall complete its mission
   1. The UxV shall begin inside the Homebase
   2. The vehicle shall prioritize Requirement #1 and maintain acceptable hazard levels
   3. The vehicle shall accomplish 100% objective acquisition.
      1. The vehicle shall acquire each of the pre-planned objective locations the point mass representing the vehicle should enter the objective area.
      2. The mission will have a total elapsed time from beginning to end to meet all objectives and to return to Homebase
         1. Individual objective locations do not have time constraints; autonomy choses proper time allotment
   4. The vehicle shall return to Homebase (RTB) after leaving the Homebase area and attempting objective acquisition.
      1. The vehicle shall leave the Homebase area to initiate the mission with a minimum fuel margin of TBD %.
      2. The vehicle shall RTB upon depleting mission resources and abort mission completion.
         1. The vehicle shall initiate an RTB at TBD% fuel margin.
         2. The vehicle shall initiate an RTB at TBD remaining mission time.
         3. The vehicle shall initiate an RTB upon receiving command from Homebase.
      3. When the mission designates the RTB mode, the terminal position of the vehicle shall remain within the Homebase area until a landing and power down is accomplished.
         1. The vehicle shall initiate a landing pattern sequence in the RTB mission mode once the Homebase area has been acquired and shall not exit the Homebase area unless otherwise commanded.
      4. The vehicle shall deliver the Data Package to Homebase at RTB complete.
         1. The information acquired from the mission is delivered when the vehicle returns, in the event the vehicle is lost there is no partial data delivery
   5. The vehicle shall self-destruct upon authenticated order from central command and will result in loss of all mission data
   6. Mission Termination
      1. Meeting the objectives (section 2.3) and completing a return to Homebase (RTB) (section 2.4) will define a successful mission
      2. In the event that the UxV Hazard Level meets or exceeds 20 then the UxV is considered ‘lost’ and the mission is considered unsuccessful.
2. There will be one vehicle.
   1. The current location of the vehicle will be defined as a point-mass location
   2. Vehicle dimensions
      1. Length: 1.5 m
      2. Wingspan: 3 m
   3. Speed:
      1. Max: 40 m/s
   4. Mass: 20 kg
   5. Load Limit:
      1. Safety Load Limit: 3G for the aircraft
         1. Exceeding the safety load sets the Threat G-Load to 1
      2. Maximum Load Limit: 5G
         1. Exceeding the maximum load sets the Threat G-Load to 20 (loss of vehicle)
   6. Energy Capacity
      1. 40000 Units Max
         1. This is an abstraction of a percentage to get us 2 decimal precision with the overall max desired mission of approximately 6 hours
            1. Ex. 56.82% = 22728 energy units
   7. Payload
      1. The vehicle is assumed to be able to carry the appropriate payload to meet mission objectives and will not be explicitly modeled/defined
   8. Flight Modes:
      1. Dash
         1. Speed: Max Speed (40 m/s)
         2. Turning Radius: (by equation):
            1. 3G Safety Barrier: ~55m
            2. 5G Max Barrier: ~35m
         3. Halos
            1. Safety Halo Size: 100m (assume one tenth of the radius)
            2. Caution Halo Size: 200m (2x Safety Halo)
         4. Energy Use: 10 units/s
            1. Maximum time of 1 hour roughly in mission if exclusive use of this mode
      2. Cruise
         1. Speed: 30 m/s
         2. Turning Radius:
            1. 3G Safety Barrier: ~30m
            2. 5G Max Barrier: ~20m
         3. Halos
            1. Safety Halo: ~60m
            2. Caution Halo Size: ~120m (2x Safety Halo)
         4. Energy Use: 5 unit/s
            1. Rational: More expensive thus reducing total mission time
      3. Loiter
         1. Speed: 20 m/s
         2. Turning Radius:
            1. 3G Safety Barrier: 15m
            2. 5G Max Barrier: ~10m
         3. Halos
            1. Safety Halo: ~27.5m
            2. Caution Halo Size: ~55m (2x Safety Halo)
         4. Energy Use: 2 unit/s
            1. Rational: Roughly 6 hours of mission time in this mode
      4. Evade
         1. Speed: 10 m/s
         2. Turning Radius:
            1. 3G Safety Barrier: ~4m
            2. 5G Max Barrier: ~2m
         3. Halos
            1. Safety Halo: 7m
            2. Caution Halo Size: 14m (2x Safety Halo)
         4. Energy Use: 1 unit/s
            1. Rational: Half the energy usage for the nominal mission time
3. Operational area
   1. Looking at the specs on the aircraft we are going to make the operational area relate to those
      1. 20 km x 20 km
         1. Roughly the size of the Indianapolis Beltway
   2. Homebase
      1. Shall be a square zone
         1. This region shall not overlap or touch Objectives
         2. This region shall not overlap or touch ROZs
         3. The region must be fully contained inside the operational area
            1. The region can touch operational area boundary
      2. UxV will be initialized in the Homebase region.
      3. A successful mission will terminate when the UxV returns to the homebase after completing mission objectives
   3. Objectives
      1. Shall be a circular zone
         1. Minimum radius of 50m
         2. Maximum radius of 200m
         3. This region shall not overlap or touch the Homebase
         4. This region shall not overlap or touch ROZs
         5. The region must be fully contained inside the operational area
      2. The objective is considered ‘reached’ if the UxV enters the objective region.
   4. ROZ
      1. Allowable quantities
         1. Min # ROZ = 0
         2. Max # ROZ = 20
      2. Allowable Dimensions
         1. Minimal distance on a side is 50m
         2. Maximum distance on a side is 5 km (5000m)
      3. ROZ locations are pre-assigned before the mission begins and are static (i.e. may not dynamically show up during the mission)
      4. Threat Levels
         1. Measure of risk to the mission and to the vehicle safety as related to the ROZ
         2. Range from 0 to 9 or 20
            1. 0 : no threat to the vehicle
            2. 1-4 : Threat to mission

Example: Vehicle detected by enemy sensors

* + - * 1. 5-9 : Threat to safety

Example: Probable incoming fire (5-7)

Example: Physical obstructions (8-9)

* + - * 1. 20 : Loss of vehicle

Example: Collision with building/ridge

* + 1. All areas that are not contained in a ROZ must be reachable without passing through a ROZ
       1. Minimal separation distance between closest edges to allow reachability: 30m
          1. Need have a corridor to traverse

ROZ separation achieved by checking both vertical sides and both horizontal sides with respect to the minimal separation offset from the vertical and horizontal edges

If either of the horizontal edges fail with respect to the horizontal boundary then the horizontal separation is not valid

If either of the vertical edges fail with respect to the vertical boundary then the vertical separation is not valid

If either the vertical separation or horizontal separation tests are valid then the separation is valid

If neither the vertical separation nor horizontal separation tests are valid then the separation is not valid

* + 1. Intersection of ROZs
       1. ROZs can completely exist in other ROZs if they are of a higher threat level than the containing ROZ
       2. ROZs can intersect other ROZs with no implication on threat levels
       3. While within multiple ROZs the highest threat level is considered the threat level

1. Intruder
   1. The intruder aircraft is not adversarial and is not necessarily an adversary
      1. This could friendly vehicle that is unaware of the UxV and is not going to make any changes to its trajectory to avoid the UxV.
   2. Behavior
      1. The intruder has a constant randomized speed between 20 to 40 m/s
      2. The intruder does not change its heading once initialize at the operational border.
      3. Intruders can’t pass through the Homebase.
      4. Intruders can pass through mission Objectives.
      5. Intruders can’t pass through ROZs that have a threat level of 5 or more (meaning physical path obstruction e.g. a building)
      6. The intruder’s initial position is on the operational boundary
         1. The initial position is at least X meters away from the UxV
            1. X = Twice the caution halo radius defined in in section 3.8.1.3.2.
      7. The intruder is considered has ‘exited’ when it is no longer in the operational area
   3. Intruder related CONOPS
      1. The position and velocity vectors of the intruder are known at the instance of entering the operational area with full observability throughout the intruder trajectory.
      2. One instance of an intruder exists at a given time.
      3. When the intruder leaves the operational area, a new intruder will be initialized in the next time step
   4. Threat Levels
      1. Identifies the risk of collision with the vehicle based on proximity and Vehicle (non-intruder) speed.
      2. Range from 0, 5 or 20
         1. 0 : no threat to the vehicle
            1. Intruder outside of Caution Halo
         2. 5 : Potential threat to collide
            1. Intruder inside Caution Halo and outside the Safety Halo
         3. 20 : loss of vehicle
            1. Intruder is inside the Safety Halo and a collision is unavoidable

[1] Hormann, Kai, and Alexander Agathos. "The point in polygon problem for arbitrary polygons." *Computational Geometry* 20.3 (2001): 131-144.

