Onboard Decision-Making for Nominal and Contingency sUAS Flight

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This study presents an onboard decision-making architecture for small unmanned aerial systems (sUAS) . The decision-maker is part of NASA's SAFE50 project that is working under the UAS Traffic Management (UTM) Technical Capability Level (TCL) 4 to provide autonomous point-to-point sUAS flight in beyond visual line-of-site (BVLOS), high-density urban environments. The decision-maker monitors various metrics to determine the safety and feasibility of the mission and categorizes flight states as Nominal, Off-Nominal, Alternate Land, and Land Now in a finite state machine. Changes in the monitored metrics serve as transitions in the state machine and trigger replanning. Navigation degradation and communication failure are simulated to show the feasibility of the decision-maker framework in appropriately switching the flight state.

I. Introduction

As unmanned aerial vehicle (UAV) flight continues to expand in complexity (e.g. surveillance,[1] traffic assistance,[2] disaster management,[3] cinematography,[4] delivery,[5] etc.), vehicle capabilities have been growing to match. For example, package delivery in an urban environment may pose problems due to GPS loss around tall buildings. Therefore, other localization methods such as LIDAR[6] or visual[7] simultaneous localization and mapping (SLAM) must be developed. Urban landscapes not only pose a detriment to localization, but can also complicate beyond visual line-of-sight (BVLOS) flight by obstructing communication lines. To mitigate these communication dropouts, UAVs may be restricted to special segregated airspace.[8] However, the FAA predicts the number of commercial small Unmanned Aerial Systems (sUAS)—which includes the UAV with the ground control and communication units—will grow to 420,000 by 2021, almost ten times the 42,000 in 2016.[9] Furthermore, these restrictions will impede wider utilization due to the multitude of stakeholders and current heterogeneity of national UAS regulations. As such, a homogeneous infrastructure must be developed to match the progression of UAV technology.

NASA's UAS Traffic Management (UTM) system seeks to enable safe and efficient low-altitude UAS operations in high-density airspace by providing services such as "airspace design and dynamic configuration, dynamic geofencing, severe weather and wind avoidance, congestion management, terrain avoidance, route planning and re-routing, separation management, sequencing and spacing, and contingency management".[10] The UTM concept of operations (ConOps) focuses on small UAS under 55lbs that operate no more than 400 ft above ground level (AGL) within Class G airspace.[11]

In researching and testing UTM, NASA has phased development into four technical capability levels (TCL).[12] TCL 1 covers minimal traffic over unpopulated landscape with little to no autonomy, with each subsequent level increasing in both operation and vehicle complexity (i.e. more traffic in populated areas with increasing autonomy). UTM is currently in the fourth and final TCL stage that focuses on:

- Beyond visual line-of-sight
- Urban environments, high density
- Autonomous, vehicle-to-vehicle internet connected
- Large-scale contingencies mitigation
- News gathering, deliveries, personal use

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To accommodate the projected high density and complexity of operation, UTM employs Operation Volumes to manage operations in a safe, efficient, and effective manner.[12] The volumes consist of an Operational Geography to define the intended airspace with overlaying geographies serving as additional buffers in the case of environmental or performance uncertainties.

A. Contribution

The contribution of this paper is a point design of the decision-making process for enabling sUAS to conduct autonomous point-to-point flight in BVLOS urban environment. The decision-maker is tested in nominal flight as well as in contingencies that compromise safe operation. While there are many use cases outlined in the ConOps, this point design is part of the NASA SAFE50 project that is focusing on Use Case 1–BVLOS operations in uncontrolled airspace.[11] Figure 1 shows what we envision Use Case 1 to look like in an urban environment. SAFE50 seeks to provide fully autonomous flight in the vehicle's perspective by putting all of the processing onboard. The SAFE50 project makes the following assumptions regarding flight operations:

- High-density
- Low-altitude
- Urban, dynamic, uncertain environment
- Constant V2X communication for cooperative sense and avoid (SAA)
- Multiple vehicles can occupy the same volume

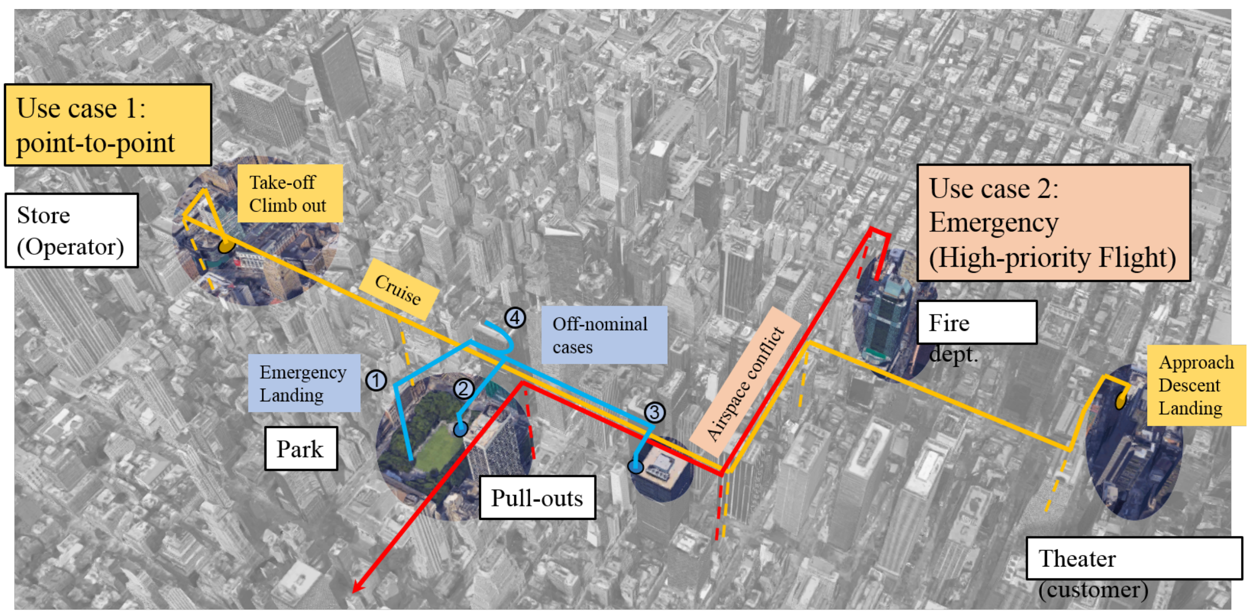

Figure 1: BVLOS point-to-point UAS flight in an uncontrolled, urban environment.

Contingency management proposed in the ConOps is comprised of protocols that outline the procedures in the event of certain contingencies such as communication loss. For this point design, we implement a finite state machine (FSM) similar to Paden et al. on autonomous urban cars.[13] The states in our FSM are based on the flight states used by Sankararaman and Krishnakumar that categorize the flight based on safety.[14] The transitions are changes in vehicle health, path feasibility, and clearance due to geofencing. Utilizing a FSM allows the decision-maker to be expanded as more protocols for contingency management are developed. Contingencies are simply added as another state with the transitions and logic pre-programmed based on the desired behavior. As of now, the decision-maker only handles single contingency situations, but managing simultaneously occurring contingencies is planned for future work.

As previously mentioned, all of the processing is done onboard the vehicle, including decision-making. The advantage of having the decision-making onboard is the reduced dependence and requirements on communications.[15] In the event of communication failure with the ground, the vehicle should still have the capabilities to either finish the mission or determine the safest alternate plan.

II. Flight Scenarios

A. Flight Phases

In our nominal point-to-point flight, the UAS will flow through the flight phases shown in Fig. 2. The Pre-Flight phase is where most of the non-autonomous tasks occur (e.g. deploying and loading the vehicle, creating the mission, making the flight plan, etc.). Once all of the Pre-Flight checks are completed, the UAS begins the Take-Off phase. During this phase, the vehicle climbs to the cruising altitude determined by the flight plan. From there, the vehicle continues in the Cruise phase until it reaches its destination and enters the Landing phase. After touchdown, the Post-Flight phase reports the mission and vehicle status.

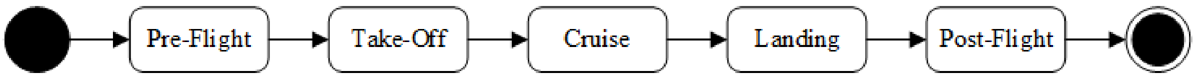

Figure 2: Flight phases in point-to-point flight.

It is important to note that the Take-Off, Cruise, and Landing phases are where most of the autonomy occurs. Throughout these phases, the UAS is continuously monitoring the vehicle health, checking clearance, and calculating flight paths. The outputs of these tasks may trigger deviations from the nominal flight plan called contingencies.

B. Contingencies

The UAS should be able to deviate from the nominal plan in certain situations to find safe alternate landing locations or return home.[10] Figure 1 shows how an emergency vehicle whose flight plan (red path) intersects the nominal point-to-point trajectory (yellow path) may invoke an emergency landing (blue path). Some of the contingencies our study focuses on includes:

- Health Monitoring
  - Air-to-Ground (A2G) Communication Failure
  - Vehicle-to-Vehicle (V2X) Communication Failure
  - Navigation degradation
  - Battery failure
  - Motor failure
- Path Feasibility
  - Dynamic ground object
  - Static aerial obstacle
  - Dynamic aerial obstacle
  - Unsafe wind here
- Dynamic Geofencing
  - Emergency message from nearby UAS
  - High priority fire message along trajectory
  - Unsafe wind ahead

Health Monitoring contingencies are based on the health of various sensors onboard the vehicle and whether or not they are capable of maintaining autonomous capabilities (this relates to the monitor vehicle health task previously mentioned in Sec. I.A). Path Feasibility contingencies are instigated by external conditions that obstruct the current path. Dynamic Geofencing contingencies occur when the overall flight plan may need to be adjusted due to a change in clearance up ahead, such as the emergency vehicle in Fig. 1. Figure 3 shows the possible hazards that cause contingencies in urban environments.[16]

Based on the status of the UAS, the flight state is categorized as one of the states shown in Tab. 1. The "Value" column shows the integer used by each state in the decision-maker and will be shown in the plots in Sec. IV. FS_NOMINAL flight is the initial accepted flight plan with full capabilities. FS_OFFNOMINAL_XXX flight has the same landing site as FS_NOMINAL, but may be mitigating some capability loss such as navigation degradation or communication failure. The FS_ALTERNATE_LAND state

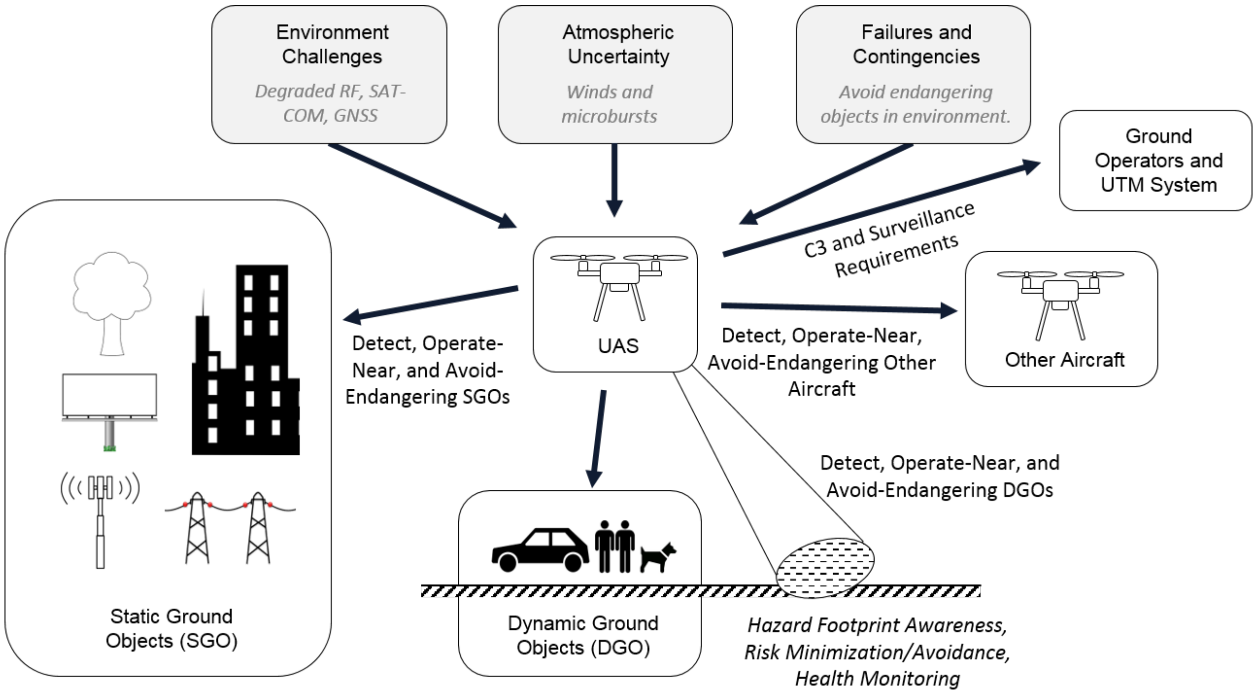

Figure 3: Urban hazards to the UAS.[17]

Table 1: Decision-making flight states.

Value	Flight State	Description
1	FS_NOMINAL	Nominal point-to-point flight plan
2	FS_ALTERNATE_LAND	Flying in contingency volume for alternate landing
3	FS_LAND_NOW	Immediately landing at current location
4	FS_OFFNOMINAL_NAV_LOSS	Flying to nominal landing site with lost navigation
5	FS_OFFNOMINAL_A2G_COM_REGAIN	Nominal flight waiting for A2G communication regain

has the vehicle fly to an alternate landing site whose volumes were allocated with the initial flight plan. Finally, during FS_LAND_NOW, the vehicle immediately lands at its current location as safely as it can.

As previously mentioned, operational volumes are allocated by UTM to safely manage high density flight operations. Figure 4 shows what these volumes look like for the flight states in Table 1 under Use Case 1. Green volumes show the allocated space the UAV can fly under Nominal (yellow path) or Off-Nominal (blue path) conditions. The red volumes for alternate landing are also allocated during Pre-Flight.

In the event of contingencies, the UAV must report its status to the ground station and nearby vehicles in the form of ICAO emergency phases[1]. Just as with the flight states in Tab. 1, the "Value" column shown in Tab. 2 shows the integers that represent the phases in the decision-maker. The Emergency Phase describes the safety capability of the UAS and the risk it poses to its surroundings.

[1]https://www.skybrary.aero/index.php/ICAO_Emergency_Phases

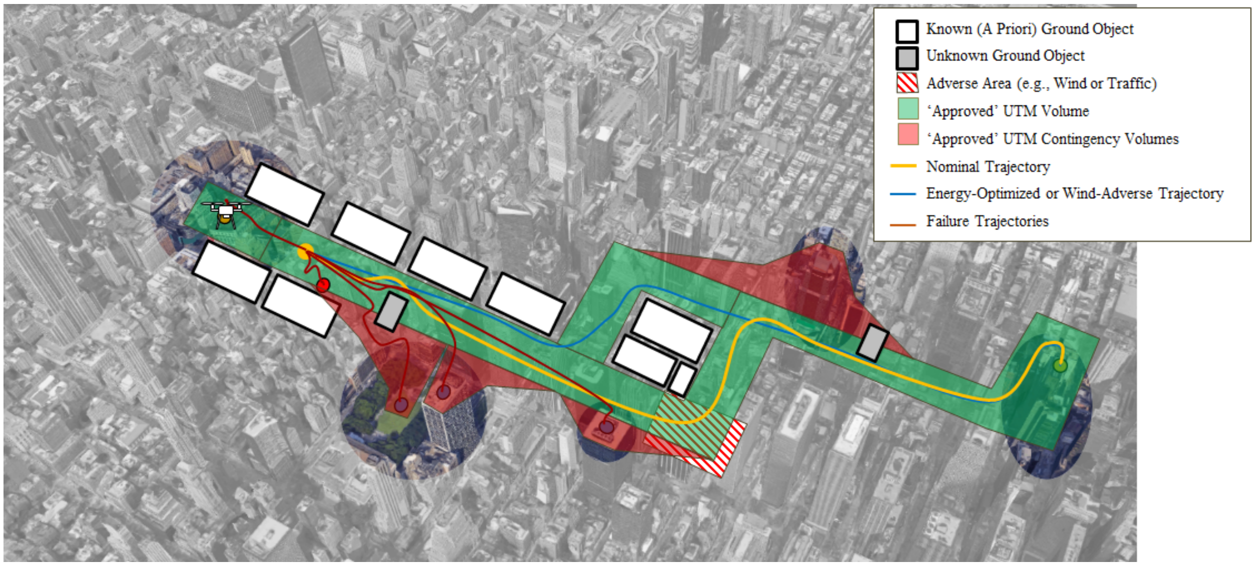

Figure 4: Operational volumes allocated for both nominal and contingency trajectories.

Table 2: Decision making emergency phases.

Value	Emergency Phase	Callout	Description
1	Nominal	NOMFA	Nominal flight with intact safe landing
2	Uncertainty	INCERFA	Off-nominal flight with intact safe landing
3	Alert	ALERFA	Off-nominal flight with compromised safe landing
4	Distress	DETRESFA	Off-nominal flight posing imminent danger to people or property

III. Architecture

A. Reflection Architecture

The decision-maker is simulated in NASA's Reflection Architecture that allows users to assemble software systems using component modules.[17] Figure 5 shows the Decision Making Module within the full Reflection system architecture. The Decision Making Module outputs the Approved Navigation Volumes to the Local Planner as well as Trajectory Generation Adjustments to the Path Planning System. The inputs to the Decision Making Module include the Environment Map, Detected Dynamic Objects, Other Vehicle State, Trajectories, Wind Information, Vehicle State, and Path Feasibility.

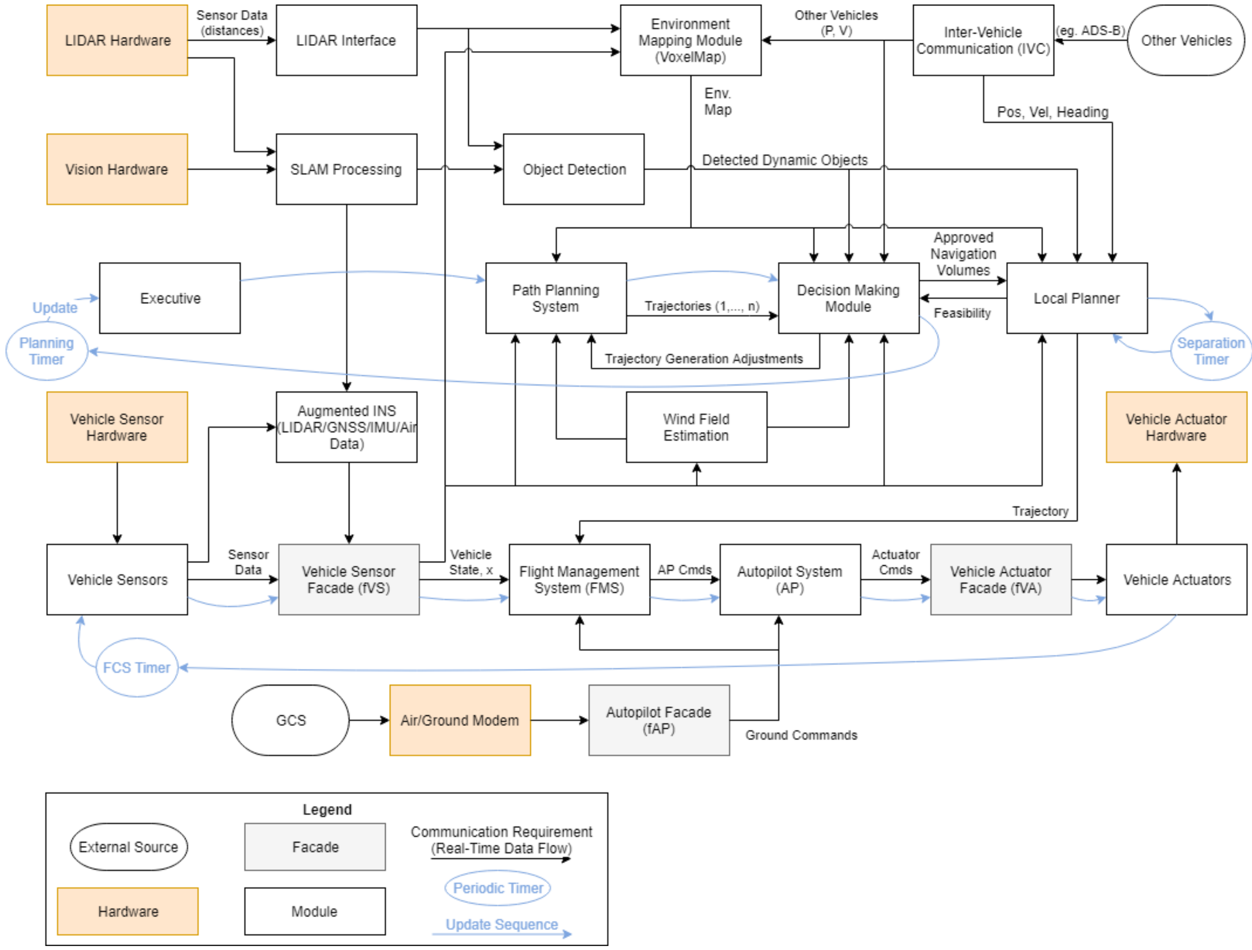

Figure 5: Architecture diagram of interacting modules in Reflection.

B. Decision-Making State Machine

As mentioned in Sec. I.A, the decision-maker is implemented in Reflection as a finite state machine of the flight states shown in Tab. 1. State machine diagrams for each implemented contingency are shown later in Sec. IV.

In order to separate planning and executing, two main states were created, DMS_PLAN and DMS_EXECUTE, shown in Fig. 6. These main states contain `switch` statements with the flight states as cases. The decision-maker begins in the DMS_PLAN state by calling for a trajectory from the Path Planning System based on its current flight state. After accepting a trajectory, it then transitions into the DMS_EXECUTE state where it stays unless the flight state changes and a new trajectory must consequentially be planned.

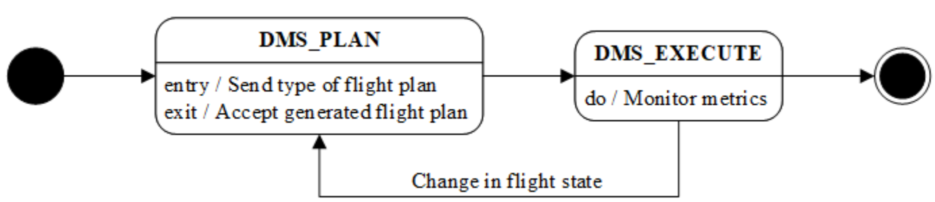

Figure 6: Planning and execute states for the decision-maker finite state machine.

C. Decision-Making Inputs and Outputs

During the DMS_EXECUTE state, the decision-maker is continuously watching the three classes of contingencies: Health Monitoring, Path Feasibility, and Dynamic Geofencing. Figure 7 shows how the Decision-Maker class interacts with the contingency and planning (TrajectoryGen) classes as well as which Reflection modules are used to simulate these classes.

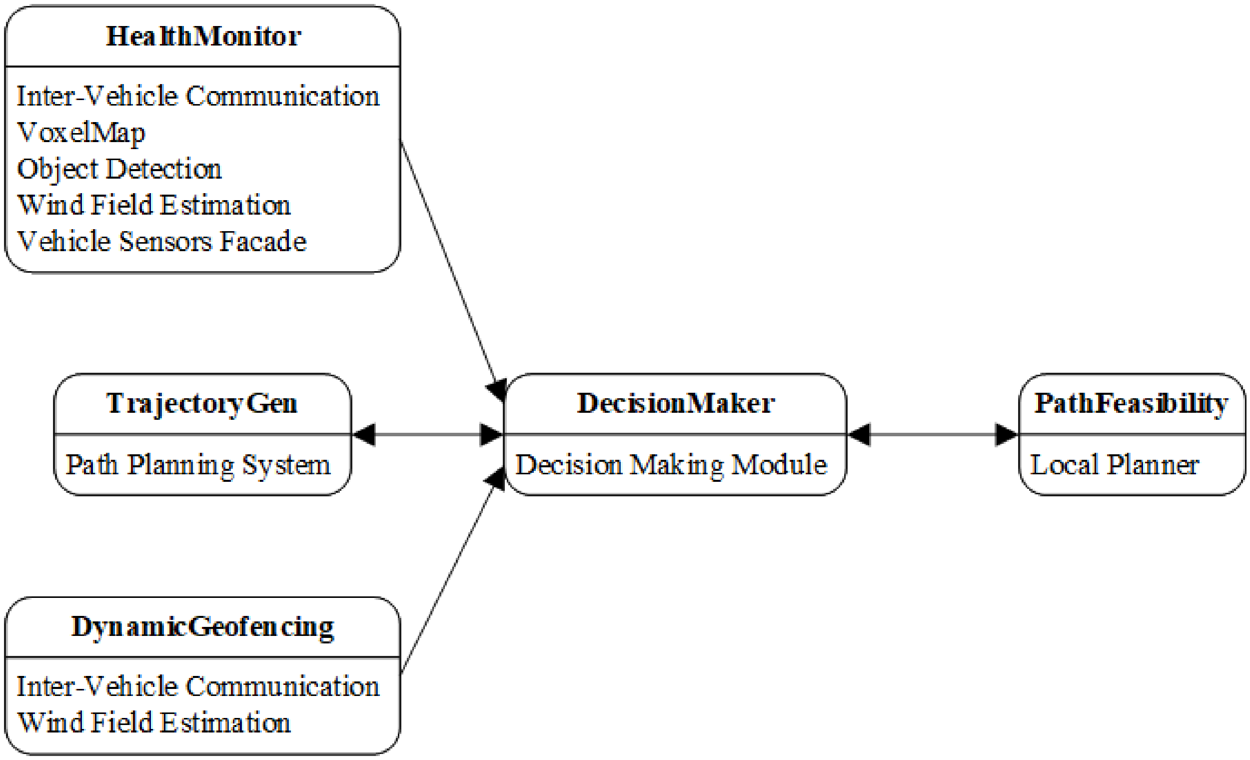

Figure 7: Decision-maker, planner, and contingency classes showing relevant Reflection modules.

The monitored health metrics shown in Tab. 3 are assumed to be provided by the relevant modules (i.e. the VoxelMap, IVC, Object Detection, Wind Field Estimation, and fVS modules must be able to report time-out and failure information). The UTM Communications and Navigation Working Group (C&N) is currently studying the criteria for communications and navigation failure during off-nominal operations.[18] A failure for one of these metrics would instigate a flight state change such as FS_OFFNOMINAL_A2G_COM_REGAIN. Some other health metrics that may be monitored but are not implemented yet are: Environment Detection Health, Attitude Determination and Control (ADAC) Health, Energy Information, and Wind Information.

Table 3: Monitored health metrics.

Health Metric	Description
Navigation Health	Status of the onboard navigation system
A2G Communication Health	Status of the communication between vehicle and ground control
V2X Communication Health	Status of communication between vehicle and other UAVs
External Surveillance	Status of localization information not coming from the navigation system

Path Feasibility contingencies are handled by the Local Planner. Based on the trajectory provided by the Decision Making Module, the Local Planner creates tree-based paths for the vehicle to track while staying within the approved trajectory. These paths are generated to avoid detected obstacles such as power lines, windy areas, and dynamic ground objects. Contingencies occur when no paths are found due to an upcoming obstruction. Thus, the decision-maker must determine whether a detour trajectory can be generated to complete the mission or if the the safest route is to abort the mission and go to an alternate landing site or land now.

Dynamic Geofencing contingencies are not yet implemented, but would rely on messages from other vehicles and the ground station to determine if the trajectory is no longer cleared to fly in.

IV. Implementation

A. Reflection Implementation

The relevant modules for implementing decision-making in Reflection were previously shown in Fig. 7. However, many of the input modules to the DecisionMaker are still in development. In lieu, a single class for each type of contingency was created—*healthmonitor*, *dynamicgeofencing*, and *pathfeasibility*. Figure 8 shows the class diagram for implementing navigation degradation and communication failure contingencies. For these contingencies, only the *decisionmaker*, *healthmonitor*, and *trajectorygen* classes are needed. All of the `struct` and `enum` subclasses are inherited by their parent class. The navHealth, A2GComHealth, V2XComHealth, and extSurv variables are routed to *decisionmaker* from *healthmonitor*. Furthermore, *decisionmaker* sends *trajectorygen* the type of trajectory to generate and in return either accepts or rejects this plan. In the case of V2X communication failure, *decisionmaker* receives the FS_ALTERNATE_LAND plan from *trajectorygen* and decide if it is feasible based on current distance to the landing site.

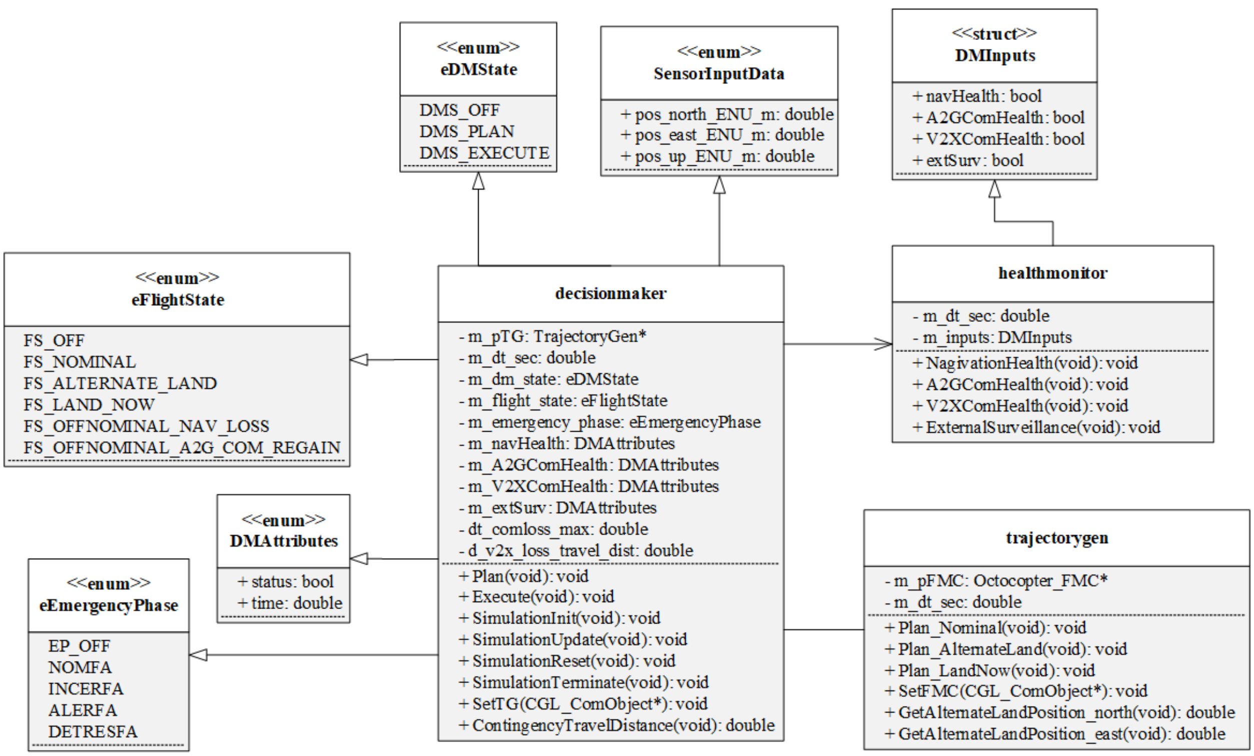

Figure 8: Class diagram for navigation degradation and A2G and V2X communication loss contingencies.

When the modules shown in Fig. 7 are implemented, they will be required to be able to report health and failures. For the time being, the inputs are triggered via GUI buttons in the Action Panel window shown in Fig. 9 where pressing a button changes the status to Good (value of 1) or Fail (value of 0) like a switch. The Action Panel includes the monitored health metrics shown in Tab. 3 and can be expanded to include other health metrics, path feasibility, and dynamic geofences.

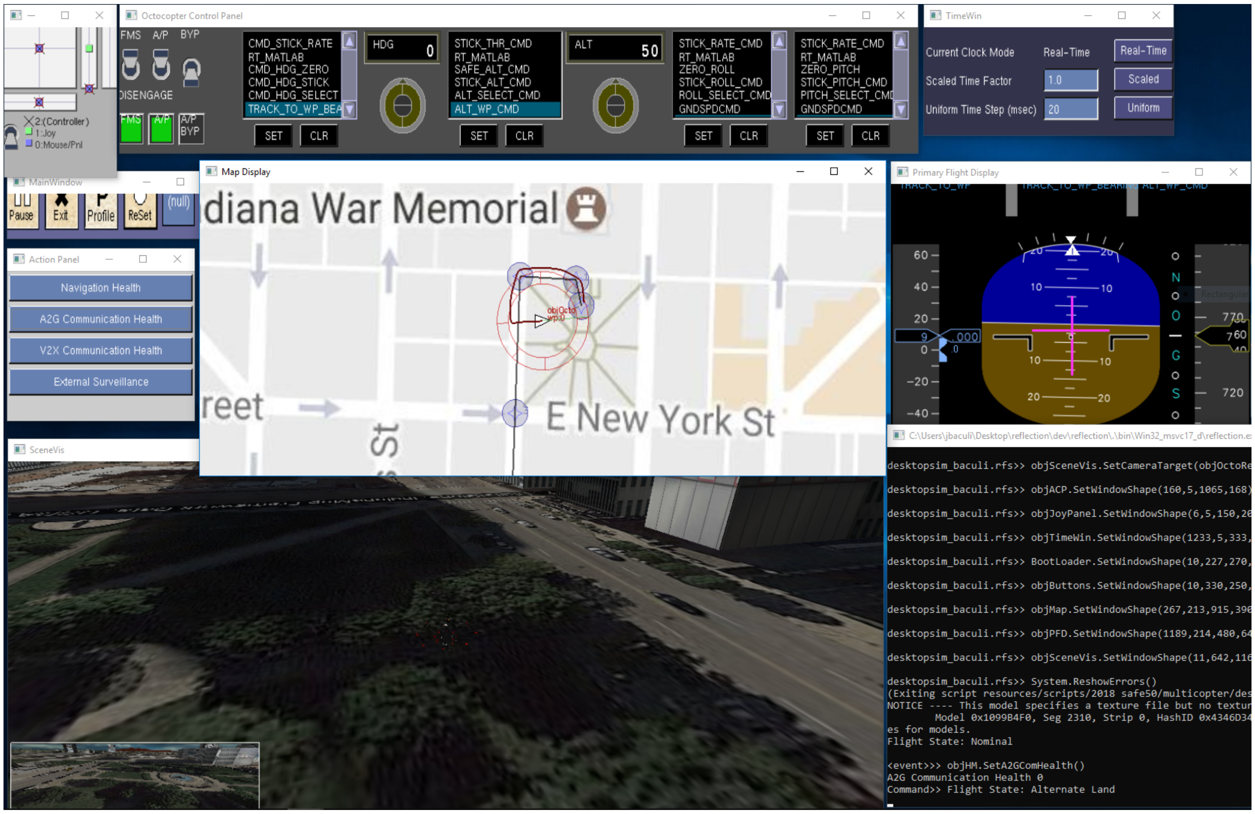

Figure 9: Reflection interface showing Alternate Land due to A2G communication failure.

B. Navigation Degradation

Figure 10 shows the state diagram for the navigation degradation contingency. During this contingency, the onboard navigation system reports degraded health. If external surveillance is still providing adequate localization, the UAS has intact safe landing capability in an off-nominal situation and so the decision-maker switches to Uncertainty phase. The Flight State switches to FS_OFFNOMINAL_NAV_LOSS, continuing the initial nominal trajectory while still feasible. If external surveillance is no longer able to provide adequate localization, then the UAS no longer has intact safe landing capability and must fly to a pre-allocated alternate landing site in one of the contingency volumes shown in Fig. 4. Thus, the Flight State and Emergency Phase are switched to FS_ALTERNATE_LAND and ALERFA, respectively. Figure 11 shows the Flight State and Emergency Phase switching in response to changes in Navigation Health and External Surveillance. The UAS is assumed to be in Cruise flight phase when navigation degradation occurs, such that the nominal landing site is farther away than alternate landing sites.

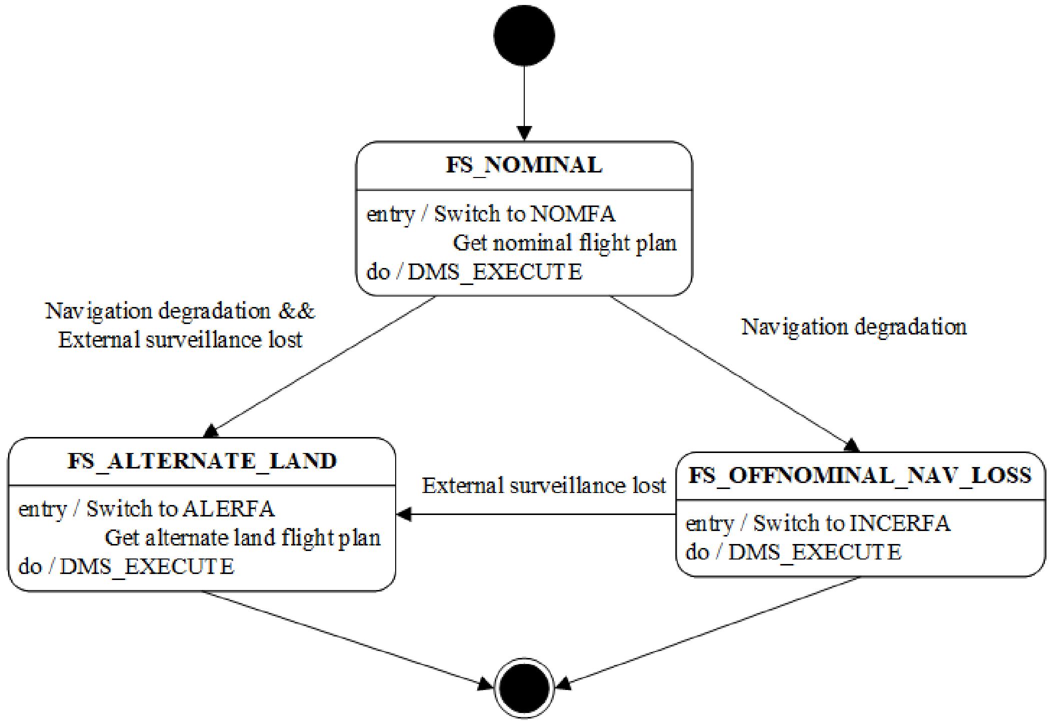

Figure 10: Navigation degradation state machine.

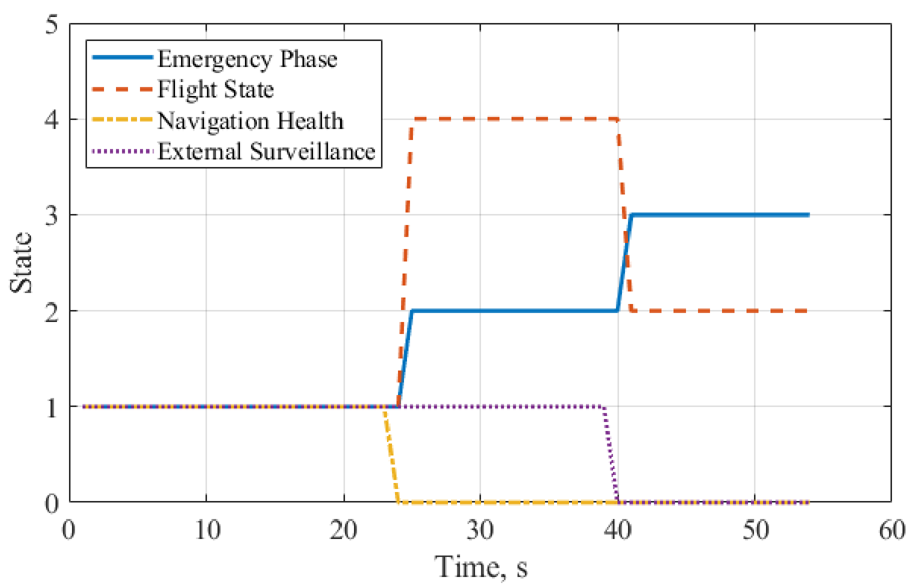

Figure 11: Plot of the navigation degradation contingency showing Emergency Phase, Flight State, Navigation Health, and External Surveillance vs time.

C. A2G Communication Failure

Figure 12 shows the state diagram for the A2G communication loss contingency. This contingency has the aforementioned FS_OFFNOMINAL_A2G_COM_REGAIN mode where the vehicle flies its nominal trajectory while trying to regain A2G communication within a specified time window. During this regain period, the decision-maker switches to INCERFA. However, if A2G communication is not regained, the flight state is then changed to FS_ALTERNATE_LAND and the emergency phase to ALERFA. Figure 13 shows the Emergency Phase and Flight State reacting to A2G communication failure. Following the protocol in Fig. 12, the UAS remains in a 10 second regain period before flying to an alternate landing site and declaring ALERFA. It is important to note that this 10 second period is for simulation purposes and actual regain timeouts should be between 5 and 10 minutes. The UAS is assumed to be in Cruise phase where the vehicle will not reach the nominal landing site within the allowed regain time.

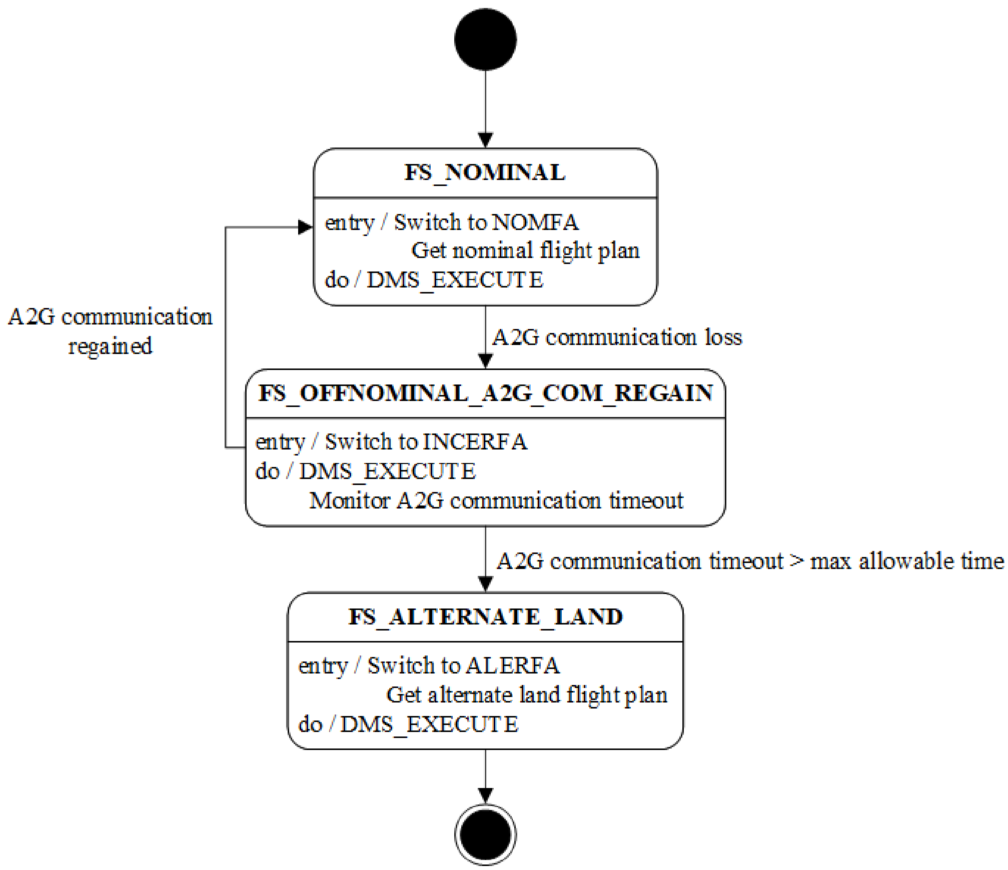

Figure 12: A2G communication loss state machine.

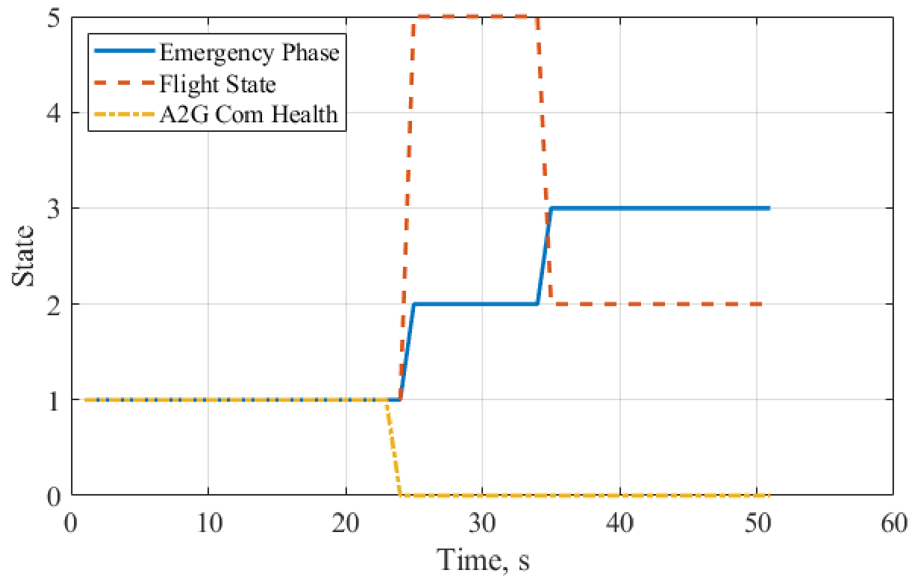

Figure 13: A2G communication failure plot showing Emergency Phase, Flight State, and A2G Com Health vs time.

D. V2X Communication Failure

While SAA methods such as LIDAR or vision may detect non-cooperative obstacles, V2X communication is the only reliable means of detecting other vehicles at high speeds. Therefore, in the event of V2X communication loss, the vehicle is vulnerable to inter-vehicle collision and must be placed under Distress phase rather than an Uncertain regain phase. Figure 14 shows that in the event of V2X communication loss, the vehicle must either fly to an alternate landing site or land now if the alternate landing site is too far. In both cases, the Emergency Phase must declare DETRESFA.

Figures 15 and 16 show the V2X communication failure contingencies resulting in FS_LAND_NOW and FS_ALTERNATE_LAND states, respectively. Both figures start at FS_NOMINAL and are assumed to be in Cruise phase when V2X Com Health is set to Fail and the Emergency Phase is subsequently switched to DETRESFA. In Fig. 15, the vehicle is already farther than the allowable distance (200m) to travel without V2X communication capabilities. Following the state machine in Fig. 14, the Flight State changes to 3 for FS_LAND_NOW. Conversely in Fig. 16, the vehicle is still within 200m of the landing site at the time of V2X Com Failure and subsequently changes the Flight State to FS_ALTERNATE_LAND.

Figure 17 shows V2X communication failure where the FS_ALTERNATE_LAND trajectory takes the UAV more than 200m away from alternate landing site. This may be due to a building obstructing a direct path or the alternate landing site being geofenced, forcing another replan. When V2X Com Health is switched to Fail, the Flight State correctly changes to FS_ALTERNATE_LAND. However, the trajectory moves the UAV more than 200m away from the alternate landing site and so the UAS goes into FS_LAND_NOW.

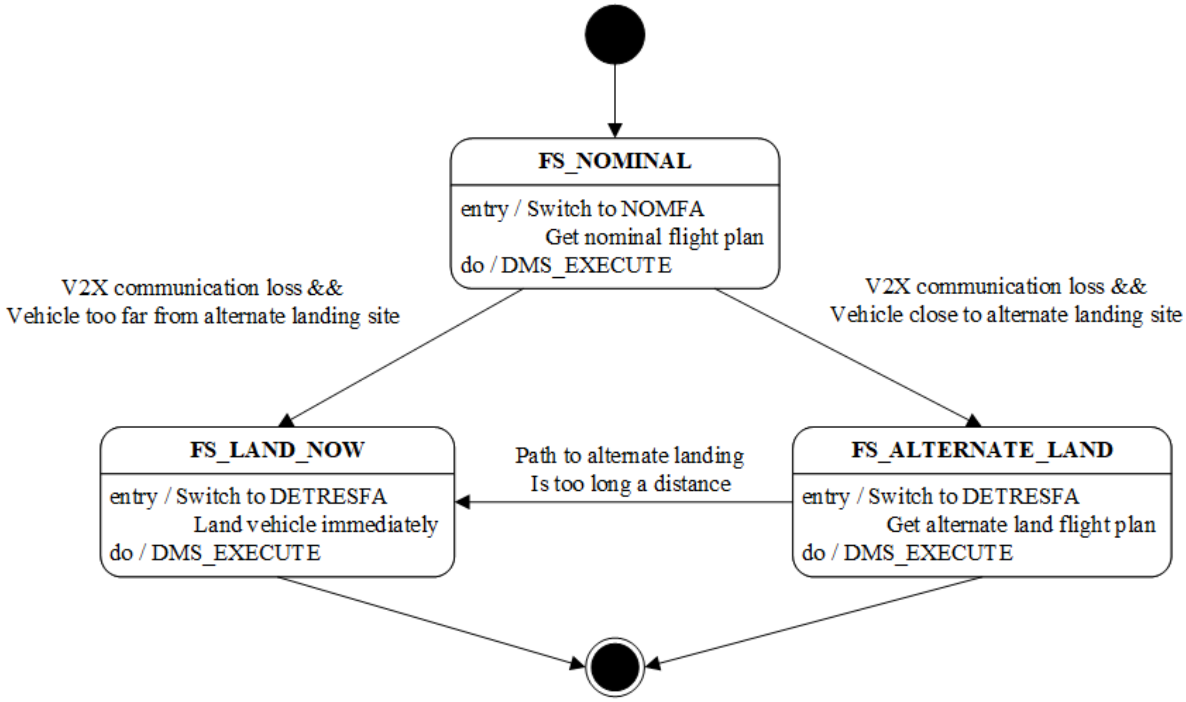

Figure 14: V2X communication loss state machine.

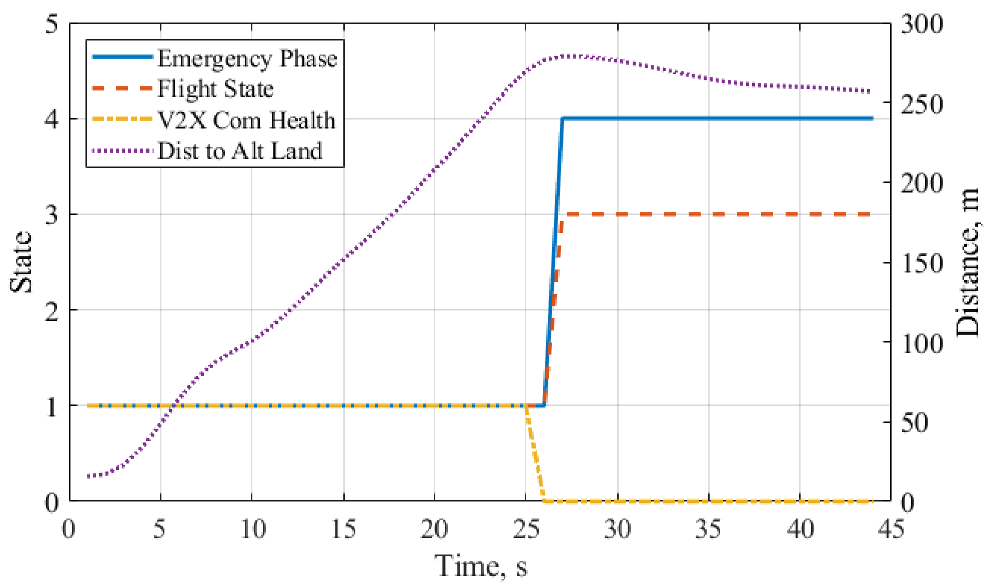

Figure 15: V2X communication failure contingency resulting in a Land Now. Emergency Phase, Flight State, and V2X Com Health vs time are shown on the left axis and Distance to Land vs time on the right axis.

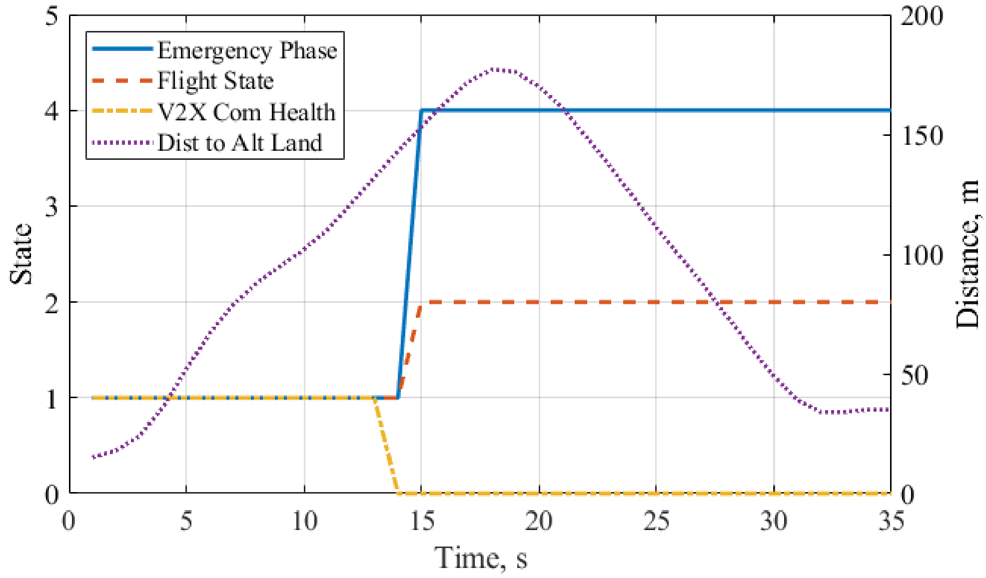

Figure 16: V2X communication failure contingency resulting in an Alternate Land. Emergency Phase, Flight State and V2X Com Health vs time are shown on the left axis and Distance to Land vs time on the right axis.

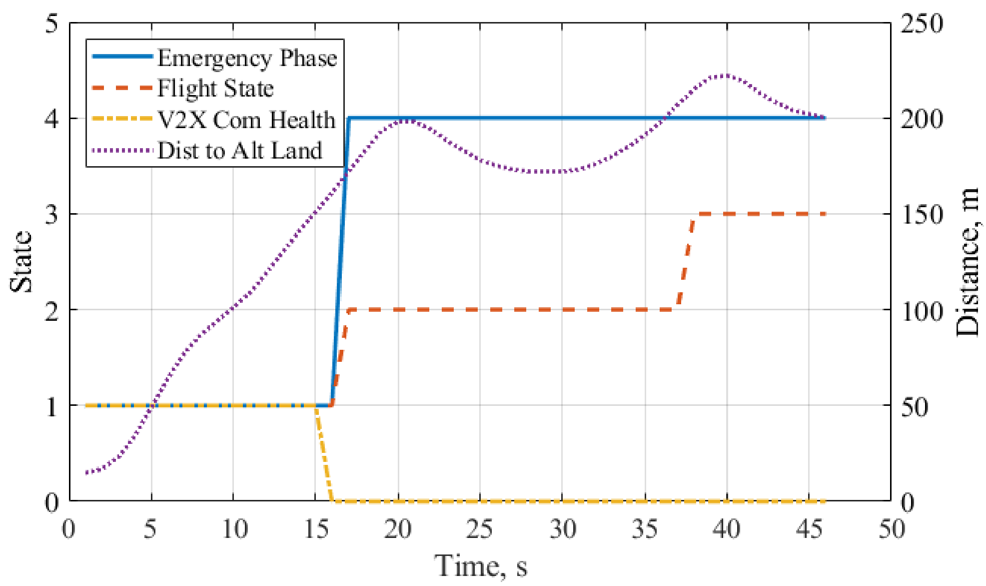

Figure 17: V2X communication failure contingency plot showing Emergency Phase, Flight State, and V2X Com Health vs time on the left axis and Distance to Land vs time on the right axis. Upon V2X communication failure, the UAS initially flies to an alternate landing site. However, the FS_ALTERNATE_LAND trajectory takes the vehicle too far from the landing site, prompting an immediate Land Now.

V. Conclusion

This study presents an onboard decision-making framework for enabling safe flight of an autonomous sUAS. The decision-maker is part of the point design being developed by NASA's SAFE50 project that focuses on autonomous sUAS under UTM. UTM's goal is to safely enable low-altitude operations for small UAS in high-density airspace. SAFE50's point design falls under UTM-TCL4 for autonomous BVLOS flight in high density urban environments and the point-to-point flight described under Use Case 1. The decision-maker is implemented in the form of a finite state machine whose main states consist of planning and executing. Furthermore, the decision-maker categorizes the flight as Nominal, some kind of Off-Nominal, Alternate Land, and Land Now, and the emergency phase as Nominal, Uncertain, Alert, and Distress. The state transitions are incurred by three categories of contingencies: health monitoring, path feasibility, and dynamic geofencing. The decision-maker is expanded by adding contingencies as states with the transitions being pre-programmed protocols.

The decision-maker is simulated in response to three different contingencies: navigation degradation, A2G communication failure, and V2X communication failure. The decision-maker is shown to be able to reassess the flight state and trigger replanning when necessary based on the desired protocol. For navigation degradation, the UAV flies to an alternate landing site when both navigation health and external surveillance return Fail. The A2G communication failure contingency also results in an Alternate Land if communication has not been regained after some time. In the event of V2X communication failure, the decision-maker switches to Alternate Land if within range of landing site or Land Now if too far.

Future work includes expanding the decision-maker state machine to include all of the planned contingencies. As of now, the decision-maker is simulated with hard coded trajectories and button-triggered inputs. The relevant modules for path planning and contingencies must be developed for integration with the Decision Making Module in Reflection. After expanding the decision-maker, protocols for simultaneously occurring contingencies, such as no feasible paths during navigation degradation, can be developed and implemented.

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References

[1]Semsch, E., Jakob, M., Pavlicek, D., and Pechoucek, M., "Autonomous UAV Surveillance in Complex Urban Environments," *Proceedings of the 2009 IEEE/WIC/ACM International Joint Conference on Web Intelligence and Intelligent Agent Technology-Volume 02*, IEEE Computer Society, 2009, pp. 82–85.

[2]Menouar, H., Guvenc, I., Akkaya, K., Uluagac, A. S., Kadri, A., and Tuncer, A., "UAV-enabled intelligent transportation systems for the smart city: Applications and challenges," *IEEE Communications Magazine*, Vol. 55, No. 3, 2017, pp. 22–28.

[3]Erdelj, M., Natalizio, E., Chowdhury, K. R., and Akyildiz, I. F., "Help from the sky: Leveraging UAVs for disaster management," *IEEE Pervasive Computing*, , No. 1, 2017, pp. 24–32.

[4]Mademlis, I., Mygdalis, V., Nikolaidis, N., and Pitas, I., "Challenges in Autonomous UAV Cinematography: An Overview," *2018 IEEE International Conference on Multimedia and Expo (ICME)*, IEEE, 2018, pp. 1–6.

[5]Hadi, G. S., Varianto, R., Trilaksono, B., and Budiyono, A., "Autonomous UAV system development for payload dropping mission," *The Journal of Instrumentation, Automation and Systems*, Vol. 1, No. 2, 2014, pp. 72–22.

[6]Hening, S., Ippolito, C. A., Krishnakumar, K. S., Stepanyan, V., and Teodorescu, M., "3D LiDAR SLAM Integration with GPS/INS for UAVs in Urban GPS-Degraded Environments," *AIAA Information Systems-AIAA Infotech@ Aerospace*, 2017, p. 0448.

[7]Tomic, T., Schmid, K., Lutz, P., Domel, A., Kassecker, M., Mair, E., Grixa, I. L., Ruess, F., Suppa, M., and Burschka, D., "Toward a Fully Autonomous UAV: Research Platform for Indoor and Outdoor Urban Search and Rescue," *IEEE robotics & automation magazine*, Vol. 19, No. 3, 2012, pp. 46–56.

[8]Stöcker, C., Bennett, R., Nex, F., Gerke, M., and Zevenbergen, J., "Review of the current state of UAV regulations," *Remote sensing*, Vol. 9, No. 5, 2017, pp. 459.

[9]Schaufele, R., Ding, L., Miller, N., Barlett, H., Lukacs, M., and Bhadra, D., "FAA Aerospace Forecast: Fiscal Years 2017–2037," *Washington, DC*, 2017.

[10]Kopardekar, P. H., "Unmanned aerial system (UAS) traffic management (UTM): Enabling low-altitude airspace and UAS operations," 2014.

[11]Rios, J. and Johnson, M., "Unmanned Aircraft Systems Traffic Management (UTM) Concepts and Architecture Overview," 2018.

[12]Homola, J., Dao, Q., Martin, L., Mercer, J., Mohlenbrink, C., and Claudatos, L., "Technical Capability Level 2 Unmanned Aircraft System Traffic Management (UTM) Flight Demonstration: Description and Analysis," *Proceedings of the 36th Digital Avionics Systems Conference (DASC), Petersburg, FL*, 2017.

[13]Paden, B., Čáp, M., Yong, S. Z., Yershov, D., and Frazzoli, E., "A survey of motion planning and control techniques for self-driving urban vehicles," *IEEE Transactions on intelligent vehicles*, Vol. 1, No. 1, 2016, pp. 33–55.

[14]Sankararaman, S., "Towards a Computational Framework for Autonomous Decision-Making in Unmanned Aerial Vehicles," *AIAA Information Systems-AIAA Infotech@ Aerospace*, 2017, p. 0446.

[15]Sankararaman, S. and Goebel, K., "A computational architecture for autonomous decision-making in unmanned aerial vehicles," *Micro-and Nanotechnology Sensors, Systems, and Applications X*, Vol. 10639, International Society for Optics and Photonics, 2018, p. 106391Y.

[16]Krishnakumar, K. S., Kopardekar, P. H., Ippolito, C. A., Melton, J., Stepanyan, V., Sankararaman, S., and Nikaido, B., "Safe Autonomous Flight Environment (SAFE50) for the Notional Last "50 ft" of Operation of "55 lb" Class of UAS," *AIAA Information Systems-AIAA Infotech@ Aerospace*, 2017, p. 0445.

[17]Ippolito, C. A., Hening, S., Sankararaman, S., and Stepanyan, V., "A Modeling, Simulation and Control Framework for Small Unmanned Multicopter Platforms in Urban Environments," *2018 AIAA Modeling and Simulation Technologies Conference*, 2018, p. 1915.

[18]Jung, J., Drew, C., Nag, S., Torres, E., Ishihara, A. K., Modi, H., and Do, M., "Initial approach to collect small Unmanned Aircraft System off-nominal operational situations data," *2018 Aviation Technology, Integration, and Operations Conference*, 2018, p. 3030.