A High Performance Contingency Planning System for UAVs with Lost Communication

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***Abstract*— Lost link (LL) in unmanned air vehicles (UAVs) can cause safety hazards to other air vehicles and can also significantly increase air traffic controllers' (ATC) workload. To the best of our knowledge, there still does not exist a systematic and automatic software tool that can generate contingency plans to deal with LL. We developed a new, comprehensive, fast, automated, and standardized lost link plan (LLP) generation framework and detailed procedures that can satisfy all the FAA regulations with respect to lost link situations. Extensive simulations were performed to demonstrate the efficacy of the proposed framework.**

Keywords- lost communication; contingency planning; UAVs; air traffic controller

I. INTRODUCTION

It is well-known that UAVs have more accidents than manned aircraft. This is probably one of the most important reasons that FAA is hesitant to open up the national airspace (NAS) to UAVs. Reliability of UAVs can be strengthened using durable engines and communication equipment, strong structural materials, advanced conditioned based maintenance and structural health monitoring procedures [1]-[9], accurate fault diagnostic algorithms [10]-[18], and robust [19]-[25] and fault tolerant controllers [26]-[29]. Despite the above measures, some equipment failures may still occur. Lost communication, otherwise known as lost link (LL), in UAVs can cause safety hazards to other air vehicles and could significantly increase air traffic controllers' workload. Currently, there are no standardized lost link plan (LLP) generation procedures. In addition, LLPs are generated manually, which is a tedious and time-consuming effort. Most importantly, in order to integrate the UAVs into the NAS, it is important to have a comprehensive, fast, automated, and standardized LLP generation system. Not only should all of the aforementioned factors satisfy all FAA regulations, but they should also provide the foundation for generating a complete LLP in minutes, which can then be utilized by all UAVs.

In this research, we have achieved several important results. First, we developed a new and comprehensive LLP generation framework and detailed procedures that can satisfy all the FAA regulations with respect to lost link situations. When given a UAV flight plan, we have the ability to first assess the potential risk of lost links in the flight plan. If the risk is high, a new flight plan is recommended. After that, we generate contingency waypoints to guide the UAVs in the event of lost links, reconnection/rally/standby waypoints, hovering waypoints near airports, and flight termination points. The first key objective of our LLP generation framework is to ensure maximum predictability of LL UAVs as well as to confirm that all the contingency waypoints are carefully selected to minimize hazards to other aircraft in the air and collateral damage to ground structures (humans and buildings). Second, we have developed a standardized LLP data structure. This data structure can be used for large and small UAVs. Third, we have built a tool to emulate different link qualities (strong, weak, and lost links). Fourth, an airspace simulator has been developed that can easily visualize different LLPs, emulate different lost link scenarios, and assess the impact of different LLPs. Fifth, over 10 scenarios, most of which came from International Civil Aviation Organization (ICAO) recommendations, have been prepared to illustrate the power of our proposed LLP generation framework. Sixth, our system also includes a case-based reasoner (CBR), which helps prepare pilots with the decision-making process before a link is actually lost.

This paper is organized as follows. Section II describes the background of this research. Section III summarizes our proposed LLP generation framework and procedures. In Section IV, we summarize extensive experiments using 6 scenarios from the ICAO. Finally, conclusions are included in Section V.

II. BACKGROUND

A. Causes of LL

Lost link can be triggered by a number of events. Here, we list some of the main ones:

- Bad weather: Heavy storms, space weather, etc.
- Occupied radio frequency
- UAV system reset
- UAV loses power
- Malicious radar jamming
- Damaged antenna
- Software errors
- Human mistakes
- On-board communication device failure

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B. Consequence of LL

The worst scenario to an ATC is that a UAV may become unpredictable after lost link. Although surveillance radar can reveal the actual location of the lost linked UAVs, the radar screen only displays the position of the UAVs periodically. The speed and heading information may change dynamically. Moreover, due to wind, rain, and other environmental conditions, there is uncertainty in estimating the UAVs' speed and location. In order to avoid loss of separation, an ATC may need to reroute many nearby air vehicles. As a result, ATCs will have excessive workload.

C. Current Solution to LL

After lost link, the pilot in control (PIC) reports the event to ATC through a telephone channel. The PIC reports the last flight status including heading, speed, position, altitude, and the preset rendezvous point. ATC then locates the current position of UAV using a surveillance radar. However, there is no tracking software to estimate the UAV flight trajectory. The flight status and contingency plan are sent to ATC through a telephone link. The PIC then checks the reasons of link failure and estimate how soon it can be restored. If link can be reestablished, the PIC will either command the UAV to continue on the original mission or come back to base. If link is not resumed, the UAV will follow a predefined plan to go back to base. ATC must clear the paths if the UAV can be landed automatically under lost link condition. If a flight termination event is triggered, the UAV will crash at an unpopulated site. A rescue and recovery plan will be activated.

In [30], some specific and simple lost link procedures are summarized. For example, in the lost link procedure of a UAV owned by Utah Water Research Laboratory, if lost link occurs for more than 10 seconds, the UAV will *immediately* proceed to a STDBY waypoint, which is located near the PIC. The procedures in [30] are for low altitude, short duration UAVs. For long range UAVs, such as those used for military surveillance operations, we were not able to obtain the lost link procedures, as they are hidden in the classified documents.

D. Problems of Current LLPs

As mentioned earlier, there is no standardized data link interface between pilot and ATC; contingency plans are verbally transmitted, which is very inefficient because some contingency plans may contain many contingency waypoints and termination points. Ideally, a standardized data link should exist between PIC and ATC and the contingency plan should be transmitted to ATC, who can use a graphical user interface (GUI) to visualize all the waypoints in the LLP.

Moreover, there is also no instant UAV status update, including its predicted trajectory to rendezvous point.

A third problem is that different vendors use different LLP representations. A standard representation for LLP should be publicized.

Finally, there do not exist any systematic procedures to generate LLP. All the LLPs are generated manually and this process is time-consuming and may take hours for long duration missions. It will be ideal to generate a comprehensive plan in less than 5 minutes and the plan should satisfy all FAA regulations. The tool developed by us will be a great contribution to the UAV community.

E. Past study on the impact of lost link on ATC

In [31], the authors evaluated different lost link procedures from the perspective of ATC. Predictability and controller workload are used as performance metrics for evaluation of lost link procedures. A UAV is claimed to be predictable if the ATC knows the contingency plan (i.e. the next waypoint that the UAV will fly to). Workload is defined as how many aircraft need to be redirected. Monte Carlo simulations were performed. It turns out that only one lost link procedure (Global Hawk) was used in the study.

In [32], the authors focused on two aspects of the command and control (C2) link. First, they analyzed the time for controllers to identify that a lost link had occurred. Second, they analyzed the time between the initial indications of a lost C2 link and the initiation of a contingency procedure. Man-in-the-loop evaluations were used in the study. It was observed that most controllers can detect the lost link within one minute. It was also found that controller load would be reduced if the time between the notification of the lost link and the aircraft was about one minute. However, the paper did not address the issue of how to generate lost link procedures.

F. Current lost link procedure generation

In [33], a framework to deal with contingencies was proposed. Lost links belong to one of the contingencies. Pre-planned flight paths are generated for each waypoint in the original flight plan. One interesting concept called intermediate waypoint was introduced to minimize uncertainty during lost link.

In [34], two challenges in the integration of UAV with NAS are mentioned:

- Lack of see and avoid capability
- Coping mechanism for vulnerable link and ATM integration

To deal with link vulnerability, the authors in [34] suggested 3 near term solutions (2-4 years). First, the lost link contingency procedures need to be standardized. Second, link needs to be robustified. Third, UAV-specific ATM procedures & separation criteria need to be developed.

It should be noted that all existing LLPs are done manually, which is time consuming, tedious, and error prone.

G. FAA Regulations with respect to LL

FAA has produced guidelines with respect to lost link procedures. The ultimate goal is to ensure predictability of UAVs after they have lost communication with the base. It should be noted that there may be some other ATC rules. Details can be referred to [35].

III. LOST LINK PLAN GENERATION FRAMEWORK

A. *Framework*

Based on the above literature survey, most studies focus on impact of lost links from air traffic controller's view point, but miss the roles of pilots and mishap UAVs. These areas include strategies and plans for prevention, mitigation, and rescuer/recovery from maintenance engineers, mission planners, and pilots.

As shown in Fig. 1, we propose a comprehensive framework to mitigate lost links in UAVs. A patent has been filed [36]. We divide our procedures into four parts: 1) risk analysis; 2) preparedness and prevention plan; 3) incident response plan; and 4) rescue and recovery plan.

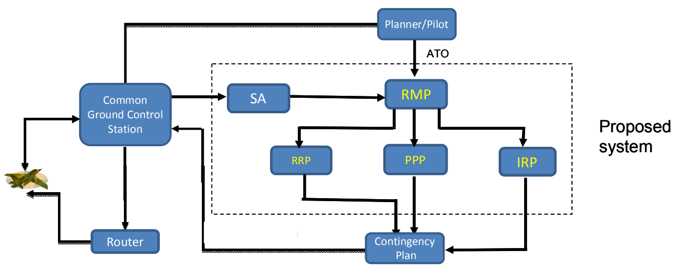

Fig. 1: Proposed lost link plan generation framework.

Here we highlight a few key points of our proposed approach:

- Risk Management Plan:
  - Analyze risk against the causes of lost link throughout the primary flight path.
  - Assess risk of LLP of multiple UAVs in the same area
  - Adjust the primary flight path to reach the destination if necessary.
- Preparedness & Prevention Plan:
  - Standardize LLP generation by maximizing predictability of mishap UAVs.
  - Standardize dynamic LLP based on situation and obtain confirmation from ATC supervisor through a standard interface. (This is currently used in military UAVs)
  - Maintain highly reliable on-board communication devices, surveillance systems, and ground control systems. Maintenance data is linked to common ground control system.
  - Before lost link happens, use CBR to help PIC to prepare for LL.
- Incident Response Plan:
  - Standardize Pilot and ATC communication.
  - Track flight status and possible trajectory for the mishap UAV (incorporate speed and time uncertainty).
  - Accelerate ATM to redirect other nearby vehicles by sending the LL plan to ATC via a data link and the use of GUI to display the LL plan.
- Rescue and Recovery Plan:
  - Renew the link when the UAV arrives at rendezvous point.
  - Specify flight termination points in the LLP (Land on the given runway if it has the capability; crash at an unpopulated area without creating collateral damages).

B. *Proposed Systematic Lost Link Generation Procedures*

Fig. 2 shows a typical flow chart of a LLP. It should be noted that our proposed system is new and nobody has done anything similar. Some of the FAA regulations are explicitly shown. For example, after lost link is confirmed, the mishap UAV continues to fly to the next waypoint and hovers using a special pattern. This satisfies Rule 1 (continue its current path for some time) and Rule 2 (communicating with ATC and PIC that it has lost link problem) of the FAA regulations Other FAA regulations are implicitly satisfied. For example, the flight termination points are pre-selected before mission starts and they are located in un-populated areas.

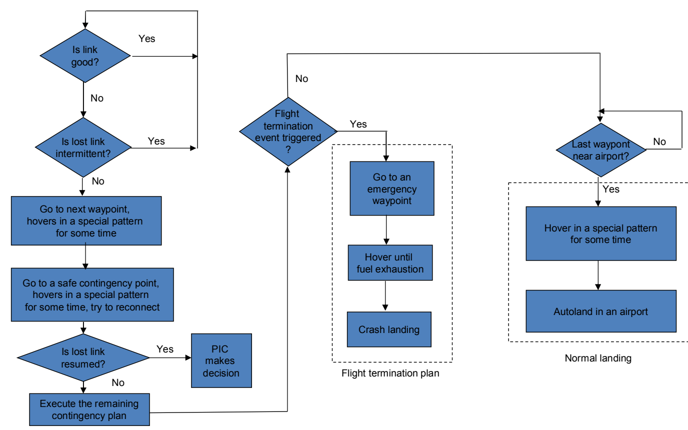

Fig. 2: Flow Chart of a Typical Lost Link Plan (LLP).

In order to quickly and automatically generate a comprehensive LLP in a few minutes, there are quite a few steps needed. Fig. 3 below illustrates the key steps in generating a complete LLP that satisfies all the FAA regulations. Step 1 is the creation of databases. As can be seen from Fig. 3, there are many databases, including FAA regulations, UAV performance models, airspace structure, ground radio towers, airport locations, flight termination points, rally/reconnection waypoints, and hovering waypoints near airports. These databases lay a crucial foundation for later steps in the LLP generation process. Step 2 is the generation of partial plans. One type of partial plan consists of a set of waypoints from rally/reconnection waypoints to airports. Another type of partial plans includes stitches to connect from any waypoints in the primary and contingency plan to the flight termination points. All of these partial plans can be generated off-line. We have adopted this approach for a Navy funded project. This will significantly reduce the contingency plan generation time. Given a new mission plan, Step 3 is to perform lost link risk assessment. For example, weather information in the mission area, communication equipment maintenance history, etc. will be used to assess the risk of lost link in the mission area. If the lost link risk is deemed high, the primary mission plan will be revised or aborted. Step 4 is the LLP generation step. Information from partial plans, landing places, airports, etc. will be integrated together to form the complete plan. In addition, if there are other UAVs flying in the same area, the potential risk of conflicting LLPs will be assessed, according to one of the FAA regulations. Rescue and Recovery Plan is also generated in this step. In addition, an expert system based on CBR is used to help PIC mitigate LL before LL actually happens. This will be a preventive measure to help PIC deal with intermittent LL. Finally, Step 5 is the on-line execution of the LLP after lost links happens.

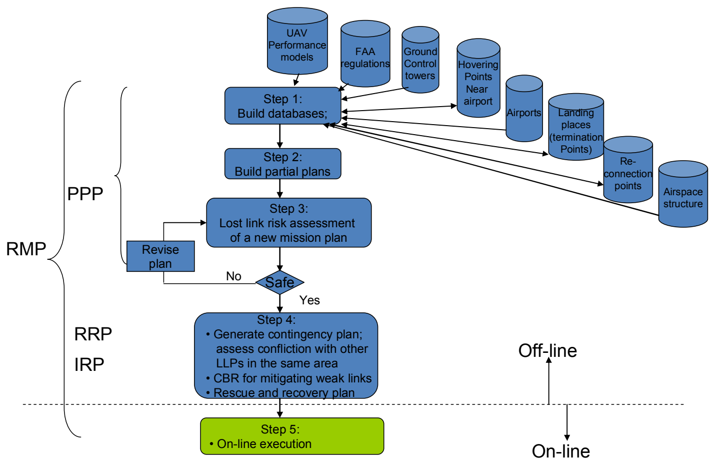

Fig. 3: Proposed Lost Link Generation Procedure.

C. Link Stability Simulations

A UAV communicates with ground station via wireless radio. The communication link may be lost due to congestion, radio jam, bad weather, system error, etc. Before the link is totally lost, there may be some symptoms such as high percentage of packet loss or high noise in the signals. In this section, we propose an approach for link quality assessment based on raw communication data. Basically, we assume that at each time step, a UAV sends out a ping message or a heartbeat signal to a ground station to test connectivity. If there is an acknowledgment message back, then we say the link is "on" for this time step. If no message comes back, we say the link is "off" at this time step. Therefore, the raw data is consisted of a sequence of on or off signals. During a period, there may be a percentage of "off" due to interference or other causes. If percentage of "on" signals is very high, say more than 80%, we then claim the link is strong. If the percentage of "on" signals is very low, say less than 10%, we can claim the link is lost. Besides strong and lost link, there are intermittent lost links and we say the link is weak. We developed a statistical assessment method to determine link status from micro-level signals. With this link assessment tool, the UAV can determine its own situation and carry out plans accordingly. For instance, when the link status transits from strong to weak, the UAV or PIC should start lost link prevention plan; when link status become lost for an extended period of time, the UAV should trigger the lost link plan.

D. UAV-NAS Integration Simulation Software

We developed a simulation software for UAV-NAS integration with focus on UAV lost link evaluation and simulation. With the simulation software, we are able to:

1. Simulate UAV trajectory based on UAV mission plan and lost link plan under different scenarios.
2. Simulate different link conditions and trigger lost link procedure for UAV.
3. Visualize UAV route overlaid on top of the national airspace structure so that possible conflicts of UAVs with manned aircraft can be easily detected.
4. Assess quality of UAV's lost link plan from the perspectives of speed uncertainty, potential conflicts with manned aircraft, and possibility of FAA regulation violation.

We chose Java programming language in the software development as some of our software modules are expected to be integrated with NASA's simulation platform – ACES, which was developed using Java. Another future integration platform is OPNET, which also has Java interface. Using Java programming language enables the system running on almost all operating systems: Windows, Unix, Linux, and Mac OS.

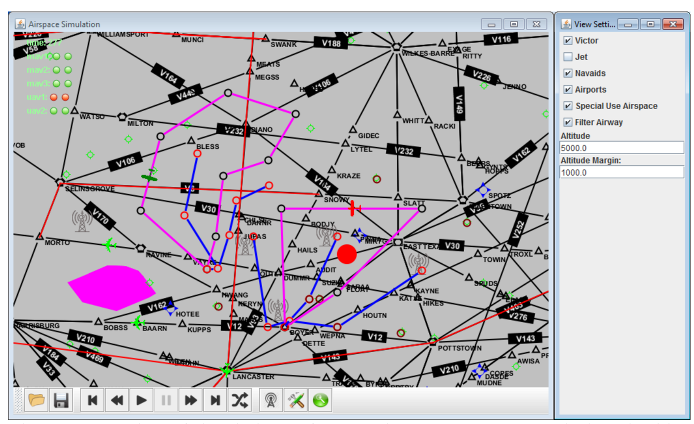

Fig. 4: Screenshot of simulation software. There are two UAV missions in this scenario.

Fig. 4 shows the screenshot of our simulation software. The black lines are FAA national airways. Only low altitude Victor airways are displayed. The data were extracted from an FAA database. Airways are connected through Navaids, including fixes (black triangles), VORTAC (black hexagons) and other types of Navaids. Manned aircraft are shown in light green planes which normally follow national flight airways. Magenta lines are UAV's mission/primary routes, which are connected through mission/primary waypoints (black circles). Blue lines are UAV's lost link contingency routes, which are connected through contingency waypoints (red circles). UAV is displayed as a green plane when it's in normal state. When lost link occurs, the UAV's color becomes yellow. After lost link procedure is triggered, its color becomes red. The right window shows a configuration panel for enroute chart drawing. Users can enable/disable specific elements. The red lines on the GUI shows the filtered airways based on altitude. In this figure, red lines represent airways with altitude from 4500 feet to 5500 feet. Link status of each airplane are shown at the top left corner. The left ball shows the low level link status. Red ball means lost link; green ball means link is good. The right ball shows the macro level link status: red ball means lost link; yellow ball means link is weak and green ball means link is strong. The macro level link status is estimated based on statistical analysis of low level link history by counting link status signals.

E. *Case Based Reasoning for UAV Pilot Decision Making*

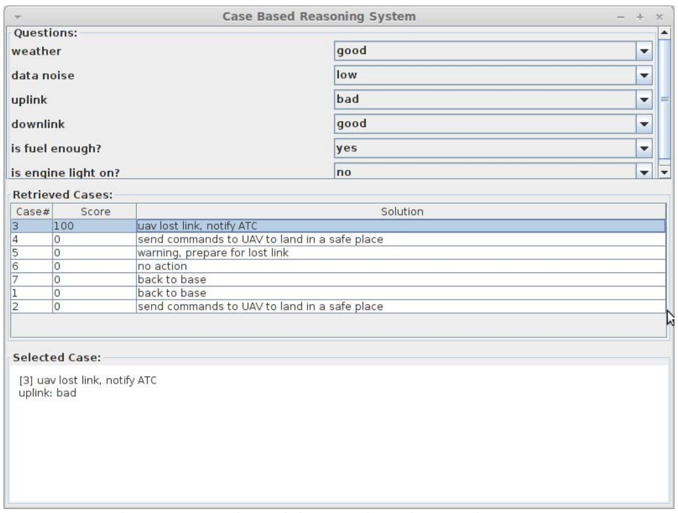

Fig. 5: Screenshot of the case based reasoning system.

We developed a case based reasoning (CBR) system to help pilot in decision making. Fig. 5 shows a screenshot of the system. Basically, the pilot can pick one or more questions to answer. Based on user's choices, the system automatically retrieve from case base the matched or similar cases. For each case in the case base, there is a solution for that case. Based on the matched cases, user is able to decide which solution to follow or adapt the solution. In Fig. 5, user selected question "uplink" and chose "bad" for the question. Based on the selection, the system found a matched case, i.e. case 3. The score 100 indicates a fully match and score 0 means not match. Case 3 says the UAV lost link and pilot should notify ATC. The CBR is easily expandable, as experts can create more cases that are realistic.

IV. EXPERIMENTS

We received a document [37] from NASA which contains 9 UAV flight scenarios (Table 1). Due to page limitations, we include 6 of the scenarios here. We used a UAV model that is the size similar to Global Hawk. In reality, big UAVs require more attention in contingency planning, as lost link may create more damage to other aircraft and ground structures.

We used Google map to locate the scenario region and picked the waypoint longitude and latitude. In all plans, the UAV starts from an airport and end in an airport. The lost link routes are selected in unpopulated regions. Most lost link waypoints are also flight termination waypoints. In addition, we try to avoid restricted regions when designing the routes. In the UAV plan images shown below, the red color circles are lost link waypoints. If the lost link waypoint is also a flight termination waypoint, the color is brown.

The performance measure is quite simple. The metric is to see whether the UAV can follow the LLP and go through every waypoint specified in the LLP. In all of our simulations, the mishap UAV can always follow the waypoints and land at certain termination points.

Table 1: Provisional unmanned aircraft scenarios [37].

	1	2	3	4	5	6	7	8	9
	High altitude surveillance/ Aerial work (search pattern)	Medium altitude surveillance/ Aerial work (search pattern)	En Route Oceanic	Low level surveillance Maritime patrol	Short En Route populated land	Medium range –Low altitude surveillance over land Below 1000 ft Above Ground Level (AGL) Linear feature and/ or search pattern	Departure Descent above 3000ft Above Ground Level (AGL)	Take-off/ land, taxi	Urban Surveillance – Very low level, short range, very small fixed or rotary wing
	(ATC radar /ADS-B control for separation)	(ATC radar control for separation)	Class A procedural ATC control	International (non Radar, Non ATC control) Class G	Class A, B ,C (ATC radar control for separation)	Class G (no ATC separation)	(ATC radar control for separation)		Class G (no ATC separation)
altitude (feet above ., unless otherwise ified)	66 000	30 000	60 000	10 000	38 000	1000 AGL	19 000	3000 AGL	400 Above Ground Level
altitude (feet above ., unless otherwise ified)	30 000	19 000	20 000	500	19 000	100 AGL	3 000 AGL	0 AGL	0.5 Above Ground Level
latitude (deg)	90	90	90	90	70	90	70	70	70
rain rate at aircraft /hr)1	0	5	20	10	20	5	20	20	3
ground speed ıding wind (knots = h)	50	300	550	250	550	150	250	200	50
ground Speed	0	100	250	80	150	40	100	0	0
Roll (deg)	10	20	10	30	10	30	20	30	20
Pitch (deg)	5	5	5	10	5	5	10	10	5
ATC Voice/Data ıd Trip Latency onds)	10	5	120	Not relevant	5	Not relevant	3	1	Not relevant
aircraft response over C2/C3 link e.g. DAA (seconds)	5	2	30	2	2	1	1	1	0.5

These scenarios are candidate for BLOS links

A. *Scenario 1: High altitude surveillance/ Aerial work*

From [37], this scenario is about UAVs flying at very high altitudes while conducting operations such as maritime surface surveillance or acting as a communication relay.

Since this scenario is for surveillance, flying patterns should follow zigzag or some specially designed pattern tailored to that mission. We selected an oceanic region near to New York and set the mission to be maritime surface surveillance. The total surveillance region is about 100 NM by 100 NM.

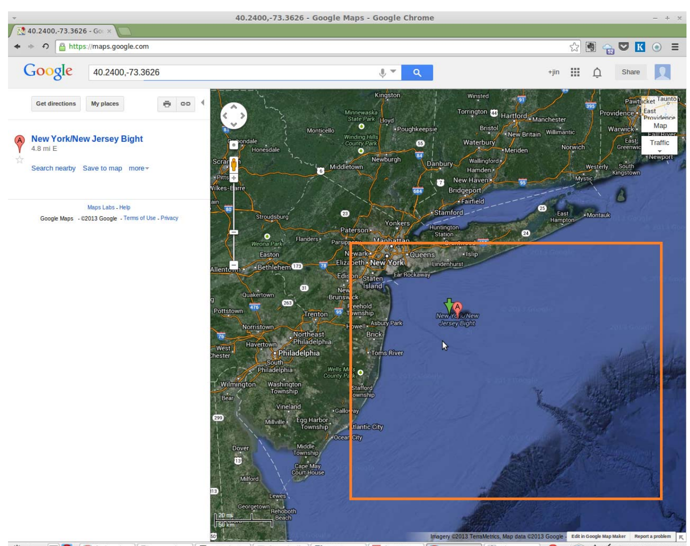

Fig. 6: Google map of scenario 1.

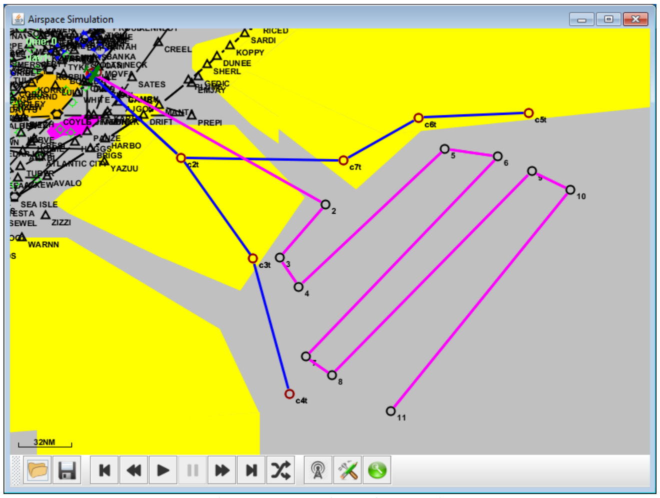

Fig. 7: UAV plan of scenario 1.

B. Scenario 2: Medium altitude surveillance/ Aerial work

According to [37], this scenario covers surveillance for monitoring international borders, forest fires, wild life, ice, volcanoes, drought, etc.

We selected an east coast area near New Jersey and set the mission to be coastal monitoring. The surveillance area is about 50 NM by 50 NM.

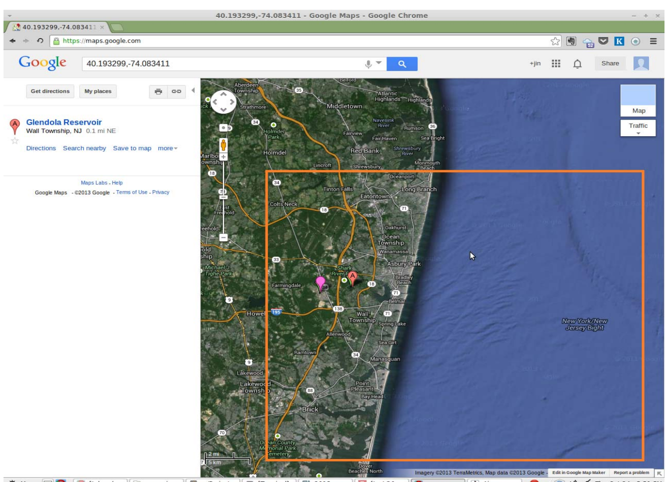

Fig. 8: Google map of scenario 2.

C. Scenario 3: En Route Oceanic

This scenario is from point A to point B and is somewhat similar to Case E (scenario 5).

D. Scenario 4: Low level surveillance maritime patrol

According to [37], this is the typical mission for detection of smuggling or illegal immigration by boat. Typical altitude will be at 5,000-10,000 feet for detection and, down to 500 feet, for identification. Fast response for C2 instructions from Pilot /mission controller will be required.

We found a sea smuggling map from Mexico to U.S. as shown in Fig. 10. Based on the map, we created a surveillance plan as shown in Fig. 11. The surveillance area is about 20 NM by 20 NM.

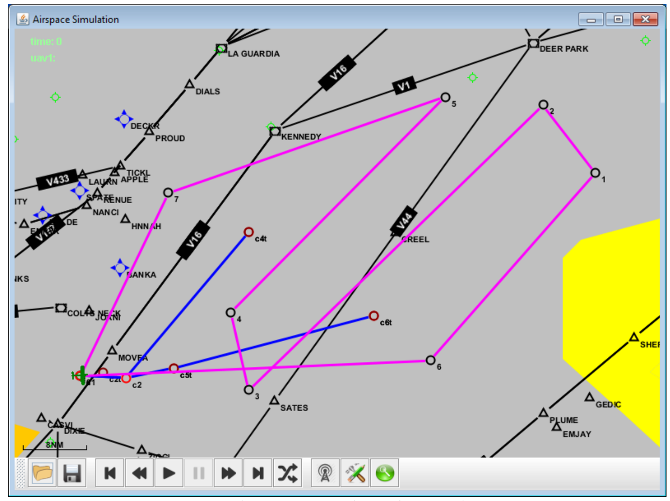

Fig. 9: UAV plan of scenario 2.

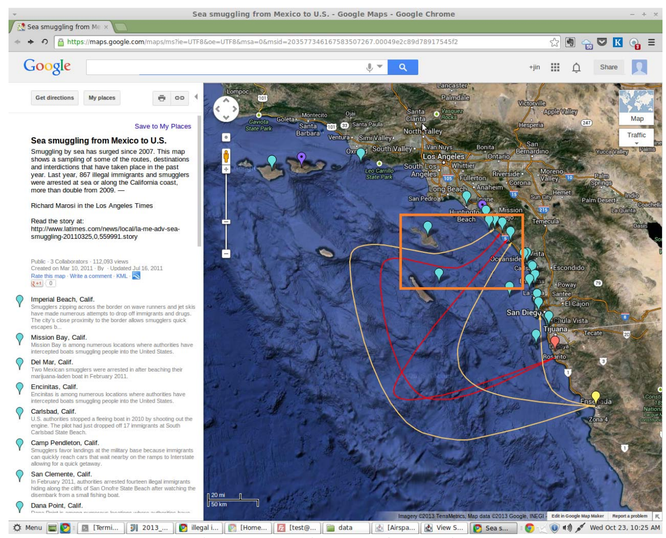

Fig. 10: Google map of scenario 4.

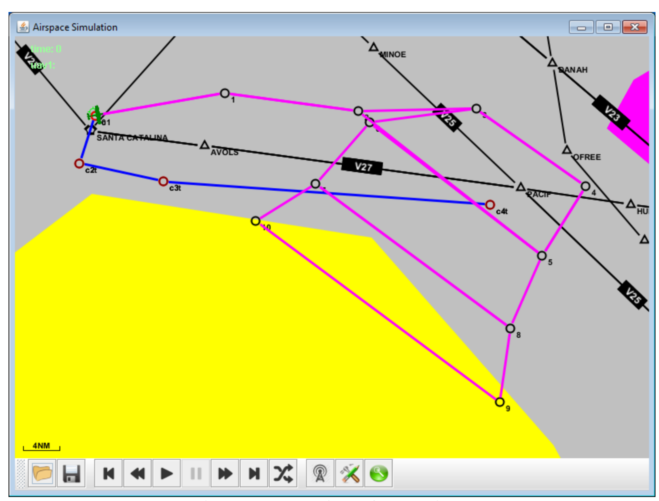

Fig. 11: UAV plan of scenario 4.

E. Scenario 5: Short en-route over populated land

According to [37], this scenario is typical for short range transit overland flight from one location to another. The overall flight consists of a climb portion, a level flight segment, and a descent portion. The flight will be under ATC control and the traffic density of the airspace is high. An effective two-way communication with ATC is required.

In this plan, UAV flies from point A to point B as shown in Fig. 12. Both point A and point B are airports. Since there is a restricted airspace in between, the UAV goes around it to avoid that airspace, as shown in Fig. 13. The travel distance is about 80 NM. We have two lost link routes to point A and point B.

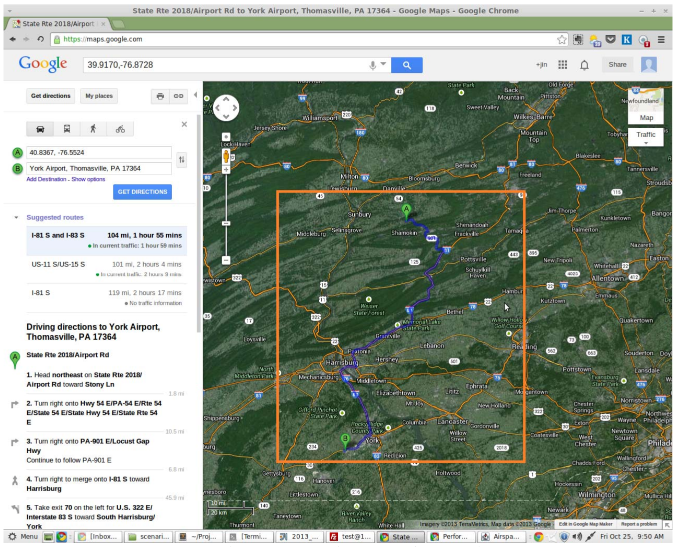

Fig. 12: Google map of scenario 5.

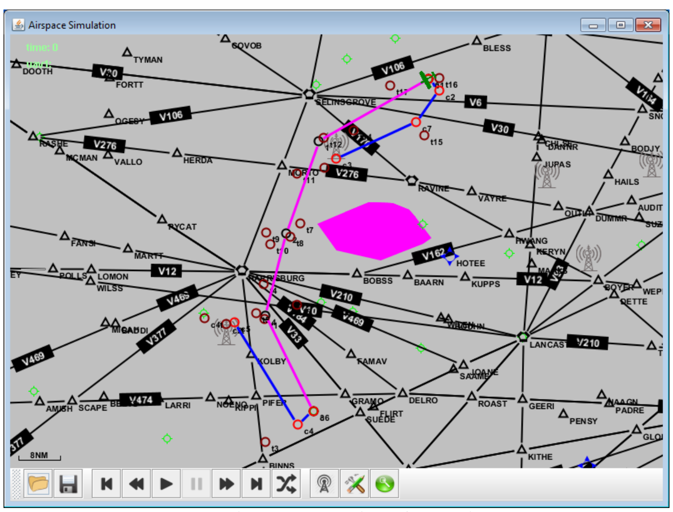

Fig. 13: UAV plan of scenario 5.

F. Scenario 6: Medium range – Low altitude surveillance over land, below 1,000 ft above ground level monitoring of linear feature and/ or executing search pattern

According to [37], this scenario covers mineral exploration survey with earth sensors such as magnetometers at low altitude. Typical missions include oil and gas pipelines or electricity pylons. Operation is at very low altitude on pre-planned missions at moderate speed, up to 150 kts – often slower, and only in reasonable weather. Occasional low latency C2 communication is required

We found Keystone XL Pipeline map online, see Fig. 14. Based on the map, we designed a plan so the UAV follows the pipeline path. Only a portion of the whole line is monitored. The flight path is about 500 NM.

V. Conclusion

A systematic framework for generating LLP for UAVs is presented here. It is in full compliance with FAA rules and regulations. The proposed fast and automated plan generation is new and will significantly improve UAV safety. More details on some of the components will be described in a future journal paper.

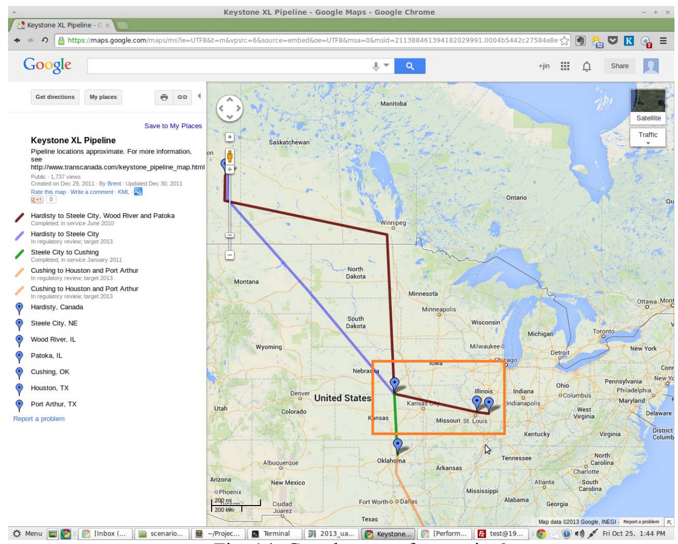

Fig. 14: Google map of scenario 6.

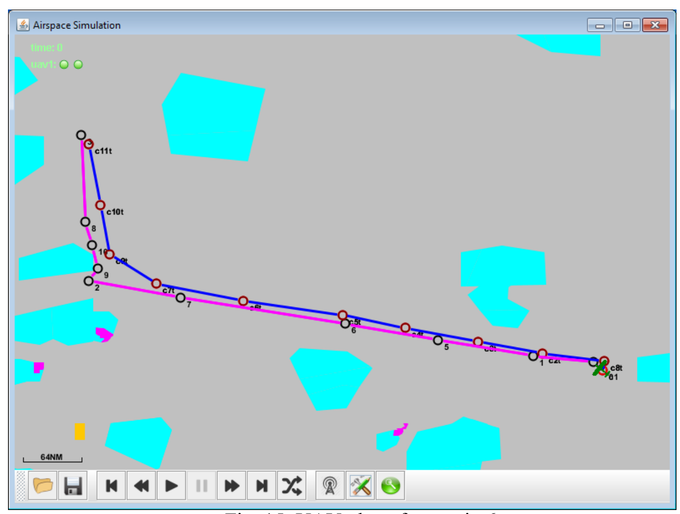

Fig. 15: UAV plan of scenario 6.

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