Inspection of Electrical Transmission Structures with UAV Path Conformance and Lidar-based Geofences

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***Abstract*— To advance unmanned aerial vehicle (UAV) technology, a high voltage infrastructure inspection reference mission was designed and flown. A compact airborne ultraviolet sensor to locate coronal emission "hot spots" was assessed. Two nonstandard navigation technologies were employed: polyhedral geofences derived from lidar maps, and trajectory management software to enforce standoff distance. Position was tracked with NASA's unmanned aerial system traffic management (UTM) technology. It is concluded that a) this low-altitude mission requires navigation methods that are not broadly available; b) the measurement operations and recording methods tested for the UV detector are viable; c) simplification of lidar maps to polyhedral obstacle maps reduces data volume by orders of magnitude. This enables real-time obstacle avoidance autonomy; d) onboard path conformance software successfully maneuvered the aircraft after a sudden lateral perturbation that models a gust of wind; and, e) tracking with UTM was a key safety component, since the flights were conducted beneath the landing approach to a heavily used runway.**

***Index Terms*—Autonomous vehicles, UAV, Corona, Air traffic control, Electrical fault detection.** [1]

I. INTRODUCTION

To provide realistic operational constraints and to bound the range of acceptable results, a specific mission was designed that requires UAV flight paths which sample the airspace near ground structures: inspection of high-voltage electrical transmission infrastructure to locate "hot spots" of ultraviolet emission. Flights with an airborne UV sensor near two test hot spot locations on a 500 kV structure are described. Comparison of the signals detected at points along the flight path to readings from a standard UV camera shows that UAV-based corona detection in real time is a viable alternative to ground-based detection.

Transient perturbations of aircraft position due to wind gusts add to the control challenge posed by radio degradation in this mission environment. Tests of a novel onboard flight path conformance software system are described for flights with and without a perturbation that models wind gusts. The system successfully maneuvered the UAV back onto the preplanned flight path after the perturbation, and did not alter the UAV path in the unperturbed flight.

The intermittency of GPS in this mission environment can be ameliorated by taking advantage of rich lidar maps of transmission infrastructure routinely collected by electric utilities. The richness of this data creates a computational challenge; unless simplified, the data volume of the raw lidar maps is too high for real time processing. Two methods of simplification are described to reduce data volume. Both methods are evaluated as aids for mission planning and for interpretation of UV sensor readings to find hot spots. The computational fitness of the simplified maps as navigational tools is analyzed, and it is concluded that the data volume reduction enables their use for rotary UAV navigation in a dense obstacle field.

Because the electrical transmission grid extends into crowded airspaces, the UAV position was tracked with UTM technology [1]. UTM tracking results are presented side by side with groundstation autopilot tracking. While UTM time sampling is lower than autopilot tracking, the UTM flight path records were found to be adequate to represent the results.

A. Significance of the Reference Task

Airborne avionics to sense transmission line faults and onboard computing to safely guide a UAV near high-voltage structures are essential components of an autonomous UAV-based electrical grid inspection capability. A fleet of UAVs equipped with these components could autonomously examine high-voltage structures, pinpointing locations of the grid with

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damage and equipment malfunction that represent potential or actual risks to power delivery. If distributed across a power grid (for example, at substations), this fleet could serve as the detection foundation of a self-diagnosing power grid (Figure 1). Imagery and other telemetry from the UAV deployments could then be interpreted remotely by experienced grid operation crews and line crews, enabling the rapid dispatch of a nearby line crew in a repair truck loaded with the components necessary to repair the fault. Given the economic and societal benefit of this concept and its need for advanced aeronautical technology, high voltage electrical infrastructure inspection with a rotary UAV was selected as a reference mission to pursue within NASA's Unmanned Aerial System Traffic Management (UTM) program.

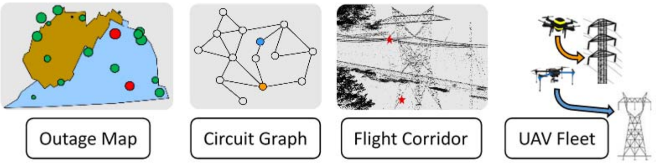

Figure 1. Components of a self-diagnosing power grid. UAVs cached at locations across the grid, such as electrical substations, can be deployed on demand to locate and characterize the faults based on geographic outage maps and topological circuit maps. *©Lidar data: Southern Company*

B. *Flight Test Technologies and Related Literature*

Tracking such a fleet in the national airspace is needed to ensure that the operation of each UAV takes into account other members of the fleet, other UAVs, and manned aircraft [1]. At altitudes above buildings and vegetation, geolocation via onboard GPS is reliable enough and accurate enough to prevent collision with other vehicles using self-separation and alerting technology [2]. At the low altitudes of transmission lines, however, the complexity of measures required for safe flight increases, since precise geolocation of nearby obstacle fields and navigational means to avoid them is needed [3].

Safe operations of small UAS vehicles in uncontrolled airspace is a major goal of NASA's Unmanned Aerial System (UAS) Traffic Management (UTM) project [1]. A far-term aim of UTM research and development is to accommodate small UAS operations throughout the National Airspace System at low altitudes for beyond visual line-of-sight operations.

This study demonstrates an integrated air-ground UAV flight platform performing an electrical transmission line inspection reference mission at low altitudes in a densely occupied flight field. The UAV was built from commercial equipment and software supplemented with the following NASA-developed technologies:

- Lidar-to-polyhedron preflight processing for obstacle demarcation to determine inspection standoff distance;
- ICAROUS flight path conformance software to monitor inspection standoff distance and correct the UAV trajectory during autonomous waypoint-based flight;
- Telemetry repeater software to send the UAV position to a NASA UTM air traffic management server for tracking in the national airspace; and,
- Compact airborne ultraviolet (UV) sensing to detect transmission line faults.

Sensors and concepts for autonomous transmission line inspection are reviewed in [4][5]. A review of compact corona detection for transmission line inspection is provided in [6]. Data reduction approaches for 3D lidar point clouds are reviewed in [7]. Airborne lidar (also known as airborne laser scanning) was adopted broadly by the utility industry in the last decade to meet transmission line safety requirements [8].

II. TEST AND MEASUREMENT FLIGHTS

A. *Flight Locations, Objectives, and Datatypes*

All flights described in this report were conducted at Southern Company's Klondike training facility in Lithonia, Georgia, on November 15 and 16, 2016, with a NASA-built UAV. The flight locations (Figure 2) were adjacent to a de-energized structure rated for 500kV electric power transmission. Video and corona cameras were placed 60 to 90 meters from the flight locations. The site is 17.5 miles due east of the bustling Hartsfield–Jackson Atlanta International Airport, beneath a landing approach corridor [9].

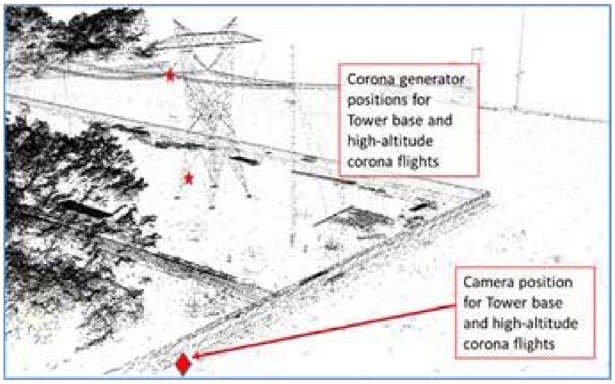

Figure 2. Flight locations (stars) and camera positions (red diamonds) at Southern Company's Klondike training facility in Lithonia, Georgia. *©Lidar data: Southern Company*

B. *Conductor height corona measurement flights*

For UV detection flights, a corona generator was attached to the cross-arm of the tower using a bucket truck. The corona generator intensity was adjusted to ensure detection at a standoff distance of six meters (twenty feet; this intensity is higher than created by a 100 kV corona; see [6] for details and a discussion of the options to increase sensor range). Two waypoint-based flights were conducted at different altitudes with flight paths that traversed the corona source and UV intensity was recorded. The weak UV signal at a 16 meter altitude showed two peaks: one from the east-to-west forward flight, and one from the west-to-east return flight (top left of Figure 3). At an 18 meter altitude, a strong signal was recorded in both the forward and return segments of the flight (bottom left of Figure 3).

UTM Path records were collected and forwarded to the NASA UTM server for these flights, and a ground-based corona camera validated the corona emissions in the 18m flight at a position corresponding to the peak sensor signal during the forward flight. The corona camera overlays red blobs on the visible image at the location of ultraviolet photon emission (bottom right image of Figure 3).

A polyhedral enclosure of the 500kV tower (top right of Figure 3) was prepared that extended from the maximum altitude at in each component polyhedron to ground (i.e., a 2.5 D enclosure; see [10] for details). This enclosure was used to verify a safe standoff distance from the tower and conductors.

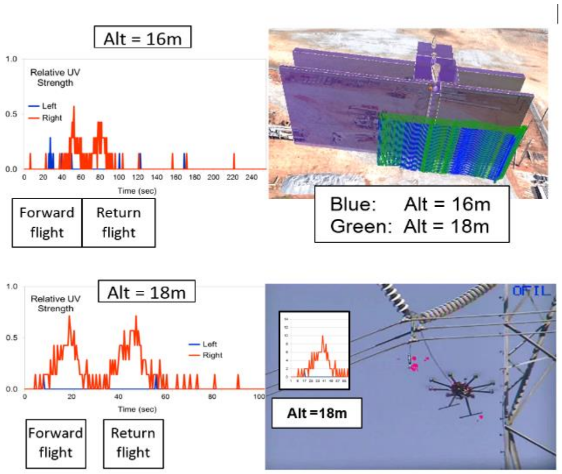

Figure 3. Conductor height corona measurement flights. Corona signal during waypoint-based flights at two altitudes (left). Forward flight paths (top right), and UV camera verification during the 18m flight (bottom right). © *Lidar data: Southern Company; Map data: Google & DigitalGlobe*

C. *Autonomous trajectory correction flights*

A further set of flights (Figure 4) tested ICAROUS [11], which is a trajectory management software technology that monitors the UAV position and corrects the trajectory to keep it within a flight corridor during autonomous waypoint-based flight. Running on an onboard 1 GHz, 8 core microcomputer, ICAROUS reads the telemetry stream that the autopilot sends to the ground station and injects commands into the telemetry stream that the ground station sends to the autopilot. ICAROUS has several capabilities, including detect and avoid [2], geofence conformance [12], dynamic planning [13], stand-off distance monitoring, and return to mission. In this test its return-to-mission capability was exercised in a control flight without wind gust perturbation and in an experimental flight with a transient lateral perturbation that models a wind gust.

In a control (unperturbed) flight (blue traces of Figure 4) the UAV followed a dog-leg path defined by four waypoints near the 500kV tower at five meter altitude. Using the same waypoint, the flight path was perturbed in an experimental flight (green traces of Figure 4): the UAV was launched along the same path, but the pilot manually perturbed the flight, yanking it to the left to emulate a wind gust. ICAROUS sensed the perturbation, yawed the aircraft back toward the centerline of the preplanned flight path, and 'drove' the UAV back to the intended path. Once the UAV was in conformance with the original flight path, the ICAROUS onboard autonomy yawed the aircraft to face the originally intended nose direction and ceased injecting commands into the autopilot-bound telemetry. The native Pixhawk autopilot waypoint-based navigation capability took over from that time point and completed the flight. These flights were tracked in the national airspace, and the flight paths that were stored on the UTM server are shown at left in Figure 4. The composite image at right in Figure 4, constructed from three key frames of the video record of the perturbed flight, illustrates the perturbation and autonomous recovery.

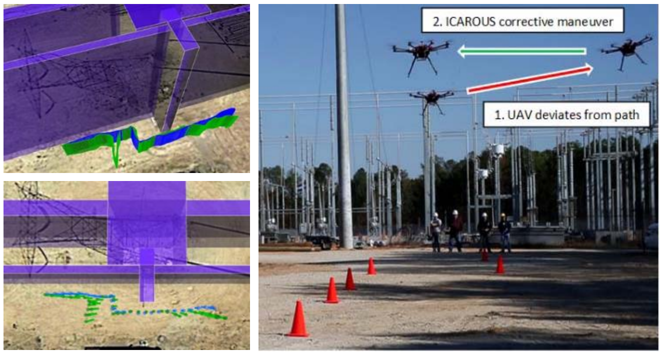

Figure 4. Autonomous trajectory correction flights. Left: autopilot flight paths (top) and UTM flight paths (bottom). Control flight, blue traces; path perturbation flight, green traces. Right: Composite overlay of video frames showing UAV position at three times during the path perturbation flight. ICAROUS trajectory management software detected that the UAV was not positioned in the planned flight corridor and maneuvered it to return to the centerline of the flight path. © *Lidar data: Southern Company; Map data: Google & DigitalGlobe*

D. *Data Preparation for Collision Avoidance Using Lidar-derived Polyhedra*

In the flights described above, the 2.5D polyhedral representation of the 500kV Klondike tower and conductors, derived from Southern Company lidar, was only used to verify path planning and to visualize results. Due to the poor reliability of GPS near metallic ground structures, the UAV was flown at enough distance from the inspection structures that collision avoidance was not required. However, techniques that determine the position of a UAV (latitude, longitude and altitude) more precisely and resiliently than standalone GPS at low altitudes near ground structures are rapidly developing [14][15]. In anticipation of their availability, lidar-derived polyhedral obstacle maps were prepared. Two polyhedra obstacle fields were prepared: the first area contains the 500kV structure and the second area contains buildings, trees and high-voltage bus bars. Both the 2.5D method shown in Figures 3 and 4 and a 3D method that considers altitude throughout the flight volume (Figure 5; see [10] for details) were computed for both areas. At eight coordinates per polyhedron, the 3D method reduces the data volume by a factor of 50-100 compared to the raw lidar data volume, while the 2.5D method reduces the data volume by a factor of 1000-5000.

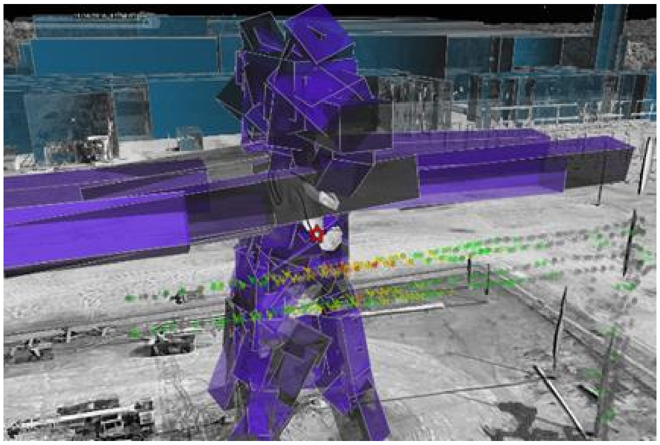

Figure 5. Mixed polyhedra representation for infrastructure inspection. The 500 kV tower and conductors are rendered with the 3D polyhedral enclosure method (foreground, purple) and distant structures are rendered with the 2.5D method (background, blue). The corona generator position is indicated by the red star. The UV time series measurements from the 16m flight (lower trace) and 18m flight (upper trace) are shown as a with a graduated color scale. Colored lines indicate the sensor orientation. © *Lidar data: Southern Company; Map data: Google & DigitalGlobe*

Input capacity and processing capacity of the version of ICAROUS used in the flights was tested with these obstacle maps. Polyhedra derived from the flight area lidar were added ten at a time until 50% of the processing time was needed for polygon processing, leaving a 50% compute margin for trajectory calculation, at a trajectory correction rate of once per second. This threshold was observed for ~ 200 polyhedra, corresponding to an area of size 150m x 130m. This result indicates that an obstacle field computed for an area of the test range without foliage using the 3D method can be processed in real time for obstacle avoidance. However, an area with extensive foliage is not simplified enough by the 3D method for real-time obstacle avoidance. A digital elevation map [16] representation of the tree canopy may lower the geometry count enough that rapid processing is possible.

Several caveats should be made about interpreting the processing capacity test [10]. Most importantly, optimization of ICAROUS is under active development, and it can run on hardware faster than the microcomputer used in these flights.

A mix of 2.5D and 3D polyhedra representations may be the most suitable way to trade off spatial detail and data volume in mapping the obstacle environment. For example, Figure 5 shows the UV signal during flights proximate to a 3D representation of the inspection target, with the an area with extensive foliage represented in 2.5D in the background. The distant background obstacle field does not require full 3D treatment, but a 3D rendition of the 500 kV tower makes it easier to pinpoint the location of a corona fault test signal (red star) and more faithfully outlines the nearby obstacle field for processing with onboard autonomy.

In concert with the 3D tower rendering, sensor results that indicate signal strength and direction help to make the inspection result intuitive. In Figure 5, a green-to-red color scale indicates the magnitude at points along the flight path of the relative UV intensity plotted in Figure 3, and direction lines are drawn that extend from the sensor. With a point emitter tip, the corona generator radiates isotropically with a $1/R^2$ drop-off in areal flux density. The flight paths approximate chords of a circular planar section of the radiated photon field, with the 18m chord (upper trace) closer to the center of the planar section and to the origin of the spherically symmetric flux field than 16m chord (lower trace). As expected from the optical geometry of Figure 5, the observed signal strength and duration are greater in the 18m flight than in the 16m flight.

III. DISCUSSION

A. *Suitability of Lidar-to-Polyhedra Preprocessing for Collision Avoidance*

By applying two methods at either side of the range of lidar-to-polyhedra simplification on a real lidar obstacle map, one can approximately bound the degree of data reduction and the corresponding suitability for spatial control of a UAV. The 2.5D method provides high data reduction at the cost of low spatial fidelity, while the 3D method sacrifices lower data reduction for high spatial fidelity. For the two examples studied, the 2.5D method provides more than an order of magnitude greater data reduction.

With the 2.5D method, the onboard trajectory management software/hardware required about two seconds to process the distant (blue) obstacle field of Figure 5. UAV velocity during inspection was 1 m/sec, so that obstacle collision avoidance during navigation is viable. More powerful computing hardware and dynamic software partitioning of the polyhedra during flight is needed if the UAV is a) moving faster or b) using a richer representation such as that produced by the 3D method.

IV. CONCLUSION

This and a previous [6] report document execution of a specific multirotor UAV reference mission, high voltage electrical infrastructure inspection. The reference mission is designed to exercise a realistic air-to-ground integration platform with a UAV sensor payload whose benefit is enabled when airborne and improved with increased navigational precision. By tying sensor result quality to operational and navigational advances, the mission design encouraged broad advances in UAS aviation.

Using a compact onboard UV sensor, measurement flights of a UAV were conducted proximate to de-energized high-voltage structures. The sensor signal was verified with a ground-based commercial corona camera. The flights described in this report explore two operational and navigational advances: autonomous path correction capability and lidar-to-polyhedron obstacle demarcation. These flight experiments show that UAV operations for a self-diagnosing power grid can be conducted safely and effectively, and that autonomous technologies can increase the level of safety and effectiveness.

The safety advantage of tracking of the UAV using the NASA UTM technology was especially salient at this site, which is 17.5 miles due east of the Hartsfield–Jackson Atlanta International Airport beneath a busy landing approach corridor. Passenger aircraft on descent approach flew 5000 feet overhead [9] at a rate of about once per minute. Before and during each infrastructure inspection flight, the UTM server verified that there were no aviation safety notifications.

High accuracy, high precision aerial lidar maps are available for most high voltage infrastructure in North America. The raw data volume of those maps is too high for airborne trajectory management at this time. Polyhedral 3D enclosures of lidar points with 30-100 times lower data volume are faithful enough for flight planning and obstacle avoidance. Even simpler 2.5D processing is sufficient for planning and safety, and reduce the data volume by a further factor of 30-100.

A set of 2.5D polyhedra that enclosed a 500 kV transmission tower and conductors was used to plan a UAV flight path past the tower and parallel to the conductors. The path was flown twice, with the autopilot listening for instructions from onboard ICAROUS autonomous path conformance technology. In the first flight, the UAV was allowed to follow the path exactly, so that ICAROUS did not need to issue course corrections. In the second flight, the UAV was veered off-course as if struck by a side wind gust. ICAROUS issued course corrections to bring the aircraft back to the center of the flight path; once the UAV was returned to a safe trajectory, the autopilot resumed the flight to completion.

In conclusion, the goals of the high voltage infrastructure inspection reference mission design were met -- UAV navigation technology was advanced while accomplishing a task with economic and societal benefit. Compelling UAV operational and detection methods were developed, airspace awareness (via UTM) was exercised in a busy flight corridor, newly implemented path management autonomy was deployed onboard to assure flight safety in an intrinsically valuable application, and creation of compact spatial geofences for UAV navigation from highly accurate industry lidar mapping data was driven from conception to flight readiness. The multiple, complementary aviation advances demonstrated in conjunction with advances specific to transmission line inspection show progress toward a self-diagnosing power grid.

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