

Geological Applications of Payload Directed Flight

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Payload Directed Flight (PDF) is a research task under NASA Aeronautics Research Mission Directorate, Fundamental Aeronautics Program, Subsonic Fixed Wing Project.

I. Introduction

THE shrinking size and increasing capabilities of microelectronic devices in recent years has opened up the doors to more capable autopilots and pushed for more real-time Unmanned Aerial Vehicle (UAV) applications. Payload Directed Flight (PDF), a research task under NASA Aeronautics Research Mission Directorate, Fundamental Aeronautics Program, Subsonic Fixed Wing Project, aims to address this by developing a set of capabilities both in hardware and software that enables such real-time applications.

Specifically, research into Payload Directed Flight examines sensor and payload-centric autopilot modes, architectures, and algorithms that provide layers of intelligent guidance, navigation and control for flight vehicles to achieve mission goals related to the payload sensors, taking into account various constraints such as the performance limitations of the aircraft, target tracking and estimation, obstacle avoidance, and constraint satisfaction.

The central problem addressed by PDF is the control of a known and controllable plant interacting with an external system based on payload and sensor data feedback that gives partial observation and understanding of the external system, to satisfy mission objectives and constraints on the combined system. This research focuses on (a) trajectory generation and flight control under varying constraints in a highly dynamic environment, (b) autonomous feature detection and estimation, and (c) modeless autopilot design concepts for multi-objective system control. Previous papers by Ippolito, 2009 and Lee, 2009 have covered initial work in (a) and (b) respectively. Application of this research is targeted towards increasing capabilities, performance, and efficiency in the execution of missions that require payload-directed and target-directed maneuvering.

Payload Directed Flight has innumerable applications in unmanned systems including: wildfire monitoring, formation flying, hurricane monitoring, mapping of weather patterns, geological surveying, etc. This paper will

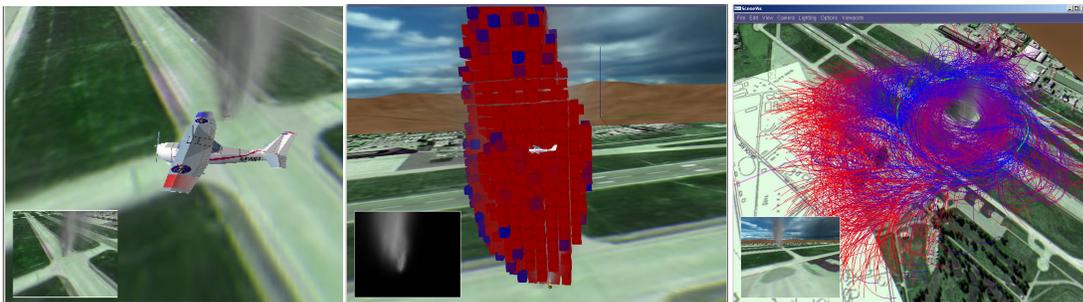


Figure 1. Simulation of a UAV monitoring a wildfire using a body-fixed imager (left), probabilistic estimation in 3-D of a smoke plume (center), and RRT-based trajectory generation (right).

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discuss some of the recent PDF technology developments towards several of the aforementioned applications.

II. Research Applications

There are many research application of Payload Directed Flight.

A. Wildfires

Every year, wildfires cause damage to countless acres of public land and private properties, and have become one of the leading environmental concerns in many parts of the world. The PDF project has developed a series of real-time algorithms to enable deployment of a UAV for the monitoring and mapping of wildfires. In the perception portion of the problem, the system is given images from a body-fixed optical camera and an occupancy grid-based algorithm is used to update probabilistic maps of the location of the fires. In the control portion, a real-time optimizing trajectory generation algorithm based on rapidly-exploring random trees (RRT) was developed to produce flight plans for the UAV. These algorithms were implemented in simulation and are presented in Fig. 1.

B. Geological Surveys

The majority of geological surveys today are performed manually. In fact, geologists typically spend most of their valuable field time in the data collection process and do not begin to analyze the data until they return to the office. Using autonomous systems for geological surveys offers a plethora of benefits to the geological community. Not only would these systems enable larger, more accurate, more repeatable, and longer duration surveys, intelligent guidance and control could even enable data collection modes that were not previously possible (e.g. complicated coordinated patterns). Moreover, “intelligent surveys”, in which the autopilot processes the data and updates survey trajectories in real-time, could greatly improve the quality of the data collected.

The Payload Directed Flight research project at NASA Ames Research Center, in collaboration with Carnegie Mellon Silicon Valley’s Innovations Lab (CMIL) is investigating autonomy and real-time aerial vehicle control based on onboard payload sensors with applications that include geological earth science monitoring and survey. The NASA team also has been closely collaborating with the United States Geological Survey (USGS) in Menlo Park on this research project, with the collaboration focusing on integration and deployment of both USGS ground penetrating radar and magnetic sensors on NASA’s MAX 5.0A rover at present, and NASA’s eXperimental Sensor-Controlled Aerial Vehicle (X-SCAV) UAVs in the future. Figure 2 shows the various unmanned assets owned and operated by the PDF team, including an unmanned ground vehicle (UGV), and two unmanned aerial vehicles (UAVs).

III. Research Technologies

Research into Payload Directed Flight has led to the development of several key technologies that were crucial to the success of these autonomous geological surveys.

A. Autonomous Vehicle Platform Technology

Towards Payload Directed Flight research, the NASA team interfaced USGS magnetic survey instruments with low-cost autonomous vehicle platforms, both aerial and ground vehicles. Both aerial and ground vehicles ran the same software, which allowed the ground vehicle tests to serve as a software verification for flight tests. The autonomous ground vehicles were deployed for these missions.

B. Payload Processing Algorithms

One of the main difficulties in performing real-time control around payload sensors is processing the data in a timely fashion. Typically, the processing of geological sensor data is done well after a survey has been completed, given the complexity of the algorithms required. The NASA and Carnegie Mellon team developed real-time software to correlate payload sensor data with a suite of onboard vehicle sensors to give precision global positioning of the collected data; onboard sensors included inertial measurement sensors, orientation sensing magnetometers, and sub-meter accurate differential GPS.

The software processes the referenced data stream to develop continuously evolving magnetic surface maps that can be utilized to optimize vehicle trajectories in real-time. In this process, data values for the unmeasured areas between traversed survey points were interpolated using the minimum curvature method, fitting third order splines to the surface. This method was first introduced by Briggs, 1974, and has been used for many years in the Geophysics and Geology communities for processing data after a survey was complete. Based on these equations, a real-time processing software module was written to run as a low priority thread in the background. As the rover

carried out the survey, sensor data was relayed to the ground station, where the algorithm calculated over the grid and produce updated contoured visual displays. This allowed scientists to quickly locate points of interest for further data collection. Gradient and integral values between points on the grid could also be calculated but were not used in these surveys.

C. Real-time Communication and Data Distribution

The NASA and Carnegie Mellon team developed software to distribute processed payload sensor data streams in real-time to scientists around the world over the world-wide web, enabling visualization of the evolving maps as the mission progresses through a Google Earth interface. During these deployment surveys, geological scientists in the field utilized this Google Earth interface to monitor the payload data stream magnetic field maps as they developed in real-time. Based on this real-time feedback, the survey team manually adapted the survey to focus on ‘hot-spot’ locations in real-time.

IV. Research Field Deployments

The magnetometer-instrumented rover was deployed on three occasions.

A. Flood Park

. In the first deployment, the UGV was deployed to Flood Park, Menlo Park to observe a large aqueduct that passed beneath. Autonomous surveys were performed in two locations: the baseball field and bocce ball court. The real-time processing algorithms were able to correctly characterize and display the aqueduct. A composite plot is shown in Fig. 3.

B. Ohlone College

. In a second deployment, the UGV surveyed part of Ohlone College, Fremont in an attempt to investigate active fault zones. It is hypothesized that the special geology of these fault zones may have characteristic magnetic signatures that can be detected by a magnetometer survey. Although the survey plots did not show any obvious signs of magnetic signatures, the data has been submitted to USGS for post-processing and further review.

C. A Murder Investigation

. In a third deployment, the NASA Payload Directed Flight research team, in collaboration with the United States Geological Survey in Menlo Park and Carnegie Mellon Innovations Lab, provided assistance to the County of Santa Clara’s District Attorney’s Office in California to solve a cold case murder investigation. The collaborative team deployed the instrumented autonomous ground vehicle to perform magnetic surveys of an old junk yard in Alviso, California, looking for buried material evidence, which included metal car parts and a possible buried body. The application of research algorithms developed by NASA and Carnegie Mellon University (CMU) together with USGS technologies provided the means to collect data and locate the buried material evidence, which was subsequently excavated. The excavation led to a successful conviction and resolution of the 18-year old case. Photographs of the deployment are shown in Fig. 4.

A critical element of this deployment was the need for rapid data collection and modeling. Legal constraints allowed for only a brief field investigation (one day and one follow-up day, if necessary), and the modeling needed to be completed within two weeks. New field techniques developed by this joint NASA-USGS effort allowed for near real-time data download, processing, and preliminary analysis. This element was key to the investigation, because it allowed USGS scientists to obtain preliminary results during the field session, when critical access to the site was available and investigators were on-site to address problems and carry out immediate follow-on investigations.

Crews spent the initial field time removing surface debris from the surface, which consisted of various metal and non-metal construction detritus such as small lengths of rebar, bolts, boards with nails, lengths of chain, cyclone fencing, etc. Once the surface was reasonably free of debris the mounted rover was carried across the study area in a row-by-row pattern. The site was surveyed in less than 30 minutes, so the diurnal correction was assumed to be negligible. As the magnetic data was received it was processed at the base station and a near real-time magnetic map was conducted as the survey progressed, allowing feedback from the base crew to the survey crew. At the completion of the survey the USGS identified areas of interest A, B, and C (Fig. 5) based on the locally high induced magnetic field, and a second, more detailed survey (Fig. 6) was conducted to better delineate the anomalies detected by the first survey. The second survey revealed three areas of interest common to the first survey, and one area from the first survey that was initially thought to be significant was revealed to be a surveying artifact. At the

completion of the second survey the magnetic map delineating the three areas of interest was given to investigative team.

Offsite, following the survey, the USGS modeled the magnetic anomalies as highly susceptible bodies (> 1 SI), consistent with large manmade objects with a high iron content. Two-dimensional cross-section modeling across each of the three anomalies indicated magnetic objects at approximately 2 meters depth. The models were given to investigators to help focus their efforts.

Three pits were dug by the investigators, each several meters across and between two and three meters deep. The USGS was not present during the exhumation, and the precise location and amount of debris was not recorded.

However, the investigators informed the USGS that several parts from an automobile were discovered in location A (Fig. 5). Only minor amounts of debris were found at locations B and C (Fig. 5). In general the amount of debris discovered was smaller in volume than the modeling predicted, suggesting the modeling used too low a value of magnetic susceptibility for the manmade parts. However, the location and relative amounts of manmade parts were consistent with the modeling.

Rapid processing and modeling of magnetic data has been demonstrated to be possible in near real-time in the field. This significant advance allows the scientists to make the most of valuable field time. Problems can be addressed and follow-on investigations can be performed in the same field session.

V. Conclusions and Future Work

Results of PDF technology have shown great promise both in mathematical simulation and in real-world deployments. Future work aims to perform autonomous magnetometer surveys on aerial vehicles and to further investigate intelligent guidance and control autopilot modes to maximize the scientific return of future surveys.

Acknowledgments

The authors gratefully acknowledge NASA ARMD Subsonic Fixed Wing project for funding this work, collaborators from the USGS, Santa Clara District Attorney's office. Summer interns, visiting scholars to the lab.

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