INTELLIGENT AUTONOMOUS SURVEILLANCE OF MANY TARGETS WITH FEW UAVS

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ABSTRACT

Unmanned Aerial Vehicles (UAVs) offer tremendous potential as intelligence, surveillance and reconnaissance (ISR) platforms for early detection of security threats and for acquisition and maintenance of situation awareness in crisis conditions. However, using their capabilities effectively requires addressing a range of practical and theoretical problems. The paper will describe progress by the "Autonomous Rotorcraft Project," a collaborative effort between NASA and the U.S. Army to develop a practical, flexible capability for UAV-based ISR.

UAV-BASED SURVEILLANCE

As long as there have been aircraft, aircraft have been used for surveillance missions. Balloons were used by both sides in the American Civil War. The Rumpler Taube monoplane was used for military surveillance before the onset of World War I. Although Tesla patented a device for remote control for boats as early as 1898, it wasn't until the middle of the twentieth century that practical systems became available for intelligence gathering using unmanned aerial vehicles (UAVs). Recent innovations in UAV hardware and software technologies, as well as economies of scale, make UAVs feasible for increasingly diverse airborne observation missions [7].

There are a variety of current and proposed applications of UAVs for US Homeland Security. The US Customs and Border Protection (CBP) Border Patrol tested UAVs in its Arizona Border Patrol Initiative, aimed at minimizing illegal and dangerous border crossings. According to the CBP [6], the advantages of UAVs included advanced image recognition systems in both day and night-time monitoring, longer dwell time (in comparison to manned Blackhawk helicopters) resulting in more sustained coverage, decreased need for human resources and the ability to work in dangerous conditions, which results in increased safety for ground agents. In addition to land border patrol, UAVs have application in maritime, harbor and littoral patrol and in monitoring

Figure 1: Autonomous Surveillance

critical infrastructure such as dams and aqueducts; energy and water pipelines; and assets in the national power grid, which may span many miles and require long, tedious but essential monitoring. UAVs can also assist situational awareness for Homeland Security operations, feeding from the air information to DHS operations about critical incidents as they occur.

FROM REMOTE CONTROL TO FLEXIBLE AUTONOMY

The current state of practice in UAV operation is direct remote control by human controllers; in other words, UAVs typically have little autonomy. For some applications this is adequate. But for others, increased autonomy offers many advantages. The primary goal is a decrease in the need for human operators, which lowers costs and may decrease the number of operators in harm's way. Additionally, because surveillance often requires monitoring for a long duration when little of interest occurs, fatigue and boredom limit the ability of human operators to maintain a high level of vigilance. UAVs do not suffer from such attentional fatigue. For certain surveillance tasks, for example, path selection for directing surveillance [3], computer systems are often better than humans. Also, the digital and network characteristics of UAVs allow surveillance intelligence to be integrated into operational activities and systems, such as the DHS Operation Center, and allows a shift towards a "sensor web" model [1].

IMPORTANT DEVELOPMENTS AND TRENDS

There are several important developments and trends which increase the usefulness of UAVs for airborne surveillance. First, the national Access 5 Alliance is an effort of the FAA, NASA, the DoD and industry participants to increase the use of UAVs in the National Airspace System (NAS). Homeland Security is a central rationale for integrating UAVs in the NAS. That there are commercial, scientific and civil applications for UAVs support the eventual integration of UAVs into the NAS.

A second important trend is that the technology underlying autonomous systems in general is becoming more capable, more reliable and less expensive. Part of this trend is due to the steadily increasing computational power, decreased cost, increased commodization, and increased reliability of computers. Advances in intelligent systems research are another part of this trend. Our research group, for example, has developed the Apex system, an autonomy architecture for constructing software for agents that can respond intelligently and responsively in demanding task environments. The goal of the Apex system is to allow autonomy developers to decrease the time, expertise and inventiveness required to create new autonomy applications. One such application is the Autonomous Rotorcraft Project, described below.

In addition to the increased capability and reliability of autonomy software, UAV platforms have themselves become more available, more reliable, and less costly. Early UAV systems were one-off systems developed at great expense; today, a variety of UAVs are available as production items.

All of these trends–the push to allow UAVs in the National Airspace System, the increased reliability and capability of artificial intelligence autonomy software, and the increase reliability and capability of UAV platforms–suggest that UAVs will play an increasingly important role in homeland security.

Figure 2: ARP RMAX research aircraft (left) and instrumentation trailer (right)

THE AUTONOMOUS ROTORCRAFT PROJECT

The Autonomous Rotorcraft Project (ARP) is a joint project of NASA and the Army's Aeroflightdynamics Division (AFDD) of the US Army Research, Development, and Engineering Command [8]. The project is being developed at the Ames Research Center. The demonstration platform for ARP is the Yamaha RMAX helicopter (Fig. 2), a relatively low-cost remote controlled helicopter originally developed for agricultural seeding and spraying, but adaptable for autonomy. With a ground weight of 184 pounds and a rotor diameter of 3 meters, the RMAX can support a payload of 65 pounds with approximately one hour of hovering flight. Given the size of this payload, and the recent advances in computer and sensor technologies mentioned above, it is possible to outfit the RMAX with the technologies needed to fly autonomously.

Its avionics payload includes a Crossbow IMU, a 900 MHz radio modem, a PC104+ flight computer, a PCI video computer, sonar, differential GPS, vibration sensors and weight-onwheels sensors. Additional sensors include a pair of actuated stereo monochrome cameras, and actuated color camera, and actuated video camera and a SICK scanning laser.

The Autonomous Rotorcraft Project makes use of a number of fixed and mobile facilities including hangar space and facilities for fabrication, maintenance and inspection at Moffett Field. The project also has a mobile ground station, which provides self-contained transport for the RMAX helicopter, workstations for the research team, and communications and telemetry facilities for communicating with the aircraft. See Fig 2.

Passive and active obstacle sensing and mapping

The stereo cameras are mounted on a vibration-isolated stub wing, with a one meter baseline. The cameras can be pitch tilted. The images from the stereo are piped through to software that produces a 160×120 pixel disparity map every five seconds, which provide accurate, passive sensing of objects. See Fig 3.

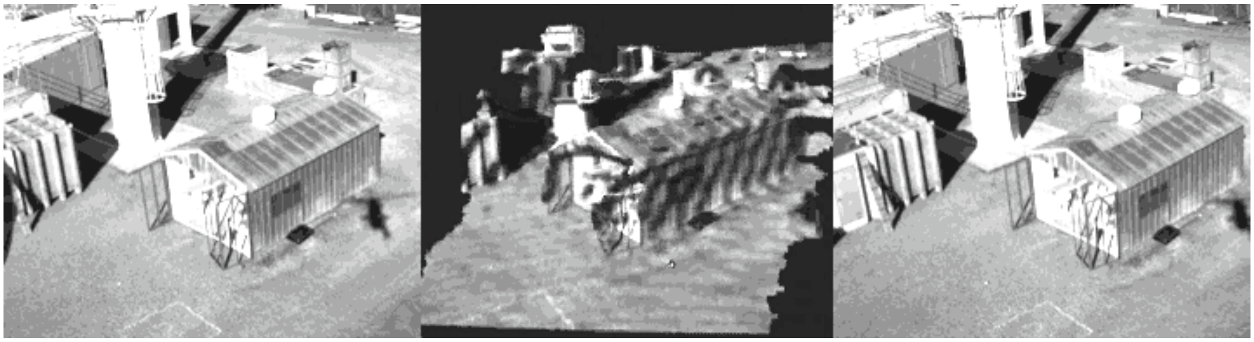

Figure 3: Passive stereo object sensing (middle) from left and right monochrome cameras

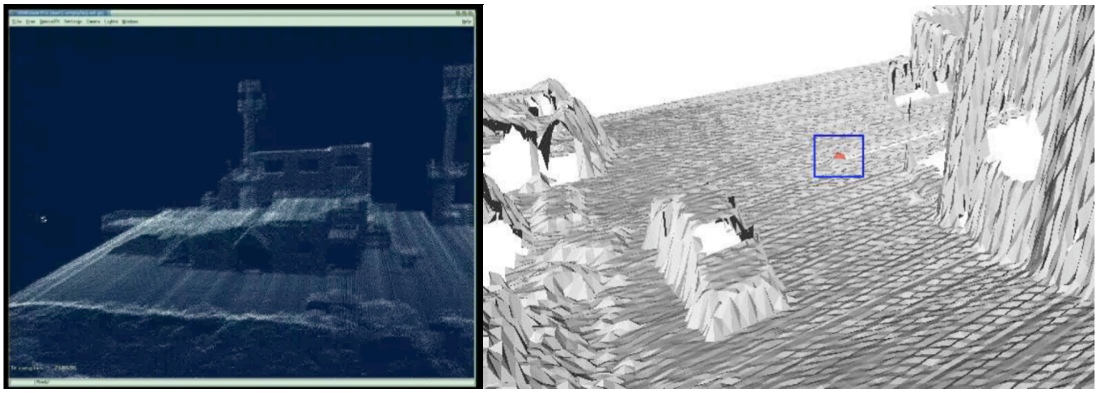

Figure 4: Laser imaging (left), change detection (right)

A SICK PLS scanning laser is mounted beneath the nose of the aircraft. It provides high resolution, active scanning, and is used for obstacle detection and mapping. It weights 3.6 lbs (lightened from its manufactured weight of 9.9 lb), and provides a 180°field of view, with an accuracy of 1 cm at 81 meters. It provides 1°of resolution at a 75 Hz scan rate, and 0.5°of resolution at 37.5 Hz. It can be repositioned on its mount depending on task requirements (for example, downward for mapping, forward for obstacle detection).

The SICK laser can also be used to detect changes in the 3D model it produces, as indicated in Fig 4.

Route planning around obstacles

The Obstacle Field Route Planner (OFRP) algorithm [4] is used for route planning in 2-space.

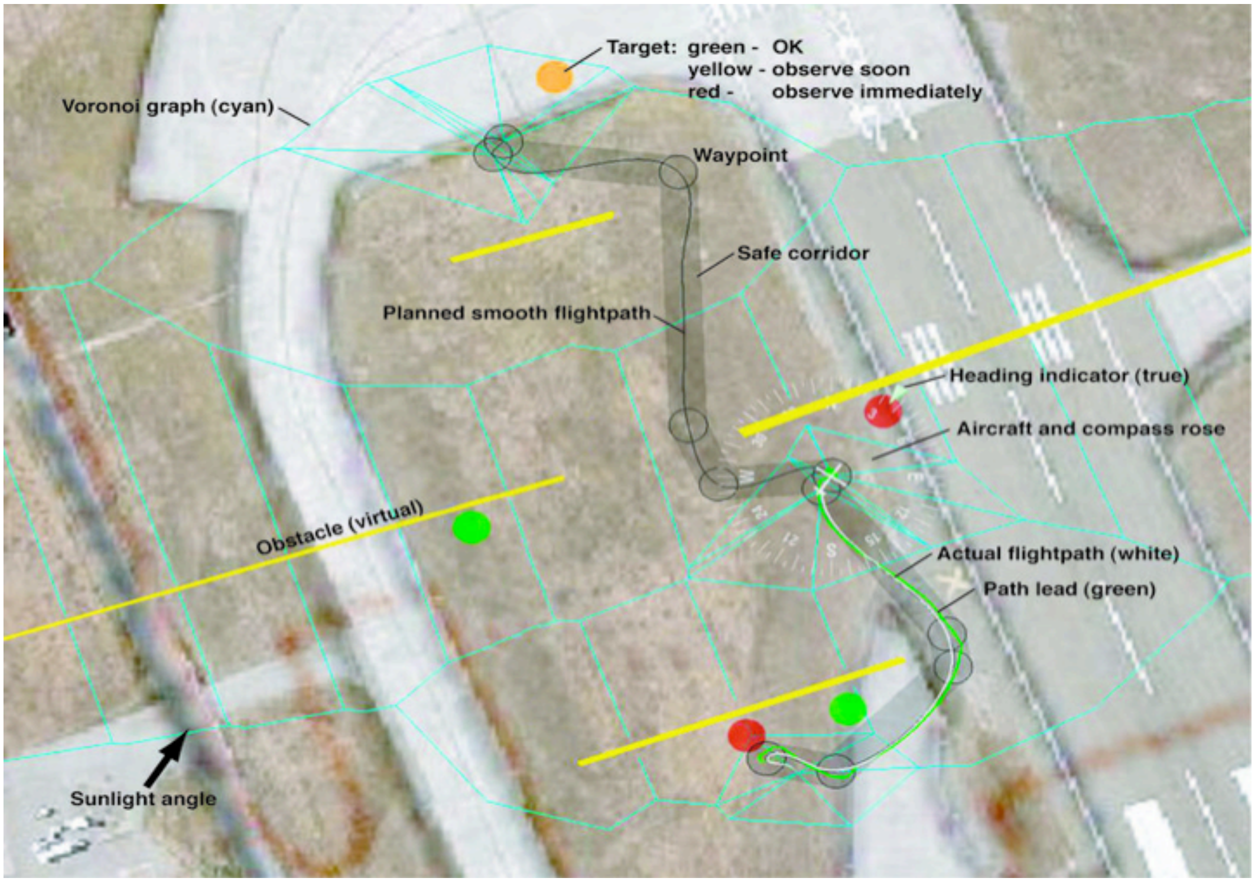

Figure 5: Route planning around obstacles

The OFRP algorithm selects a route in a series of stages. From a map indicating obstacle edges, a Voronoi graph is generated. Then, the graph is culled using binary space partioning. Path culling is then done using Dijkstra's method while checking path boundaries. Paths are then further subdivided and culled. Fig 5 shows an example route. The route planning is integrated into the mission autonomy software and flight control laws.

Safe landing area determination

The ARP system uses the JPL Safe Landing Area Determination (SLAD) algorithm [5] to find a safe landing area, without the direct use of the differential GPS. Surveillance vehicles may need to land in a "GPS-denied" state due to GPS failure (for example, occlusions due to buildings), as a safety precaution (for example, lack of precise coordinates), or intentional interference by foes. The SLAD algorithm–developed as part of the NASA Precision Autonomous Landing Adaptive Control Experiment, or PALACE–evaluates surface roughness, slope and available area using stereo camera images. The object ranging techniques described above are also used.

MISSION-LEVEL AUTONOMY

In addition to hardware and software for obstacle avoidance and target identification, route planning, and safe landing determination, the Autonomous Rotorcraft Project also contains software for creating autonomous systems at the mission level. High-level autonomy control is provided by Apex, a reactive procedure-based task execution system and planner [2]. Creating realistically robust surveillance systems requires task execution and scheduling that can react quickly to rapid changes in the situational context, as well as to rapidly changing user needs. Robust autonomous surveillance requires the capability to manage multiple tasks and subtasks concurrently, in rapidly changing conditions. Surveillance, like other multitask activities, will be subject to such environmental characteristics as:

- Failures (such as the loss of a sensor or communication channel)
- Interruptions (such as a request by a user for a new surveillance target)
- Opportunities (such as an unexpected break in the weather that allows flight in areas previously considered too dangerous)
- Side Effects (such as flights near residential areas creating undesirable noise)
- Instability (such as the closure of a road that reduces the likelihood of intrusion at nearby targets)
- Synergies (such as two targets being close enough to be viewed from the same vantage point)
- Glitches (such as temporary loss of sight due to sun angle),
- Slack (such as under-utilization of UAV resources surveying lower-value targets)
- Deterioration (such as gradual or sudden loss of a communication channel).

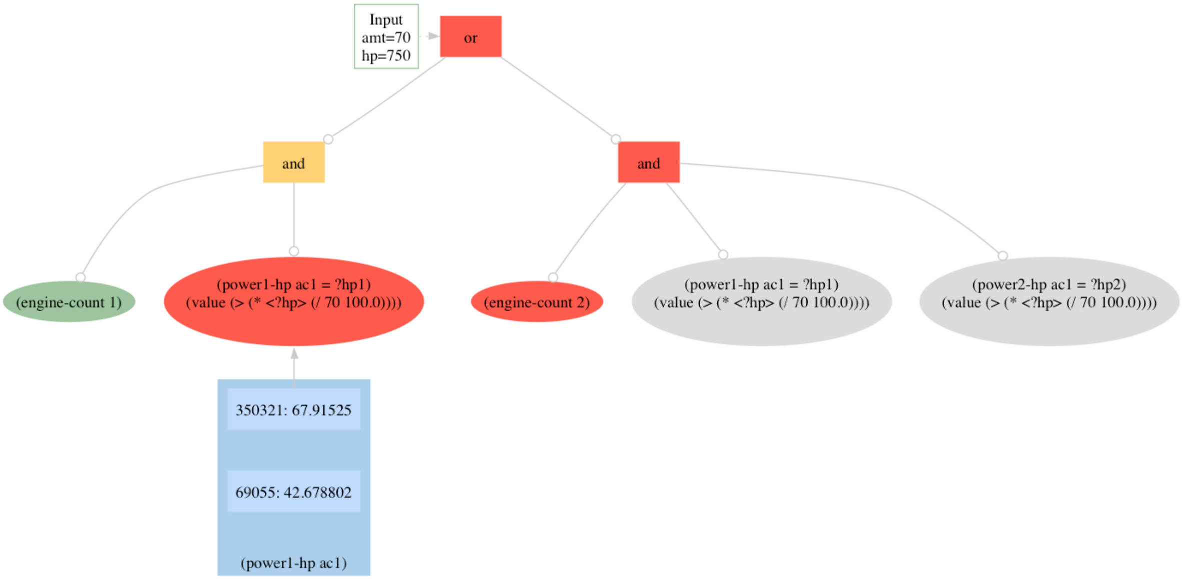

Figure 6: Detail of the Sherpa tool, showing the state of a running monitor

A high-level task executive will require many capabilities to handle such environmental exigencies. Among these capabilities are:

- Closed-loop control. The executive should treat mission-level planning and execution as a control problem, closing the loop over high-level reasoning processes (not just low-level flight control processes).
- Contingency Handling. The executive must be able to handle uncertain, even ambiguous conditions, including failure conditions. If communications fail, for example, an autonomous surveillance system must record relevant data in the event that communications are recovered, or the aircraft returns safely to base.
- Procedural Reasoning. The executive must enforce routineness and predictability in many behaviors, which is often a requirement for safe, legal operation. Furthermore, it must take advantage of routineness of behavior whenever possible to make the intelligent system processes more transparent and computationally tractable.
- Fast Replanning. Because conditions may change rapidly, the executive must be able to quickly replan its actions. For example, for surveillance for situational awareness, the UAV will need to react to a changing situation.
- Smart Monitoring. Handing contingencies and replanning assume that the system is able to monitor for conditions as they change. Monitoring has to be “smart” in at least two ways: first, monitoring for a wide variety of conditions must be possible; second, monitoring must be as efficient as possible without degrading system performance. A smart surveillance system will monitor for the condition that a target is no longer visible (which could involve a number of subconditions), but if that monitoring takes too much time, its overall mission is imperiled. Fig ? shows a debugging display of a complex monitor.
- Multitask Management. The task executive must be able to manage the execution of multiple tasks at once, which are likely to be hierarchical in nature. For example, a

helicopter might be able to perform certain checkout duties as it begins its initial hovering.

- Resource Projection. The task executive must be able to project resource use, and what to do about it. For example, a helicopter must return to base before it runs out of fuel.
- Integration of specialized expert reasoners. Expert reasoning systems, such as the path planners mentioned above, will be more conveniently expressed in direct procedural code. This must be smoothly integratable into the task execution system.

Such concerns have been central to the research that led to the development of Apex, and the Autonomous Rotorcraft Project has both confirmed and expanded the requirements list for mission-level autonomy. Additional information about the Apex system can be found at http://human-factors.arc.nasa.gov/apex.

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