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Arctic Test Flights of the CMU Autonomous Helicopter

Ryan Miller, Omead Amidi, and Mark Delouis
Carnegie Mellon Robotics Institute
Pittsburgh, Pennsylvania U.S.A.
http://www.ri.cmu.edu/project/chopper

Abstract

This paper presents our experiences during the test flights of the CMU autonomous helicopter in the Canadian Arctic, the first deployment of this technology for a real-world application. The mission required building dense topological maps of Devon Island's Haughton crater for NASA scientists studying Mars-analog environments. The paper presents our system design and preparation, flight test results, and example maps produced by the on-board laser-based mapping system during the mission.

1. Introduction

At Carnegie Mellon Robotics Institute, we have been developing a number of research autonomous helicopters since 1991. (See Appendix A for project history) Over the years, critical components have matured enough to form a framework for several autonomous systems in service as testbeds for aerial robotics research. In the summer of 1998, we took a step beyond research alone and deployed an autonomous helicopter in the Canadian Arctic to build high-accuracy topological maps for NASA geologists. This paper presents our objectives, challenges and the results of this mission to Devon Island, Canadian Northwest Territories.

2. Mission Purpose

The primary purpose of the mission was to assist NASA scientists in their geological study of Devon Island's Haughton crater, a Mars-analog environment [1]. The study of such environments is important to scientists in preparation for future manned missions to Mars. Of particular interest was an accurate 3D map of the crater because available maps did not represent the desired level of detail for NASA geologists, so we were assigned a mission to investigate the feasibility of applying our autonomous helicopter technology to accurate aerial mapping of the crater.

This mission provided a unique opportunity to study a potential application of our unmanned aircraft technology. It was unique for several reasons. First, our aircraft could fly over uninhabited areas without concern for endangering human lives and property. Second, our system could perform a real-world mission, to build highly accurate topological maps. Third, our helicopter could fly in a very different environment compared to its limited test flight area near Carnegie Mellon. This was especially valuable because the Arctic region's unique navigational challenges could test the robustness of our flight controls. Finally, our system's ease of transport and deployment could demonstrate the advantages and applicability of unmanned aerial aircraft for mapping tasks in inaccessible locations.

3. Expected Mission Challenges

Aside from the obvious challenges posed by the weather and remote and rugged terrain of Devon Island, we expected several navigational challenges stemming from the Island's geographic location. Of particular concern were helicopter heading alignment and GPS-based position estimation.

3.1 Heading Alignment

Accurate navigation and mapping requires accurate heading alignment and measurement. Our helicopter system aligns heading using a magnetic compass or gyro-compassing. Inertial sensors use this initial alignment and maintain accurate heading during flight with infrequent updates from the compass to eliminate drift.

Unfortunately, we could not use a magnetic compass for heading alignment at the crater. As illustrated by Figure 1, Devon Island (75.25° N, 88.00° W) is approximately 300 miles from the magnetic North pole (78.30° N, 104.00° W). At this location, the magnetic field is nearly vertical, rendering any magnetic heading device useless.

Figure 1. Devon Island's proximity to magnetic North pole

Similarly, gyro-compassing [2] based on measuring the Earth's rotation for initial alignment would be inaccurate at the crater. At Devon Island's latitude, the relevant portion of the Earth rate for heading alignment is about a third of its value in Pittsburgh. Our system can not accurately sense heading with this reduced (~4°/hr) component at this location.

We chose to deploy an experimental multi-antenna Global Positioning System (GPS) receiver for initial alignment and to rely on the inertial sensors to maintain heading during short (20-30 min) flights. Multi-antenna GPS receivers measure heading by tracking GPS signals received by two or more antennas separated by a known baseline. [3]

3.2 GPS Coverage

Our helicopter measures position using GPS and visual feedback. Due to payload constraints, we did not support both on-board systems and chose to rely on GPS alone for position estimation. The helicopter supports a dual-frequency carrier phase differential GPS system, the NovAtel MillenRT2. For proper operation, the system re-

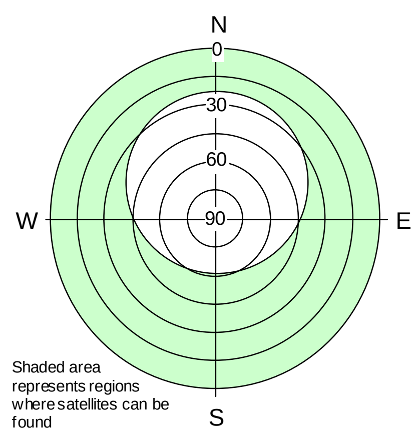


Figure 2. Satellite locations in the sky

quires at least 5 satellites in view of both the differential base station and the helicopter. Predicting GPS satellite orbits demonstrated adequate coverage for our mission but low satellite elevation angles. Figure 2 shows the regions in the sky where satellites were expected to appear during the mission. Of major concern was not the satellite count but rather the satellite elevation angles. All satellites in view were below 60° elevation, possibly a condition that could introduce reduced positioning precision due to satellite geometry and multi-path errors due to signal reflections from the surrounding crater terrain.

3.2 GPS Differential Correction

Our differential GPS receivers require corrections from a nearby base station for accurate positioning. The absolute accuracy of the station's location and its proximity to the helicopter determines the helicopter positioning quality. With no available stations nearby, we expected to set up a temporary differential correction station at the crater. This posed a challenge of determining an accurate measure (within an acceptable margin of 1-2 meters) of the station's position at the crater. We expected to average raw single-receiver GPS positions for long period of time to achieve this level of accuracy. Since it was unclear that averaging single-ended GPS data would yield this desired accuracy, we planned to use a commercial satellite-based differential data source, an OmniStar receiver, during our station localization. Although the crater was well North of the published OmniStar coverage area, the company indicated that there was a chance of receiving useful corrections during certain periods of the day if the antenna were pointed South, toward their satellites.

4. Mission Mapping Hardware

Much previous work has been done with active sensing of 3-D structure from both aerial and ground vehicles. Lockheed Martin is developing an airplane-based mapping system, which builds digital elevation maps of very large regions using synthetic aperture radar. [4] These systems employ high-altitude aerial vehicles, which concentrate on generating coarse (3-m accuracy) maps of large areas. In contrast, our mission required close-proximity flight to areas of interest to create highly accurate (20 cm) 3D maps. Our autonomous helicopter systems were specifically designed for such flight maneuvers, including fully autonomous takeoff, flight path tracking, accurate (<20 cm) stationary hover, and landing. [5] These basic capabilities allow the helicopter to be used as a highly maneuverable sensing platform; providing access to remote and confined locations without putting human pilots at risk. These capabilities, along with the on-board mapping system, were key to meeting the needs of the Haughton crater mission.

4.1 Mapping system

The on-board mapping system [6] senses terrain range with a planar laser scanner, which is integrated with the flight control computers. The integrated system measures Earth-referenced 3-D coordinates from up to 6000 terrain points a second within the 100 meter range of the scanner. These coordinates are expected to be within 20 cm of their actual position in space. Achieving this level of accuracy is difficult, given the helicopter's highly dynamic motion profile and its limited payload capacity, restricting the choices of available range sensors.

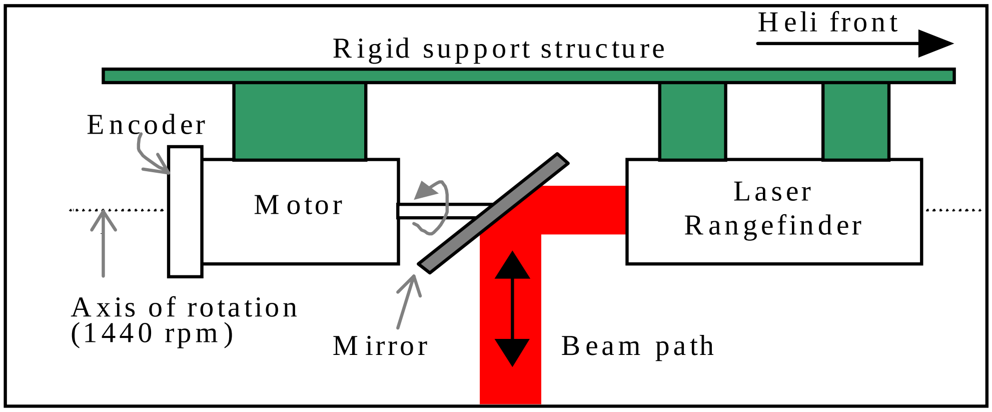


Figure 3. Planar laser scanner

The scanner design is shown in Figure 3. It is a single degree of freedom mechanism, which scans the environment by reflecting a laser rangefinder's beam off a spinning aluminum coated mirror mounted at 45 degrees. As a motor rotates the mirror through an entire cycle, the laser is redirected to scan out a plane perpendicular to the axis of rotation. This mechanism is desirable because of its simplicity and lightweight construction.

The laser rangefinder is a time-of-flight sensor. When triggered, it transmits a short (1 ns) pulse of laser energy and measures the light travel time until it reflects off a target and returns to the sensor. This time is a direct measurement of the distance to the target. The rangefinder measures, within 2 centimeters, the range and intensity of reflection for targets up to 100 meters.

The motor is instrumented with an encoder to measure the mirror's angle. The encoder provides 2000 counts per rotation, yielding a 0.18 degree resolution. The laser is synchronized to fire only at each encoder pulse edge, thus increasing the accuracy of the scan angle.

The scanning mechanism is mounted underneath the helicopter fuselage so that the resulting scanning plane is perpendicular to the forward flight direction (Figure 4). With this configuration, the combination of the scanner's motion and the helicopter's forward motion provides coverage of the ground. This configuration for aerial scanning is referred to as across-track or whiskbroom scanning. [7]

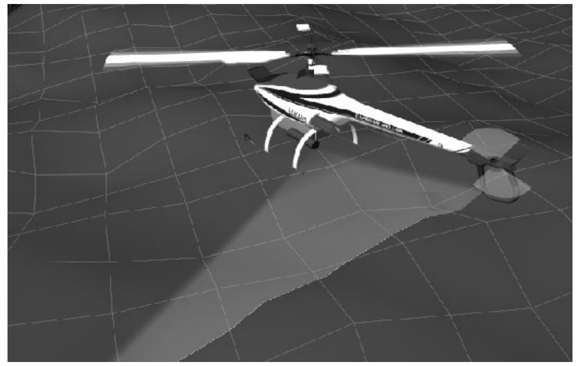


Figure 4. Aerial mapping with a planar scanner.

Note that, in this configuration, the laser is scanned through a full 360 degrees. Some of this time, the laser will be looking up at the sky, and not measuring anything of significance. Many other scanning mechanism designs could have avoided this problem, but we have chosen to accept this inefficiency in favor of the scanner's simplicity and lightweight construction.

The scanning system integrates a number of components already present on the autonomous helicopter. A block diagram of the main components of this integrated system is shown in Figure 5.

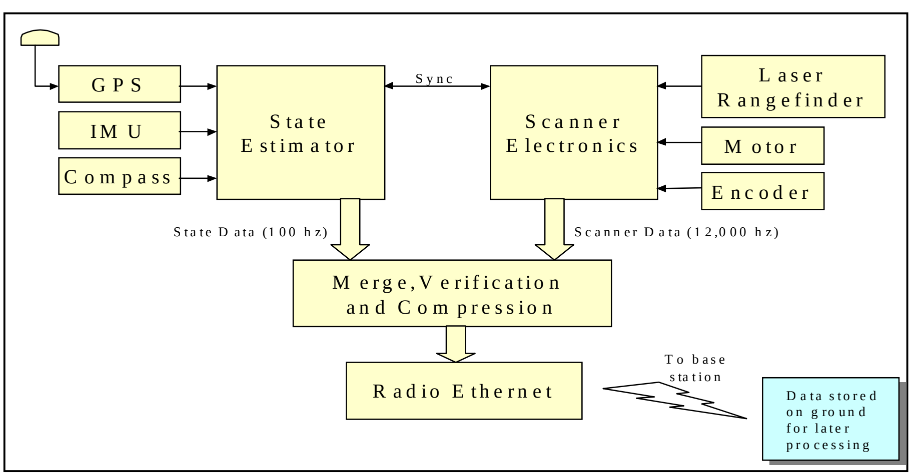


Figure 5. Block diagram of key components.

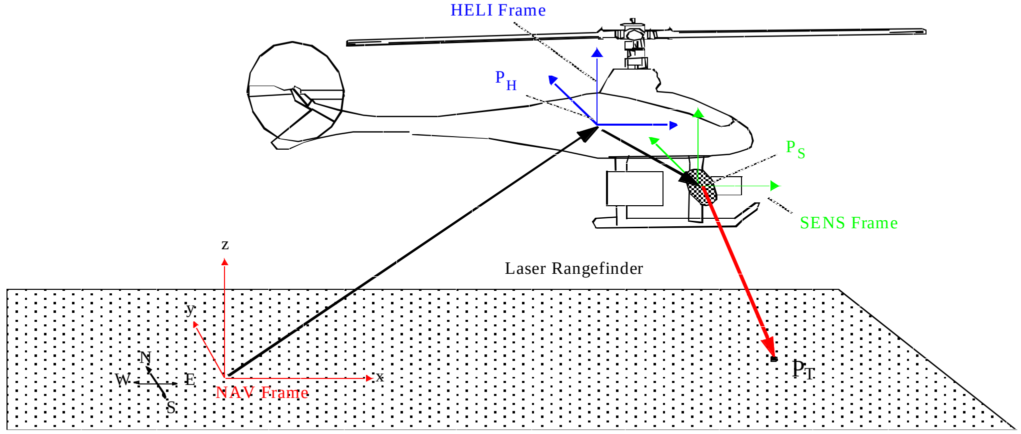
The key components and specifications of the system are shown in the following table.

Riegl LD-90 laser rangefinder	Range 2-100 meters. Accuracy: 2cm. 12,000 samples per second. 3 cm transmit aperture, 3 mrad beam divergence.
Scanning motor and encoder	Positions the scanning mirror within scan plane. 24 rotations per second (typical rate), 2000 counts per rotation encoder resolution.
Scanner Electronics	A custom electronics board controls the scanning process. Data is gathered from the encoder and laser rangefinder, and output at 12,000 Hz.
Novatel RT-2 GPS receiver	Dual-frequency, carrier phase differential system. Accuracy: 2 cm CEP. Four measurements per second. Uses dedicated radio link for differential correction.
Litton LN-100 Inertial Measurement Unit	Three fiber optic gyroscopes and three silicon accelerometers. 400 measurements per second.
KVH flux-gate compass	Measures magnetic north. 10 measurements per second
State Estimator	A custom processing module, which combines data from the GPS, IMU and compass using an extended Kalman filter. State estimates are output at 100 Hz.
Breezecom radio Ethernet	Primary link to base station. 3 Mbps bandwidth is sufficient to continuously download all scanner data in real-time for storage and later processing.

4.1.2 Measurement Process

In order to build accurate 3-D maps of the terrain, the Earth referenced 3-D location of each laser reflection must be determined. This measurement process is illustrated in Figure 6, and consists of three kinematic steps:

1) The laser scanner measures a distance and mirror angle to the target, determining the position of the target with respect to the laser scanner, ${}^{SENS}\mathbf{P}_T$.



$$ {}^{NAV}P_T = {}^{NAV}P_H + {}^{NAV}_{HELI}R \cdot {}^{HELI}P_S + {}^{NAV}_{HELI}R \cdot {}^{HELI}_{SENS}R \cdot {}^{SENS}P_T $$

GPS IMU Calibration Laser Scanner

Figure 6. Geometry of measurement process.

2) Previous calibration measurements provide the location of the laser scanner on the helicopter, determining the location of the target with respect to the helicopter itself, ${}^{HELI}\mathbf{P}_T$.

3) The onboard state estimator measures the location of the helicopter, determining the position of the target with respect to the Earth, ${}^{NAV}\mathbf{P}_T$.

5. Deployment

We prepared two autonomous helicopters, modified Yamaha R50s, for the mission. We reached the crater with the two helicopters on July 8th. We had surprisingly little difficulty transporting our crafts, support equipment, and crew of three people using one Twin-Otter aircraft. At the crater, helicopter flight conditions were overall fair considering the 20-30 knot winds. After our initial setup the first day and bad weather conditions the second day, we launched our first flight on the third day. We were pleased to discover that with the OmniStar antenna pointed South, the system provided useful corrections for localizing our base station. However, the two other difficulties we expected to face, heading alignment without reliable compass data and low GPS satellite elevation angles, were readily apparent. The helicopter's onboard compass, normally used to keep heading measurements from drifting, was not functional. We deployed an experimental multi-antenna GPS system (kindly lent to us by NovAtel) to help solve this problem. The system worked extremely well for ground alignment and we relied on angular rate sensors thereafter during flight. However, the crater posed a fundamental problem for the GPS-based positioning, a primary source of feedback for autonomous flight. As we had predicted, all GPS satellites were below 60 degrees elevation at the crater with most under 30 degrees, almost near the horizon. We found that most satellites were occluded by the surrounding hills and the remaining visible satellites were at times lost as the helicopter banked with each turn. We also encountered many situations with inconsistent GPS data, most likely due to reflected satellite signals from the hills and canyons surrounding the crater. The helicopter's guidance computer successfully flew the helicopter under computer control but was not fully dependable for safe out-of-sight flight. We relied on our ground safety pilot to remotely take over and fly the helicopter as necessary to proceed with our mapping mission.

The helicopter's laser mapping system proved perfectly operational in spite of marginal GPS coverage. The system monitored GPS satellite access and collected range data only during suitable GPS satellite configurations. The system built accurate 3D area maps by collecting time synchronized (within 1 μsec) laser, video, and vehicle state information at each site and merging this information after each flight.

We successfully mapped a number of breccia [1] hills for NASA geologists who were monitoring active layer detachment slides and slope changes of such areas. We also mapped small oases, which were of interest to NASA microbiologists.

5. Results

Following our data collection flights, the raw data logs, which had been stored to disk in the base station, were processed to generate 3-D models of the geographic features within the crater we had scanned.

Figure 7 illustrates the steps taken to process the raw data collected by the mapping system and generating a 3-D for one of the cliffs in the crater. Figure 7a is a photograph of the cliff. It is approximately 50 meters tall and we show mapping an area approximately 300 meters across. Figure 7b is a point cloud visualization of the data collected during

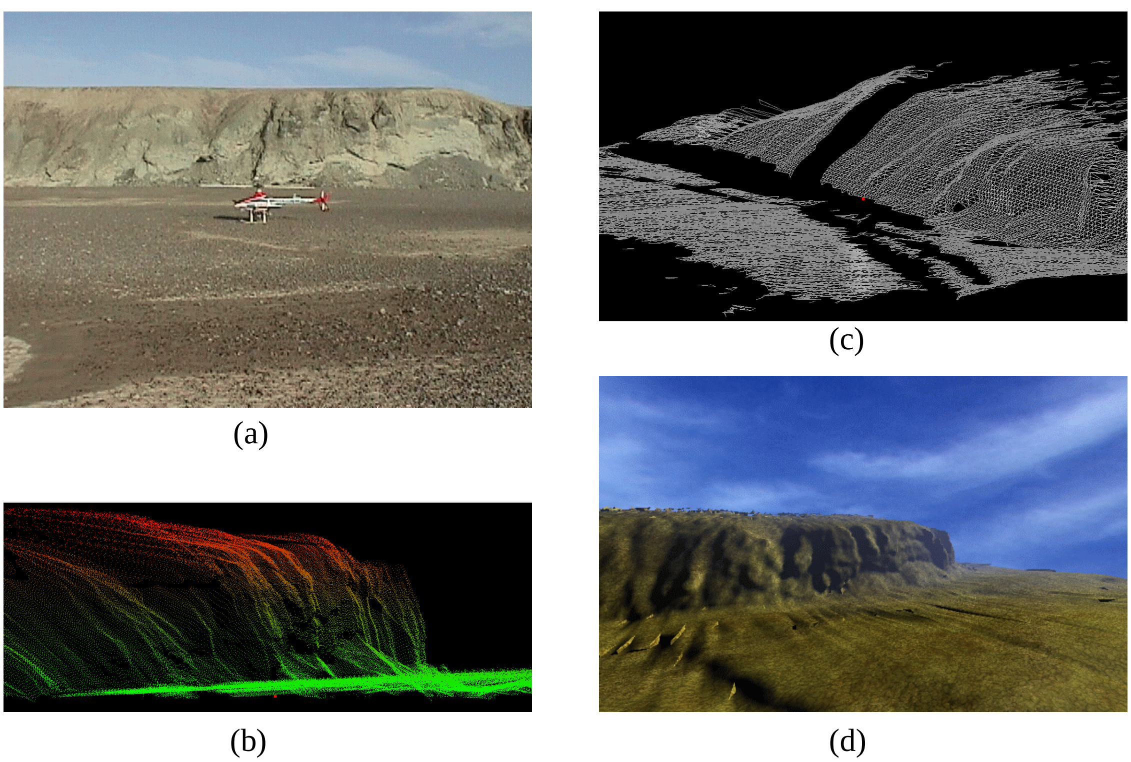


Figure 7. Example cliff mapping results

this flight, consisting of over one million 3-D data points sampled from the terrain during a single pass. Figure 7c is a triangular surface mesh generated from the point cloud by gridding a manually selected viewpoint and tessellating it. The number of points has been reduced (~40,000) and the surface connectivity generated. The missing data along the base of the cliff is the Haughton River, which does not provide usable laser reflectance to be measured. This surface mesh is the type of 3-D model needed for numerous terrain calculations, and also for generating realistic terrain features in virtual environments. Figure 7d is an example of a virtual world created by combining the surface mesh with various textures and rendering effects.

7. Discussion and Future Plans

Overall we have accomplished our primary goal of demonstrating the capabilities of an unmanned aircraft for accurate aerial mapping and site observation. We encountered situations that reaffirm our research philosophy of self-sufficient autonomous flight. It is not enough to rely on external resources, such as satellites or beacons, for critical flight controls in an airborne autonomous system. On-board sensing and controls alone must ensure the most basic stability and survival capabilities with external resources exploited when available.

We chose to deploy a sophisticated on-board mapping system, which could not incorporate our basic vision-based flight controls for this mission. Our basic approach was not only to exploit the GPS data for aerial mapping, but also to utilize it as a primary source of feedback for stable flight. We encountered many situations where GPS alone was not sufficient for safe flight. Clearly, a self-sufficient on-board positioning sensor, such as our visual odometer [5], would have filled in the void caused by intermittent GPS coverage. Vision is particularly well suited for this environment given the high contrast rugged crater terrain with rich visual cues, the absence of vegetation, and constant 24-hour daylight.

We plan to revisit the crater with our next generation helicopter system, which will augment GPS and inertial sensing with vision to eliminate the sensing gaps encountered in this mission.

8. References

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[5] O. Amidi, T. Kanade and R. Miller, "Vision-based Autonomous Helicopter Research at Carnegie Mellon Robotics Institute." *Proceedings of Heli Japan '98*. Gifu, Japan, April 1998.

[6] R. Miller and O. Amidi, "3-D Site Mapping with the CMU Autonomous Helicopter", *Proc. of 5th International Conference on Intelligent Autonomous Systems. (IAS-5)*, June 1998.

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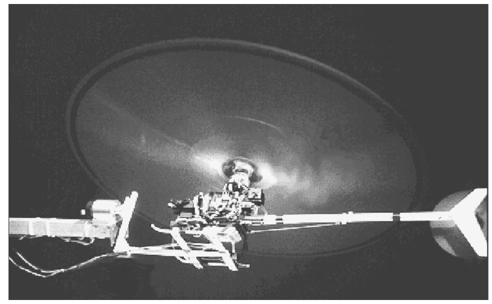
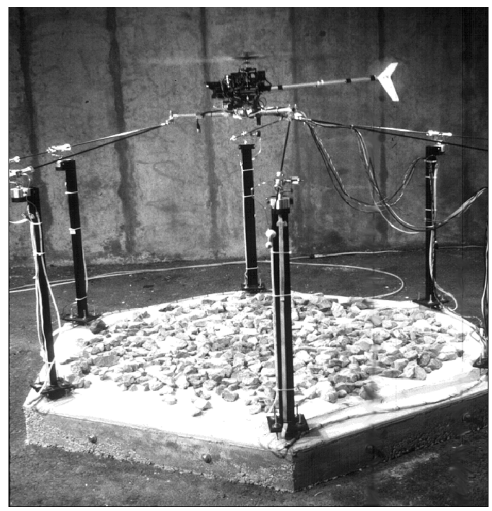
Appendix A: Carnegie Mellon Autonomous Helicopter Project History

September 1991: Initial attitude control experiments



- Developed to test and tune attitude control system. Electrical model helicopter mounted on a swiveling arm platform.
- Optical encoder mounted with frictionless bearing measures ground-truth angles in real-time.
- Configurable for roll, pitch, and yaw.

February 1992: Free flight and vision-based state estimator



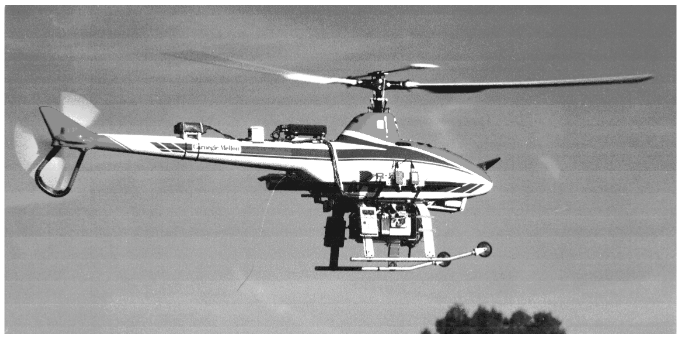
- Six-degree-of-freedom testbed developed for evaluating various position estimation and control systems.
- Electrical model helicopter attached to poles by graphite rods for safety and helicopter ground-truth position estimation.
- Lightweight composite material and custom-designed frictionless air bearings allow unobtrusive helicopter free flight in a cone shaped area.
- Mechanical stops prevent the helicopter from crashing or flying away.

September 1994: First autonomous platform

- Indoor testbed developed as a step toward autonomous operation.
- Used for testing the vision system, control/ sensor platform, power system, RF interference, and overall system integrity.
- Allows relatively large (1.5 meter) longitudinal travel. Severely limits helicopter travel laterally and vertically.
- Helicopter is tethered with ropes, which are fastened to the ground, and poles positioned on either side of the platform.
- Steel rod with hooks on either end connects the ropes to the helicopter. Steel rod is secured to the helicopter's center of gravity to eliminate any torque from restraining forces, which could cause dangerous rotations.

October 1995: Autonomous Helicopter #1

- Visual odometer (4 cm accuracy, 60Hz), tracks image patches and templates with helicopter motion.
- Initial computer control trials performed at relatively high (~15m) altitudes to allow safety pilot time to override computer.
- GPS used for ground-truth measurements.



August 1996: Autonomous Helicopter #2.

- Control system for autonomous takeoff, landing and smooth trajectory following.
- System tested in harsh conditions (40-45 mph wind gusts).
- State estimator fusing data from a dual-frequency carrier-phase GPS receiver, 3-axis angular rate and inertial sensors, and field-rate vision-based odometry.
- Custom-designed vision system capable of field-rate position sensing, multiple object tracking, color discrimination, and aerial intensity map building. Custom-designed camera stabilization system.
- 3D laser line scanner.
- Power system for up to 33 minutes autonomous operation.
- Winning entry in the 1997 International Aerial Robotics Competition.
- Deployed to map Haughton crater, Devon Island, Canadian Northwest Territories.