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VISION-BASED AUTONOMOUS HELICOPTER RESEARCH AT CARNEGIE MELLON ROBOTICS INSTITUTE
1991-1997

O. AMIDI, T. KANADE, and R. MILLER
CARNEGIE MELLON ROBOTICS INSTITUTE

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Vision-based Autonomous Helicopter Research at Carnegie Mellon Robotics Institute
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Omead Amidi Takeo Kanade Ryan Miller
Carnegie Mellon Robotics Institute
Pittsburgh, Pennsylvania U.S.A.

Abstract

This paper presents an overview of the Autonomous Helicopter Project at Carnegie Mellon Robotics Institute. The advantages of an autonomous vision-guided helicopter for a number of goal applications are enumerated through possible mission scenarios. The requirements of these applications are addressed by a central goal mission **for** the project. Current capabilities, including vision-based stability and control, autonomous take **off,** trajectory following, and landing, aerial mapping, and object recognition and manipulation are presented. In conclusion, the project future directions are discussed.

1. Introduction

Precise maneuverability of helicopters makes them useful for many critical tasks ranging from rescue and security to inspection and monitoring operations. Helicopters are indispensable air vehicles for finding and rescuing stranded individuals or transporting accident victims. Police departments use them to find and pursue criminals. Fire fighters use helicopters for precise delivery of fire extinguishing chemicals to forest fires. More and more electric power companies are using helicopters to inspect towers and transmission lines for corrosion and other defects and to subsequently make repairs. **All** of these applications demand dangerous close proximity flight patterns, risking human pilot safety. An unmanned autonomous helicopter will eliminate such risks and will increase the helicopter's effectiveness.

Typical missions of autonomous helicopters require flying at low speeds to follow a path or hovering near an object of interest. Such tasks demand accurate helicopter position estimation relative to particular objects or landmarks in the environment. In general, standard positioning equipment such as inertial navigation systems or global positioning receivers can not sense relative position with respect to particular objects. Effective execution of typical missions is only possible by on-board relative sensing and perception. Vision, in particular, is the richest source of feedback for this type of sensing.

At Carnegie Mellon Robotics Institute, we have been investigating the applicability of on-board vision for helicopter control and stability since 1991. Through an incremental and step-by-step approach, we have developed a number of vision-guided autonomous helicopters. We started our development by building a number of indoor testbeds for calibrated and safe experimentation with model helicopters. Using these testbeds, we developed and verified different system components individually before deploying them on-board free flying autonomous helicopters. Over the years, critical components have matured enough to form a framework for several autonomous systems currently in service. These systems can autonomously fly mid-sized (14 ft. long) helicopters using on-board vision, inertial sensing, global positioning, and range sensing. The latest system can autonomously take off, follow a prescribed trajectory, and land. In flight, the system can build aerial intensity and elevation maps of the environment, scan and locate objects of interest by using previously known appearance or color, and track the objects if necessary.

This paper presents an overview of the Autonomous Helicopter Project at Carnegie Mellon Robotics Institute. The paper discusses the project's goals, current status, and future plans.

2. Goals

Autonomous helicopters guided by on-board vision can carry out a wide range of useful tasks. In particular, the goal applications we focus on include: search and rescue, law enforcement, inspection, aerial mapping, and cinematography. Figures **1** and **2** show scenarios involving autonomous helicopters in these applications.

2.1 Goal Applications

Search** and **Rescue: A group of autonomous helicopters can collaborate to quickly and systematically search a very large area to locate victims of an accident or a natural disaster. They can then visually lock on to objects **or** stranded victims at the site to guide rescue forces to the scene. The helicopters can help focus the efforts of search and rescue crews on the rescue operation instead of the time consuming search operation. They can be more readily deployed in weather conditions which would normally prevent human piloted search and rescue. They can be sacrificed in very dangerous conditions **to** save human lives. Typical tasks may include flying close to a forest fire to look for stranded individuals, searching in contaminated areas, and identifying potential radioactive leaks after **a** nuclear reactor accident.

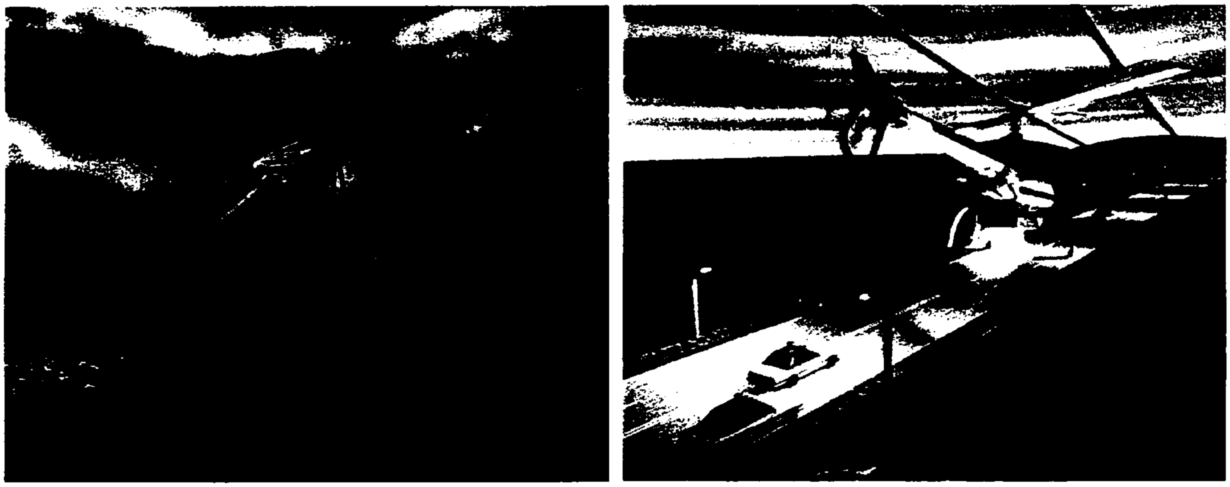

Figure 1. Rescue and crime fighting goal applications

Law Enforcement: Vision-guided robot helicopters can fly overhead to aid the police in dangerous high-speed chases or criminal search operations. Stationed on top of buildings in urban areas, they can be dispatched in seconds to take off and relay images from trouble spots. This real time imagery is crucial to the tactical assessment of the situation by human experts who dispatch police units to the area.

Inspection: Vision-guided robot helicopters can inspect high voltage electrical lines in remote locations. They can inspect large structures such as bridges and dams cost effectively. They can be quickly called upon to inspect buildings and roads for potential damage after an earthquake. They can locate hazardous materials in waste sites by providing aerial imagery to human experts or by automatically identifying waste containers or materials by on-board vision.

Aerial Mapping: Vision-guided robot helicopters can build more accurate topological maps than conventional aircraft at a substantial cost savings. Unlike airplanes, they can fly close to the ground while carrying cameras or range sensors to build high resolution **3D** maps. They can fly in smaller and more constrained areas to build highly detailed elevation maps.

Cinematography: Vision-guided robot helicopters can be a director's eye-in-the-sky camera. Because they can fly precisely under computer control, the need for skilled human pilots for aerial photography is eliminated. They can automatically track subjects with their on-board vision-based object trackers. They can fly a prescribed path over and over again to help plan shots or to aid in producing special effects.

Figure **2.** Inspection and cinematography goal applications

2.2 *Goal Mission*

We are pursuing a prototype ***goal mission*** which addresses the crucial technologies required by all of the above goal applications. This goal mission requires a robot helicopter to:

1. Automatically start operation and take off.
2. Fly to a designated area **on** a prescribed path while avoiding obstacles.
3. Search and locate objects of interest in the designated area.
4. Visually lock onto and track or, if necessary, pursue the objects.
5. Send back images to a ground station while tracking the objects.
6. Safely return home and land.

It is important to realize that accomplishing this goal mission is only the first step toward an ultimate goal of building reliable and useful intelligent aerial vehicles. Many important issues ranging from safety and fault tolerance to vision algorithm robustness require strict testing and evaluation in controlled environments before deployment of such vehicles in real life applications.

3 Capabilities

Over the past few years, we have been developing a number of basic capabilities to accomplish the project's goal mission. These capabilities include: vision-based stability and control; autonomous take off, trajectory following and landing; aerial mapping; and object recognition and manipulation. This section presents an overview of these capabilities.

3.2 Vision-based Stabilitv and Position Control

The most basic capability our goal mission requires is robust autonomous flight. A truly autonomous craft can not completely rely on external positioning devices such as GPS satellites or ground beacons for stability and guidance. Rather, the craft must sense and interact with its environment. We chose to experiment with on-board vision as the primary source of feedback for this interaction.

Our initial efforts toward vision-based flight has produced a "visual odometer" [1] which tracks helicopter position based on visual feedback. The odometer first determines the position of objects appearing in the camera field of view in relation to the helicopter, and thereafter tracks the objects visually to maintain an estimate of the helicopter's position. As the helicopter moves, older objects may leave the field of view, but new objects entering the scene are localized to continue tracking the helicopter position.

The odometer tracks objects by image template matching. Image templates are rectangular windows containing the objects of interest. Template matching between consecutive images provides lateral and longitudinal image displacement which may result from both helicopter translation and rotation. Template matching in two images, taken simultaneously by a pair of stereo cameras, measures helicopter range. The odometer estimates 3D helicopter motion by combining the lateral and longitudinal image displacements and range estimates with helicopter attitude, measured by on-board synchronized angular sensors.

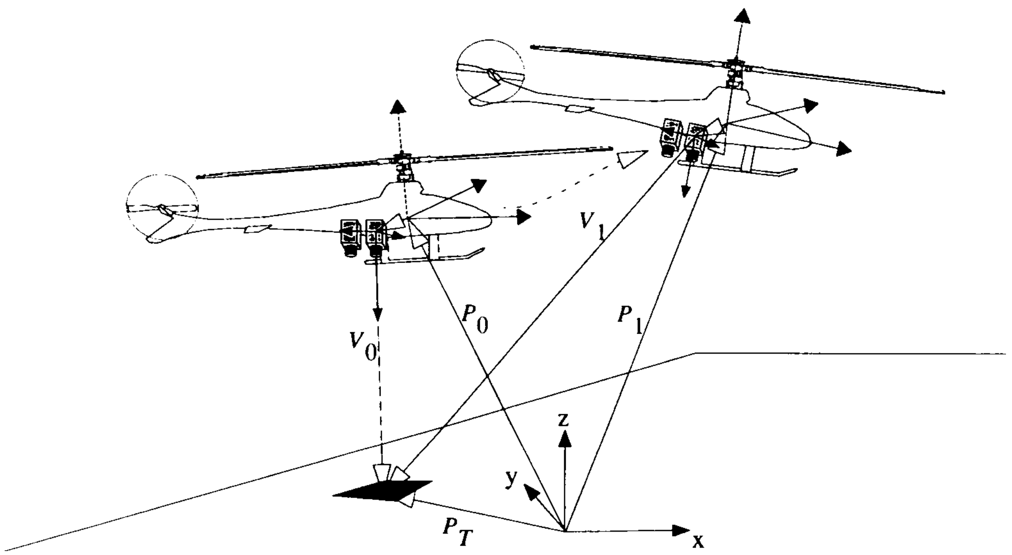

Figure 3. Visual Odometer positioning cycle

The visual odometer relies on a "target" template initially taken from the center of an on-board camera image. This process is shown in Figure 3. The **3D** location of the target template, P_T , is first determined by sensing the camera range vector, V_0 , at the image center given current helicopter position, P_0 , and attitude. Relying on the target template's sensed position, the odometer can estimate the helicopter position vector, P_1 , by visually locking on to the target template to estimate the new template vector, V_1 . In anticipation of losing the current target template, the odometer selects and localizes a new candidate target in every cycle to guarantee uninterrupted operation.

Because the target template will change in appearance as the helicopter rotates and changes its altitude, the odometer tracks pairs of target templates with a small baseline. Before matching templates, the odometer scales and rotates the target template pair using the magnitude and angle of the baseline from the previous match. The current implementation of the odometer tracks pairs of (32x32) pixel templates using a custom-made TI C44-based vision system. The system can support up to six C44s, each tracking one pair of templates at 60 **Hz** with 24 ms latency. Images are preprocessed by an 8x8 convolution **ASIC** (GEC Plessey) before matching. The current visual odometer, integrating a pair of b/w video cameras, a set of inexpensive angular sensors (Gyration gyro-engines and **KVH** digital compass), has been shown to successfully stabilize and maneuver (< 15 m.p.h.) small to mid-sized model RC helicopters. See Appendix for more details. Figure **4** shows the odometer's aerial view during autonomous flight over a grassy field. Figure 5 compares the odometer's positioning accuracy (solid) to ground truth (dashed) during indoor and outdoor helicopter flight.

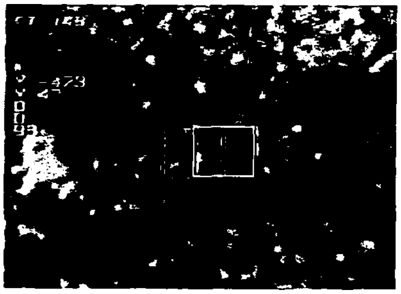

Figure 4. Odometer's view

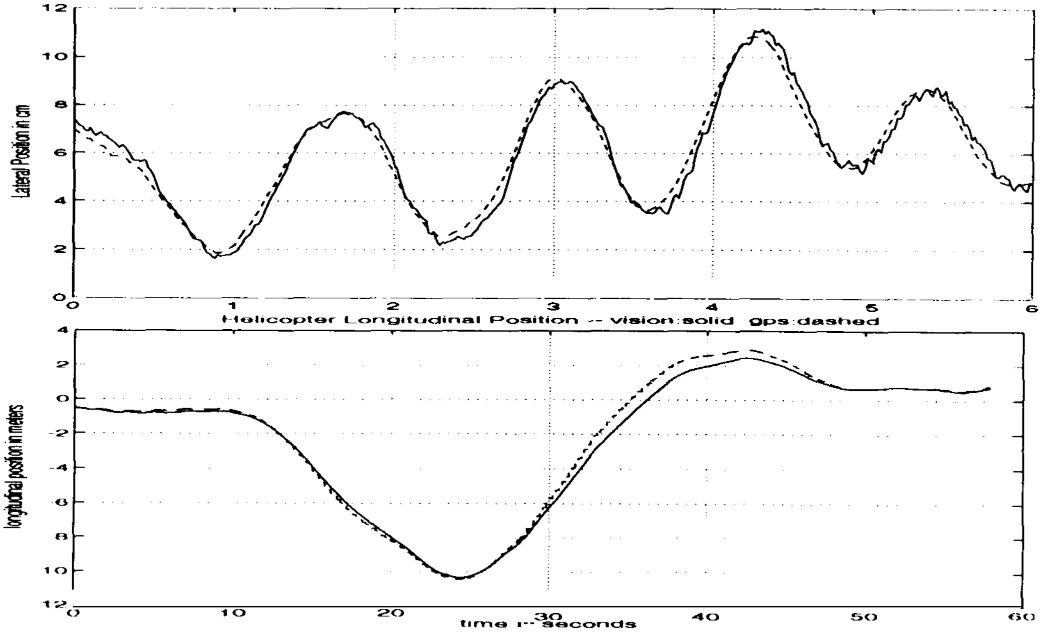

Figure 5. **Visual Odometer positioning accuracy indoor (top) and** outdoor (bottom)

3.2 Precise Autonomous Flight: Takeoff, Trajectory Following, and Landing

Our goal mission can not be accomplished without highly precise helicopter maneuvers. Precise helicopter maneuvering is a game of accurate force control. Inherently, vision alone can not provide the necessary feedback for this control mode. This is because vision can sense only the motion created by applied forces, not the forces themselves. It is impossible for a controller to completely eliminate undesired movements due to disturbances *after* they are sensed. Precise helicopter maneuvers such as take off, trajectory following, and landing require inertial sensing.

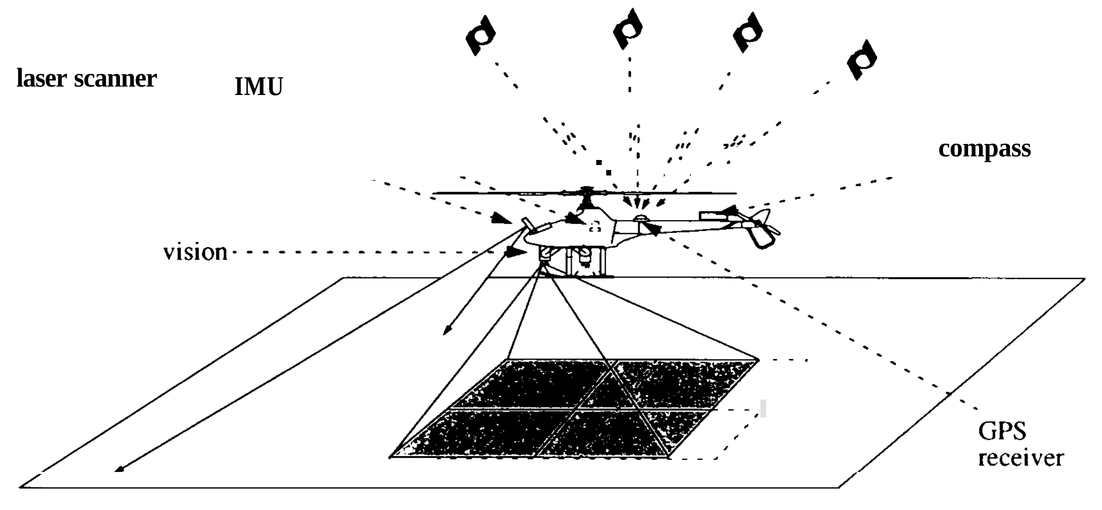

Figure 6. Integrated vision-based navigation

Combining vision with other low-level sensors such as accelerometers and range sensors can produce very robust autonomous navigation systems. A notable example is the work of Dickmanns [2] who applies an approach that exploits spatio-temporal models of objects in the world to control autonomous land and air vehicles. He has demonstrated autonomous position estimation for an aircraft in landing approach using a video camera, inertial gyros, and an air velocity meter.

We have begun following this approach by integrating an array of on-board sensors with vision to form a robust state estimator. The state estimator will ultimately fuse data from the visual odometer, an inertial measurement unit (IMU), a GPS receiver, a flux-gate compass, and a laser range finder (See Figure *6.)* These sensors form an integrated vision-based navigation system for our autonomous helicopters. The current state estimator integrates an IMU (Litton LN-200, 3-axis Silicon accelerometers, and angular rate sensors), a GPS receiver (NovAtel MillenRt2 dual-frequency camer-phase unit, 2 cm accuracy positioning using nearby (<20 miles) ground differential correction stations) and a digital compass (KVH Industries).

The systems employs lat-lon mechanization (See [3] for details) for inertial navigation. The data from the sensors is fused by a 12th order Kalman Filter which keeps track of latitude, longitude, height, 3-axis velocities, roll, pitch, yaw, and accelerometer biases (Gauss-Markov model).This data fusion is demonstrated in Figure 7. The jagged graph (marked by x) is GPS data, the solid line is ground truth, and the third (marked by +) is the Kalman filter output.

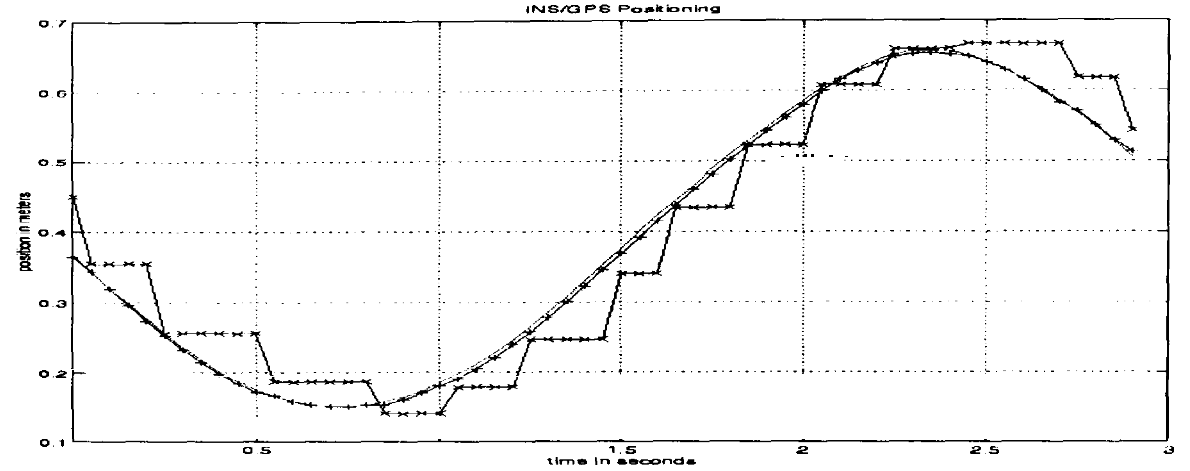

Figure 7. IMUIGPS fusion result

An on-board classical (feed-forward **PD)** controller controls the helicopter on smooth (cubic spline) trajectories planned by a flight path editor. As displayed in Figure **8,** the flight path editor's console shows the planned trajectory between goal points supplied by a human operator. The helicopter can be programmed to maintain its heading tangent to the path or to always orient itself toward a point in space. The console also displays **3D** range data collected by the mapping system (See Section **3.4)** to help in selecting goal points.

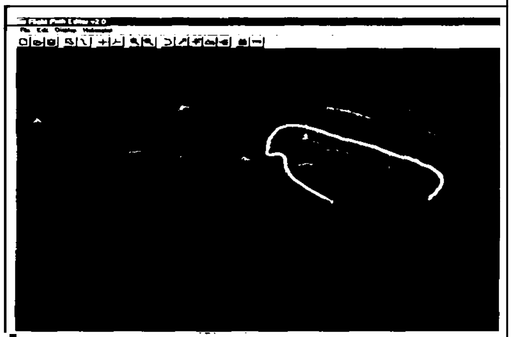

Figure 8. Flight path editor

3.4 Aerial Mapping

Our goal mission requires **3D** range sensing for autonomous obstacle detection and aerial mapping. In general, aerial vehicles are particularly well-suited for **3D** mapping for the following two main reasons:

- While carrying on-board active sensors, aerial vehicles can quickly and efficiently scan very large areas.
- The performance of active sensors such as laser rangefinders on-board aerial vehicles is superior to that of ground-based systems due to the fact that aerial sensors receive better signal returns than sensors on-board ground vehicles.

Our first prototype mapping system integrates a laser rangefinder (Reigl LD90), custom synchronization hardware, and our inertial state estimator on-board an autonomous helicopter. The system scans the environment line by line using a spinning mirror during helicopter flight. Each line, consisting of an array of range measurements, is tagged with helicopter state and is registered in memory to incrementally build a **3D** map. Figure **9** compares an aerial photograph with its corresponding **3D** elevation map built by the mapping system.

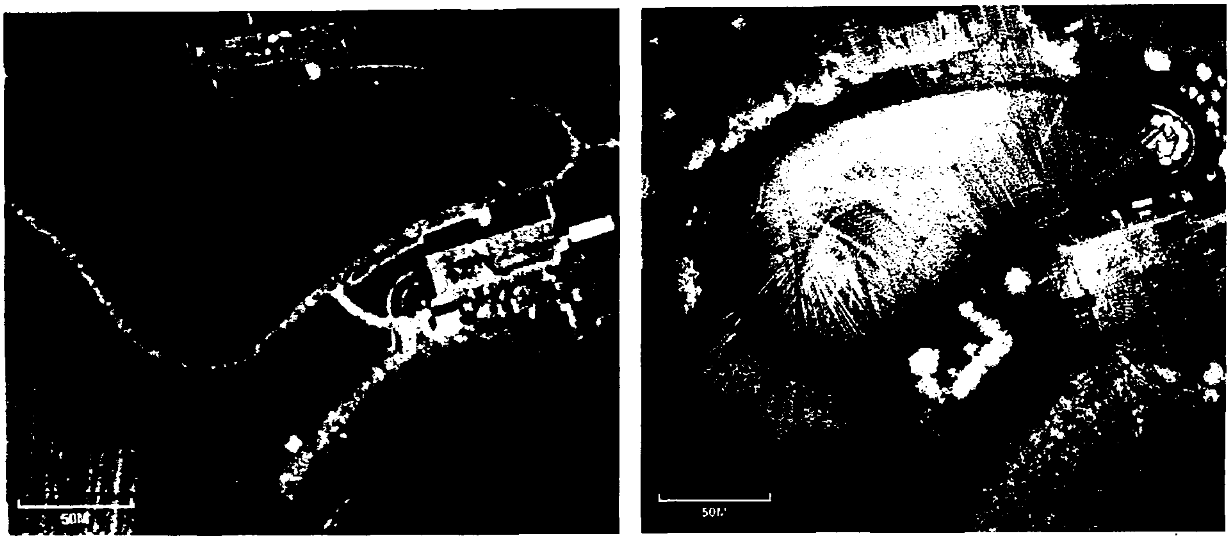

Figure 9. Aerial 3D elevation map

3.4 Object Recognition & Manipulation

Our goal mission requires detecting, tracking, and possibly manipulating objects during autonomous flight. Our current prototype systems can detect and track objects based on color and appearance.

The color-based detector is, in essence, a color discriminator. Built by high-speed digitally controllable analog hardware, the discriminator can be configured at NTSC field rate (60 Hz) to look for as many RGB color combination as necessary in sequential image fields. The discriminator normalizes RGB intensity levels to eliminate the effects of lighting, determines the difference between each pixel color from the target color, and penalizes each pixel based on this distance. Most recently, for the 1997 Unmanned Aerial Robotics Competition [4], the discriminator was used to pick up an orange disk from a barrel on the ground. The image sequence below, taken prior to the contest, displays a successful pickup attempt. The pickup system tracked a blue magnet and aligned it with the orange disk as the helicopter descended to the estimated range to the disk. (Helicopter range to the disk was measured by triangulation.)

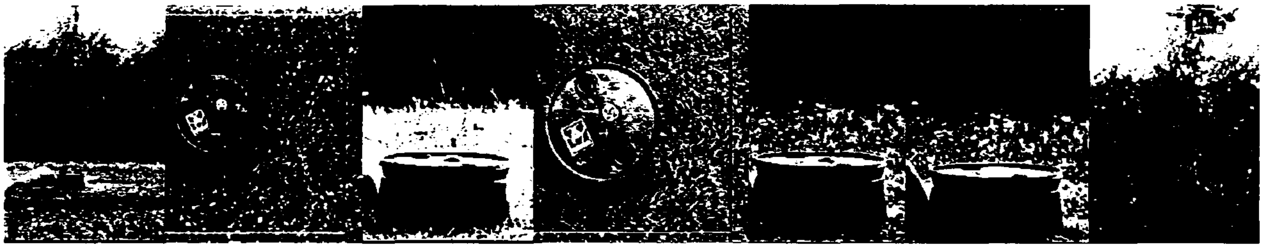

Figure 10. Autonomous vision-based object pickup

The template-based detector locates objects based on appearance. To find a potential match, the detector locates image regions which resemble a picture of the object. Because searching every image for a the object's picture or template in any orientation requires enormous computational power, the detector exploits principal component methods to reduce its work load. The detector employs Karhunen-Loeve [5] expansion to reduce computational complexity and storage of necessary templates. Rotated template images differ slightly from each other and are highly correlated. Therefore, the image vector subspace required for their effective representation can be defined by a small number of eigenvectors or eigenimages. The eigenimages which best account for the distribution of image template vectors can be derived by Karhunen-Loeve expansion [6].

The detector has been used to carry out a number of tasks. Most notable is the successful identification of all warning barrel labels for the 1997 Unmanned Aerial Competition. The detector successfully identified the location, orientation, and type of three different labels. A picture of each label was supplied to the detector **prior** to flight. Figure 11 shows the these labels. They are typically affixed on radioactive, biological hazard, and explosive containers.

Figure 11. Hazard labels

Figure 12 compares *25* radioactive hazard symbol templates, rotated at 15 degree intervals, to the 8 principal templates used by the detector for matching. In the competition trials, the 8 principal templates never failed to detect the radioactive hazard label, provided the helicopter height was kept close to (within 1 meter) the target camera range when the original template was recorded.

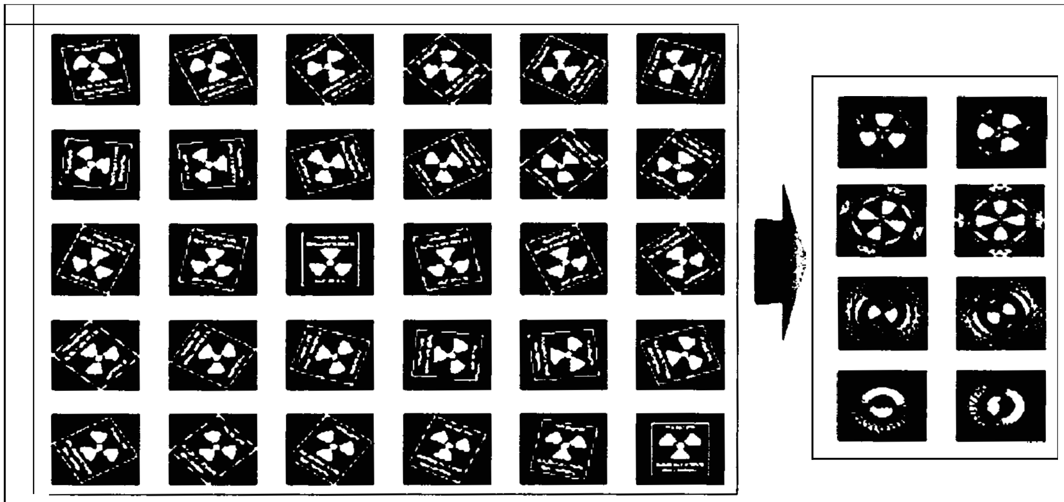

Figure 12. Principal component analysis

Future Work

The current prototype flight systems have demonstrated the potential of vision-based autonomous flight. Current prototype systems have shown useful capabilities such as autonomous take off, trajectory following and landing, aerial mapping, and object recognition and tracking. These capabilities form the building blocks of future research on aerial robots.

We plan to continue this research by improving the current template-based positioning strategy as well as by developing new optical flow-based systems for flight. The list of current activities include: texture analysis to automatically locate and select high contrast image areas for the target template to improve the current visual odometer performance; fusion of optical flow estimates in the Kalman filter with inertial and global positioning data for more robust position estimation; development of high resolution laser scanners to detect overhead electrical lines; and system identification to model helicopter dynamics.

References

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[2] E. Dickmanns. A General Dynamic Vision Architecture for UGV and UAV. *Journal of* ***Applied Intelligence,*** 2:251–270, 1992.

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[5] **S.** Yoshimura and T. Kanade. Fast template matching based on the normalized correlation by using multiresolution eigenimages. In ***IEEE/RSJ International Conference on Intelligent Robotics and Systems,*** Munich, Germany, August 1994.

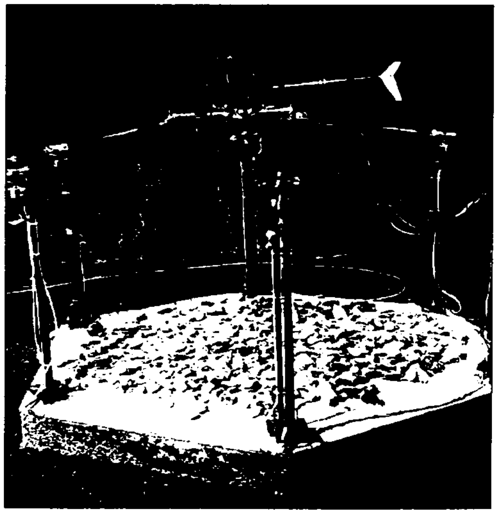
[6] **M.** Uenohara and **T.** Kanade. Vision-based object registration for real-time image overlay. In ***Computer Vision, Virtual Reality and Robotics in Medicine. First International Conference, CVR Med'95; Nice, France,*** Nice, France, April 1995.

Appendix: Carnegie Mellon Autonomous Helicopter Project History

September 1991: Initial attitude control experiments

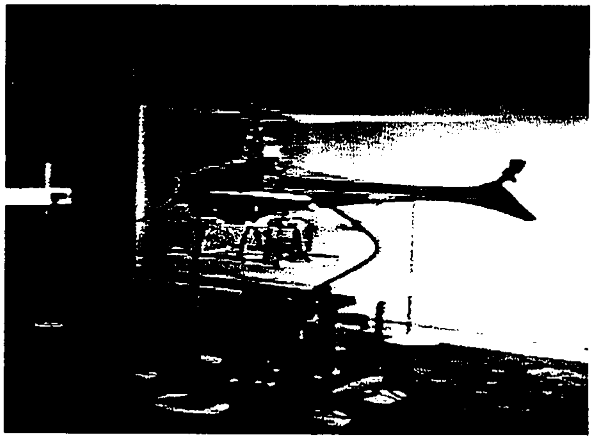
- Developed to test and tune attitude control system. Electrical model helicopter mounted on a swiveling arm platform.
- Optical encoder mounted with a frictionless bearing measures ground-truth angles in real-time.
- Configurable for roll, pitch, and yaw.

February 1992: Free flight and vision-based state estimator



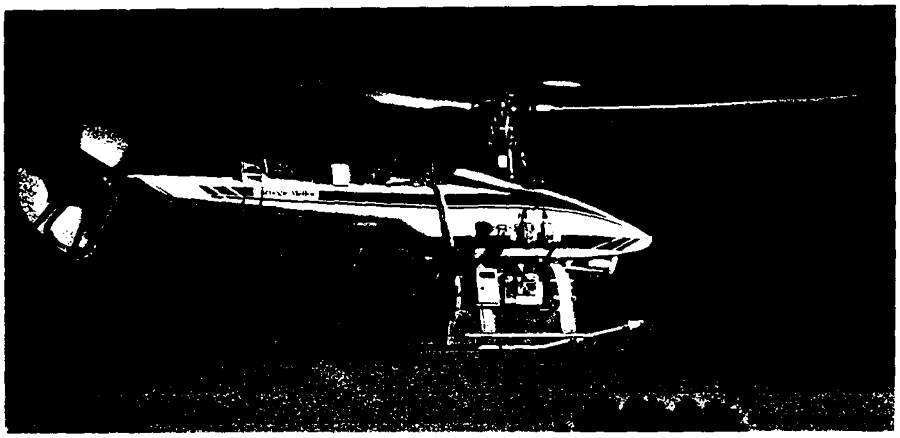
- Six-degree-of-freedom testbed developed for evaluating various position estimation and control systems.
- Electrical model helicopter attached to poles by graphite rods for safety and helicopter ground-truth position estimation.
- Lightweight composite material and custom-designed frictionless air 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 an 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 torques 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.
- Latitudinal and longitudinal controls were first tested by mixing human control for height and heading with the computer commands.
- 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 m.p.h. 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.