3-D Site Mapping with the CMU Autonomous Helicopter

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Abstract

This paper describes a scanning laser rangefinder developed for integration with the Carnegie Mellon University autonomous helicopter. The combination of an unmanned, autonomous helicopter with a 3-D scanning laser rangefinder has many potential applications; such as terrain modeling or structure inspection. To achieve high accuracy (10 cm) in each 3-D measurement, careful attention must be paid to minimizing errors, in particular, errors in measuring the direction of the laser's beam. This paper discusses our approach to minimize these errors. Results are presented from early test flights.

1.0 Introduction

This paper describes a scanning laser rangefinder developed for integration with the Carnegie Mellon University (CMU) autonomous helicopter. The combination of an autonomous, unmanned helicopter with a highly-accurate 3-D perception system has the potential for use in a variety of applications, and provides a platform for further research and development.

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 uses synthetic aperture radar to build digital elevation maps of very large regions. [1] Optech Inc. has flown scanning laser rangefinders aboard manned helicopters to map the ocean floor. [2] Many ground vehicles also have utilized laser scanners to scan the regions in front of the vehicle.

The systems using aerial vehicles have historically concentrated on generating coarse maps of very large areas. For example, the Lockheed Martin DTEMS is attempting to map the entire U.S. with 3m spacing. In contrast, the ground vehicles can provide highly dense and highly accurate maps, but only of the limited areas which they can access. Additionally, ground vehicles usually must use much more complicated 2-DOF scanning mechanisms which allow an entire area to be imaged. Our interest is in utilizing the advantages of the autonomous helicopter of being precisely controllable and its ability to safely fly within close proximity to objects of interest while generating highly dense and highly accurate 3-D models of these objects in possibly remote locations.

The CMU autonomous helicopter is a mid-sized, unmanned helicopter capable of fully autonomous takeoff, flight path tracking, accurate ($<$ 20 cm) stationary hover, and landing. [3] These basic capabilities allow the autonomous helicopter to be used as a highly maneuverable sensing platform; allowing access to remote and confined locations without putting human pilots at risk.

To realize these capabilities and experiment with their possibilities, we have developed a

planar laser scanner which can be mounted on the CMU autonomous helicopter and integrates with its flight control systems. The integrated system provides 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 10 cm of their actual position in space.

Achieving this level of accuracy is difficult from a mid-sized helicopter. The helicopter has a limited payload capacity, limiting the types of sensors which can be used. The helicopter is also highly dynamic in nature. Careful attention must be paid in designing the scanning system to minimizing errors, particularly those which affect the computed direction of the laser beam.

The remainder of this paper describes the scanning system in detail, outlines our approach to minimizing errors and presents preliminary mapping results.

2.0 The Scanning System

We choose to build a single DOF laser scanner as shown in Figure 1. A motor spins an aluminum coated mirror which is mounted at 45 degree in front of a laser rangefinder. As the motor rotates through an entire cycle, the laser is redirected to scan out a plane perpendicular to the motor's axis of rotation. This mechanism is desirable because of its simplicity and light weight construction.
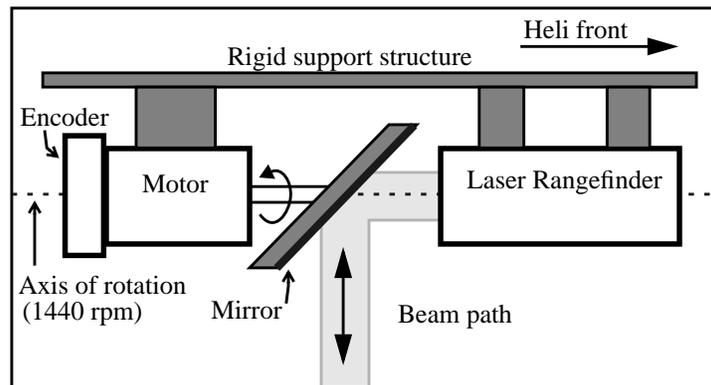

Figure 1 - Configuration of a single DOF, planar laser scanner.

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

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 the encoder pulse edge, thus increasing the accuracy of the scan angle.

The scanning mechanism is mounted underneath the helicopter fuselage so the resulting scanning plane is perpendicular to the forward flight direction. (Figure 2.) 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 not new, and is referred to as across-track or whiskbroom scanning. [4]
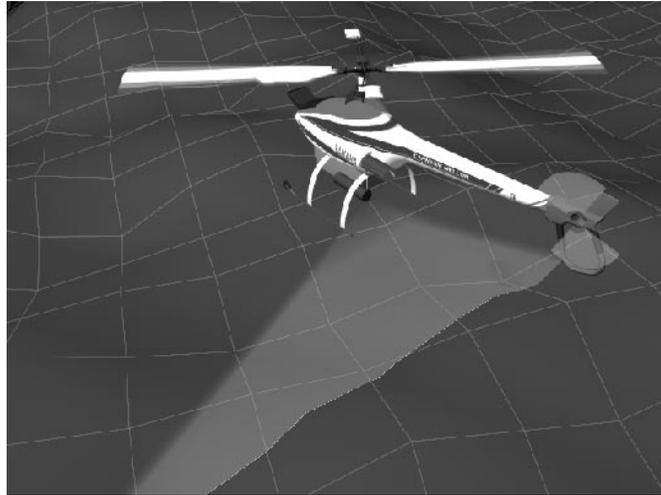
Figure 2 - Aerial mapping with a single planar scanner.

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 its much simpler and lighter mechanism.

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 3.
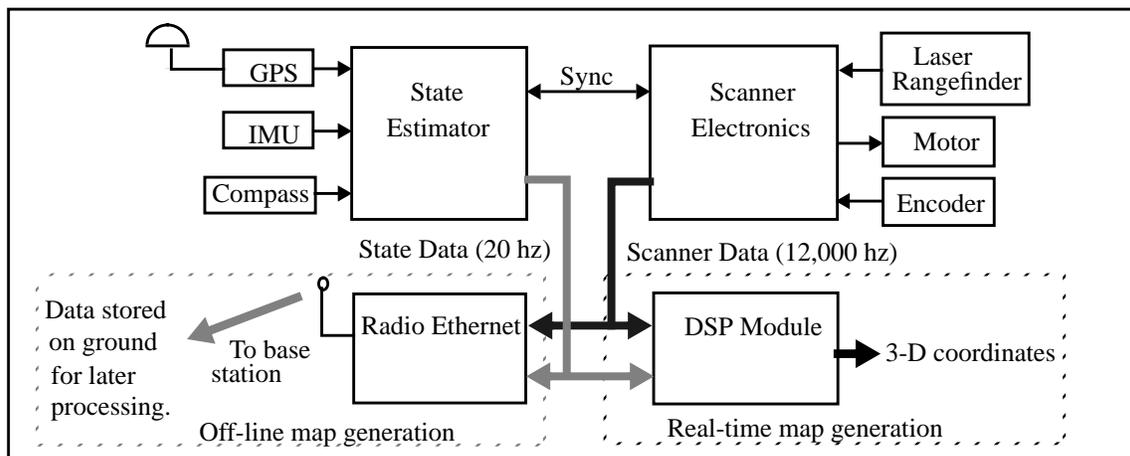

Figure 3 - Block diagram of key components of scanning system.

The key components of the system are:
- 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/encoder - Positions the scanning mirror within scan plane. 24 rotations per second typical rate, 2000 counts per rotation encoder resolution.

- Scanning 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. 4 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 20 hz.

- TI 'C44 DSP processors - Provide real-time calculation and filtering of scanner data. (Not presently used.)

- Aironet radio ethernet - Primary link to base station. 1 Mbps bandwidth is sufficient to continuously download all scanner data in real-time for storage and later processing.

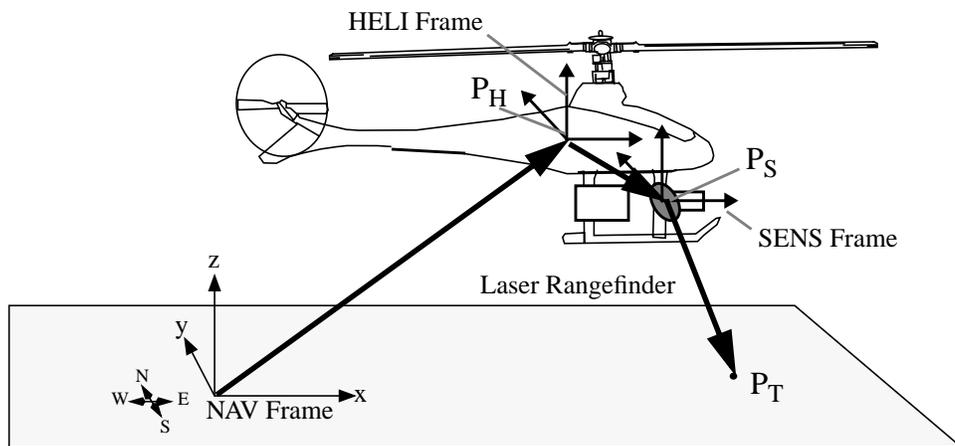## 3.0 The Measurement Process

Figure 4 - The geometry of the measurement process.

The goal of the measurement process is to convert laser measurements of a target point into 3-D coordinates in an Earth fixed reference frame, $^{NAV}P_T$. The following steps describe the kinematic calculations required to locate the coordinates: (refer to Figure 4.)

1) The state estimator provides the position and attitude of the helicopter. The position of the HELI frame (located at the helicopter's center of gravity) in an Earth-fixed NAV coordinate system is $^{NAV}P_H$. The attitude data is used to calculate $^{NAV}_{HELI}R$, a 3x3 rotation matrix used to transform points from the HELI frame to the NAV frame.

2) A rigid transform (translation and rotation) is required to locate the SENS (sensor frame) from the HELI frame. The plane in which the laser scans defines the Y-Z plane of the SENS frame. Additionally, the Z axis of the SENS frame is coincident with the laser path when the mirror is at its 0 degree position. The translational and rotational offsets, $^{HELI}P_S$ and $^{HELI}_{SENS}R$ are constant and were determined through calibration.

3) The scan angle, θ_S, is measured by the encoder on the spinning mirror, and the distance to the target, r_S is measured by the laser rangefinder. The coordinates of the tar-

get point in the SENS frame are: $^{SENS}P_T = \begin{bmatrix} 0 \\ -r_S \sin\theta_S \\ r_S \cos\theta_S \end{bmatrix}$

4) Using these definitions, the coordinate of the target in the NAV frame can be computed: $^{NAV}P_T = {}^{NAV}P_H + {}^{NAV}_{HELI}R \cdot {}^{HELI}P_S + {}^{NAV}_{HELI}R \cdot {}^{HELI}_{SENS}R \cdot {}^{SENS}P_T$

This configuration provides all of the information needed to recover the 3-D structure of scanned surfaces. Unfortunately, errors affect each step of the measurement process and corrupt the final 3-D maps. Reducing these errors is critical for achieving highly accurate results.

4.0 Errors

A brief look at the sensitivity of the measurement process shows that our system needs to be most concerned with errors which affect the expected direction of the laser beam. The basic argument follows that for small errors in GPS position ($^{NAV}P_H$), sensor translation ($^{HELI}P_S$), or laser range measurement (r_S), the result is an equally small error in target position ($^{NAV}P_T$). On the other hand, a 1 degree angular error in attitude estimation ($^{NAV}_{HELI}R$), sensor orientation ($^{HELI}_{SENS}R$), or mirror angle (θ_S) produces an equally large error in the expected direction of the laser beam, resulting in an error of more than a meter in $^{NAV}P_T$ at 60 m range. This motivates the attempt to remove as many sources of angular error as possible.

There are two fundamental sources of angular error in our system: errors due to incorrect scanning geometry, and errors due to unmodeled helicopter motion. The first source is reduced by careful calibration, and the second is reduced by synchronizing the various data sources and interpolating between measurements.

4.1 Calibration

Our calibration procedure uses the difference between the measured position of a target and its known position to determine the calibration parameters. Using this technique with large distances between the helicopter and target allow the angular parameters to be determined with high accuracy.

Initially, we calibrated each of the component in our system individually to remove systematic errors such as biases and scaling errors. Likewise, the transformation between the HELI frame and SENS frame was determined "in the lab" using various measurement instruments.

As discussed earlier, our system is very sensitive to angular errors. To further reduce these errors a calibration of the system as a whole was performed. This compensates for the combined effect of many unmodeled errors in the system.

We use a special retroreflective target placed at a known location for calibration. The helicopter scans the target from many different locations, orientations, and ranges. It generates a set of data corresponding to the laser hitting the same actual point in the world. Using this data, an iterative method is used to refine the $^{HELI}_{SENS}R$ rotation matrix for reducing the measurement errors.

For each measurement of the target, the $^{HELI}_{SENS}R$ matrix is adjusted to reduce the distance

between the actual target position and the calculated target position. The procedure is as follows:

1) Given the known target position in the NAV frame, $^{NAV}P_A$, we compute the coordinates of the actual target and of the measured target in the sensor frame as:

$$^{SENS}P_T = \begin{bmatrix} 0 \\ -r_S \sin\theta_S \\ r_S \cos\theta_S \end{bmatrix}$$

$$^{SENS}P_A = \left(^{HELI}_{SENS}R\right)^T \left(^{NAV}_{HELI}R\right)^T \left(^{NAV}P_A - {}^{NAV}P_H - \left(^{NAV}_{HELI}R \cdot {}^{HELI}P_S\right)\right)$$

2) The difference between these coordinates is the error which we want to minimize. Minimization could be achieved by rotating the measured position around the perpendicular axis: $v = {}^{SENS}P_T \times {}^{SENS}P_A$

by the angle: $\theta = \text{asin}\left(\dfrac{\left\|^{SENS}P_T \times {}^{SENS}P_A\right\|}{\left\|^{SENS}P_T\right\|\left\|^{SENS}P_A\right\|}\right)$

3) We apply a small portion of this correction to the $^{HELI}_{SENS}R$ parameter:

$$^{HELI}_{SENS}R_{n+1} = {}^{HELI}_{SENS}R_n \cdot R_v(\eta\theta)^1.$$

where η is a small constant. This reduces the error for this single measurement.

This process is repeated until the average error over all of the measurements is no longer reduced by subsequent iterations. This iterative refinement is similar to gradient descent [5] in that each measurement applies only a small correction, but after many iterations, the $^{HELI}_{SENS}R$ matrix adjusts to a compromised value which typically minimizes the error over all of the measurements.

Calibration is effective to reduce the errors due to the static geometric errors in our system.

4.2 Synchronization and Interpolation

A helicopter is an inherently unstable platform. It must make quick attitude changes to reject disturbances, such as wind. Since the scanning system is rigidly attached to the helicopter, these attitude changes must be measured precisely to achieve proper reconstruction of the 3-D scene.

There are two primary streams of data: helicopter state data (arriving at 20 hz), and laser scanner data (arriving at 12,000 hz). The manner in which they are merged has a significant effect on how the helicopter motion affects the resulting 3-D map.

The state estimator and scanning systems have been designed to precisely synchronize these data streams. The state estimator's electronics generates synchronized triggering pulses for the GPS, compass and IMU. In this manner, the state estimator knows the exact time at which each measurement is made, allowing better tracking of highly dynamic maneuvers. The scanning system synchronizes its data with the state data by monitoring these triggering pulses and "tagging" the laser measurement which occurs at the trigger time. These tags allow the state measurements to be aligned properly with the scanner mea-

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1. $R_v(\eta\theta)$ is the rotation matrix equivalent to rotating by $\eta\theta$ about axis v.

surements.

Having synchronized the data streams, the system knows the precise state of the helicopter at every 600th laser measurement (20 hz). From this, we must determine the state of the helicopter at each of the other 599 measurements in between. A simple sample-and-hold strategy proves insufficient, as by the 599th measurement, the state is 1/20th of a second old. Previous flight recordings show that the attitude of the helicopter can change by more than a degree in this short time period, resulting in an error of more than a meter in 3-D position. To improve this situation, we interpolate between consecutive attitude measurements.

5.0 Results

As a test of the scanning system, we mapped one of our flight testing fields. The site is approximately 300m x 300m, and has an asphalt road surrounding an open field with two large buildings and trees surrounding the area. Our test pilot manually flew the helicopter about 10 meters above the road as the system scanned the surrounding environment.

The resulting 3-D data are shown in Figure 5. The collected data consists of over 2.5 million 3-D data points. Figure 5a shows a point cloud visualization of the site. For display purposes, each point is shaded based on a combination of elevation, and on return intensity of the laser. As such, the road is readily visible. It should also be noted that since the helicopter was flown above the road, the low density of measurements from the center of the field is expected. Figure 5b shows a smaller portion of the dataset viewed from above.
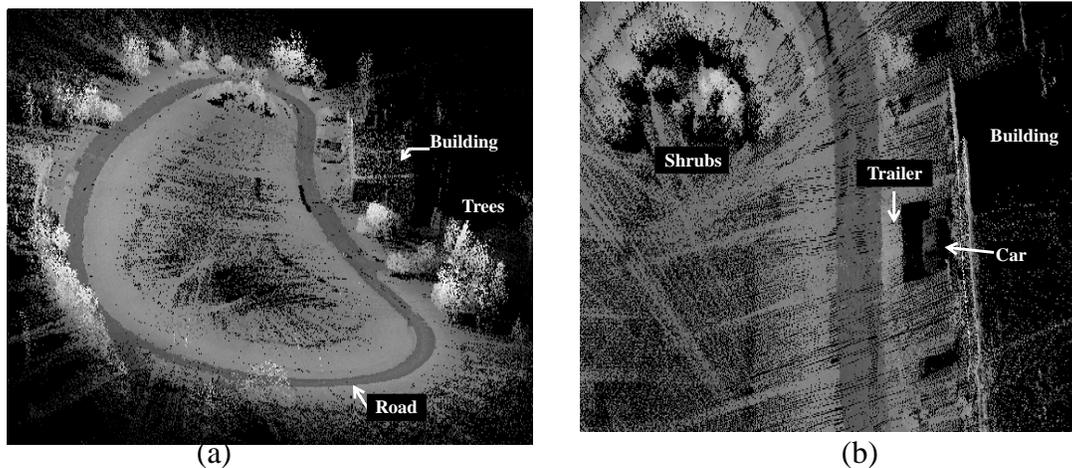

(a)   (b)

Figure 5 - (a) Perspective view of 3-D point cloud from test scan. (b) Downlooking view of smaller area.

Figure 6a shows an aerial photograph of the test site. The image is geo-registered, such that the latitude and longitude of the four corners are known, and each pixel is exactly 0.5m wide. This provides an independently established ground truth with which we can compare our scanning system and improve the mapping process.

Figure 6b shows a digital elevation map (DEM) generated from the scan data collected during our test flight. The DEM has been generated such that the location of the four corners are the same as the aerial photo, and each pixel is also 0.5m in width. The intensity of each pixel indicates the average elevation measured for that location.

A pixelwise comparison of these two images shows that the DEM closely matches the aerial photograph. This is an indication that the mapping system is producing reasonable

results, and encourages future work to precisely identify the accuracy attainable by this system.
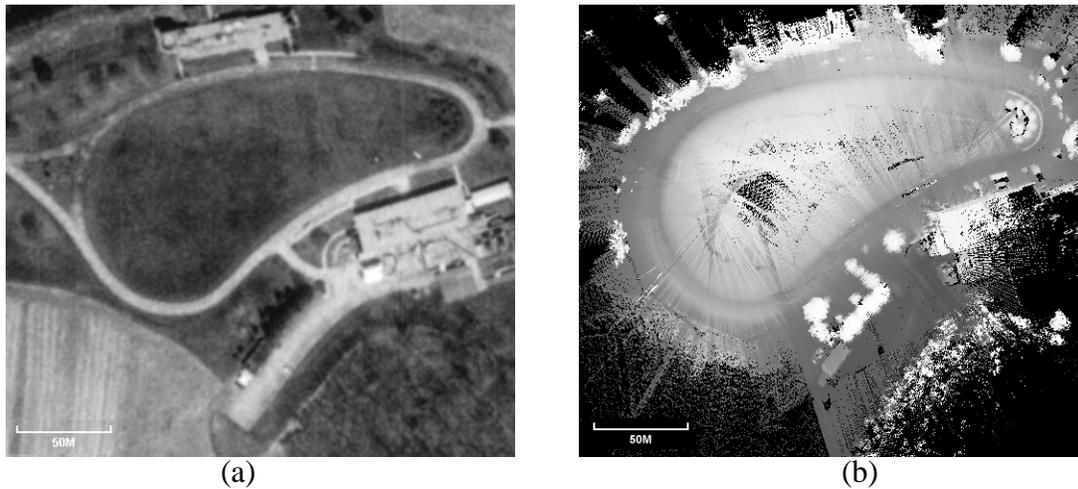

Figure 6 - (a) Aerial photograph of test site. (b) Corresponding digital elevation map.

6.0 Conclusions

In this paper, we presented an integrated laser scanning system for an autonomous helicopter. The combination of a highly maneuverable, unmanned helicopter with a highly accurate 3-D scanning system has the potential for use in many applications. We have built a prototype system and demonstrated its ability to generate reasonably accurate maps (better than 50cm) maps of large areas.

We are encouraged by these initial results. Future work includes a careful study of the present system to determine its actual accuracy, and better techniques for generating DEM's from the point cloud data.

7.0 References

[1] H. A. Malliot, "Digital Terrain Elevation Mapping System." *IEEE Aerospace Applications Conference*, 1996.

[2] Banic, Sizorics, O'neal "Scanning lidar bathymeter for water depth measurement." *Proceedings of the SPIE*, Vol 663(A26), 1986. pp 187-95.

[3] 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.

[4] A. Samberg, "Mathematical model for time-varying system employing across-track scanning." *Proceedings of the SPIE*, Vol 3065, 1997. pp 214-23.

[5] *Numerical Recipes in C.* Cambridge University Press. 1988.