PROGRESS IN MINI-HELICOPTER TRACKING WITH A 3D LASER RANGE-FINDER

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Abstract: This paper approaches detection and tracking of an aero-modelling helicopter with a laser range-finder. The sensing device can complement vision for aerial vehicle control in operations such as landing or taking off from the ground. To this end, a conventional 2D laser scanner has been adapted for 3D operation by means of a motorized base. First experimental results are presented for a small-scale four-rotor remote-controlled helicopter.

Keywords: Helicopter control, range finders, target tracking, position estimation, remote control.

1. INTRODUCTION

Unmanned aerial vehicles (UAVs) can significantly weigh and cost less than human-driven aircrafts, while eliminating pilots in risky situations. Recent technological advances have promoted the employment of aero-modelling-like vehicles as small-scale mobile robots (Amidi, 1996). Thus, they are increasingly being incorporated into applications such as disaster response, urban search, exploration missions, or in combination with another mobile robots.

Among UAVs, helicopters are particularly useful because of their maneuverability regarding hovering and vertical motion for landing and take-off. Nevertheless, helicopter flight control implies dealing with a nonlinear unstable system characterized by fast dynamics. Therefore, reliable perception becomes a critical issue in order to close the control loop, since a fault may easily result in crashing (Heredia *et al.*, 2004).

In general, the limited payload of this kind of miniature vehicles severely restricts the amount of perception and control computation that can be carried out onboard (Roberts *et al.*, 2003). Thus, remote sensors on the ground can provide an extra aid for pose estimation (position and attitude), for autonomous flight control, and especially for landing and take-off.

Several types of sensors can be considered. Proprioceptive sensors can include inclinometers and magnetic compasses, which are slow for aerial robots, and inertial sensors (i.e., gyroscopes and accelerometers) which are very useful to quickly stabilize the vehicle but inevitably accumulate errors during navigation.

Differential Global Positioning Systems (DGPS) can provide suitable position estimations (Harbick *et al.*, 2001) but they imply embedding an antenna and a receptor in the UAV, they are not useful in indoor environments, and a fixed base with a transmitter is required to generate differential corrections.

Light onboard camera devices as well as external remote cameras are easily available (Altug *et al.*, 2003), but their sensing capacities are limited: they present the problem of unstructured light conditions and a limited field-of-view. Hence, it seems that work on additional on-the-ground sensors would be desirable to further improve mini-helicopter performance.

Commercial laser scanners can provide a wide field of view on a plane. This kind of sensor has been extensively used in robotics and automation, including tracking of moving obstacles from a mobile robot (Mandow *et al.*, 1997). However, tracking a helicopter from the ground implies 3D perception. Nowadays, 3D scanners are expensive and have a long scan interval, which makes them unattractive for many real-time control applications.

An alternative solution is to mount a 2D laser scanner on a base with a servo-drive that provides an extra degree of freedom. This arrangement has been devoted to the localization and mapping problem in terrestrial mobile robotics (Surmann *et al.*, 2003). In this case, the extra drive is meant to provide the widest sweep in order to reach most of the surrounding environment. In the application of tracking an aerial vehicle, however, scanning has to be continually focused on the target.

So far, we have not found any documented application to track UAVs in this way. A loosely-related work employs very specialized laser devices to track beacons on a spacecraft by active triangulation (Blais *et al.*, 2001).

This paper reports progress in the use of a 3D outdoor ground laser range-finder as an aid for detection and tracking of a mini-helicopter, particularly during take-off and landing operations.

The paper is organized as follows. After this introduction, next section discusses two possible configurations for scanning the sky from a ground laser range-finder. Section 3 presents a solution for mini-helicopter detection and tracking. Section 4 presents first experimental results. Finally, section 5 is devoted to conclusions and future work.

2. SKY SCANNING CONFIGURATIONS

Standard 2D laser range finders provide range measurements on a plane by incorporating a rotating mirror onto a 1D laser beam. Similarly, 3D range data can be obtained by adding a second rotation axis driven by a servo-motor.

Different 3D scanning methods result from the possible combinations of the rotation axis and the alignment of the 2D scanner. These mainly differ in the measurement densities, which decrease with the distance to the new rotation axis (Wulf and Wagner, 2003).

To perceive the helicopter from the ground, two sky scanning methods can be employed: the rolling and yawing scans (see Fig. 1). Note that the third possible revolution (i.e., pitch) is redundant because it is coincident with the laser mirror rotation.

The 3D laser device provides the angle of the 2D scan α, the angle of the extra axis β and a range r for the helicopter localization. These can be used to compute cartesian coordinates on a fixed frame located at the center of the laser scanner mirror (see Fig. 2).

For the rolling scan configuration, the following equations apply:

$$\begin{aligned} x &= \cos(\beta)\ \cos(\alpha)\ r \\ y &= \cos(\beta)\ \sin(\alpha)\ r \\ z &= \sin(\beta)\ r \end{aligned} \tag{1}$$

Similarly, the cartesian coordinates can be obtained from the yawing scan as follows:

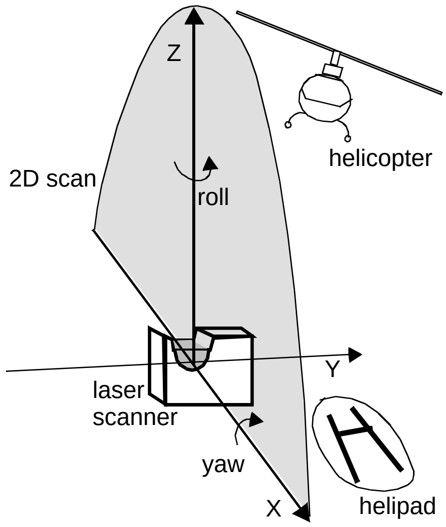

Fig. 1. Sky scanning methods.

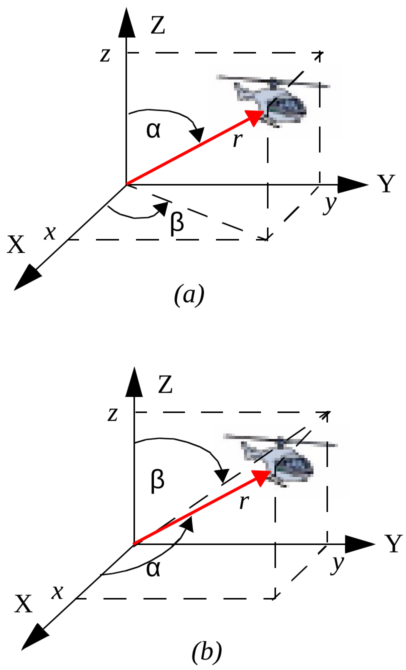

Fig. 2. 3D localization. (a) Rolling scan. (b) Yawing scan.

$$\begin{aligned} x &= \cos(\alpha)\ r \\ y &= \sin(\alpha)\ \sin(\beta)\ r \\ z &= \sin(\alpha)\ \cos(\beta)\ r \end{aligned} \tag{2}$$

Fig. 3 and Fig. 4 show the domes resulting from plotting constant ranges for the rolling and yawing scans, respectively. A complete dome is obtained by scanning 180º on the extra axis. Darker lines shown on the domes are the result of considering only a partial scan angle.

Note that in order to take advantage of the maximum range density during takeoff and landing, the helipad

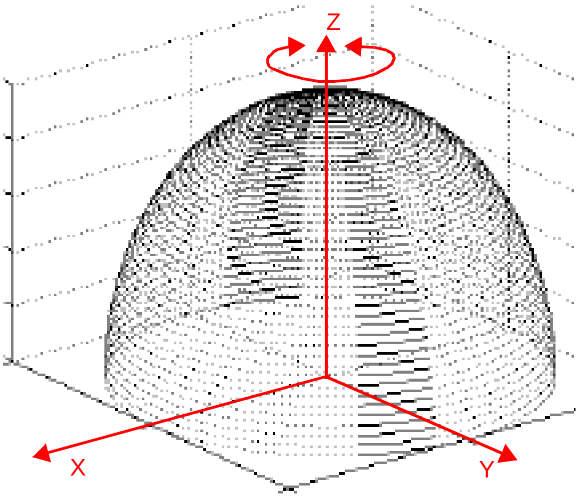

Fig. 3. Rolling scan.

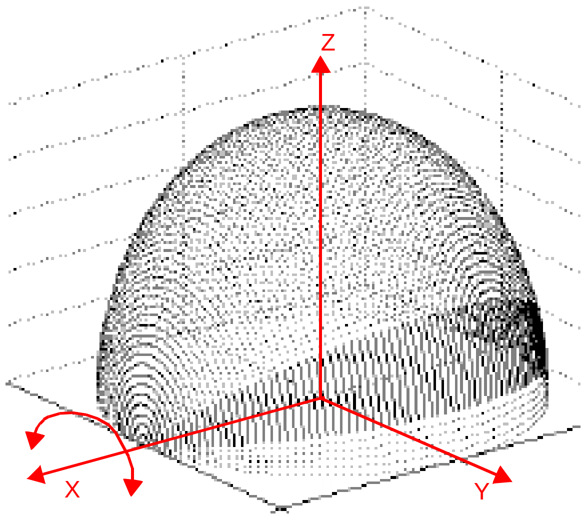

Fig. 4. Yawing scan.

should be located near the laser range-finder for the rolling scan, whereas it should be placed close to the X axis for the yawing scan.

Taking into account that measurement density decreases with distance, it is important to determine the maximum range *L* that the helicopter can fly away from the laser device that guarantees that it can be perceived by the sensor.

This value depends on the maximum laser range *D*, the angular resolutions of the 3D laser: $\Delta\alpha$ and $\Delta\beta$, and the minimum physical dimension of the helicopter *H*. Note that the rotor blades can be scanned in motion by the laser device, because the laser beam is faster than blade rotation.

For both scanning configurations, assuming small angular resolutions, the visibility criterion for any possible helicopter attitude can be approximately formulated as follows:

$$L \le \min\left(\frac{H}{\Delta\alpha}, \frac{H}{\Delta\beta}, D\right) \qquad (3)$$

In this work, the yawing scan configuration has been chosen and tested, although both 3D scanning methods are almost equivalent. Note that the roll configuration poses one mechanical problem: for endless turning, it requires slip rings for data and power wiring.

3. HELICOPTER SEARCH AND TRACKING

An overview of the control system is shown in Fig. 5. Two cascaded loops can be observed. Firstly, the inner perception loop, which is the purpose of this work, drives the laser servo-motor in order to detect and track the mini-helicopter. Secondly, autonomous flight control could be eventually performed from the computer by means of a radio link.

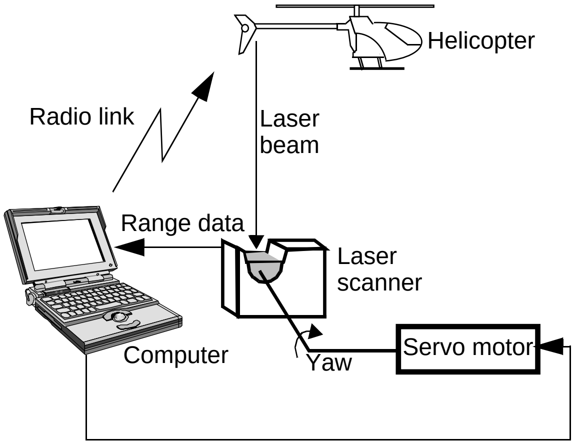

Fig. 5. Control system overview.

The extra drive of the laser scanner is to be dynamically controlled according to the evolution of the tracked object. This same principle was applied to a mobile robot in order to follow a person with a motorized 1D sonar (Pozo-Ruz *et al.*, 1997). However, there is a significant difference that complicates tracking, which is the fast maneuverability of mini-helicopters.

Two major problems have to be dealt with in order to achieve helicopter tracking: detection of the UAV from each single 2D scan, and yaw control strategies for target search and tracking.

Regarding target detection, in this work it will be assumed that no more than one UAV is to be simultaneously within the scanner range, which is reasonable for takeoff and landing. Also, no obstacles are supposed to stand between the helicopter and the sensor. Each 2D scan is analyzed in order to discriminate the potential presence of a helicopter from the rest of surrounding objects. This is achieved by detecting points in the scan that stand out some threshold distance from the background. These points are discarded if the apparent size is greater than the known dimensions of the helicopter.

Once the target is detected, position information from previous scans can also be considered. For takeoff, the initial position of the helicopter is known to be on the helipad. Moreover, the remote control orders sent to the helicopter could be useful for tracking as well.

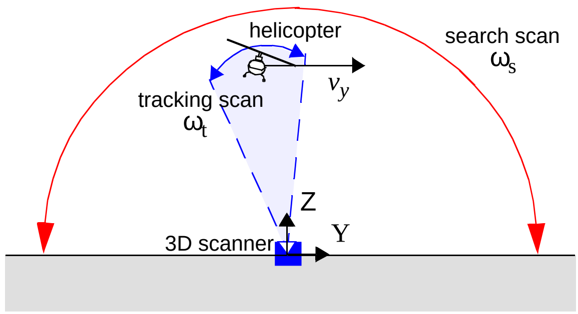

Fig. 6. Yaw control for search and tracking modes.

As for yaw control, the perception loop incorporates two different strategies: search and tracking (see Fig. 6). The search is performed either when no helicopter is being tracked or when track might be lost due to abrupt maneuvers.

In search mode, successive 2D scans are obtained by producing increments in the whole range of the sensor yaw angle β. This can be defined as a *search scan*. The search scan is performed with a constant yaw angular velocity ω_s, which depends on the 2D scan frequency and the minimum yaw step size Δβ.

The main goal of the tracking mode is to avoid losing track of the helicopter. It can be assumed that the vertical velocity component v_z is generally dominant in takeoff and landing. With the yaw configuration, the effect of v_x is to change the position of the helicopter within the same yaw plane, which relies on the target detection algorithm. On the other hand, the Y component of the UAV velocity v_y poses the problem of finding a new yaw angle for the sensor. Therefore, the tracking problem can be stated as controlling the yaw angle in order to keep track of the helicopter in spite of its v_y velocity component.

This is achieved by performing a *tracking scan*, which consists on incrementally changing the yaw angle β in a fixed direction (forward or backward) until the target is surpassed, and then reversing the direction until surpassing it again.

The oscillation of the tracking scan is necessary to account for v_y. If the yaw angle was fixed once the UAV is detected, the direction of search would be unknown if it moved away from the current scan plane.

The main limitation for this tracking strategy is that the helicopter may surpass the yaw angle in the direction of motion. Thus, yaw control would reverse motion and the target would be lost, so the search mode would activate. To reduce this problem, ω_t has to be made inversely proportional to the measured range. Note that the width of the tracking scan depends on the size of the UAV and its distance to the sensor.

4. EXPERIMENTAL RESULTS

The laser device employed for the experimental setup is a commercial time-of-flight range scanner (Sick, 2002). It has the following maximum features: 180º field-of-view, Δα= 0.5º of angular resolution, up to D= 50 m range, and ±4cm range error. With these values, scan time is 26 ms. A serial port interface transmits range data at the maximum rate of 500 Kbaud to the computer.

A stepper-motor has been employed to move the outdoor laser scanner with a maximum resolution of Δβ= 1/3°. With this motor, the system yields a complete 180º scan at maximum resolution in 35 seconds. The axis of revolution is centered in the laser-mirror in order to avoid false range displacements while rotating the laser device (see Fig. 7).

In this work, a commercial hobby-class electric quadrotor has been employed. A quadrotor is a four rotor helicopter. This kind of helicopter is controlled by varying the rotor speeds; i.e., by changing the lift forces. Thus, it is an underactuated dynamic vehicle with four inputs and six output coordinates.

This aerial vehicle is equipped with a small color video camera with transmitter. In order to facilitate flight control, the quadrotor is partially stabilized by three onboard gyroscopes. For the experiments, the helicopter has been manually remote controlled.

Battery autonomy during flight is 15 minutes. The diameter of the vehicle is 0.53 m, and diameter of the blade is 0.29 m. It weights 0.5 Kg and accept a maximum payload of 0.1 Kg (Draganfly, 2002).

The only modification made is the incorporation of a bigger soil-contact base built of balsa wood that serves several purposes: to facilitate landing, to prevent blades from striking the ground, to provide more rigidity to the structure, and to enhance its visibility from the laser scanner (see Fig. 8).

Since the minimum dimension of the helicopter is its height H= 0.12 m, the maximum separation from the laser scanner should be H/Δα= 13.75 m (see Eq. 1). However, this is a very conservative limit that assumes that the quadrotor can fly with a 90º

Fig. 7. The 3D laser range-finder.

Fig. 8. The free flight of the quadrotor.

inclination, which is impossible for this UAV. Thus, a more realistic limit is L= H/Δβ= 20.62 m.

Figure 9 shows a single 3D tracking scan of the helicopter hovering in an outdoor environment, with direct sunlight over the laser scanner. The estimated position of the quadrotor relative to the laser device is x= 5.5 m, y= -0.54 m and z= 2.32 m, corresponding to α= 0.41 rad, β= -0.23 rad and r= 6 m.

It has been observed that the sun does not interfere with the measurements, and that open sky is correctly represented because no spurious readings appear. Note also that the laser shadow of the UAV is projected onto a wall of the nearest building.

Moreover, tracking experiments have been performed in an indoor environment. An experiment in which a quadrotor trajectory is tracked by the scanner system appears in Fig 10. The discontinuous trajectory corresponds to the position of arbitrary points of the UAV actually detected by the scanner in the tracking process. This means that the position of a given fixed reference point of the UAV cannot be precisely tracked. Nevertheless, the method provides reliable information about the presence of the helicopter and its approximate position.

In this case, discrimination of the helicopter from the surrounding objects is a bit more difficult than in open sky. Fig. 11 shows one vertical 2D scan where the UAV is detected in the hall of a three-story building. The detection algorithm discards groups of points that stand out from the background but are greater than the size of the helicopter, such as the vertical lines due to floor parapets in Fig. 11. In this particular example, the known size of the hall has been also considered so as not to contemplate ranges greater than its height (i.e., 14 meters). Note that the algorithm detects the target even if its points are discontinuous due to the shape of the quadrotor.

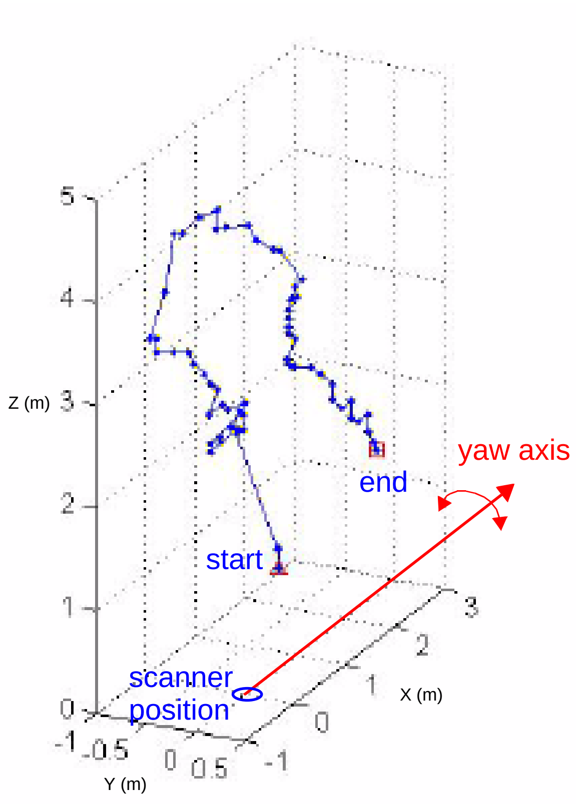

Fig. 10. UAV trajectory as perceived by the 3D scanner.

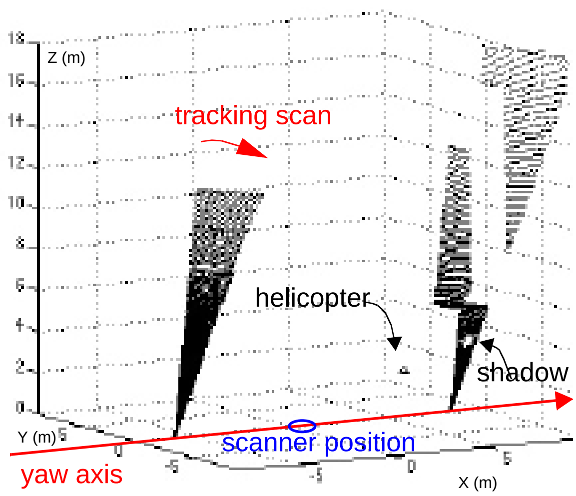

Fig. 9. A 3D tracking scan of the helicopter during a quasi-stationary flight.

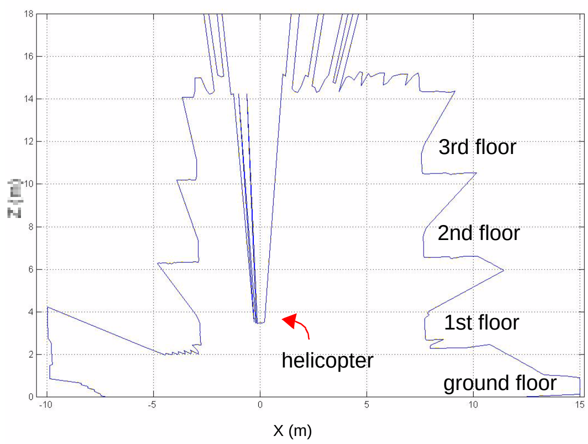

Fig. 11. A single 2D scan with helicopter discrimination in an indoor environment.

5. CONCLUSIONS

The novelty of this paper consists on using an on-the-ground laser scanner to track the position of an unmanned helicopter. The main advantage of this approach is that a 3D range sensor provides reliable information in a direct way that can complement another aerial navigation sensors.

The mechanical design of the 3D laser scanner makes use of a conventional 2D laser device with an additional degree of freedom. Different configurations for the sensor have been discussed in detail in the paper.

Both detection from 2D scans and tracking strategies based on the control of the extra axis have been developed in this work.

First experiments with a small radio controlled helicopter have shown promising results in both indoor and outdoor environments. However, this tracking system only provides a raw localization of the helicopter and no attitude at all. Consequently, it can not be straightforwardly applied for helicopter control.

The scan time for the new axis can be improved by considering alternatives to the current stepper motor, since only one third of the time is actually used for the 2D scans. Other future work includes the integration of the proposed sensor with cameras for autonomous landing and take-off. Furthermore, the incorporation of the laser device into a terrestrial mobile robot equipped with an helipad to enable docking onboard is an interesting application.

6. ACKNOWLEDGEMENTS

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