Vision-based Autonomous Landing of an Helicopter on a Moving Target

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This paper presents the design and implementation of an algorithm for landing a helicopter autonomously on a moving target. The target is neutral; it is neither adversarial nor cooperative. A downward-looking camera is used to acquire and track the target. A template matching algorithm is used for acquiring the target in the images. This is integrated with a trajectory controller for landing the helicopter. The position of the target in the image is the input to a robust Kalman filter for tracking in successive frames. A linear controller based on a kinematic model of the helicopter is used to perform trajectory following and landing. We present results from experimental trials showing successful trajectory tracking and landing on moving targets.

I. Introduction

In recent years, considerable resources have been devoted to the design, development and operation of unmanned aerial vehicles. The applications of such unmanned aerial vehicles are diverse, ranging from scientific exploration and data collection, to provision of commercial services, military reconnaissance, and intelligence gathering. Other areas include law enforcement, search and rescue, and even entertainment.

Unmanned aerial vehicles, particularly ones with vertical takeoff and landing capabilities (VTOL), enable difficult tasks without endangering the life of human pilots. This potentially results in cost and size savings as well as increased operational capabilities, performance limits, and stealthiness. Currently the capabilities of such unmanned aerial vehicles are limited. A helicopter is a compact VTOL capable platform; it is also extremely maneuverable. Autonomous helicopters equipped with the ability to land on moving targets would be very useful for various tasks as search and rescue, law enforcement, and military scenarios where micro air vehicles (MAVs) may want to land on a convoy of enemy trucks.

We have previously developed a system which was successful in landing a helicopter autonomously on a stationary target using vision and global positioning system. In this paper we focus on the problem of tracking and landing on a moving target using an autonomous helicopter as a platform. We track a moving target using a downward looking camera mounted on a helicopter. Trajectory planning is performed to allow the helicopter to land on the target. Data from flight trials show that our tracking system performs well. Based on the tracking information, our controller is able to generate appropriate control commands for the helicopter in order to land it on target.

II. Related Work

Classical visual target tracking has concentrated on object recognition using edge detection techniques followed by a velocity field estimator based on optical flow. Edge detection may be bypassed altogether using inter-temporal image deformation for heading prediction through feature matching. discusses the merits of “good” feature selection and offers a motion computation model based on dissimilarity measures of weighted feature windows. The idea of feature selection and point matching has been used to track human motion. In eigenfaces have been used to track human faces. They use a principal component analysis approach to store a set of known patterns in a compact subspace representation of the image space, where the subspace is spanned by the eigenvectors of the training image set. In, a single robot tracked multiple targets using a particle filter for object tracking and Joint Probabilistic Data Association Filters were used for

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measurement assignment.\textsuperscript{9} described a Variable Structure Interacting Multiple Model (VS-IMM) estimator combined with an assignment algorithm for tracking multiple ground targets. Although considerable research has been performed on tracking moving targets from both stationary as well as moving platforms for mobile autonomous systems,\textsuperscript{8} almost no work has been done on using autonomous helicopters for such a task. This paper focuses on tracking a moving target from the air and landing on it using an autonomous aerial vehicle.

![Image of autonomous helicopter with avionics](image_url)

**Figure 1. Autonomous Helicopter with Avionics**

Several techniques have been implemented for vision based landing of an autonomous helicopter on stationary targets. The problem of landing as such is inherently difficult because of the instability of the helicopter near the ground.\textsuperscript{10} In,\textsuperscript{11} a vision-based approach to landing is presented. Their landing pad had a unique shape which made the problem of identification of the landing pad much simpler. In,\textsuperscript{2} invariant moment descriptors were used for detection and landing on a stationary target.

### III. Problem Formulation and Approach

We divide the problem of landing on a moving target into four stages. The first stage consists of detecting the target. We use vision for this purpose. We assume the target shape is known and no distractor targets are present. The second stage is tracking the target. We formulate the tracking problem as a Bayesian estimation problem and under linear system and Gaussian white noise assumptions solve it using a Kalman filter. The third stage is motion planning which plans a desired landing trajectory for the helicopter to land on the moving target. The fourth and last stage is control, which regulates the location of the helicopter over time, in accordance with the planner output.

The general problem is given a mechanical system (whose state is given by $x$) and initial and final conditions $x_0$, $x_f \in \mathbb{R}$ where $\mathbb{R}$ is the state space of the mechanical system, we have to find a control signal $u : t \rightarrow u(t)$ such that at time $t_f$ the system reaches $x_f$. The generalized problem is to find control inputs for a model helicopter for the entire range of a family of trajectories. Although such problems have been considered for general cases,\textsuperscript{12} to our knowledge, this is the first time that such a formalization is being applied to a combination of tracking a moving target and landing on it using an unmanned helicopter.

#### III.A. Assumptions

Real time target tracking for an autonomous mobile robot in a general dynamic environment is an unsolved problem. However with reasonable assumptions and constraints regarding the environment, the target tracking problem can be tractable. We make several assumptions which simplify the problem for our application but are not restrictive. These assumptions do not change the general nature of the problem but simplify the visual processing part.

- The most difficult aspect of tracking is the discrimination of the target from the background. We assume that the shape of the target is known (we use a helipad with the letter H painted on it). Also we ensure that there is a high contrast between the target and the background.
- It is assumed that the target moves slowly enough for the helicopter to track it. We also assume that the target is not evasive or malicious.
• The target is smaller than the size of the image plane, in relative terms. Thus the target feature points do not span an area larger than the pixel dimensions of the focal plane.

• We assume that the helicopter is oriented such that the focal plane of the camera mounted on it is parallel to the target plane and this attitude is maintained throughout the tracking and the landing process. This ensures that we do not have to consider image skew.

• The target is allowed to move in the x and y directions only. This allows us to employ an orthographic projection model for image acquisition.

IV. Target Detection using Vision

The target detection algorithm is described below in three parts; preprocessing, geometric invariant extraction, object recognition and state estimation.

The goal of the preprocessing stage is to locate and extract the target, which is done by thresholding the intensity image and then segmenting and performing a connected component labeling of the image. The image is converted to gray scale and a $7 \times 7$ Median-filter is applied to the thresholded image for removing noise and to preserve the edge details effectively. The image is scanned row-wise until the first pixel at a boundary is hit. All the pixels which belong to the 8-neighborhood of the current pixel are marked as belonging to the current object. This operation is continued recursively until all pixels belonging to the object are counted. A product of this process is the area of the particular object in pixels. Objects whose area is less than a particular threshold area ($\leq 80$ pixels) are discarded. Similarly objects whose area is $\geq 700$ pixels are discarded. The remaining objects are the regions of interest and are candidates for the target.

The next stage is to extract the target from the image which is performed by using Hu’s moments of inertia.$^{13}$ These are normalized set of moments of inertia which are invariant to rotation, translation and scaling. The reader is referred to$^2$ for a complete discussion of the Hu’s moments of inertia and their application for landing using an autonomous helicopter on a stationary target. After the extraction of the target from the image, the coordinates of the target are transformed into helicopter coordinates.

![Figure 2. An typical image obtained from the downward pointing camera on the helicopter during one of the trials.](image)

The coordinates of the target so obtained are in the image coordinate frame. These coordinates are transformed into state estimates relative to the helicopter, based on the height of the helicopter above the ground. The height of the helicopter is obtained from the on-board differential GPS. The x-coordinate of the target in the helicopter frame of reference is given by

$$x_{heli} = \frac{\text{height} \times \tan \frac{\Phi_h}{2} \times x_{image}}{\text{camera res along the x axis}} \tag{1}$$
where $\phi_h$ is the field of view of the camera in the x direction, $x_{image}$ is the x-coordinate of the target in the image plane. Similarly the y-coordinate of the target is given by

$$y_{helit} = \frac{\text{height} \times \tan \frac{\phi_h}{2} \times y_{image}}{\text{camera res along the y axis}}$$  \hspace{1cm} (2)$$

Since the helicopter is near hover at all instances we assume that the roll, pitch and yaw angles of the helicopter are negligible for computing the world coordinates of the target with respect to the helicopter.

V. Target Tracking using a Kalman Filter

The output of the target detection (i.e. the measured x and y coordinates of the target on the ground) is the input to the tracker. Based on a second order kinematic model for the tracked object we can model the equation of the target as a linear system described by

$$X_k = \Phi_{k-1}X_{k-1} + w_k$$  \hspace{1cm} (3)$$

where $w_k$ is the random process noise and the subscripts on the vectors represent the time step. $X_k$ is the state vector describing the motion of the target (its position $p$, velocity $v$ and acceleration $a$). The measurement vector at time $k$ is given by

$$Z_k = H_kX_k + u_k$$  \hspace{1cm} (4)$$

where $H_k$ is known and $u_k$ is a random measurement noise. The Kalman filter is formulated as follows.

Suppose we assume that the process noise $w_k$ is white, zero-mean, Gaussian noise with a covariance matrix $Q$. Further assume that the measurement noise is white, zero-mean, Gaussian noise with a covariance matrix $R$, and that it is not correlated with the process noise. The system dynamics are given by

$$\begin{bmatrix} p_k \\ v_k \\ a_k \end{bmatrix} = \begin{bmatrix} 1 & T & T^2/2 \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} p_{k-1} \\ v_{k-1} \\ a_{k-1} \end{bmatrix} + w_k$$

where $a_{k-1}$ is a random time-varying acceleration and $T$ is the time between the steps $k$ and $k-1$. The state propagation and update equation for the discrete Kalman filter are given by

$$\hat{X}_k(-) = \Phi_{k-1}\hat{X}_{k-1}(-)$$  \hspace{1cm} (5)$$

$$P_{k}(-) = \Phi_{k-1}P_{k-1}(+)\Phi_{k-1}^T + Q_{k-1}$$  \hspace{1cm} (6)$$

$$S_k = H_kP_k(-)H_k^T + R$$  \hspace{1cm} (7)$$

$$K_k = P_k(-)H_k^T S_k^{-1}$$  \hspace{1cm} (8)$$

$$P_k(+) = (I_n - K_kH_k)P_k(-)$$  \hspace{1cm} (9)$$

$$\hat{X}_k(+) = \hat{X}_k(-) + K_k(Z_k - H_k\hat{X}_k(-))$$  \hspace{1cm} (10)$$

In the above equations, the superscript $T$ indicates matrix transposition. $S$ is the covariance of the innovation, $K$ is the gain matrix, and $P$ is the covariance of the prediction error. Also we distinguish between estimates made before and after the measurements occur; $X_k(-)$ is the state estimate that results from the propagation equations alone (i.e., before the measurements are considered) and $X_k(\cdot)$ is the corrected state estimate that accounts for measurements. $P_{k}(-)$ and $P_{k}(\cdot)$ are defined similarly.

VI. Trajectory Planning

We approximate the desired trajectory to be followed by the helicopter for tracking and landing by a cubic polynomial where the altitude $z$ varies with time $t$ at a given position $x$ and $y$ as follows:

$$z(t) = a_0 + a_1 \cdot t + a_2 \cdot t^2 + a_3 \cdot t^3$$  \hspace{1cm} (11)$$

The following boundary conditions should be satisfied.
\[ z(0) = z_0 \quad z(t_f) = z_c \quad \dot{z}(0) = 0 \quad \dot{z}(t_f) = 0 \]

where \( t_f \) is the final time. In the above equations \( z(t) \) represents the height of the helicopter above the ground at time \( t \) (parameterized as a cubic spline). \( z(0) \) represents the height of the helicopter at time \( t = 0 \). \( z(t_f) \) represents the final altitude given by \( z_c \) since the target is at a height \( z_c \) above the ground. Also \( z(0) \) and \( z(t_f) \) represent the initial and the final velocities in the \( z \) direction and they should be zero. Finally when the helicopter has landed on the target the velocity of the target and the helicopter should be the same. This is represented by \( x_h = x_{\text{target}} \). We restrict the class of trajectories by imposing these additional set of constraints:

\[
\dot{z} \leq z_{\text{max}} \quad x_h(0) = 0 \quad \dot{x}_h(t_f) = \dot{x}_{\text{target}}(t_f) \\
\]

The above constraints provide a lower bound on the time of flight \( b \) i.e, the time of flight for the helicopter can never be less than \( t_{\text{min}} \) where \( t_{\text{min}} \) is given by

\[
t_{\text{min}} \geq \frac{-4a_2 + \sqrt{4a_2^2 - 12a_3a_1}}{6a_3} \quad (12)
\]

\[
V_{\text{max}} \leq \frac{x}{t_{\text{min}}} \quad (13)
\]

![Figure 3. Schematic for landing on a moving target](image)

We assume that the helicopter has to intercept the target and land on it at a distance of \( X \) meters [See Figure 3]. Initially the helicopter is at a height of \( z_h \) from the ground. It has to land on a target at a distance of \( X \) meters and at a height of \( z_c \) from the ground. Since the maximum velocity of the helicopter is given

\( a \) \( t = 0 \) is the time when the helicopter first acquired the target
\( b \) We only start landing trajectories after we have determined that \( \dot{z} \) over the entire trajectory is less than \( z_{\text{max}} \)
by $\dot{z}_h$ and has to follow the cubic spline trajectory given by equation 11, the minimum time needed for the helicopter to land is given by equation 12. Hence the maximum velocity of the target is bounded by $V_{max}$ given by equation 13. This can be seen in figure 3.

Since the altitude is obtained from a cubic spline interpolation, the first and the second derivatives exist and are continuous. For landing on a moving target the helicopter altitude is required to follow the above profile with a specified altitude clearance of $z_c$.

$$z = g(t)$$  \hspace{1cm} (14)

In Equation 14, $z$ is the helicopter altitude.

### VII. Experimental Results

In order to validate our algorithm, we performed experiments with an Autonomous Helicopter as shown in Figure 1.

The helicopter was hovered manually at a height of 15 meters. The pilot controlled the helicopter to be in the hover position all the time, while the target (which was a ground robot in our experiments) was commanded to move in a straight line. The image data were processed offline. The goal position for the helicopter was 12 meters from the starting point, i.e, the helicopter should track the helipad for 12 meters and then land on it.

Figure 2 shows a typical image obtained from the downward pointing camera on the helicopter. The target is marked with an H and moves in the x-direction for a distance of 12m. Figure 4 shows three curves. The solid line is ground truth. It is the location of the target as measured on the ground by the odometry of the target robot. The dotted line is the location as measured by the camera without filtering. This is obtained by first detecting the target in the image, finding its image coordinates and then transforming them to the helicopter’s reference plane as shown in Section IV. The dashed line is the location of the target deduced by the Kalman filter as explained in Section V.

![Kalman Filter Performance](image)

Figure 4. Kalman filter tracking performance

Figure 5 shows the simulated trajectory followed by the helicopter while tracking the target. The plot shows the trajectory of the target (solid) and the trajectory of the helicopter (dashed). As can be seen the helicopter is able to track the target quite well.

Figure 6 shows the height of the helicopter with respect to time. During simulation it was found that updating the trajectory of the helicopter every time step the Kalman filter made a new prediction was not necessary. Only a discrete number of modifications were made to the trajectory and a cubic spline trajectory as described in Section VI was used. It may be noted that during the actual flight tests we will probably use a straight line interpolation of the cubic spline which is also shown in Figure 6.
VIII. Conclusions

This paper describes the design of an algorithm for landing on a moving target using an autonomous helicopter. We use a Kalman filter as an estimator to predict the position of the target and plan the trajectory of the helicopter such that it can land on it. Given conditions about the distance at which the helicopter should land on the target, we perform discrete updates of the trajectory so that we can track and land on the target. We have performed experiments in manual control mode where a human pilot was controlling the helicopter and holding it in hover while we collected data of a ground target moving in the field of view of the helicopter. The estimator and the trajectory planner were run offline to test the validity of the algorithm. Figures 4, 5, 6 show the results obtained by using the Kalman filter in conjunction with an object recognition algorithm.

VIII.A. Limitations, Discussion and Future Work

In the future we plan to test the algorithm on our autonomous helicopter. Several limitations exist with the current algorithm:

- We assume that the helicopter is in hover (zero roll, pitch and yaw values and zero movement in the northing and easting directions). This is almost impossible to achieve in an aerial vehicle. We plan to integrate the errors in GPS coordinates and attitude estimates into the Kalman filter so that we are able to track the target more precisely.

- Currently we use an algorithm based on the intensity of the image for object detection. We also assume that the object is planar. This is quite restrictive in nature. We plan to integrate our algorithm with a better object detector and a camera calibration routine so that the coordinates of the tracked object obtained during the vision processing stage are much more accurate.

- We will extend the algorithm in the future such that we are able to track multiple targets and then land on any one of them. Also we intend to investigate algorithms to be able to pursue and land on evasive targets.

References

Figure 6. Height trajectory commanded for tracking and landing


