# Towards an UAV Visual Air-to-Ground Target Tracking in an Urban Environment

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***Abstract*— This paper develops an UAV navigation and guidance system for air-to-ground target tracking in an urban environment. The integrated optical-flow/inertial navigation filter is designed to simultaneously estimate the target and UAV states without using GPS. The guidance law which achieves target tracking and obstacle avoidance while enhancing the navigation accuracy is proposed. The entire system is to be implemented and tested in actual flights.**

## I. INTRODUCTION

Two main challenges associated with an UAV operation in an urban environment are; i) an access to GPS signals can be denied, and ii) there are obstacles to be avoided. This paper considers a problem in which an UAV is required to pursue a moving ground target while maintaining a position-dependent safety altitude (given a-priori from the vision-based 3D obstacle mapping system in [1], for example). In order to achieve this mission, an accurate global localization of a target as well as of an own-ship aerial vehicle is necessary. There is a large body of research on visual SLAM (simultaneous localization and mapping) applied to an UAV navigation in a GPS-denied environment[2][3]. By combining ideas of visual SLAM and visual target tracking, the authors have developed an integrated vision/inertial navigation system for simultaneous tracking and self-localization[4]. This system utilizes optical flow estimation to complement the GPS information. The guidance law which makes an UAV track the target's horizontal position and follow the safety altitude profile along its trajectory is designed and integrated with the navigation. It is well-known that the vision-based navigation performance significantly depends on a camera motion relative to objects of interest. The observer trajectory optimization for estimation enhancement was firstly treated in [5], and since then many similar studies have been done especially for a bearing-only localization problem[6][7]. This paper suggests applying the one-step-ahead suboptimal guidance design developed in [8] in order to achieve the tracking mission while maximizing accuracy of both the target- and self-localizations. Figure 1 depicts an entire UAV flight system for visual target tracking.

## II. IMAGE PROCESSING

Two tasks are devoted to image processing: target tracking and optical flow estimation. The algorithms used in this paper have been developed based on basic image processing routines that can be found on the Kovesi's website[9]. Suppose the fact that the target's gray-level is significantly higher than the background. Then the target tracker simply consists in convolving the current image by a Gaussian kernel, and in selecting a position attaining the maximum. The optical flow estimation is focused on the surroundings of the detected target position. First, the feature points are detected by Harris-Stephen operator[9] on the current and previous images. Then feature matching between the two images is performed based on a back and forth correlation. Finally, an affine motion model is robustly fitted to the estimated flow vectors. An example of the image processing results is illustrated in Figure 2.

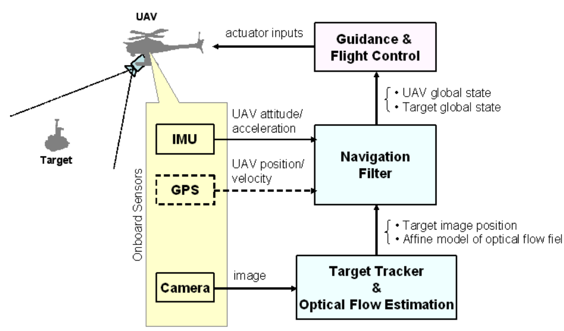


Fig. 1. Visual Target Tracking System

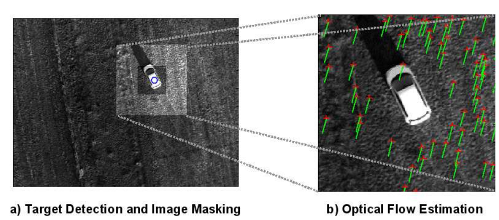


Fig. 2. Example of Image Processing Results

## III. NAVIGATION FILTER DESIGN

A navigation filter is designed to estimate the global position and velocity of the UAV and also those of the target by fusing the onboard inertial sensor data with the image processing outputs. The optical flow measurements contain information about the UAV velocity and height with respect to the ground surface, while the target pixel-coordinates provide the target position relative to the UAV.

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Since these measurements are nonlinear to the estimation state, an extended Kalman filter (EKF) is applied. In the EKF design, a non-accelerating target model is used. See [4] for details.

## IV. Guidance Design

Suppose that a safety altitude map $h_d(X, Y)$ is given based on a-priori knowledge of the environment. Figure 3 shows an example of the altitude map created from a 3D obstacle mapping result. Then an UAV guidance objective is to track the position $\boldsymbol{X}_d = \begin{bmatrix} X_t & Y_t & -h_d(X_v, Y_v) \end{bmatrix}^T$, where $(X_t, Y_t)$ and $(X_v, Y_v)$ are the global horizontal positions of the target and the UAV respectively. Define the state vector $\boldsymbol{x}(t)$ by

$$\boldsymbol{x} = \begin{bmatrix} \boldsymbol{X}_v - \boldsymbol{X}_d \\ \boldsymbol{V}_v - \dot{\boldsymbol{X}}_d \end{bmatrix}$$

Then the tracking mission can be formulated as the following optimization problem.

$$\min_{\boldsymbol{a}_v(t)} J_k = \frac{1}{2} \int_{t_k}^{\infty} \left( \boldsymbol{x}^T(t) A \boldsymbol{x}(t) + \boldsymbol{a}_v^T(t) B \boldsymbol{a}_v(t) \right) dt \quad (1)$$

subject to the dynamics of $\boldsymbol{x}(t)$ with an initial condition $\boldsymbol{x}(t_k) = \boldsymbol{x}_k$. $\boldsymbol{a}_v$ is the UAV acceleration input. Let $\boldsymbol{a}_v^*(t, \boldsymbol{x}_k)$ denote its optimal solution. This optimal guidance, however, is not realizable in the real-world since the true state $\boldsymbol{x}_k$ is unaccessible. A conventional way to derive the guidance input is to simply replace the true state in $\boldsymbol{a}_v^*(t, \boldsymbol{x}_k)$ by its estimate $\hat{\boldsymbol{x}}_k$. Figure 4 presents an example of the target tracking results with the safety altitude map given in Figure 3. This approach coincides with solving the optimization problem (1) under an assumption of zero estimation error, and hence it can cause a large tracking error when having a large estimation error.

A performance of the navigation filter designed in Section III depends on the camera motion relative to the target and to the ground surface. In order to maximize the tracking performance by creating motions which improves the estimation accuracy, this paper adopts the one-step-ahead suboptimal guidance law developed in [8]. This guidance policy solves the optimization problem (1) under an assumption that there will be only one more final measurement at one-time-step ahead. The resulting input at the current time step $t_k$ becomes

$$\boldsymbol{a}_v(t_k) = \boldsymbol{a}_v^*(t_k, \hat{\boldsymbol{x}}_k) + \Delta \boldsymbol{a} \quad (2)$$

An additional input $\Delta \boldsymbol{a}$ in (2) is determined so that an expected value of $J_k$ is minimized under the onea-step-ahead assumption. Through preliminary simulation results, it has been discovered that an exicitation in the horizontal motion enhances the target height estimation while the verical motion enhances the optical flow-based UAV horizontal localization. What is interesting particularly in our problem is that the vertical tracking performance depends also on the accuracy of the horizontal localization because of the position-dependent altitude command. The one-step-ahead suboptimal guidance law is expected to introduce some 3D motions to improve the overall tracking accuracy.

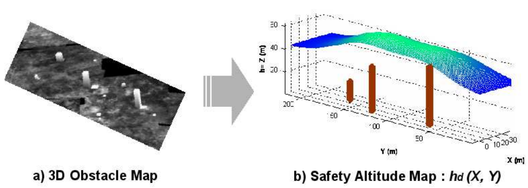


Fig. 3. Example of Safety Altitude Map

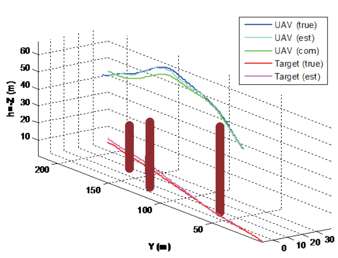


Fig. 4. Example of Navigation and Tracking Result

## V. Conclusion and Future Work

This paper proposed the UAV navigation and guidance system to achieve a vision-based ground target tracking in a GPS-denied obstacle field. The suboptimal guidance law which creates motions to improve the navigation accuracy and achieves a good tracking performance was suggested. After a guidance performance analysis through simulations, all the algorithms will be implemented and tested onboard on the ONERA ReSSAC UAV helicopter[1]. Results from closed-loop flight experiments will be included in the final paper.

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