System Development and Flight Experiment of Vision-Based Simultaneous Navigation and Tracking

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This paper develops a UAV onboard vision-based system for simultaneous navigation and tracking. The system consists of i) image processor, ii) navigation filter which localizes both a UAV and a ground moving target by fusing onboard sensor measurements and the image processing outputs, and iii) guidance and control system which makes the UAV pursue the target by using the navigation results. Each algorithm is implemented as a component of the Orocos robotic architecture, and integrated with the automatic flight control system of the ONERA ReSSAC unmanned helicopter. The developed system will be evaluated through flight experiments.

I. Introduction

This paper considers a UAV air-to-ground target tracking mission in an unknown urban environment. The mission is divided into three different operational phases: global obstacle mapping, target search and tracking (Figure 1). First, the UAV explores the operation site at a sufficiently high altitude to gather information which is post-processed to construct a 3D obstacle map. Then, the UAV searches a target at a lower altitude along a search path pre-planned based on the obstacle map. Once the target is detected, the UAV starts localizing and pursuing it while avoiding obstacles. The first phase can be achieved using the vision-based mapping algorithm developed in [1]. This paper focuses on developing the autonomous visual target search and tracking system. One of the challenges in this system is to enable an accurate global localization of both the UAV and the target while operating in a GPS degraded/denied environment. Two suggested approaches are used in combination. In case of GPS loss, the integrated vision/inertial navigation which utilizes sparse optical flow to complement the UAV velocity information is applied [2]. Furthermore, the guidance law is designed to enhance the navigation performance while achieving the tracking mission. Such an idea is called dual control or observer trajectory optimization, and was first treated by Speyer [3]. This paper adopts the one-step-ahead optimization approach proposed in [4] so that the resulting guidance law creates motions preferable to the vision-based navigation.

Another challenge addressed in this paper is real-time implementation and in-flight evaluation of the suggested visual navigation and tracking system. The onboard system of the ONERA ReSSAC unmanned helicopter consists of the basic flight controller and the decisional architecture developed based on Orocos (Open RObot COntrol Software) [5]. Each algorithm in the tracking system can be implemented as a

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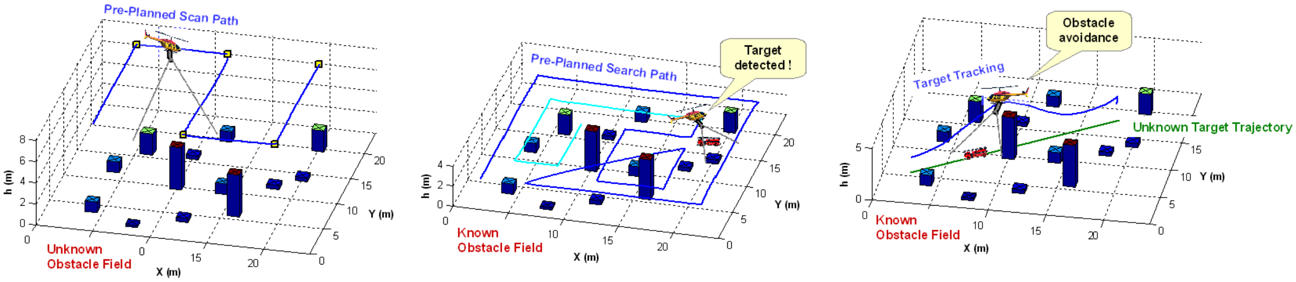


i) Obstacle Mapping   ii) Target Search   iii) Target Tracking

Figure 1. Air-to-Ground Target Tracking Mission Scenario

component within this Orocos architecture. In order to ensure flight safety, this paper introduces a supervisor which manages global mission tasks, monitors data-flows between Orocos components, and controls their execution. The supervision consists in executing a hierarchical state diagram [6] that is linked to the controlled components. Finally, the entire system is going to be evaluated in actual flights of the ReSSAC helicopter and validated by autonomously performing the mission scenario described in Figure 1.

II. Vision-Based Navigation and Tracking System

Figure 2 summarizes the entire onboard flight system for the vision-based target search and tracking mission. The system includes i) image processor, ii) navigation filter, and iii) guidance and control system. Each of these components is detailed in the following subsections.

A. Image Processor

Two main tasks are devoted to the embedded image processor: ground motion estimation and target detection and tracking. Both tasks lead to problems of very different difficulty depending on the imaged scene: typically the urban environment is quite challenging. In urban areas, ground motion estimation uses optical flow estimation [7], but it is necessary to reject image regions which belong to superstructures (buildings, trees, etc.) and to moving objects. Starting from the output of a general-purpose point tracker one can design a process to robustly fit a parametric motion model over a group of frames, so as to maintain the temporal consistency of the registration ground plane. This video registration process is the basic block of a video tracking technique dedicated to aerial image-sequencing over urban areas described in [8].

In this paper, the target detection and tracking problem is made simpler by assuming a-priori knowledge of the target color and size. For example, the automatic detection illustrated in Figure 3 is performed based on the fact that the target's graylevel is significantly higher than the background. Given the detected target position, the ground motion can be more easily estimated in its neighborhood by making the hypothesis that ground surface around the target is flat. After a step of sparse optical flow estimation, an affine model is again estimated by robust techniques (Figure 4). This fast process is used in the flight experiment described in Section IV.

B. Navigation Filter

The navigation filter design applies an extended Kalman filter (EKF) to simultaneously estimate the global position and velocity of the UAV and those of the target by fusing the onboard sensor measurements with the image processing outputs. The GPS/INS navigation in general gives a very accurate estimate of the UAV state, while the INS-only navigation solution diverges very quickly due to an accumulation of the measurement bias. In order to prevent such a navigation divergence in case of occasional GPS loss, the ground motion estimation result of the image processor is utilized as a complementary velocity measurement of the UAV. This additional measurement also aides the target state estimation by providing ground height (i.e. the target vertical position) information. The details of this integrated vision/INS navigation design is described in [2]. Its performance has been verified through offline simulations using the actual vehicle state

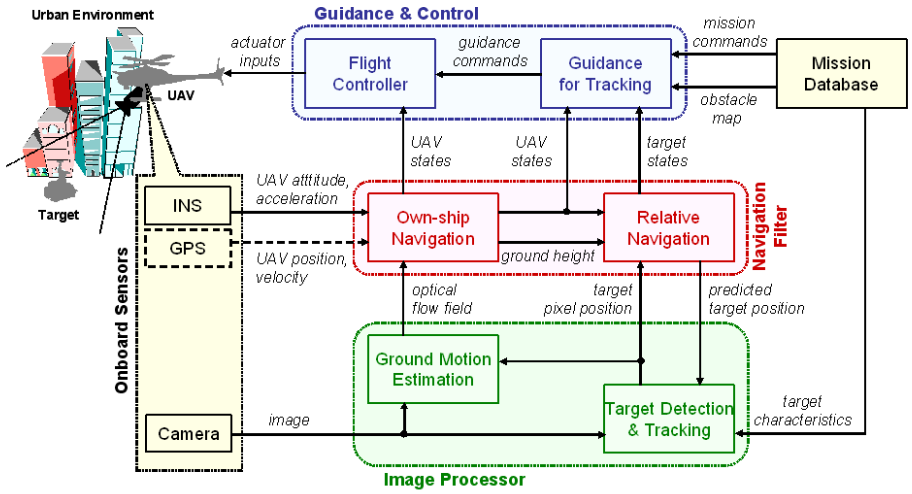
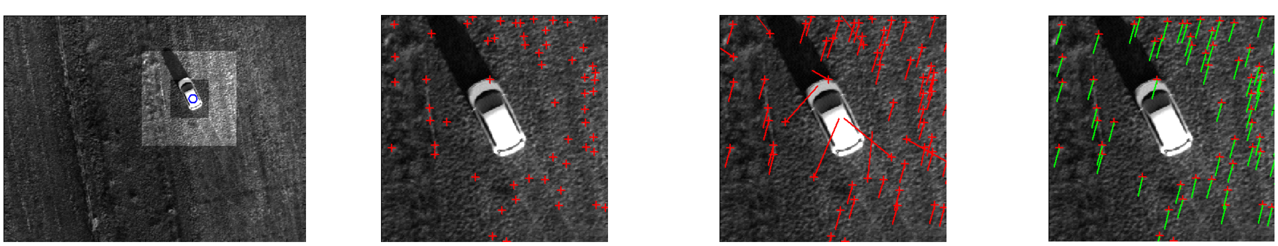


Figure 2. Vision-Based Navigation and Tracking System

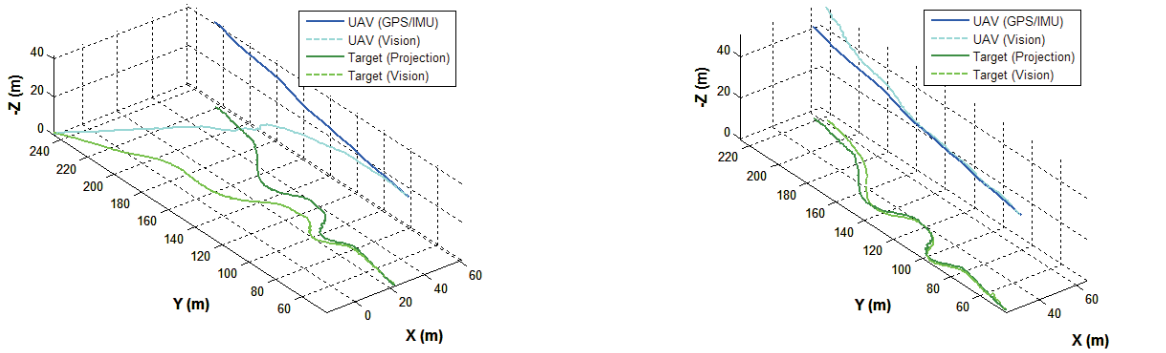
a) Original Image b) Binarized Image c) Object Extraction d) Target Detection

Figure 3. Automatic Target Detection



a) Target Detection b) Feature Point Selection c) Feature Point Matching d) Affine Approximation

Figure 4. Ground Motion (Sparse Optical Flow) Estimation



a) INS-Only Navigation b) Vision/INS Navigation (with Optical Flow)

Figure 5. Navigation Results with and without Optical Flow Measurement

data synchronically recorded with the onboard camera images in open-loop flight of the ONERA ReSSAC helicopter. Figure 5 compares the self- and target-localization results of the INS-only navigation and the suggested vision/INS navigation when assuming an absence of GPS measurements. It is clear from the result that the optical flow measurement effectively complements the GPS information and eliminates the divergence in the INS-only navigation solution.

C. Guidance Design

A UAV guidance objective of the target search operational phase is to follow a pre-planned search path (say $\boldsymbol{X}_{ref}$), and that of the target tracking phase is to track the target while avoiding obstacles. There is a large body of research in UAV urban navigation, including an optical flow-based biomimetic approach to obstacle avoidance [9]. For simplicity, it is suggested performing obstacle avoidance by maintaining a position-dependent safety altitude $h_d(X, Y)$ that is determined based on an obstacle map obtained during the first operational phase. Then, the UAV guidance problem becomes a position tracking problem where the desired position is given by

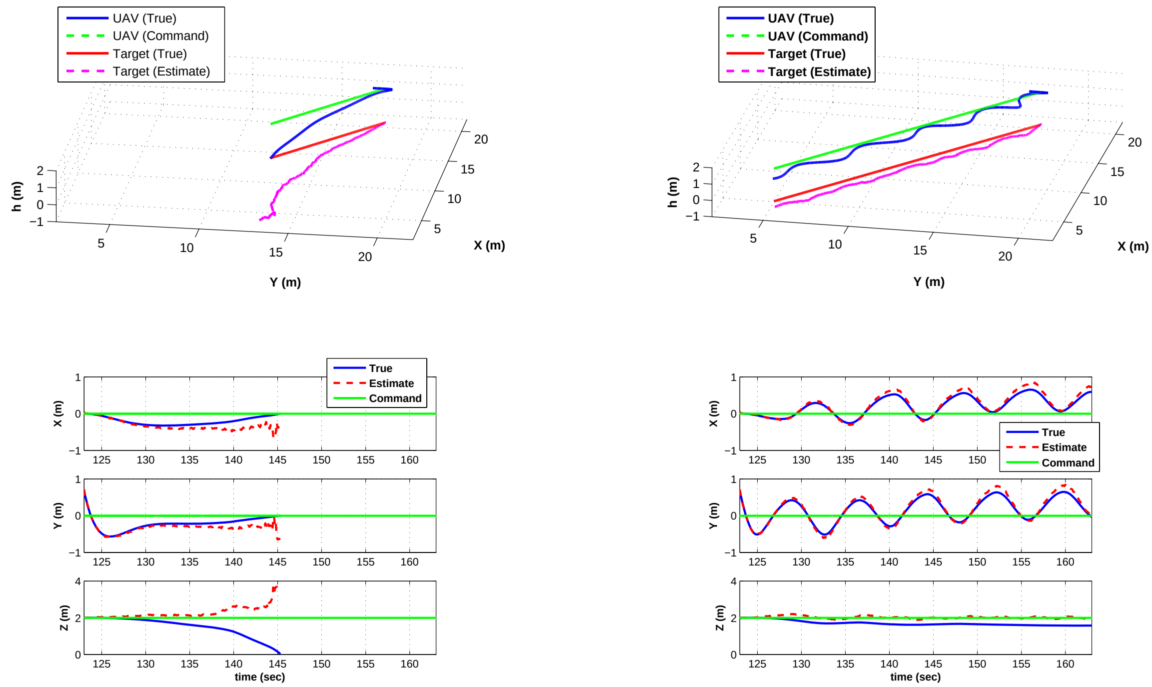
$$\boldsymbol{X}_d(t) = \begin{cases} \boldsymbol{X}_{ref}(t), & \text{during target search} \\ [\, X_t(t) \quad Y_t(t) \quad -h_d\left(X_v(t), Y_v(t)\right)]^T, & \text{during target tracking} \end{cases}$$

(X_t, Y_t) and (X_v, Y_v) are global horizontal position of the target and the UAV respectively. As shown in Figure 2, the guidance input is calculated by using the estimated state of the UAV and the target. The following linear feedback law is the simplest and most commonly used approach to determine the UAV acceleration input for position tracking.

$$\boldsymbol{a}_{com}(t) = -K_P(\hat{\boldsymbol{X}}_v(t) - \hat{\boldsymbol{X}}_d(t)) - K_D(\hat{\boldsymbol{V}}_v(t) - \hat{\dot{\boldsymbol{X}}}_d(t)) + \hat{\ddot{\boldsymbol{X}}}_d(t)$$

However, this guidance can cause a large tracking error when the estimation error is large.

In vision-based navigation and control problems in general, the separation principal does not hold between estimation and control. It means that the navigation performance highly depends on relative motion of a camera with respect to objects of interest (e.g. target, ground surface). Particularly in bearing-only relative navigation, the depth information becomes unobservable when there is no lateral relative motion [10]. Therefore, this paper suggests introducing an extra input $\Delta\boldsymbol{a}_{com}$ to create motions that enhance the estimation performance and minimize the expected position tracking error. Because of its realtime applicability, the one-step-ahead optimization approach proposed in [4] is applied to obtain $\Delta\boldsymbol{a}_{com}$. This approach performs the optimization under an assumption that there will be only one more measurement at the one time step ahead. Figure 6 compares simulation results of visual target tracking when using the nominal linear guidance law and the one-step-ahead optimal guidance law. When using the linear guidance, the UAV ends up crashing due to a drift in the height estimation. On the other hand, the optimal guidance generates a small lateral motion to maintain the height observability and prevents the crash from occuring. It has been also verified through simulations that the proposed guidance law is effective for the optical flow-based self-navigation.



a) Nominal Linear Guidance b) One-Step-Ahead Optimal Guidance

Figure 6. Vision-Based Relative Navigation and Target Tracking Result: UAV and target trajectories (top), true and estimated relative positions (bottom)

III. Onboard System and Flight Experiment

An ultimate goal of this work is to implement the vision-based navigation and target tracking system designed in Section II onboard on the ONERA ReSSAC unmanned helicopter, and to evaluate the system in its flights. This section explains the embedded architecture of the ReSSAC UAV and presents some preliminary flight experiment results.

A. The ONERA ReSSAC Unmanned Helicopter

The ONERA ReSSAC helicopter is an experimental platform that has been developed based on an industrial unmanned helicopter YAMAHA RMax. Table 1 summarizes its specifications. The onboard system of the ReSSAC helicopter is composed of two processors. The first one is dedicated to a basic flight controller including the GPS/INS navigation and auto-pilot system that have been described in previous publications [11]. The second one is for the decision architecture which is in charge of mission management, decision-making and supervision. The system proposed in this paper is implemented on this second processor. These two processors interact and communicate through a serial connection. This connection allows the decision architecture to obtain the UAV estimated state from the self-navigation and also to send a guidance command request to the auto-pilot.

Table 1. Specifications of the ONERA ReSSAC Helicopter

Length (including main rotor)	3.63 (m)
Empty Weight	60 (kg)
Payload	20 (kg)
Onboard Sensors	GPS, INS, Compass, Barometer, Camera etc.

B. Orocos-Based Decision Architecture

The decision architecture is executed on a Linux Debian system and is based on Orocos middleware [5]. Orocos is an open source robotic framework, which offers a real-time toolkit (RTT) that manages interactions and execution of components that are defined and developed by a user. An Orocos component interface is shown in Figure 7. Such a component may be connected to hardware devices (camera, controller etc.) or it may integrate processes. For the visual target tracking system, the image processor, the navigation filter and the guidance law are implemented as Orocos components in C++ based on the Orocos RTT library. The entire system is built by connecting and activating these components.

Execution of each component is monitored and controlled by a supervisor, which is considered as a central component in terms of control flow. The supervision is performed by executing hierarchical finite state machines that are represented by the UML state diagram model [6]. The state machine manages data flows (connection between components), execution (start or stop components) and recovery modes (reaction to events). The supervision state machine is written in the Orocos scripting language within a component called *Deployer*, which is executed with the highest priority among all the components. Figure 8 shows an example of the supervision state machine for visual target tracking mission.

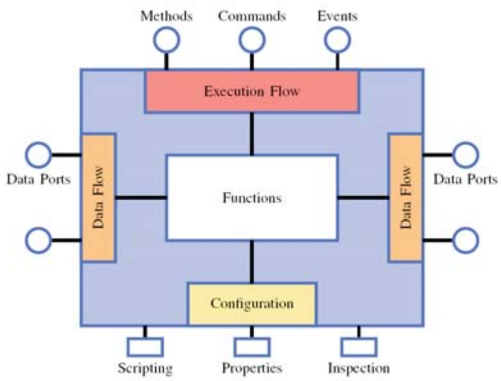


Figure 7. Orocos Component Interface

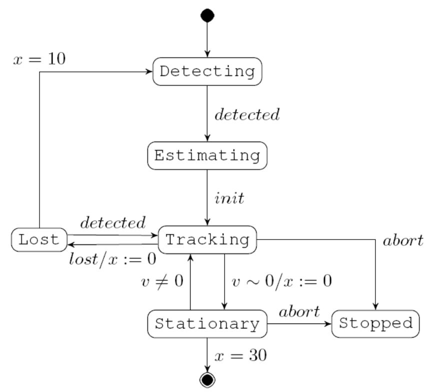
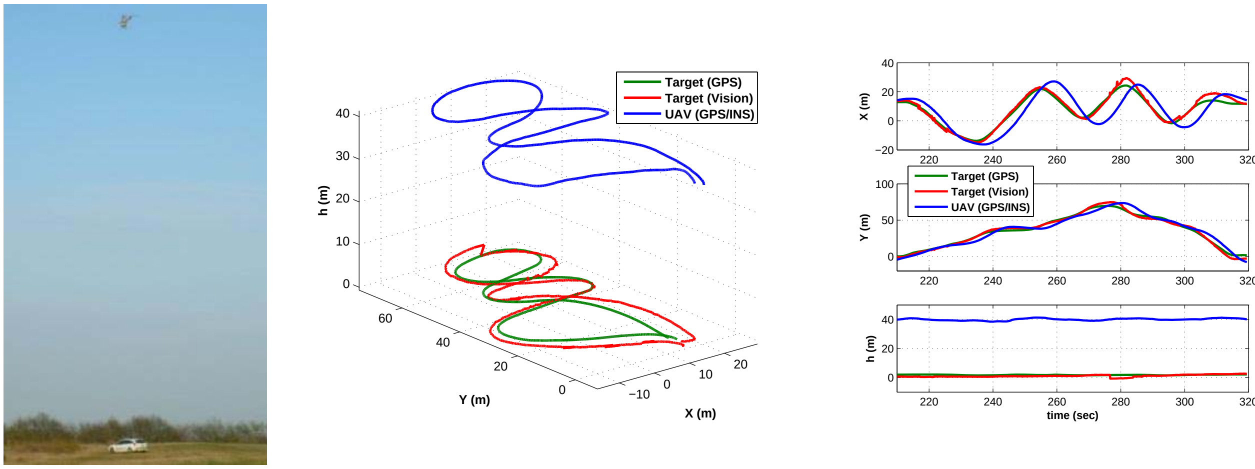


Figure 8. Example of Supervision State Machine

C. Flight Experiment

A simplified version of the target tracking system (assuming no obstacles and no loss of GPS signal, and hence without the optical flow estimation algorithm) has already been developed and implemented in the Orocos architecture onboard the ReSSAC helicopter. An entire process including the image processor (automatic detection and target tracker), the relative navigation filter and the linear guidance law runs at 10 Hz. The guidance law outputs a UAV horizontal velocity, height and heading angle commands based on the visually estimated relative state, and passes these commands to the flight controller which calcultes actuator inputs of the helicoter to achive the command while stabilizing the vehicle. Flight experiments of air-to-ground target tracking have been conducted using a manually-driven car as a moving ground target, and purely vision-based closed-loop flights have been successfully achieved. Figure 9 presents the flight test results of the UAV tracking trajectory and the target GPS-measured and vision-based estimated trajectories. To ensure flight safety, constant height and heading angle commands were used in this experiment. It can be concluded from the result that the target is accurately localized by using its pixel coordinate information, and hence the UAV tracks the target with a good precision.

This embedded system will be completed by the optical flow estimation, the optical flow-based self-navigation, the one-step-ahead optimal guidance law, and the obstacle avoidance algorithms. The next step in flight experiment is to evaluate the optimal guidance law for the relative navigation, and also to attain the real-time optical flow estimation onboard. The ultimate goal is to perform closed-loop target tracking in the presence of obstacles and occasional loss of GPS signals. This will be the first attempt of a GPS-free automatic flight of the ReSSAC helicopter.



a) Experiment Scene b) 3D Trajectory c) Global Position Profile

Figure 9. Flight Test Result of Closed-Loop Vision-Based Target Tracking

IV. Conclusion and Future Work

This paper outlines a UAV navigation and guidance system for vision-based air-to-ground target search and tracking in a GPS-denied obstacle field. It is suggested to utilize sparse optical flow to aide UAV self-navigation when GPS information is not available. Moreover, the optimal guidance law is applied to improve navigation accuracy. An embedded software architecture is developed in order to implement the suggested system into the onboard processor of the ONERA ReSSAC helicopter. Closed-loop vision-based target tracking has successfully been achieved in flight with this architecture.

Flight experiment results of the simultaneous visual target tracking and optical flow-based navigation are expected in the final paper. For future work, we aim to augment the system with mission planning and decision making algorithms so that it can be applied to a more complex mission scenario than the one presented in Figure 1.

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