Robotics and Autonomous Systems 57 (2009) 591–602

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Optic flow-based vision system for autonomous 3D localization and control of small aerial vehicles

Farid Kendoul [a,*], Isabelle Fantoni [a], Kenzo Nonami [b]

[a] Heudiasyc Lab., UMR CNRS-UTC 6599, University of Technology of Compiegne, 60200 Compiègne, France

[b] Robotics and Control Lab., Electronics and Mechanical Engineering Department, Chiba University, 263-8522, Chiba City, Japan

ARTICLE INFO

Article history:
Received 29 July 2007
Received in revised form
4 February 2009
Accepted 5 February 2009
Available online 20 February 2009

Keywords:
UAV
Autonomous localization
Optic flow
Structure-From-Motion (SFM)
Flight guidance and control
Visual SLAM

ABSTRACT

The problem considered in this paper involves the design of a vision-based autopilot for small and micro Unmanned Aerial Vehicles (UAVs). The proposed autopilot is based on an optic flow-based vision system for autonomous localization and scene mapping, and a nonlinear control system for flight control and guidance. This paper focusses on the development of a real-time 3D vision algorithm for estimating optic flow, aircraft self-motion and depth map, using a low-resolution onboard camera and a low-cost Inertial Measurement Unit (IMU). Our implementation is based on 3 Nested Kalman Filters (3NKF) and results in an efficient and robust estimation process. The vision and control algorithms have been implemented on a quadrotor UAV, and demonstrated in real-time flight tests. Experimental results show that the proposed vision-based autopilot enabled a small rotorcraft to achieve fully-autonomous flight using information extracted from optic flow.

1. Introduction

Recent advances in cost-effective inertial sensors and accurate navigation systems, such as the GPS, have been key determinants of the feasibility of UAV systems. Milestones in manned and unmanned aircraft have been achieved using conventional navigation sensors such as standard IMUs for orientation, GPS for position, pressure sensors for altitude sensing, radar, ultrasound and laser range-finder for detection of obstacles. Our particular interest, however, involves small and micro UAVs flying close to the ground in cluttered environments like urban and indoor environments. Therefore, GPS information may not be available. Furthermore, the substantial weight and energy constraints imposed by small and micro UAVs preclude the use of conventional sensors. On the other hand, visual sensors are passive, lightweight and can provide rich information about the aircraft's self-motion and surroundings structure. Therefore, computer vision can be used for autonomous localization, which is a crucial step for small aerial robot's control and guidance. However, the design of a reliable vision system for aerial vehicles has many unsolved problems, ranging from hardware and software development to pure theoretical issues, which are even more complicated when applied to small flying machines operating in unstructured environments. Moreover, the difficulty found when using imaging sensors is the high bandwidth of data, and the resulting heavy computational burden.

Using computer vision for autonomous localization leads to the visual servoing problem [1]. Recently, there has been a growing interest in applying visual navigation principles of insects for UAVs control and guidance. Indeed, recent experimental research in biology has discovered a number of different ways in which insects use optic flow in order to deal with the 3D flight control problem [2,3]. We believe that flying insects can provide us with ingenious solutions and efficient flight behaviors which are appropriate for implementation in artificial flying machines. We thus, take inspiration from insects in order to develop a vision-based autopilot that functionally imitates the vision-control system of flying insects. indeed, the proposed autopilot is based on a minimum-sensor suite that includes a single onboard camera and a low-cost IMU. This paper focuses on the development of a real-time vision algorithm that jointly performs optic flow computation and interpretation (recovery of 3D motion and structure) using insect-inspired sensory systems. Our motivation for this work is to develop a fully embedded, lightweight, and low-cost solution for autonomous localization in an arbitrary and unknown environment using optic flow. The proposed computational framework is based on 3 Nested Kalman Filters (3NKF) which allowed one to combine three algorithmic concepts stemming from different areas of research (optic flow

* Corresponding author. Tel.: +33 620571272.
E-mail addresses: fkendoul@restaff.chiba-u.jp, fkendoul@hds.utc.fr (F. Kendoul), ifantoni@hds.utc.fr (I. Fantoni), nonami@faculty.chiba-u.jp (K. Nonami).

0921-8890/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.robot.2009.02.001

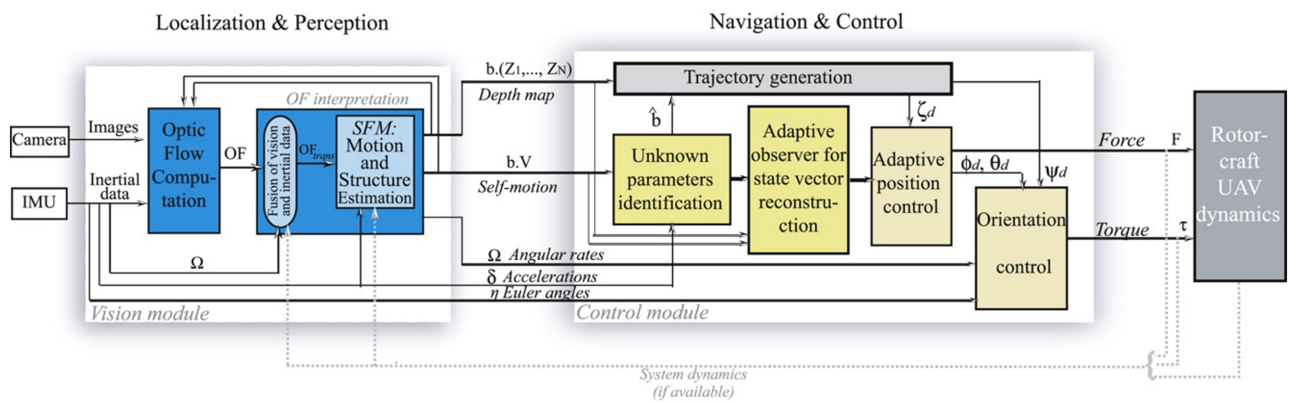

Fig. 1. Optic flow-based autopilot for small rotorcraft UAVs control and guidance.

computation, data fusion, SFM problem) in a favorable manner (see Fig. 1). The novelty of the approach is based on the fact that each sub-system is connected to other systems, thereby allowing a bidirectional exchange of data between them. The resulted 3NKF-based algorithm is fast, accurate and robust, which make it suitable for aerial robotic applications.

Section 2 summarizes related research in optic flow computation and interpretation, and presents some existing works on bio-inspired vision-based aerial navigation. In Sections 3 and 4, the philosophy behind the vision algorithm as well as its mathematical bases are described. Section 5 provides details about the aerial platform and the real-time implementation of the vision-control system. Experimental results are presented and discussed in Section 6. Conclusions are given in Section 7 with some directions for future work.

2. Related work and the proposed 3NKF framework

In this section, we give a short overview on existing methods for optic flow computation, cite some approaches for camera ego-motion and structure estimation, and present some examples about the application of image optic flow for UAVs navigation control.

2.1. Optic flow computation

The optic flow is defined as *the apparent motion of the image intensities caused by the 2D projection onto a retina of the relative 3D motion of scene points*. The standard optic flow techniques can be classified into four main groups according to the assumptions they make: *differential or gradient methods* [4,5], *correlation and block matching schemes* [6], *energy and phase-based methods* [7], and *sensor-based approaches* [8]. The simplest and the most used technique is the image matching or correlation method. However, this technique suffers from a lack of sub-pixel precision, quadratic computational complexity and inaccuracy in presence of image deformation due to rotation. On the other hand, the well-known differential models suffer from sensitivity to noise due to derivative computation, and their inability to handle large optical flow. A general way of circumventing these problems is to apply optical flow techniques in a hierarchical, coarse-to-fine framework [6]. Although the hierarchical techniques improve the optic flow computation, they suffer from a severe trade-off between efficiency and the maximum image displacement that can be computed. A review and comparison of the most popular OF algorithms can be found in [9]. Much progress has been made in optical flow computation and yet, its efficient and accurate estimation in real-time remains difficult, especially when it is used for robotic applications.

2.2. Structure From Motion problem

The problem of Structure From Motion (SFM) concerns the estimation of the camera ego-motion and the reconstruction of the 3D structure of a scene from its projection onto a moving two-dimensional surface (image sequences). SFM has been a central problem in computer vision for many years, and the literature comprises a variety of schemes that differ in the description of the system model (linear, non-linear), the projection model (orthographic, affine, perspective), input measurements (optic flow, feature tracking, image brightness), time-frame (continuous-time or discrete-time models), and data processing techniques (batch optimization, recursive estimation). The paper [10] provided a critical study of existing SFM techniques.

SFM estimation using sparse feature correspondences has been investigated for nearly 30 years [11–13]. Because of the high-speed requirement, low image quality, and rapidly changing of camera attitude, feature tracking may not be a trivial task [14]. Optic flow-based algorithms are an interesting alternative for the SFM problem [15]. Our choice for using optic flow is also motivated by the fact that insects rely heavily on optic flow to extract useful information for flight control and navigation. Given a set of measured optic flows, motion and structure parameters can be recovered modulo some scale factor using optimization algorithms like the least-squares technique [16]. Fusing-based algorithms like Extended Kalman Filter (EKF) [17,12] are the second traditional approach to SFM after an optimization framework.

There are many critical issues and limitations that are related to the SFM problem. First, extracting useful visual information (feature-detection and tracking or optic flow computation) in real-time and in natural environments is a challenging task which is not entirely solved yet. Second, it is well known that the mathematical system describing the SFM problem is not observable [14]. Hence, absolute translational velocities and real distances to perceived objects cannot be recovered. This is known as the scale factor problem. Third, ambiguities in 3D motion recovery from noisy flow fields have been reported by many researchers [13,18]. One dominant ambiguity arises from the similarity between the flow fields generated by translation parallel with the image plane and associated rotation. An interesting way to eliminate this translation-rotation confusion is to exploit angular rate data obtained from a camera-mounted rate sensor [13].

2.3. Bio-inspired vision-based aerial navigation

Many researchers have been interested by the world of flying insects, and recent experimental research in biology has discovered a number of different ways in which insects use cues derived from optical flow for navigational purposes. Indeed, insects