Computers and Electrical Engineering 000 (2017) 1–16

Contents lists available at ScienceDirect

Computers and Electrical Engineering

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

Multiple RGB-D sensor-based 3-D reconstruction and localization of indoor environment for mini MAV☆

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ARTICLE INFO

Article history:
Received 7 May 2016
Revised 12 August 2017
Accepted 15 August 2017
Available online xxx

Keywords:
Mini MAV
Visual sensor network
3-D reconstruction
Indoor localization
Kalman-consensus filter
Data fusion

ABSTRACT

Micro aerial vehicle (MAV) with lower cost, smaller size and more flexible flight performance plays a greater role in the global position system-denied (GPS-denied) indoor tasks. This paper focuses on the realization of three-dimensional (3-D) panoramic environment reconstruction and target localization without relying on any external navigation aid. By establishing a visual sensor network (VSN) composed of multiple RGB-Depth (RGB-D) sensors, a fast 3-D model of the observed environment is built utilizing an improved speeded up robust feature (SURF) extraction algorithm and iterative closest point-based (ICP-based) reconstruction algorithm. A distributed data fusion algorithm known as kalman-consensus filter (KCF) is then used to estimate a more accurate global position and trajectory of mini MAV. Both software simulations and real indoor flight experiment results demonstrate that the proposed approach achieves a fast and reliable 3-D map of the indoor environment and the accuracy of localization is largely improved.

1. Introduction

MAV is a form of robot that allows one to sample the environment and to act on it where no other sensor can reach, e.g., to monitor the environment at altitude [1], to search and rescue in the earthquake site [2] or fire disaster. Benefit from the development of micro-electro mechanical systems (MEMS), automatic control technology, new materials and battery technologies, mini MAV with lower cost, smaller size, lighter weight, more flexible flight performance and better concealing will play a greater role in surveying, aerial photography, medical escort, urban management [3] and other commercial and service areas.

In all these application cases, the mini MAV needs to be aware of the map of the environment and its own position in the 3-D space. To this end, positioning technologies and devices are needed in the system to efficiently accomplish these tasks. For outdoor applications, the GPS is widely used to sense object location, such as the vehicle tracking system and electronic maps in smart phones. However, when moving the applications into indoor environment, GPS may not be suitable since it requires a direct line-of-sight communication to the satellites which is not possible in indoor environment. Furthermore, the moving space of indoor environment is limited and has changeable furniture and moving people, which is usually more complex and challenging for mini MAV. New challenges and higher requirements of positioning accuracy, dependability and efficiency are faced.

☆ Reviews processed and recommended for publication to the Editor-in-Chief by Guest Editor Dr. A. H. Mazinan.

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http://dx.doi.org/10.1016/j.compeleceng.2017.08.011

This paper focuses on the GPS-denied indoor applications of mini MAVs and deals with the problems of the realization of 3-D panoramic environment reconstruction and target localization. A VSN composed of multiple overlapping active RGB-D sensors is established to cover the whole indoor surveillance area. The sensors employed in the 3-D VSN are rigidly mounted in the environment to capture the scene from different perspectives instead of fixing on the MAV or being held by user's hands and moving around to cover the whole area. This configuration reduces the load of the mini MAV and enables flexible network size.

Compared with the existing 3-D reconstruction and MAV localization systems and approaches, the main contributions of this paper are as follows:

(1) We present a 3-D panoramic reconstruction method of the observed indoor environment using only RGB-D data provided by multiple RGB-D sensors. A hole filling algorithm based on local color matching and the ICP-based registration method are proposed to ensure a fast and consecutive 3-D panoramic reconstruction.
(2) We propose a KCF-based data fusion approach to estimate the global position and the trajectory of mini MAV. By referring to the estimations of all sensors that viewing the same target, our method attains a 3-D consistent global localization of the mini MAV, which is more synthetic, accurate and reliable than the method using only one single sensor.
(3) We establish a 3-D VSN composed of only RGB-D sensors to enable indoor applications of mini MAVs in GPS-denied environments without relying on any external navigation aids. Moreover, we validate the efficiency of the proposed 3-D reconstruction and KCF-based data fusion localization methods on the real-time platform. The comparison experiments and real flight experiments demonstrate that our approach achieves a fast, reliable and comprehensive 3-D map of the indoor environment and the accuracy of localization is greatly improved.

The rest of this paper is organized as follows. Section 2 gives a review of the related methods, enabling technologies and system implementations of indoor localization. Section 3 states both the hardware architecture and the software process of the proposed 3-D reconstruction and localization approach. Section 4 and Section 5 introduce the details of the proposed SURF and ICP-base environment modeling and the KCF-based data fusion localization methods respectively. Results and discussions of both simulations and real flight experiments are presented in Section 6. Finally, we conclude our work in Section 7.

2. Related work

The researches have offered broad approaches in the indoor localization field. One alternative solution is to use localization technologies based on wireless network. In recent years, researchers have implemented several successful indoor localization systems using different wireless technologies such as IEEE 802.11 wireless local area network (WLAN), Zigbee and radio frequency identification devices (RFID). RADAR System is a building-wide WLAN-based tracking system developed by Microsoft Research Group [4]. Since this approach utilized the existing wireless networking infrastructure of the building, only a few base stations were needed. Sugano et al. implemented an indoor localization system based on the ZigBee standard in a wireless sensor network [5]. The system automatically estimated the distance between sensor nodes by measuring the received signal strength indicator (RSSI). Álvarez et al. also provided a RSSI-based indoor person/assets location method and implemented it in a wireless sensor network using Zigbee standard [6]. They improved the positioning accuracy to 0.75 m by a correction based on the difference between the free space field decay law and the measured RSSI. In LANDMARC system, RFID technology was used for locating objects inside buildings [7]. The system calculated the position of the tagging object according to the information of nearest known reference tags. UBIRO is a mobile robot navigation system using passive RFID deployed on the ground [8]. According to the Cartesian coordinates of the tags in a regular grid-like pattern, it was able to estimate the robot's location and orientation by using trigonometric functions. The experimental results showed that the localization error was 13.3 cm at X-axis and 5.7 cm at Y-axis in average. Instead of using RSSI measurements like the previse two RFID-based systems, Yang et al. provided a millimeter-level accuracy localization and tracking system named Tagoram by leveraging the RF phase value of the backscattered signal to estimate the location of the object [9].

All the localization systems introduced above were implemented in two-dimensional (2-D) situation and it is difficult to apply the same methods and system implements to 3-D space because they could only use one-dimensional (1-D) wireless signals, whether RSSI or RF phase. Moreover, they all suffered from unstable signals intensity, inevitable signal interference and the localization accuracies were not satisfied even though the targets were not moving in the space.

Therefore, other researchers have emphasized on newer technologies that could provide richer environmental information. Chowdhary et al. used a scanning 2-D laser rangefinder and a streamlined simultaneous localization and mapping (SLAM) algorithm to provide a position and heading estimate [10]. This implementation only works well in environments with vertical structures and was not suitable for complex 3-D indoor environment. Weiss et al. developed an autonomous navigation system of a micro helicopter by using a single monocular camera and inertial sensors onboard [11]. Carrillo et al. utilized stereo camera and inertial motion estimation system to realize autonomously take-off, positioning, navigation and landing in unknown environment for unmanned aerial vehicle (UAV) [12]. A kalman filter fusion method of using stereo visual odometry and inertial measurements was used to provide accurate estimates of the UAV position and velocity. These methods relied on computation-intensive algorithms to execute the localization, because the vision data contained rich environmental information. In order to speed up the visual localization and increase accuracy, other methods may have to be