WhyCon: An Efficent, Marker-based Localization System

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***Abstract*— We present an open-source marker-based localization system intended as a low-cost easy-to-deploy solution for aerial and swarm robotics. The main advantage of the presented method is its high computational efficiency, which allows its deployment on small robots with limited computational resources. Even on low-end computers, the core component of the system can detect and estimate 3D positions of hundreds of black and white markers at the maximum frame-rate of standard cameras. The method is robust to changing lighting conditions and achieves accuracy in the order of millimeters to centimeters. Due to its reliability, simplicity of use and availability as an open-source ROS module (*http://purl.org/robotics/whycon*), the system is now used in a number of aerial robotics projects where fast and precise relative localization is required.**

I. Introduction

Precise and reliable pose estimation is one of the main problems of mobile robotics. Robots not only need to estimate their own pose, but, in the case of multi-robot and swarm systems, they also need to determine the relative poses of their peers. While both the self-localization and pose-estimation problems can be tackled by several methods, these might still be too computationally intensive for deployment on robots with constrained processing power. Thus, a popular solution to the problem of localization is the use of artificial markers, which are tailored for reliable detection and accurate localization.

This paper presents a precise, fast, reliable, easy to use, and open-source vision-based localization system based on off-the-shelf components [1]. Unlike widely used commercial systems, the presented system does not require any special equipment and is significantly faster than the ArTag- [2] and OpenCV-based solutions. A thorough description of the method is presented in [3], [4] and a complete hardware and software solution comprising a lightweight embedded module that runs an early version of the described algorithm is presented in [5].

II. Description

The core of the presented system is based on efficient detection of a black and white roundel (see Figure 1) with known dimensions. The algorithm combines on-demand thresholding, a flood-fill technique, and on-the-fly calculation of the detected pattern statistics.

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Fig. 1. Decentralized formation flight based on relative localization performed by the presented method. Courtesy of the GRASP laboratory, UPENN.

In the first stage, the algorithm employs a fast flood-fill technique to search for contiguous segments of dark pixels. The ratio of each segment's pixels to its bounding box area is then compared to a value calculated from the known dimensions of the searched pattern. If the test is passed, the method starts to search around the segment's centroid for another continuous area of bright pixels and again verifies if the number of pixels conforms to the value calculated from its bounding box dimensions. Successful pass of the second test indicates that the method found two elliptical, roughly concentric patterns and the subsequent stage verifies if the ratio of their areas, concentricity and semi-axes dimensions conform with the known shape of the searched pattern. Once the segments found pass this test, the pattern's 3D position is calculated based on its known dimensions, camera parameters, and the user-defined coordinate system. The aforementioned consecutive steps allow for a quick rejection of outliers in the early stages of the detection, which improves the algorithm's performance. More importantly, the flood-fill technique can be initiated from any position in the processed image without a performance penalty, which allows to start the search at a position predicted from the previous detection. This typically results in a quick search that processes only pixels that belong to the actual pattern and its immediate vicinity, which significantly reduces the computational cost.

The localization system is available as a ROS package [1], which includes both a shared library containing the main functionality and a series of *nodes*. A base node performs target detection and 3D position estimation in camera coordinates. For the case of targets moving on the plane, a simple calibration can be performed resulting in increased localization precision. For the full 3D motion case, another node can estimate the position in user-defined coordinates. Finally, by using a pattern composed of three circles forming an "L" shape, orientation can be directly obtained.

III. Performance

The accuracy of the position estimation and computational efficiency of the detection were thoroughly examined in [4], which presents comparisons of the method to the popular ArUco [2] system and an OpenCV-based solution. The results presented in [4] show that the typical search time of a single pattern in an 1-10Mpix image is about 40 μs on a standard desktop and 1-5 ms on the Raspberry Pi, which is two orders of magnitude faster than ArUco or OpenCV. Furthermore, [4] reports that the system accuracy is about 1% for the full 3D and 0.2% for 2D position estimation, which outperforms slightly the other two baseline methods. The paper [4] also presents a mathematical model which allows to determine the system accuracy, processing time and coverage based on the camera and processing hardware parameters.

IV. Applications

The presented system is used by several research groups internationally, both 'off-board' as a low-cost alternative to precise motion-capture-based localization systems and 'on-board' for detecting other robots and important environment cues. A typical example of its 'off-board' application is its use as an external reference to evaluate the precision and efficiency of visual-based UAV navigation [6], [7] and localization methods [8]. Other research teams used our software on-board UAVs as a computationally efficient and precise module for relative localization of other quadrotors [5], [9], which allowed to deploy quadrotor swarms in surveillance [10] and plume tracking [11]. The ability to accurately determine relative positions of other robots also allows for precise formation control of both UAV [12] and heterogenous UAV-UGV teams [13], [14]. Moreover, the system is precise and robust enough to allow autonomous landing of the UAV's on a slowly moving UGV [15].

The system was also used outside of the aerial robotics domain, e.g., to evaluate the accuracy of ground robot navigation [16], [17] and efficiency of motion planning in evolutionary robotics [18], [19]. Due to its computational efficiency and ease of use, it has found applications in swarm robotics, e.g., for visual-based docking to power sources [20], as a component of artificial pheromone systems [21], and in automated analysis of the swarm behaviour [22].

V. Conclusions

We present a computationally efficient and precise vision-based system intended for marker-based localization. The system allows real-time detection and precise localization of large numbers of black-and-white markers on computationally-constrained hardware. Source code for the presented method is publicly available at [1], either as a standalone application or as a component of the Robot Operating System (ROS) framework. The system reliability, ease of use, and the fact that it utilizes only low-cost, off-the-shelf components makes it a popular choice in aerial and swarm robotics research.

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