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Dual Active Marker Modules for Enhanced 6D Pose Estimation

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Abstract: This study proposes the development and application of dual active marker tracking modules for enhanced 6D pose estimation, aiming to overcome the limitations of traditional marker-based pose estimation methods. Traditional approaches, which rely on the installation of multiple 2D markers or volumetric markers, often encounter issues like marker loss, damage, and recognition difficulties from certain angles. To address these challenges, our system incorporates two synchronized marker tracking modules, each equipped with an embedded computer, a 2-axis actuator, an augmented reality (AR) marker, and a camera. These modules actively track each other's markers, ensuring reliable performance even in large workspaces. By aggregating data from both modules and employing a Kalman filter (KF), our system achieves precise estimation of the relative positions and orientations between the modules. Through the integration of dual active marker tracking modules, our approach not only enhances pose estimation accuracy but also expands the possibilities for innovative applications in robotics, virtual reality, and AR applications.

Keywords: pose estimation; marker detection; active tracking

1. INTRODUCTION

The 6D pose estimation of objects is crucial across various fields, encompassing computer vision, robotics, virtual reality (VR), augmented reality (AR), automotive, and medical sectors [1], [2]. In robotics, accurately estimating an object's 6D pose is essential for determining the precise location and orientation of robots within their operating environments, thus enhancing system efficiency and accuracy [3], [4]. This capability facilitates precise posture control of robots and accurate interaction with their surroundings, ensuring effective task execution and significantly improving robot performance.

This study is motivated by the limitations and challenges identified in existing pose estimation methods. The proposed system employs a pair of marker detection and tracking modules. Each module comprised an embedded computer, a 2-axis actuator, an ArUco marker, and a camera. By combining a panel equipped with markers and a camera with a 2-axis actuator, each module can cover a wide range and track the marker mounted on the opposite module. In addition, allowing each module to face the opposite marker enhances the accuracy of the 6D pose between them. Through active detection and estimation of each other using two modules, the system efficiently mitigates issues related to limited FOV and narrow coverage associated with fixed markers. By fusing and filtering measurements from the two modules, accurate and robust 6D pose estimation is achievable. The proposed module and system hold potential applications in various fields requiring precise and robust 6D pose estimation, including mobile robots, drones, and AR and VR systems.

2. DESIGN OF ACTIVE MARKER MODULE

2.1 Hardware design

The proposed active marker module comprises an embedded computer, a robotic arm utilizing a 2-axis actuator, and a panel featuring an ArUco marker and camera, as illustrated in Fig. 1. The dimensions of the module is 12 cm $\times$ 10 cm $\times$ 27 cm (width $\times$ depth $\times$ height).

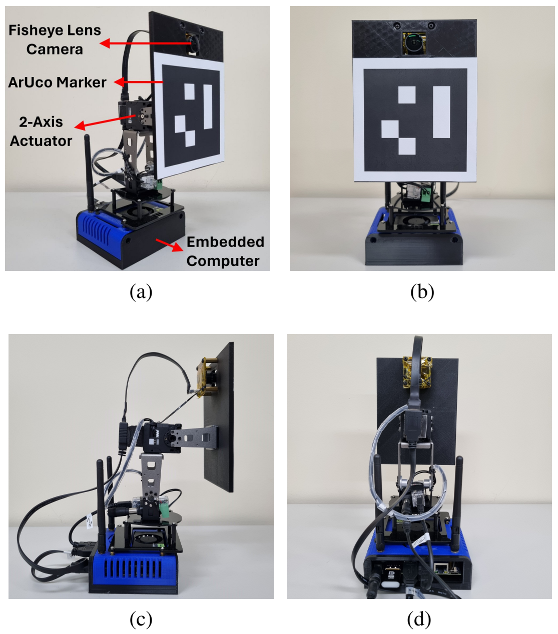

Fig. 1.: The active marker module: (**a**) overall, (**b**) front, (**c**) side, and (**d**) rear views.

The embedded computer utilizes the NVIDIA Jetson Orin Nano, a compact artificial intelligence (AI) computing platform developed by NVIDIA. The Jetson Orin Nano module is equipped with an NVIDIA Ampere architecture GPU, featuring 1024 CUDA cores, 32 thirdgeneration Tensor Cores, and a 6-core ARM CPU, facilitating high-performance AI-based inference. The operating system of the embedded computer is Ubuntu 20.04, and is integrated with the robot operating syste (ROS) 2 Foxy framework for the 6D pose estimation of ArUco markers and actuator control.

For the 2-axis actuator, the Dynamixel 2XC430-W250 from ROBOTIS is utilized. This actuator incorporates a controller based on an ARM CORTEX-M3 (72 MHz, 32-bit) microcontroller, enabling PID control. It offers a stall torque of 1.8 Nm and resolution of 4096 pulses/rev. Additionally, it supports multiple-turns via extended position control, allowing users to monitor and adjust motor operations in real-time through built-in communication interface, facilitating straightforward control of the robotic system. Communication between the actuator and the embedded computer is facilitated by the U2D2 communication module, which converts the actuator's RS-485 communication to USB communication for the embedded computer.

The camera employed for ArUco marker detection and pose estimation is the oCam-5CRO-U-M from WITHROBOT. This high-resolution color camera offers 5 megapixels and supports high-speed data transfer via USB 3.0, with UVC compatibility allowing for wide usage without the need for special drivers. The camera is configured to operate at a resolution of 1280 $\times$ 960 with 45 frames per second. The Arducam M23325H12 fisheye lens, mounted on the camera, provides a wide FOV essential for recognizing ArUco markers, offering 150°, 120°, and 83° of view in horizontal, vertical, and diagonal directions, respectively. By utilizing the fisheye lens, it is possible to track the movement of the opposite module quickly and accurately, even when it moves rapidly.

3. EXPERIMENTS

3.1 Experimental setup

To evaluate the proposed 6D pose estimation system, we established an experimental environment using a UR3 robot and two marker modules, as depicted in Fig. 2a. One module, termed the fixed module, was positioned on the table, while the other module, called the moving module, was attached to the gripper of the UR3 robot arm. The UR3 robot controlled the gripper to move along a predefined 3D path in the y-z plane with an x-value of 50 cm (Fig. 2b), ensuring zero 3D rotation between the base frames of the moving and fixed modules. The path depicted in Fig. 2b comprised seven subpaths. The moving module initiated its movement from Subpath 1, which formed a circle with a radius of 5 cm. Subsequently, it progressed through each subpath, incrementing the radius by 5 cm at each step, until it finally followed Subpath 7 with a radius of 20 cm.

In the experiments, the proposed system was operated in both passive and active modes to assess the effectiveness of active marker tracking. In the passive mode, all actuator angles of the marker modules were fixed at 0°, while in the active mode, the actuators were controlled to align the markers of both modules facing each other.

3.2 Results

In the experiments, the performance of the 6D pose estimation in both passive and active modes was evaluated. Fig. 3 displays the 3D positions of the moving module in passive and active modes. It can be observed that as the moving module traverses subpaths with larger radii, the passive mode failed to estimate the 3D positions due to an opposing marker exiting the camera's FOV, resulting in drift. In contrast, the active mode continuously tracks the opposite marker using actuators, ensuring a stable 3D position estimation regardless of the radius of the subpaths.

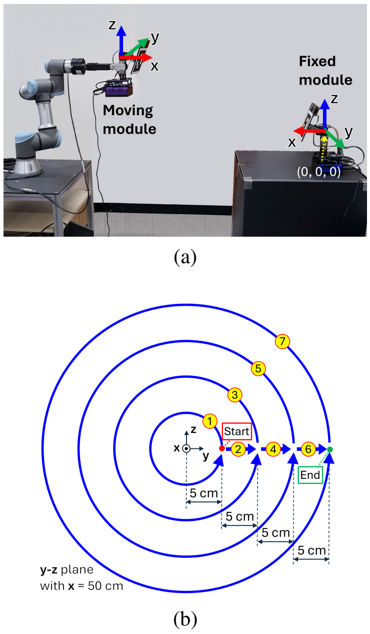

Fig. 2.: (a) Moving module attached to gripper of robot arm and fixed module on a table. (b) Predefined path of the moving module with respect to the fixed module.

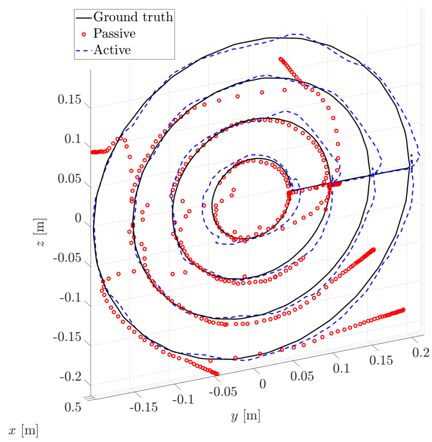

Fig. 3.: The 3D trajectory of the base frame origin of the moving module.

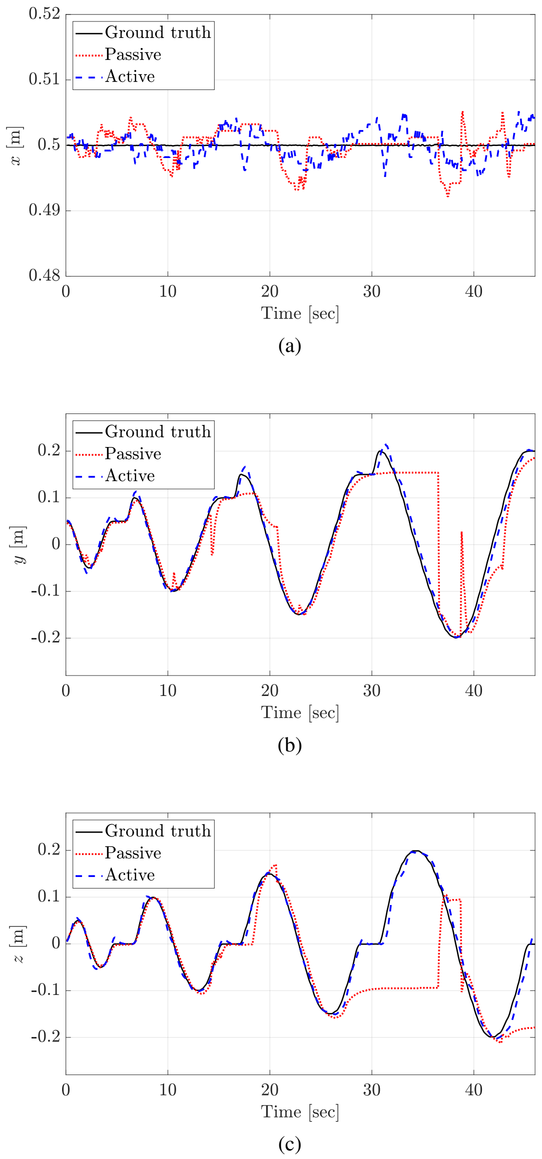

Fig. 4.: (a) x-, (b) y-, and (c) z-values of base frame origin of moving module over time.

Fig. 4 illustrates the estimated position values over time for the passive and active modes. The moving module moves in the $y-z$ plane with an x value of 0.5 m relative to the base frame coordinates of the fixed module, as shown in Fig. 2b. Therefore, the ground truth value for x remains fixed at 0.5 m, as depicted in Fig. 4a. In passive mode, as the radius of the subpaths increases, there are instances where the detection of the opposite marker fails. In such cases, estimation relies on the last successful marker detection. If the last estimation closely approximates the ground truth by chance, a small error may still be observed even if detection fails. Because the ground truth remains constant along the $x-$axis, even if marker detection fails in passive mode, a minimal error is incurred based on the previous estimations. As a result, both passive and active modes exhibited errors of less than 0.01 m.

However, as the moving module continuously moves in the $y-z$ plane, errors increase in the estimation of the $y-$axis and $z-$axis values if marker detection fails in the passive mode. As shown in Figs. 4b and 4c, during Subpath 7 (from 30 to 45 s), the passive mode failed in marker detection, leading to a noticeable deviation from the ground truth.

4. CONCLUSIONS

The study introduces dual active marker tracking modules for enhanced 6D pose estimation, offering a significant improvement over traditional marker-based methods. These modules address common challenges like marker loss and recognition difficulties by actively tracking each other's markers, thereby ensuring reliable performance in large workspaces. Through data fusion and Kalman filtering, robust and precise relative positions and orientations between modules were obtained. The proposed system not only overcomes limitations of previous methods but also opens new avenues for innovation in robotics, VR, and AR. Experimental validation demonstrated the effectiveness and reliability of the system. Future work will focus on further refining performance and exploring diverse real-world applications.

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