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RAPPORT de Projet

Autonomous Navigation and Tracking: Implementing Aruco Marker Detection on Parrot Drones

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Abstract

This report presents the development of an autonomous system for detecting and following ArUco markers using a Parrot drone. Leveraging computer vision techniques and a Proportional-Integral-Derivative (PID) control algorithm, the system enables the drone to dynamically align itself with a detected marker and maintain a consistent distance. Camera calibration was performed to enhance the accuracy of marker detection, and PID parameters were tuned through trial and error to achieve responsive and stable control along three axes. Despite hardware limitations, such as a blurry camera, the system successfully maintained the drone's position and distance within predefined thresholds. Challenges, including sporadic initialization errors, were resolved through system restarts. The results demonstrate the viability of marker-based navigation for autonomous drones and provide insights for enhancing reliability and performance in future implementations.

Keywords: Drone Navigation, PID Control, Computer Vision, UAV Control

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Introduction

ArUco markers, a type of fiducial marker, have become an essential tool in the field of computer vision due to their simplicity, robustness, and versatility. These black-and-white square patterns, embedded with unique identification codes, are widely used for tasks like pose estimation, object tracking, and robotic navigation. Paired with autonomous systems such as drones, they unlock a range of possibilities for precision-guided operations. The Parrot drone, a lightweight and adaptable unmanned aerial vehicle (UAV), serves as an excellent platform for exploring such applications due to its advanced onboard sensors, stable flight dynamics, and compatibility with computer vision frameworks.

Figure 1: Parrot AR.Drone 2.0

This project focuses on leveraging the capabilities of ArUco markers and Parrot drones to create an autonomous marker detection and following system. The primary goal is to enable the drone to detect ArUco markers in real-time, interpret their spatial orientation, and execute dynamic path adjustments to follow the marker autonomously. Such a system holds significant promise for real-world applications, including automated delivery systems, industrial inspection in confined spaces, and search-and-rescue operations. This report outlines the design, implementation, and evaluation of this system, providing insights into its performance and potential for further development in the field of autonomous robotics.

Literature

ArUco Markers

ArUco markers are 2D binary-encoded fiducial patterns designed to be quickly located by computer vision systems. They consist of a wide black border and an inner binary matrix, which determines their unique identifier. The black border facilitates fast detection in images, while the binary coding allows for error detection and correction. These markers are widely used in applications such as camera calibration, pose estimation, and augmented reality.

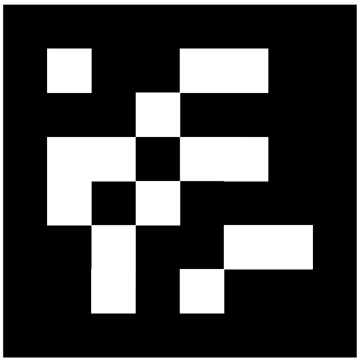

Figure 2: ArUco Marker: 6x6, ID: 50

The development of ArUco markers has significantly advanced augmented reality (AR) applications. By providing a reliable method for camera pose estimation, they enable the seamless integration of virtual objects into real-world environments. This capability has been leveraged in various fields, including education, entertainment, and industrial training, to create immersive experiences that enhance user engagement and learning outcomes.

Drone-Based Marker Detection Systems

Integrating ArUco marker detection with drones has been explored to enhance autonomous navigation and control. For instance, the Eachine E010 drone has been controlled using Python, a webcam, and an ArUco marker, demonstrating the feasibility of marker-based tracking for drone guidance. Additionally, the Tello drone has been programmed to autonomously track ArUco markers, showcasing the potential for implementing such systems in educational and research settings.

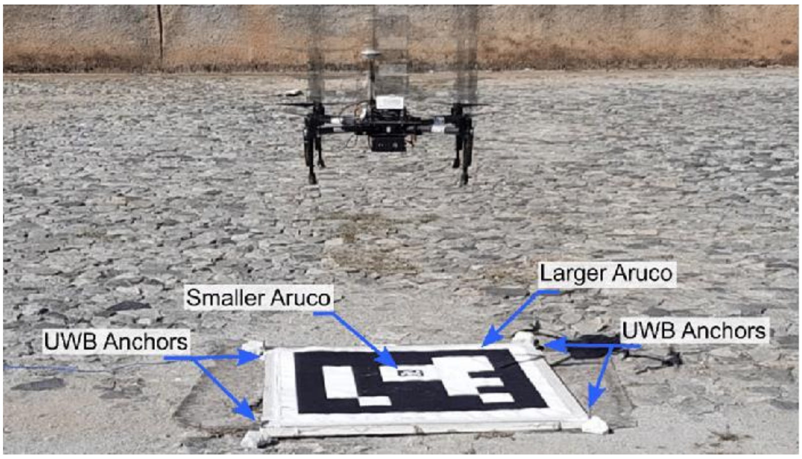

Figure 3: Landing a drone using arUco markers

A study on the Parrot AR Drone 2 demonstrated the use of convolutional neural networks (CNNs) for real-time object detection and tracking [1]. By integrating CNNs with the drone's onboard systems, researchers achieved improved accuracy in detecting and following targets marked with ArUco markers. This approach highlights the potential of combining traditional marker-based methods with advanced machine learning techniques to enhance drone autonomy and performance.

Computer Vision and Marker Tracking

In computer vision, detecting and estimating the pose of ArUco markers involves several algorithms and techniques. OpenCV provides functions like *cv2.aruco.detectMarkers()* for marker detection and *cv2.aruco.estimatePoseSingleMarkers()* for pose estimation. However, for improved accuracy, especially in high-resolution images, using *cv2.solvePnP()*

is recommended, as it allows the selection of different Perspective-n-Point algorithms. Additionally, refining detected marker corners to subpixel accuracy can enhance pose estimation results.

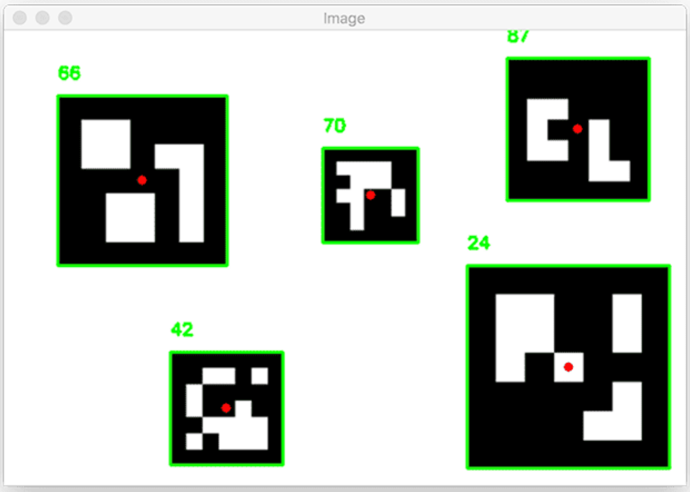

Figure 4: ArUco Marker detection with OpenCV

Recent advancements have explored the integration of deep learning techniques to improve marker detection robustness under challenging conditions. For example, the development of DeepArUco, a deep learning-based framework, aims to enhance detection and classification of ArUco markers in adverse lighting environments. This approach addresses limitations of traditional algorithms, offering improved performance in scenarios with varying illumination and partial occlusions.

Autonomous Drone Navigation

Vision-based navigation enables drones to operate in environments where GPS signals are weak or unavailable. Path planning algorithms that utilize visual inputs, such as images from onboard cameras, allow drones to navigate complex environments by recognizing and following visual markers like ArUco tags. This approach has been applied in scenarios like indoor navigation and GPS-denied environments, enhancing the autonomy and versatility of drones.

The integration of ArUco markers in autonomous drone navigation has been demonstrated in various applications, including automatic navigation and landing of indoor drones. By utilizing monocular vision systems to detect ArUco markers, drones can achieve accurate and continuous position estimation, facilitating precise landing and navigation in confined spaces. This method reduces reliance on external sensors and enhances the drone's ability to operate autonomously in indoor environments.

Gaps in Existing Research

While ArUco markers are effective in controlled environments, their performance can degrade under challenging conditions such as inadequate lighting or motion blur. Traditional marker detection algorithms may struggle in these scenarios, leading to reduced accuracy. To address these challenges, research has proposed deep learning-based frameworks like DeepArUco, which aim to improve detection and classification in adverse lighting conditions.

Additionally, there is a need for more research on the integration of ArUco markers with advanced sensor technologies to enhance detection robustness. Exploring the use of infrared imaging, for instance, could improve marker detection in low-light conditions. Furthermore, developing adaptive algorithms that can adjust to varying environmental factors in real-time would contribute to more reliable and versatile marker-based systems.

Overview

Building upon existing research, this project aims to develop a robust system for ArUco marker detection and autonomous following using a Parrot drone. By addressing challenges such as varying lighting conditions and dynamic environments, the project seeks to enhance the reliability and applicability of marker-based navigation systems. Implementing advanced computer vision techniques and real-time processing will contribute to the development of more autonomous and adaptable drones, with potential applications in areas like search and rescue, industrial inspection, and delivery services.

Moreover, this work will explore the integration of deep learning frameworks to improve detection accuracy and robustness. By combining traditional computer vision methods with machine learning techniques, the project aims to create a more resilient system capable of operating effectively in diverse and challenging environments. This approach has the potential to advance the field of autonomous robotics and contribute to the development of intelligent systems with enhanced perception and decision-making capabilities.

Control Technique

In robotics, several control techniques are employed to achieve stability, precision, and responsiveness in motion and navigation. Proportional-Integral-Derivative (PID) controllers are one of the most widely used techniques due to their simplicity and effectiveness. Other advanced techniques include Model Predictive Control (MPC), which optimizes control actions over a finite horizon while considering system constraints, and Fuzzy Logic Control (FLC), which emulates human decision-making to handle uncertainties. State-Space Control, rooted in control theory, is often used for systems with multiple interdependent variables, offering robust performance for complex dynamics. Additionally, Reinforcement Learning (RL) has gained attention for adaptive control, where a robot learns optimal strategies through trial and error. Each method has its strengths, depending on the complexity and requirements of the system being controlled.

PID

For this project, PID control was chosen to guide the Parrot drone in detecting and following ArUco markers. The PID controller's design simplicity, computational efficiency, and ability to handle real-time feedback make it ideal for embedded systems like drones. PID's proportional term ensures immediate response to errors by correcting deviations, while the integral term accumulates past errors to eliminate steady-state offsets. The derivative term dampens oscillations by predicting error trends, resulting in smoother control. These characteristics are crucial for achieving stable and responsive marker following, especially in dynamic environments. Furthermore, PID control does not require a detailed mathematical model of the system, making it suitable for the Parrot drone, whose precise dynamics may vary with payload or environmental factors. This balance of performance and practicality positions PID control as the optimal choice for this application.

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}.$$

Where:

- $u(t)$: Control signal or output at time t.
- K_p : Proportional gain that determines the response to the current error.
- $e(t)$: Error that is defined as the difference between the desired setpoint and the current process variable at time t.
- K_i : Integral gain that determines the response to the accumulated error over time.
- K_d : Derivative gain that determines the response to the rate of change of error.
- $\int_0^t e(\tau)d\tau$: Integral of the error over time.
- $\frac{de(t)}{dt}$: Derivative of the error with respect to time.

Algorithm

The proposed algorithm for controlling the drone begins with establishing a reliable connection to the drone's onboard camera over a 2.5GHz Wi-Fi network. This ensures a stable video feed, which is critical for real-time image processing and navigation. Using OpenCV, the drone captures frames from its camera, forming the foundation for subsequent computer vision tasks. To ensure accurate marker detection, camera calibration is performed by capturing up to 30 images of a checkerboard pattern at varying orientations and positions. This step corrects lens distortions and aligns the camera's intrinsic parameters for precise spatial measurements.

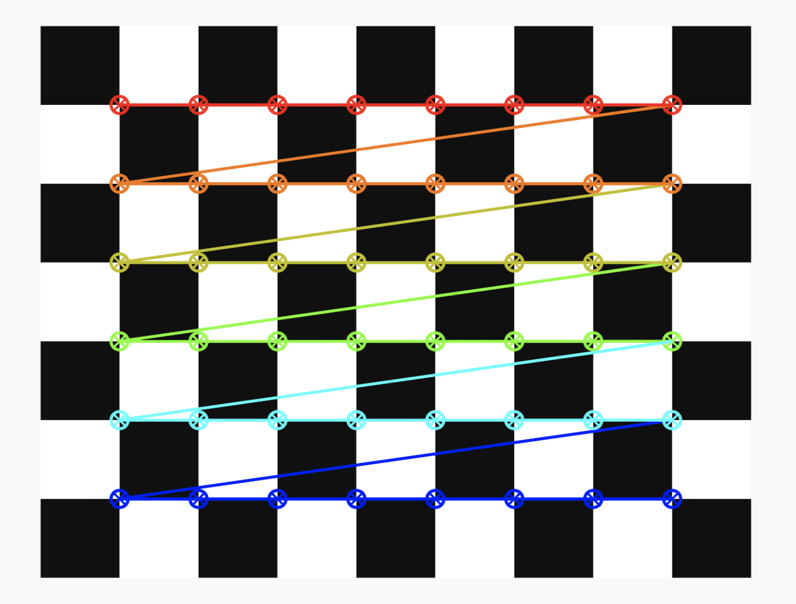

Figure 5: Checkerboard Pattern for Camera Calibration

Once the camera is calibrated, the algorithm focuses on ArUco marker detection within the video feed. OpenCV's marker detection module identifies the unique marker patterns and determines their pixel coordinates within the image. The center of the marker is compared to the center of the image, and the distance between these two points is calculated. This distance, interpreted as an error, reflects the deviation of the drone from its target alignment. The error serves as input for the PID control algorithm, tasked with minimizing the discrepancy and stabilizing the drone's movement.

Thresholds are defined to manage the acceptable range of deviations. Horizontally, the center of the ArUco marker is allowed to shift within ±25 pixels from the image center, while vertically, a range of ±20 pixels is tolerated. Additionally, the drone's proximity to the marker is maintained within a distance range of 75 cm to 100 cm. These thresholds guide the PID controller's behavior, ensuring the drone remains within the defined spatial constraints while dynamically adjusting its position.

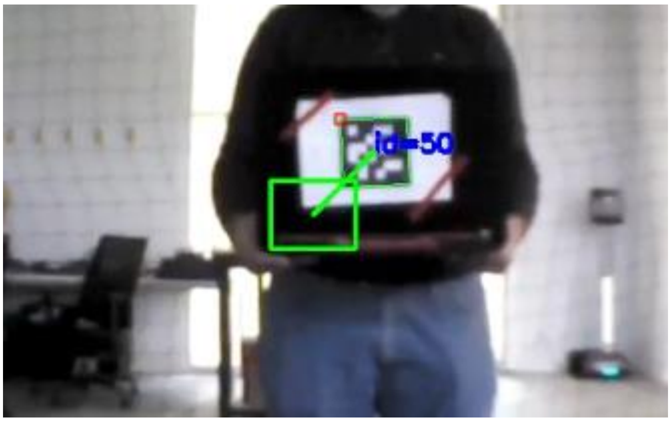

Figure 6: ArUco Marker Detection with Threshold Bounding Box

PID controllers are implemented across three axes — horizontal, vertical, and depth — each tailored to minimize error along its respective direction. The PID parameters for each axis are tuned through a systematic trial-and-error process. Initially, focus is given to the horizontal axis, iteratively adjusting the proportional, integral, and derivative gains until the controller achieves stable and responsive movement. Once optimal parameters are identified for one axis, the process is repeated for the remaining axes, culminating in a well-balanced control system.

The final step involves extensive testing and fine-tuning of the control algorithm in diverse environments. This iterative process ensures the system is robust and adaptable, capable of maintaining accurate and consistent drone navigation under varying real-world conditions. By combining precise vision-based measurements with dynamic error correction through PID, the algorithm achieves effective and reliable control of the drone for marker following tasks.

Results and Discussion

The results of the project demonstrate the effectiveness of using ArUco markers and a PID control system for drone navigation, albeit with some limitations. The drone's onboard camera, affected by a persistent blurriness, presented challenges for consistent marker detection. This issue was particularly noticeable at greater distances, where the image resolution and clarity were insufficient for reliable detection. Despite this limitation, the system was generally able to detect the marker when within the intended range, enabling the PID controller to function effectively.

When the ArUco marker was detected, the PID control system successfully maintained the drone's alignment and distance within the specified thresholds. The drone reliably kept the marker's position within ±25 pixels horizontally and ±20 pixels vertically from the image center, while also maintaining the prescribed distance range of 75 cm to 100 cm. This demonstrates the robustness of the PID algorithm dynamically adjusting the drone's movement to correct for positional errors. However, the project encountered intermittent anomalies, such as the drone initiating unexplained movement in a specific direction upon startup. This behavior was resolved through a simple system restart, suggesting possible initialization glitches in the hardware or communication.

Overall, the system achieved its objectives, showcasing the feasibility of marker-based navigation for autonomous drones. Despite the constraints imposed by hardware limitations, such as the blurry camera, the results validate the core methodology. These findings underscore the importance of robust calibration and fault tolerance in future implementations, where hardware enhancements and additional fail-safes could further improve system reliability and performance.

Conclusion

This project successfully implemented a system for ArUco marker detection and autonomous following using a Parrot drone, demonstrating the feasibility of vision-based navigation with PID control. Despite challenges such as a blurry onboard camera, the system reliably detected markers within close range and maintained the drone's position and distance within predefined thresholds. The use of PID controllers across three axes proved effective in dynamically adjusting the drone's movements, ensuring alignment and stability in real-time. Although occasional initialization anomalies were encountered, they were mitigated through simple resets, highlighting the need for improved hardware robustness in future iterations. Overall, the project achieved its intended objectives, offering a solid foundation for further exploration of vision-guided autonomous systems.

References

[1] A. Rohan, M. Rabah and S.-H. Kim, "Convolutional Neural Network-Based Real-Time Object Detection and Tracking for Parrot AR Drone 2," *IEEE Access,* vol. 7, pp. 1-1, 2019.