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Warehouse Inventory Management through Autonomous Drones using WhyCon Marker Localization System

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Abstract--- **In large warehouses, when conducting an inventory check or stock check, staff members are generally lifted up to high shelves utilizing a forklift, a truck, or scissor lift where they physically reach and examine/scan each standardized packet/item or box. This process is tedious, expensive, risky, and energy ineffective. To overcome this problem, we propose an autonomous drone-based technology using WhyCon Marker Localization System. Autonomous drones can navigate in storage areas very efficiently. They can scan and localize a maximum number of items/boxes on the go while sending live feedback of the stock inventory to the base station without any manual control. Generally, for autonomous drones, GPS based navigation system is used, but considering indoor warehouses GPS technology gives less accuracy for navigation. To counter this problem, we have used WhyCon Marker Localization System which uses a marker on a drone and an overhead camera to track the marker which in turn tracks the drone. This method is relatively inexpensive, can be implemented on lightweight drones, and gives high navigation accuracy in GPS denied environments as compared to other methods like SLAM, GPS, etc. For simulation and analysis, we have chosen an environment based on the Robot Operating System (ROS) and Gazebo simulator.**

***Index Terms*—** **Warehouse Inventory Management, WhyCon Marker Localization, Autonomous Drones, ROS, Robotics**

I. INTRODUCTION

The utilization of robots and drones in warehouses has been increased significantly over the past decade and it is estimated that the warehouse drone-based solutions market will rise to $29 billion by 2027 at an annual growth rate of 20% [1]. Before adapting to this technology, the main problems these warehouses faced were safety worries, prolonged time for inventory checks, inaccurate stock data thereby incurring huge financial losses to the companies. In an article by Forbes, Walmart (an American multinational retail corporation) lost $3 billion in 2013 due to inventory management problems [2].

Drones in indoor warehouses can be used for many tasks like stock checking, cycle counting, inventory maintenance, and audit. For implementing autonomous navigation in drones there are pre-existing GPS-based technologies available, but the major drawback of GPS-based technology is that it is very inaccurate when it comes to indoor environments. For navigating in a GPS denied environment there are techniques called SLAM (Simultaneous Localization and Mapping) which heavily rely on bulky sensors like lidars and require high computational resources. These components often make drones very heavy and large which counters our sole purpose to navigate in narrow aisles. To overcome this problem, we have used a vision-based external localization system namely WhyCon Marker Localization System [3]. It is computationally efficient, easy-to-deploy, and low-cost which can be deployed even on low-end processors.

This paper presents an alternate solution to the traditional warehouse inventory management process which is reliable, fast, inexpensive giving high accuracy. Unlike other widely used systems, the following presented system does not require any special components/sensors and is faster than OpenCV-based solutions. A thorough description of the WhyCon localization system and its integration with the base station is presented in subsequent chapters followed by a trivial technique to detect QR codes (pasted on boxes/items for inventory identification) using a camera module.

II. EXISTING TECHNOLOGIES

In this segment, a literature review about the navigation of existing autonomous UAV (unmanned aerial vehicle) systems, different SLAM algorithms, and GNSS systems are discussed. This section is followed by the implementation of the WhyCon Marker Localization system for our use case in section C.

A. Simultaneous localization and mapping (SLAM)

SLAM is mainly used in unmanned autonomous systems for building and updating maps/regions of unknown environments for navigation while the robot retains the information about its current location.[4] which consists of several steps. The goal of SLAM is to use the environment

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to update the position of the UAV/robot. One of the ways of getting the position of the robot is using odometry data (which gives UAVs/robot's position) although we cannot completely rely on this method due to drift errors from the UAV which can lead to inaccurate position estimation. In SLAM to correct or estimate the positions of the robot, laser scans of the environments are used. This process is accomplished by using an EKF (Extended Kalman Filter). EKF is responsible for updating the positions of the robot based on the estimated features from the laser scans and odometry data. EKF retains the track of an estimate of the uncertainty in the UAVs/robot's position and also the uncertainties in these landmarks it has seen in the environment. Most of the 2D SLAMs use lidar (light detection and ranging) sensors for laser scans. The major drawback of these systems primarily in the field of UAVs are high amounts of memory usage, bulky lidar sensors which not only require higher onboard computational resources but also are impractical for deployment on lightweight and inexpensive UAVs.

B. Global Navigation Satellite System (GNSS)

GNSS is widely used in outdoor drones which is based on position calculation on Earth's surface by measuring distances from a minimum of three known satellites and by using a fourth satellite, the altitude of a drone could also be calculated. But considering warehouses, this technology doesn't offer accuracy in indoor environments.

C. External Marker-based Localization System

Position-estimation and self-localization can be solved by many other navigation methods, but these might be computationally intensive for drones with constrained processing and storage power. Hence a popular solution developed for this problem is to use artificial markers which are to be detected by overhead cameras for accurate detection and localization of drone. ArTag, ArCuo marker, WhyCon marker, etc. are some of the popular external marker localization systems. The following paper presents the use of WhyCon marker system for pose estimation and localization of drones in warehouses as this system is significantly faster than ArTag and other OpenCV-based solutions [5].

III. SYSTEM DESIGN

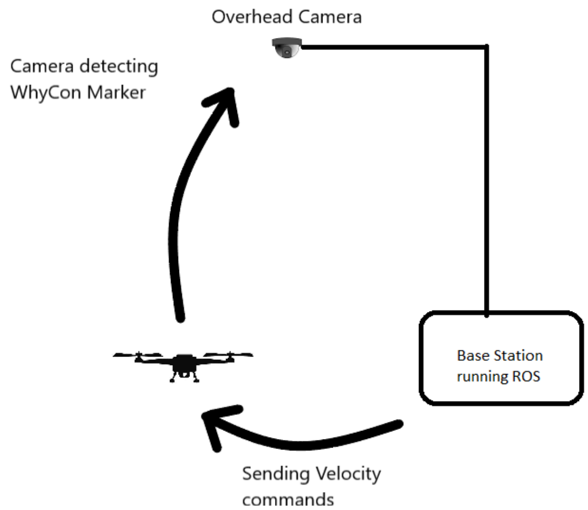

Figure 1: Overview of Drone-Base Station Communication

In the presented system the base station detects the WhyCon marker on the drone through the camera which is explained in section A. The drone sends its accelerometer and gyroscope data along with its battery status to the base station. According to the destination coordinates given by the user, a continuous closed-loop PID system is implemented on the base station using the data sent over by the drone and the WhyCon coordinates (drone's current position). The base station sends the appropriate PWM data based on the PID system which is explained in section B. Once the drone reaches its destination coordinates it will hover and scan the inventory using an onboard camera and give live feedback to the base station.

D. WhyCon Marker Detection using Overhead Camera

Figure 2: WhyCon Marker Detection

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The main crux of this system is dependent on the detection of a black and white roundel (Figure 1) with preconfigured dimensions. The algorithm for detection of the marker combines a fast flood-fill technique to search for contiguous segments of dark pixels, on-demand thresholding along with on-the-fly calculation of detected pattern statistics [3].

Referring to figure 1 and figure 2 estimation and localization of the drone using the WhyCon marker is possible using overhead cameras. The 3D coordinates (position) of the WhyCon Maker can be perceived by detecting the roughly two concentric (or elliptical) patterns, the dimensions with the preconfigured or known shape of the concentric pattern, some intrinsic camera parameters, and user-defined coordinate system with respect to the camera frame. The blue text in figure 1 specifies the 3D coordinates of the WhyCon marker in the world frame whereas the number 0 at the last denotes the number of WhyCon marker detected (Starting from 0). The outer and inner diameters of the concentric circles are preconfigured to estimate the Z coordinate for the system. Hence using this technique multiple WhyCon markers can be detected using multiple cameras forming a fleet of drones which would even further reduce inventory cycle time.

E. Warehouse Environment

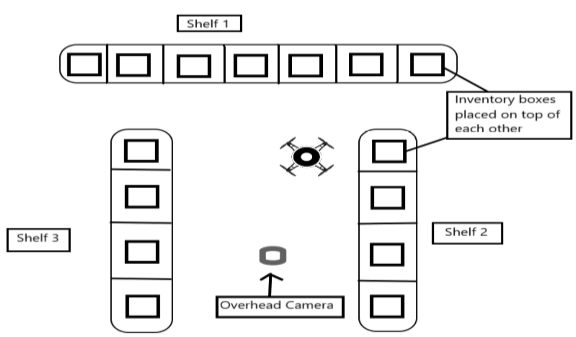

Figure 3: Warehouse Environment

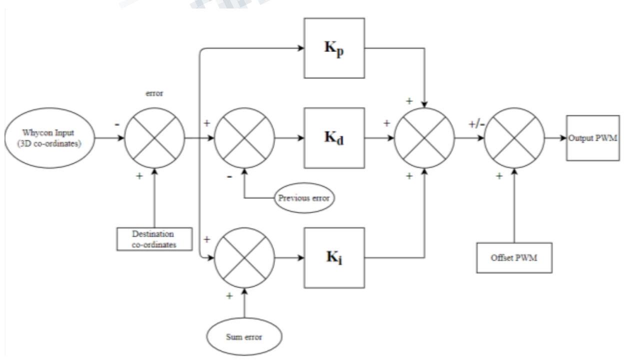

Figure 4: PID System Design

Figure 3 shows a reference environment of a warehouse in which the drone will navigate autonomously and scan inventory. The inventory boxes are stacked on top of one other on the shelves. The predefined path or destination (waypoints) for the drone to navigate are to be stated by the user with respect to the field of view of the overhead camera and user-defined coordinate system.

F. PID Control System

The WhyCon input consists of 3D coordinates (X, Y, and Z coordinates) of the WhyCon marker which is placed above the drone (figure 3). Suppose the destination coordinates are (*X', Y', Z'*), then the difference of the coordinates (*X'-X, Y'-Y, Z'-Z*) will be fed as an input to the P-controller. The product K_p*error will be added or subtracted to the offset PWM needed to the final output PWM.

The previous error holds the last error generated by the PID system. The differential gain K_d is multiplied with the co-ordinate difference error and the previous error keeping the sample time in consideration. The resultant is further added/subtracted to the offset PWM for the final PWM output.

Variable sum error sums up the errors over specified sampling time. This resultant is further added/subtracted to the offset PWM for the final output which is sent from the base station to the drone over WIFI. A predefined path (waypoints) for drone navigation is required to be set by the user with respect to the overhead camera field of view and user-defined coordinate system.

G. Inventory Scanning System

The drone travels to the destination coordinates one by one which are shelf locations. While navigating, the drone scans the QR code pasted on the inventory boxes (figure 5) using an onboard camera and sends the inventory data along with the location of the inventory box back to the base station. The base station simultaneously updates the inventory data in its database system. The inventory scanning system can scan QR codes as well as Bar codes using the OpenCV library.

Multiple inventory boxes can be scanned from the camera on the go which speeds the process relatively faster than traditional manual scans which scan one at a time. Along with camera-based scanning, the drone also equips an RFID reader so that the boxes on which the QR code is not visible or partially visible can be scanned thereby reducing error while inventory checking significantly.

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Figure 5: QR code detection

IV. HARDWARE DESIGN

The following were some of the important factors put into consideration during the designing of the drone (quadcopter).

A. Quadcopter Frame (Body)

The frame of the drone selected for the presented application was made of glass fiber keeping the weight of the drone to its lightest. The frame size was 160mm and the height was 50mm. Other frames having carbon fibers or aluminum were considered but were ruled out due to their bulky nature.

B. Motors

Before finalizing the motors for the drone, the total weight of the drone was estimated and then the thrust was calculated using a rule of thumb: (Considering 2:1 thrust/weight ratio)

$$\text{Thrust} = \frac{(weight \times 2)}{4} \qquad (1)$$

Where, weight is the total estimated weight obtained by adding individual weights of all motors, camera, propellers, sensors, etc. Following are the estimated individual weights which are tabulated in Table 1 below:

Table I: List of Components with their respective weight estimates

Sr. No.	Components	Estimated weight per unit	Number of Units	Total Weight
1.	Motors (DC)	4g	4	16g
2.	LiPo Battery	16g	1	16g
3.	Frame	12g	1	12g
4.	Propellors	1g	4	4g
5.	Camera	8g	1	8g
6.	Flight Controller	8g	1	8g
Total				64g

Assuming all other minor components like sensors the overall weight can be approximated to 80g. For the drone to lift, the 4 motors must produce a combined thrust of at least 80g i.e., each motor must produce 20g of thrust in order to beat gravity. According to the 2:1 thrust to weight ratio, each motor then must produce a thrust of 40g. From the above estimate, 60000 RPM DC motors were chosen for the quadcopter and were found out to be correct verifying experimentally.

C. Onboard Camera

The image/video capture device is FPV (First Person View) camera having a resolution of 5 MP. It can support video feed at 720p/1080p. The camera module is WIFI compatible supporting a range of up to 30m with a frame rate of 25fps. The minimum supply voltage required for this module is 3.4V.

D. Flight Controller

The flight controller used for the drone is PrimusX which comprises of STM32F303CC microcontroller with having a frequency of 72MHZ and a flash of 256kb. The board consists of 9-axis IMU (Inertial Measurement Unit), barometer, 4 X N-channel MOSFET(3A), 4 X H-Bridge drives (3A), etc. The main factors for selecting this flight controller were the onboard voltage regulator and onboard ESP12F module for WIFI communication between the drone to the base station.

V. SIMULATION DESIGN

The simulation environment for the presented system was chosen as ROS (Robot Operating System) which is free and open source. It comes with several integration tools, libraries, platforms, frameworks and provides good hardware abstraction. ROS is based on a Publish/Subscribe model in which data communication between two entities (nodes) is done through topics. In ROS, the simulation was carried out in a robot simulator called Gazebo which enables the user to simulate robots in complex environments. In this environment, several shelves along with boxes were placed to replicate a warehouse-like environment (figure 6 & 7).

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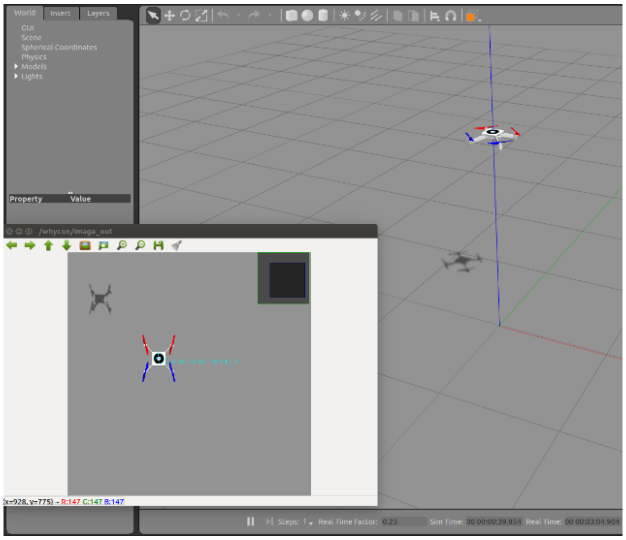

Figure 6: Gazebo Simulation Environment-Drone

Custom models of robots or objects can be created in Gazebo in a three-dimensional space using URDF or SDF files. The same models can be configured as static or dynamic in the environment. For example, the shelves (figure 7) are configured as static objects in Gazebo whereas the drone is configured as a dynamic object.

Figure 7: Gazebo Simulation Environment-Shelves

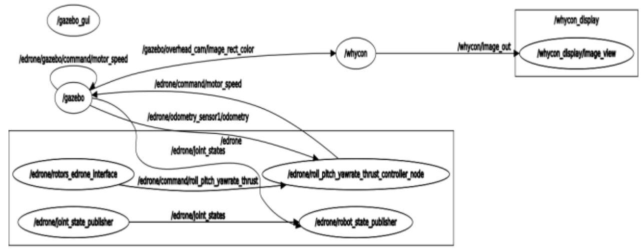

Figure 8: ROS node graph

The node graph shown in figure 8 indicates the different publisher and subscriber nodes (inscribed in oval shapes) along with the topics (shown on the arrows). The */edrone* node refers to the entities of the drone whereas in the simulation environment */gazebo* node is acting as a base station sending and receiving commands to and from the drone. The */whycon_display* is used to display the overhead camera feed as shown in a left bottom window in figure 6.

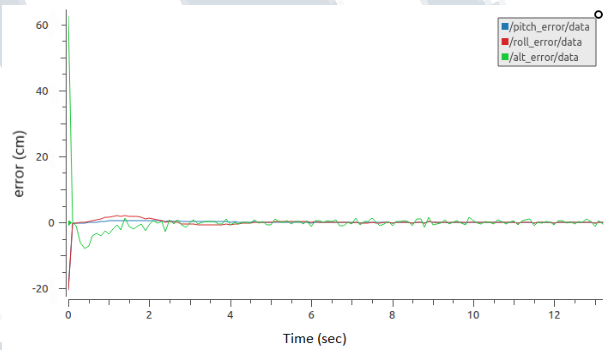

Figure 9: PID Controller Graph – ROS

The following plot (figure 9) shows the error estimation of pitch, roll, and yaw in cm over time in seconds. The package used for plotting the graph was Plotjuggler in ROS. The PID values for drone control were tuned and simultaneously results were plotted. Figure 9 is a plot of the error and time of a PID controller when the drone was navigating from source point to destination point. Hence after the destination point was reached only small altitude errors (alt_error) were observed because of the drone hovering at the point leading to minor oscillations.

VI. FUTURE SCOPE AND LIMITATIONS

The presented system assumes localization of only one drone using only one camera. However multiple cameras could localize multiple drones, thereby making a fleet of drones. This fleet of drones could localize externally and manage the whole warehouse making the inventory scanning process a lot faster in large warehouses [6].

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Along with inventory scanning, the same localization system can be used to perform surveillance checks to detect any defective boxes or avoid any malpractices in warehouses.

Even though the external localization system has some advantages it has its own limitations. One of the major limitations is that if the drone goes out of sight of the overhead camera, then the base station will not be able to localize the drone and it may result in a crash. To avoid this a dedicated path (waypoints) must be set by the user through which the camera could continuously track the drone or multiple cameras need to be installed. The batteries required for these drones are also small since the system is based on low-cost embedded devices [7] and lightweight drones. Hence these drones are prone to have less flight time because if bulky batteries are installed it the drone would be bulky which itself counters this use case. To rectify this problem docking stations can be installed in which if the drone's battery voltage falls down a certain value it would automatically navigate to the docking station and charge itself. Once the drone is charged it will navigate to the previous point and resume its operation.

VII. CONCLUSION AND PERSPECTIVES

Drones can be a viable alternative to replace the manual stock checking and updating operations in warehouses which will save important resources like time, money and eliminate human errors. From this system, it is observed that warehouse inventory cycle checking can be implemented using lightweight and cost-effective drones thereby reducing the time in manual inventory scanning significantly. External localization system gives an advantage in GPS denied environments and is lightweight as compared to systems that require high on-board computation power.

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