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# A Low-Cost Vision-Based Tracking System for Position Control of Quadrotor Robots

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***Abstract*— Developing an Autonomous navigation algorithm for a quadrotor robot requires that 3D position and orientation (pose) of robot be measured. We describe an innovative and low-cost pose tracking system, which can be used as a high-performance testbed to study various algorithms in position control of flying robots. Total cost of the tracking system would be less than $100 which system makes it a suitable solution for small research groups with limited financial funds. A custom build quadrotor will be introduced as a testing platform and a linear successive-loop controller is proposed to regulate velocity and position of the quadrotor. Performances of the tracking system and position controller are validated through multiple experiments.**

***Index Terms*—Robotic, Pose estimation, Quadrotor, Position control**

## I. Introduction

VTOL (Vertical Take-Off and Landing) aerial robots have been subject of numerous researches in the past decade. A quadrotor robot is a VTOL-UAV that has four rotors mounted on a rigid frame, which have fixed-pitch angles. This type of structure makes the robot mechanically simpler, cheaper, more durable, and more agile compared to conventional helicopters. These flying robots can be utilized in a variety of applications including aerial mapping, search and rescue missions, surveillance, and inspection in both indoor and outdoor environments [1]. Autonomous navigation of an aerial robot in GPS-denied environment is highly dependent on its motion controller as well as accurate environmental information. To develop a suitable motion control algorithm for a quadrotor robot, an appropriate testbed is required to provide global position and orientation of robot.

Measuring position of a flying robot in a confined 3d space has been studied in the past years. Although commercially available motion-tracking systems provide accurate position and orientation data in an enclosed space [2], [3], the cost of such a system is relatively high. Achtelik, et al. [4] presented a cost-efficient visual tracking system based on identically constructed active markers. Their system used two webcams as a stereo camera setup to reconstruct pose of the quadrotor. Custom stereo cameras are much cheaper than commercial tracking systems, but calibrating these systems are complex and time-consuming. To reduce the system's complexity and cost even further, Lange, et al. [5] proposed a simplified method which uses a single cost-efficient camera as measurement unit. But, total cost of this system is still relatively high and a noticeable latency exists in the tracking system's output.

In this paper we propose a light-weight, low-cost tracking system based on PixArt IR camera and multiple active markers. This system can be used in a variety of research projects addressing motion control of a mobile robot. To validate system's performance, we regulated position of a custom quadrotor based on the tracking system.

The rest of this paper is organized as follows. In section II the utilized hardware for the tracking system and a custom build quadrotor will be introduced. Section III briefly explains how position and orientation of quadrotor can be estimated. Section IV describes mathematical model of a quadrotor and control law. In section V experimental results are presented. Conclusion and future works are in section VI.

## II. Hardware

In recent years, quadrotor systems have become a standard platform for research and study on VTOL robots. We used a custom build quadrotor as main testbed to evaluate proposed tracking system. Our experiment setup is consisted of two systems: a tracking system and a quadrotor.

### *A. The Tracking System*

We used a PixArt IR camera as main component of tracking system. The camera chip features an integrated multiobject tracking (MOT) engine, which provides high-resolution, high-speed tracking of up to four simultaneous IR light sources [6]. The camera's exact specifications are unpublished, but based on its output data, the PixArt camera can provide location data with a resolution of 1024x768 pixels at 100 Hz refresh rate over I2C bus.

Using a PixArt camera as marker tracker has several advantages over typical webcam-PC tracking systems. First of all a PixArt camera do not need any additional processor to compute marker's position, in fact, all of necessary computations are carried out by internal MOT engine and output of PixArt camera would be position of detected markers. Calculating position of markers without any external processor will significantly reduce the total cost of system.

TABLE I. The tracking system costs

| **Component** | **cost** |
|---|---|
| Wiimote controller | $40 |
| Driver board | $15 |
| Driver board-PC interface | $25 |
| Active markers | <$10 |
| **In total** | **≈$90** |

Secondly, a PixArt-based tracking system has a compact size and lower weight compared to typical tracking systems and as a result, it can be mounted on small mobile robots as a compact sensor. Finally, performance of PixArt camera is a level higher than typical camera-PC tracking system. A low cost camera cannot stream a 1024x768 video at 100 fps and processing these data needs a high end PC.

A stand-alone PixArt IR camera is not commercially available, but it can be found in Nintendo Wiimote game controllers at very low cost. The total costs of this tracking system are given in table I.

Although built-in Bluetooth interface of Nintendo Wiimote provides the PixArt camera's data, by removing camera from Wiimote we can have direct access to camera using I2C interface, which has following benefits:

- PixArt camera has significantly smaller size and lower weight compared to Wiimote controller
- I2C interface provides higher data update rate in lower latency
- Using I2C interface, PixArt camera can be integrated in embedded control board of a quadrotor system

For using this camera as a tracking system, a set of 940nm IR LEDs should be placed on the target robot as active markers and by placing camera in a fixed position, the tracking system setup is complete. A small driver board was designed to communicate with camera using I2C protocol (Fig. 1). This board reads position of active markers from PixArt camera and transmits them over UART PORT to be used in a PC or an embedded controller.

With a horizontal and vertical field of view of 41° and 31°, this system can be easily calibrated and used as a positioning system. In fact, the set of PixArt camera with the driver board can be used as a low-cost, high data rate, accurate, and highly portable tracking system. This system can be used as ground truth positioning system for a variety of mobile robots, including quadrotor robots.

### *B. The Quadrotor*

We have designed a custom quadrotor system to be used as research platform at AUT University of Technology (see Fig. 2). Having four 90 W brushless motors, it can carry up to 300 g of payload in a 15 minutes flight time. Speed of each motor is controlled by an ESC (Electrical Speed Controllers) using 400 Hz PWM signals.

The controller board is based on two ATMega324 microcontrollers running at 20 MHz clock. One of them manages sensors data and reads receiver's PWM signals (RC inputs); while the other runs the control program to stabilize the system.

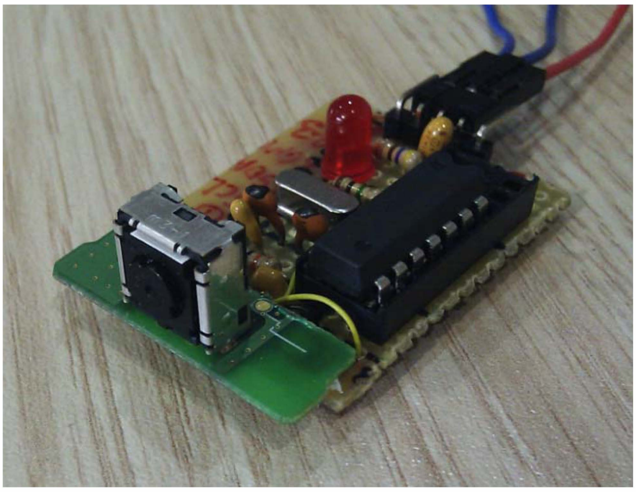

Fig. 1. The prototype of driver board for communicating with PixArt camera. The small camera in the left side of picture is the PixArt camera.

The microcontroller used for data acquisition reads 3Axis gyroscope and 3Axis accelerometer sensors over I2C bus at rate of 100 Hz and estimates the quadrotor's orientation based on DCM filtering algorithm [7]. In addition to orientation sensors, a sonar sensor is attached to the frame of quadrotor which delivers robot's altitude information to the microcontroller. The filtered Euler angles, altitude data, and captured PWM signals from receiver, will be transmitted to second microcontroller using serial interface.

On the second microcontroller, two set of PID controllers are implemented to regulate attitude and position of the system. Also a wireless data-link is established between PC and controller board for making higher level control possible. The quadrotor's system architecture is shown in Fig. 3.

Fig. 2. Picture of our custom build quadrotor.

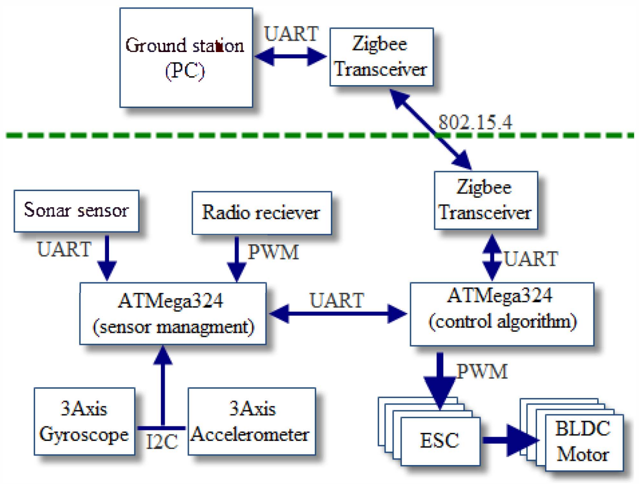


Fig. 3. System architecture of the quadrotor and ground station.

## III. Pose Estimation

Determining the relationship between two coordinate systems through the use of sets of corresponded feature measurements is known as the absolute orientation problem [8]. It has several applications in the areas of photogrammetry, robotics, as well as estimating position and orientation of an object (pose estimation). As a result, it is possible to extract position and orientation of a quadrotor from 2D information of the markers, given by the PixArt camera. In other words, by finding transformation matrix ${}^{A}_{B}T$ in Eq.1 pose of the quadrotor in a 3D space can be estimate.

$$^{A}P = {}^{A}_{B}T \, {}^{B}P$$

$$ {}^{A}_{B}T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

Where ${}^{A}P$ and ${}^{B}P$ are positions of marker described in reference and quadrotor frame, $r_{ij}(i,j = 1,2,3)$ are rotation matrix elements, and $t_i(i = 1,2,3)$ represent translation values.

A large number of algorithms have been developed to estimate position and orientation of an object in a picture using some feature-points of object and corresponding points on the image [9], [10]. Estimating pose of an object in 3D space needs that at least six constraints be determined. Each point-to-image correspondence will provides us two constraints [11]. Thus a minimum of three non-collinear reference points is required for pose estimation of a rigid body. However, using only 3 reference points, generates up to four possible solutions in critical configurations which cannot be ignored in general .To overcome this problem, four or greater number of non-coplanar points are needed.

Dementhon, et al. [12] developed an iterative optimizing algorithm for pose estimation using a minimum of four reference points, named POSIT. This method is computationally efficient and can be implemented on a standard PC as well as an 8-bit microcontroller. Therefore, we choose POSIT algorithm as pose estimator in our experiments.

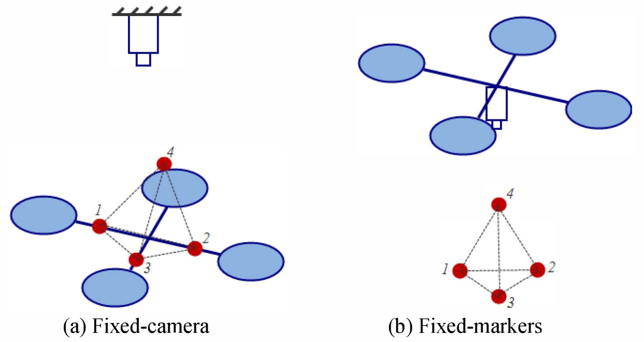


Fig. 4. Markers and camera configurations.

The proposed tracking hardware can be used in two configurations: fixed-camera and fixed-markers. In a fixed-camera configuration, camera will be placed on a fixed position and a set of four non-coplanar active markers will be mounted on quadrotor frame (see Fig. 4(a)). On other hand, placing markers on a fixed position and mounting the camera on quadrotor would result in a fixed-markers setup (Fig. 4(b)). In both of these configurations, position and orientation of quadrotor can be measured by the tracking system. In a fixed-camera setup, pose of quadrotor will be calculated in PC software and results will be sent back to the quadrotor system over the wireless data link. While in a fixed-marker configuration all of calculations regarding pose estimation will be done on quadrotor system.

In our work we focus on the fixed-camera configuration. As the first step, the markers should be activated one by one in a specific order. This helps camera to assign an ID for each marker and later on, markers will be recognized as their ID (1, 2, 3, or 4), and then the PixArt driver board sends the position of markers to PC. For calculating position and orientation of quadrotor, we use the POSIT algorithm provided by OpenCV library [13]. Due to the availability of markers' position from previous step, no additional image processing is necessary and pose estimation would be calculated in less than 1ms. Finally, pose information will be sent back to the quadrotor's controller board.

## IV. Quadrotor Modeling and Controller Design

A quadrotor is an under-actuated aircraft with four fixed pitch angle rotors as shown in Fig. 5. Each motor represents an input force which is the thrust generated by a propeller. The control inputs for system are defined as:

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = \begin{bmatrix} \frac{1}{m} & \frac{1}{m} & \frac{1}{m} & \frac{1}{m} \\ \frac{l}{I_x} & -\frac{l}{I_x} & 0 & 0 \\ 0 & 0 & -\frac{l}{I_y} & \frac{l}{I_y} \\ -\frac{1}{I_z} & -\frac{1}{I_z} & \frac{1}{I_z} & \frac{1}{I_z} \end{bmatrix} \begin{bmatrix} Th_1 \\ Th_2 \\ Th_3 \\ Th_4 \end{bmatrix} \qquad (2)$$

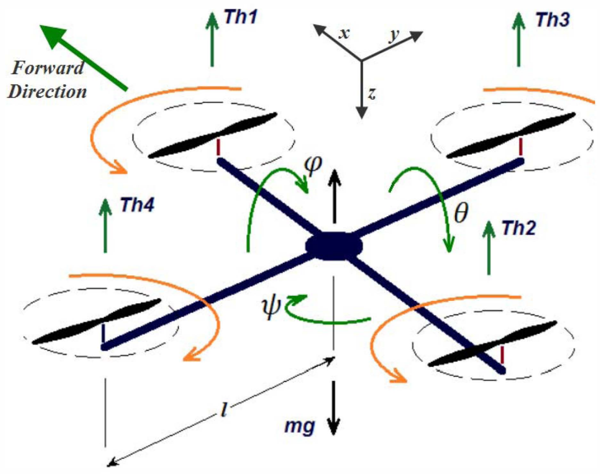


Fig. 5. The quadrotor schematic.

Where:
$u_1$: sum of vertical thrust produced by motors
$u_2$: pitching moment
$u_3$: rolling moment
$u_4$: yawing moment
$Th_i$: thrust generated by motor i
$m$: total mass of quadrotor
$I_i$: the moment of inertia with respect to i-axes
$l$: length of quadrotor's arm

A simplified model of quadrotor can be obtained from dynamic equations as follow [14]:

$$\begin{cases} \ddot{\theta} = u_2 - \frac{lk_1\dot{\theta}}{I_x} \\ \ddot{\varphi} = u_3 - \frac{lk_2\dot{\varphi}}{I_y} \\ \ddot{\psi} = u_4 - \frac{k_3\dot{\psi}}{I_z} \end{cases} \tag{3}$$

$$\begin{cases} \ddot{x} = u_1(-Cos\varphi Sin\theta Cos\psi - Sin\varphi Sin\psi) - \frac{k_4\dot{x}}{m} \\ \ddot{y} = u_1(Sin\varphi Cos\theta Cos\psi - Sin\theta Sin\psi) - \frac{k_5\dot{y}}{m} \\ \ddot{z} = -u_1(Cos\theta Cos\varphi) - g - \frac{k_6\dot{z}}{m} \end{cases} \tag{4}$$

Where $k_i$ (i = 1,2, … 6 ) are drag coefficients, $\theta$ is pitch angle, $\varphi$ is roll angle, $\psi$ is yaw angle, and $g$ is the gravitational constant.

For position control of a quadrotor, the position in z axis is directly actuated using the total thrust control, while the positions in x and y axis are actuated by coupling thrust force with the orientation of the quadrotor. Therefore, designing a high-speed trajectory tracker for this system is not an easy task. In this paper we focus on designing a conventional linear controller for position regulation of quadrotor at hovering state.

Assuming roll and pitch angles are less than 15°, $\psi = 0$, and movement speed is limited, then the drag coefficients can be neglected. So System model would be approximately linearized as follow:

$$\begin{cases} \ddot{\theta} = u_2 \\ \ddot{\varphi} = u_3 \\ \ddot{\psi} = u_4 \\ \ddot{x} = u_1(-\theta) \\ \ddot{y} = u_1(\varphi) \\ \ddot{z} = -u_1 - g \end{cases} \tag{5}$$

The system model in Eq. 5 is consisted of two set of equations: orientation equations and position equations. In contrast with position equations, the orientation of quadrotor is directly controllable by control inputs $u_2$, $u_3$, and $u_4$. Additionally, quadrotor's orientation has a faster dynamic response in comparison with velocity and position dynamics. In other words, in a short period of time, roll and pitch angles can change without any significant effect on position and velocity of the quadrotor.

The velocity of quadrotor can easily controlled by roll and pitch angles. For example, to attain positive velocity in the y-axis, the quadrotor has to be given a positive roll rotation about the x-axis. This would apply a component of thrust in that direction. Due to this force, speed of the quadrotor in the y axis will be increased till the orientation is maintained. To stop the quadrotor, a force in the negative y axis has to be given, which can be applied by a negative roll rotation about the x axis. The proportional integral derivative (PID) controllers in Eq.6 can regulate velocity of the quadrotor:

$$\begin{aligned} \int \theta_d &= -k_{vp}\,{}^F v_{ex} - k_{vi}\int {}^F v_{ex} - k_{vd}\left(\frac{d\,{}^F v_{ex}}{dt}\right) \\ \int \varphi_d &= -k_{vp}\,{}^F v_{ey} - k_{vi}\int {}^F v_{ey} - k_{vd}\left(\frac{d\,{}^F v_{ey}}{dt}\right) \end{aligned} \tag{6}$$

Where $\theta_d$ and $\varphi_d$ are desired pitch and roll pattern to achieve certain velocity in x and y axis. $k_{vp}, k_{vi}, k_{vd}$ are the PID gains. ${}^F v_{ex}$, ${}^F v_{ey}$ represent velocity errors in x and y directions described in the quadrotor frame. Equation 7 shows direct cosine matrix (DCM) which relates the velocities in quadrotor frame and inertial frame.

$${}^F v_e = \begin{bmatrix} C_\theta C_\psi & C_\theta S_\psi & -S_\theta \\ S_\varphi S_\theta C_\psi - C_\varphi S_\psi & S_\varphi S_\theta S_\psi + C_\varphi C_\psi & S_\varphi C_\theta \\ C_\varphi S_\theta C_\psi + S_\varphi S_\psi & C_\varphi S_\theta S_\psi - S_\varphi C_\psi & C_\varphi C_\theta \end{bmatrix} {}^I v_e \tag{7}$$

So, control inputs would be:

$$u_1 = -k_{vp}\,{}^F v_{ez} - k_{vi}\int {}^F v_{ez} - k_{vd}\left(\frac{d\,{}^F v_{ez}}{dt}\right) \tag{8}$$

$$U = \begin{bmatrix} u_2 \\ u_3 \\ u_4 \end{bmatrix} = -k_{\Theta p} e_\Theta - k_{\Theta i} \int e_\Theta - k_{\Theta d} (\frac{e_\Theta}{dt})$$

Where ${}^{F}v_{ez}$ is velocity error in z direction and $e_\Theta$ is error between desired and actual orientation.

## V. Experiments and Results

To evaluate system's capabilities, we have conducted two experiments. One for validate the tracking system's accuracy and the other for demonstrating the functionality of whole system.

### A. *Accuracy of the Tracking System*

The tracking system can measure quadrotor's 3D position and orientation. These outputs of the tracking system will be compared with reference values. The quadrotor's onboard inertial measurement unit (IMU) will be considered as a reference for orientation of quadrotor. This sensor has been calibrated before and can measure static roll and pitch angles with accuracy of 0.2°. And the position of quadrotor will be measured manually in 1 mm resolution.

As the first experiment, position and orientaion of quadrotor has been measured in 480 different poses. In this experiment, position of quadrotor was changed in 200 mm steps within a working volume of 2.0 m width (x), 2.0 m length (y), and 1.0 m height (z). By choosing a square area, effective resolution of camera is 768x768 and therefore one pixel displacement in camera's output represents about 2.6 mm displacement in realworld. Figure 6(a) shows distribution of error in position estimation results. The roll and pitch angles also have been measured in a range between -45° to +45° in 15 degree steps (Fig. 6(b)).

Based on achieved result, the tracking system has following characteristics:

- Mean positioning error is about 7 mm
- Orientation can be measured by mean error of 1.4°
- Total latency of measurement is less than 20 ms
- The positioning data can be updated at rate of up to 100 Hz

### B. *Velocity and Position Controller*

To control the horizontal velocity of the quadrotor, we

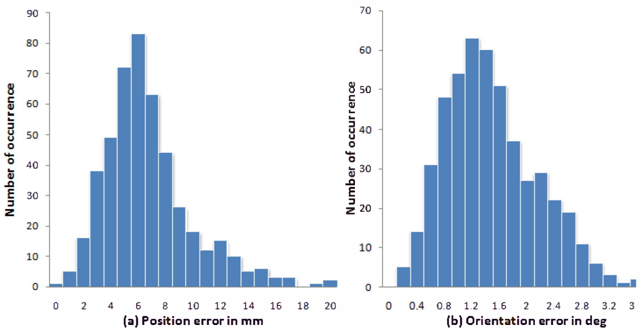

Fig. 6. Distributions of position and orientation errors measured in the 2x2x1[m$^3$] working space.

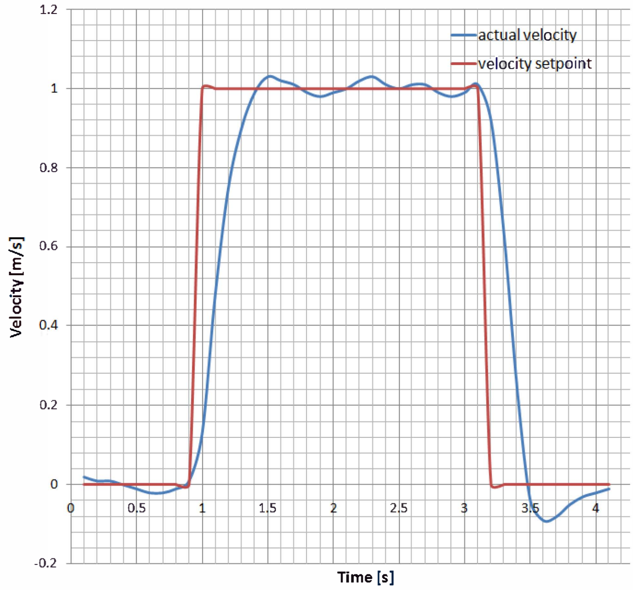

Fig. 7. System's velocity response to a pulse input

implemented the linear controller described in section IV, on quadrotor's on board controller. Altitude of quadrotor is regulated separately by the sonar sensor feedback, while velocity is measured by the tracking system. In this experiment response of system to a pulse input has been examined (Fig. 7). Due to limited size of test area, quadrotor is moving diagonally with a fixed altitude. This exprement shows the linear controller can regulate speed of quadrotor in a planar movement, but a general movement in 3D space would require a more sophisticated controller.

In another experiment we used a linear successive-loop controller to move quadrotor in a sequence of set-points. To realize position control of system, the position error should

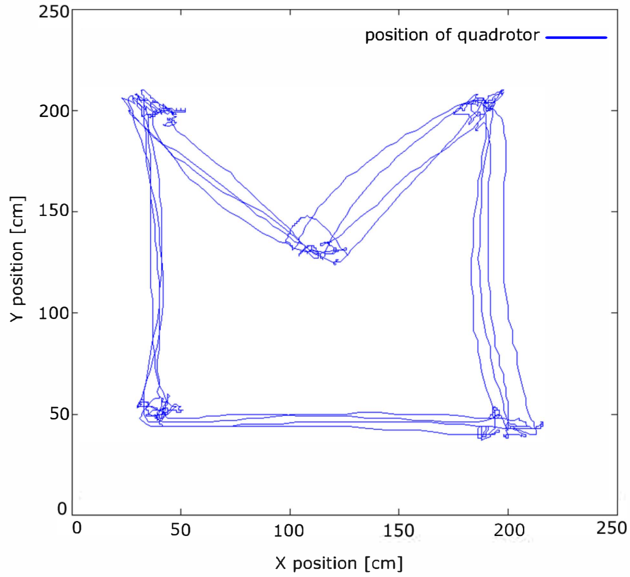

Fig. 8. Position regulation in a set of five different points.

generate an appropriate velocity trajectory. A simple trajectory can be generated by setting velocity proportional to the position error. A saturation function is added to output of controller to make sure that it does not exceed considered speed limits. We tested the position controller with a sequence of five set-points and speed-limit of 0.5 m/s. Result of this experiment is illustrated in Fig. 8.

## VI. Conclusions and Future Work

This paper described an innovative low-cost pose tracking system based on the PixArt camera. Although total cost of this system is less than $100, its technical specification is comparable to that of more expensive and commercial tracking systems. Using the POSIT algorithm and a set of active markers, we successfully estimated 3D pose of a quadrotor robot. Performance of the tracking system evaluated in practice based on multiple experiments including position control of a quadrotor robot.

In future work we will use multiple cameras to increase accuracy, robustness, and working space of the tracking system. Furthermore, a more agile position control of the quadrotor will be studied using the proposed tracking system.

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