Autonomous Patrol and Surveillance System using Unmanned Aerial Vehicles

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***Abstract*—Unmanned aerial vehicles (UAVs) are increasingly popular for civil applications due to their flight capabilities and mobility. This paper proposes an indoor autonomous patrol and surveillance system using unmanned aerial vehicles. The system consists of six components: (1) a low cost vision-based pose estimation of UAVs, (2) vision-based state estimation, (3) UAV patrol path planning, (4) UAV controller to desired waypoints, (5) manual joystick controller and (6) assignment of priority hierarchy to multiple control inputs of a robot. The components were integrated successfully and the designed system was experimented in an indoor setup. Results has shown that the proposed system is suitable and feasible to be used as an autonomous patrol and surveillance agent for indoors use.**

Keywords—unmanned aerial vehicle; autonomous system; patrol; UAV surveillance; indoor security; vision-based state estimation; UAV control; path planning; robot control hierarchy; smart building

I. Introduction

There is a growing interest amongst researchers in unmanned aerial vehicles (UAVs), also known as drones. They were initially used in military missions but in recent years, many ideas and development have expanded their significant applications in civilian domains, such as public surveillance, transportation and inspection. For example, UAV has been proposed to perform surveillance task in natural disasters [1]. The aim is to facilitate the identification of critical regions and to assist local municipalities to plan for rescue. Researchers have also identified UAV as an effective means for surveillance in complex urban environments [2] and power lines surveillance and inspection. Computer vision algorithms were developed for power lines recognition [3, 4].

With advances in control technology, accurate control algorithms have enabled precise and aggressive navigation of a UAV [5]. UAVs are capable of performing quick and complex maneuvers such as navigating through narrow window and performing multiple flips [6, 7]. Researchers envisioned a swarm of UAVs cooperating to carry out tasks effectively, for example, building a cubic structure [8], playing ping pong [9], autonomously using advanced control algorithms.

In this paper, an autonomous patrol and surveillance system that is a viable alternative to traditional human patrol and CCTV surveillance system is described. Patrols by security personnel have many disadvantages. These include, among others, the number of patrols that can be done in a period of time, overlooking certain places, human memory retrieval in investigation and fatigue due to prolonged working hours. Surveillance camera or CCTV, are subject to blind spots unless many of these are installed. To monitor larger buildings or areas, the set up cost for extended cabling and multiple cameras are too costly. Therefore, an unmanned aerial vehicle autonomously patrolling certain locations of buildings on a regular basis at a higher speed and frequency can either complement or replace patrols by security personnel and CCTV systems. The live camera view of the UAV is transmitted to the office to be monitored by security personnel. If any suspicious people or potential crimes is observed, the authority can override the autonomous control of the UAV to track the criminal using a remote control joystick. As compared to CCTVs, a UAV can cover a larger area without any blind spots with much lower set up cost.

This paper is organized as follows. Section II examines the state of the art in UAV surveillance and compares proposed method of state estimation with other methods. Section III outlines the proposed framework with details in designing the autonomous patrol and surveillance system using an UAV. In Section IV, the experimental setup and results are presented. Lastly, the work is concluded in Section V.

II. Literature Review

In UAV navigation, state estimation is usually based on the integration of accelerometer and gyroscope data. This however, is subject to drift effect and noise. Alternatives include the use of Global Position System (GPS) [10]. However, GPS performance is subject to atmospheric conditions, quality of receiver and presence of signals blockage [11]. Hence, precision and reliability are the major drawbacks [12]. This limits the usage of the UAV to open, outdoor spaces. Indoor environments and narrow corridors are not suitable for such technique.

Another method requires odometry and mapping of a ground robot. Saska et al [13] described an indoor surveillance model by a heterogeneous ground robot and aerial robot system. The ground robot carries the UAV on a deck to different locations of a building. The UAV then takes off for inspections of locations inaccessible by the ground robot. The aerial robot then lands on the ground robot to be navigated to other places.

Other methods for estimating the state of a UAV include an external motion capture system, for example, the VICON motion tracking system. It gives the pose of the UAV at 150Hz with millimeter accuracy [8]. However, it limits the system developed for use in a laboratory set up only because of the requirement of properly calibrated cameras set up [14]. Also, it is very costly. Another popular idea is to use a laser range finder for localization in an indoor environment [15, 16]. This, requires a heavy laser range sensor with high power consumption [14, 17]. Also, the UAV can lose track of its position because of the limited range that the laser sensor can detect [18].

In this a paper, a monocular camera is utilized together with printed fiducial markers to estimate the state of a UAV [19]. RGB (Red, Green, Blue) monocular camera provides rich information in addition to being low weight and small [20]. It has low power consumption and costs less than a laser range finder. Furthermore, monocular camera is virtually unlimited in terms of sensing range [14]. Fiducial markers, on the other hand, can be easily detected using standard pattern recognition algorithms and conventional classification methods [21]. A geometric approach is employed for pose estimation from the appearance of markers in perspective projection [19].

III. Proposed Framework

The proposed framework consists of six main modules, namely vision-based pose estimation, vision-based state estimation, UAV patrol path planning, PD controller, joystick controller and a master control program. Fig. 1 shows the system architecture of the autonomous patrol and surveillance system using unmanned aerial vehicle.

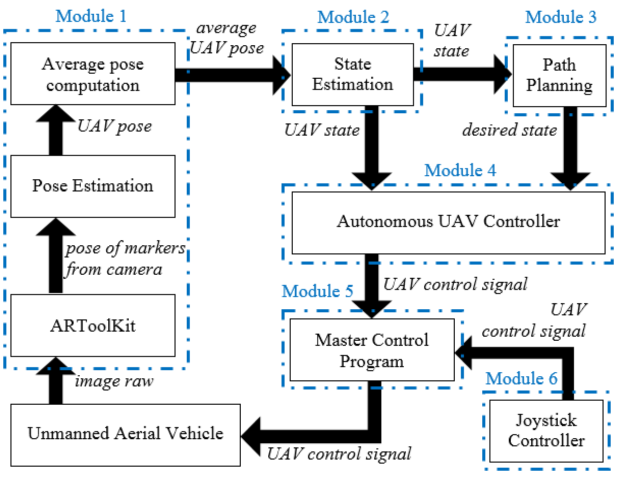

Fig. 1. System architecture of the autonomous patrol and surveillance system using unmanned aerial vehicle

The first module employs a vision-based algorithm that recognizes fiducial markers and provides their positions and orientations (poses) with respect to the UAV onboard RGB-camera. In an indoor setup, where a number of markers of known size and poses are attached to the wall or ceiling, the pose of the UAV can then be inferred with a series of transformation matrices. The second module further processes the pose data obtained at different times to compute the linear and angular velocity and acceleration of the UAV.

The third module decides the path which the drone travels to carry out its patrol. It contains a series of waypoints and orientations. The UAV current pose is compared with a desired pose. Once the UAV achieves a desired pose, the following desired pose serves as the input for the controller signal computation. The fourth module takes the drone state data and desired pose as inputs and outputs the control signals for roll, pitch, yaw and vertical acceleration of UAV.

The fifth module is a joystick teleoperation of the UAV. It allows manual control of the drone movement using a joystick. Lastly, the sixth module functions as a master control program that monitors whether control signal from module four or module five, is sent to the UAV.

A. Software Platform

This autonomous patrol and surveillance system is implemented in Robot Operating System (ROS) [22]. ROS is an open source platform that serves as a middleware for developing robotics software. It encourages community sharing and collaboration so that robotic applications designs can be accelerated [23]. The significance of using ROS in this research is that the designed system and modules developed can then be utilized in a wide variety of robotic applications especially using UAVs supported by ROS.

B. Vision-based Pose Estimation

A popular software library for creating augmented reality (AR) applications, ARToolKit is used for fiducial marker recognition [24]. It recognizes and differentiates one marker from another and computes the pose of the markers in terms of translation and rotation around three axes using homography transformation. Examples of these markers are shown in Fig. 2.

The pose data of markers, camera and UAV in world coordinate frame are represented in a graphical manner using RVIZ, a 3D visualization tool for displaying sensor data and state information in ROS [25]. Fig. 3 is a representation of the world coordinate frame, markers, camera of UAV and UAV in RVIZ. It provides an intuitive way of visualizing the relative position of one component to another.

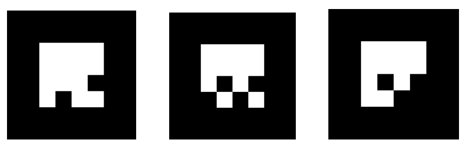

Fig. 2. Examples of fiducial markers recognizable by ARToolKit

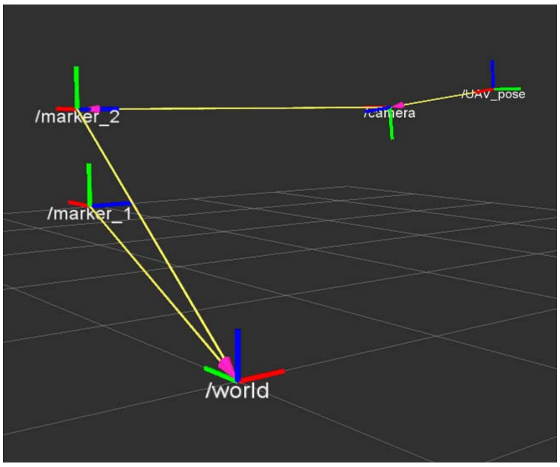

Fig. 3. Graphical representation of components poses in RVIZ

The pose estimation begins with an on-board camera pose computation from markers captured by the camera. This is followed by the computation of UAV pose based on the on-board camera pose [26].

a) Camera pose computation fixed markers

The transformation matrix from camera to marker, $\boldsymbol{T}_{camera}^{marker}$ is the output of ARToolkit, after which the pose of the marker, $\boldsymbol{p}_{marker}$ can be computed from pose of the camera, $\boldsymbol{p}_{camera}$ using (1). Equations (2) and (3) show the derivation of the equation needed to determine the pose of the onboard camera of UAV, since the pose estimation module deploys fixed markers to determine the pose of moving camera and UAV. The inverse of the transformation matrix from camera to marker, $\boldsymbol{T}^{-1marker}_{camera}$ is used to compute $\boldsymbol{p}_{camera}$, given $\boldsymbol{p}_{marker}$, which depends on the placement of the markers.

$$\boldsymbol{p}_{marker} = \boldsymbol{p}_{camera}\boldsymbol{T}_{camera}^{marker} \tag{1}$$

$$\boldsymbol{p}_{marker}\boldsymbol{T}^{-1marker}_{camera} = \boldsymbol{p}_{camera}\boldsymbol{T}_{camera}^{marker}\boldsymbol{T}^{-1marker}_{camera} \tag{2}$$

$$\boldsymbol{p}_{camera} = \boldsymbol{p}_{marker}\boldsymbol{T}^{-1marker}_{camera} \tag{3}$$

For autonomous patrol using a UAV, multiple markers have to be used. This enables pose computation at any time. Once any of the markers is detected, it will look up for the known pose of the marker and compute the camera pose with respect to the marker based on (3).

When multiple markers are captured in a single image, the average of the camera poses, $\boldsymbol{p}_{camera}$ with respect to each of the markers is determined using (4). This improves the accuracy of the pose computation. Furthermore, the algorithms can compute the average pose in an interval specified by user. In this application, a 15Hz pose data is desired, as this lower frequency data can reduce the noise and fluctuation of the results, and hence, reduce power consumption of rapidly changing control signals. As such, the average pose is computed every 0.0667 seconds. Equation (4) is used for the average pose computation, where n is the number of camera pose added in the time interval.

$$\boldsymbol{p}_{camera,average} = \frac{\sum \boldsymbol{p}_{camera}}{n} \tag{4}$$

b) Computation of UAV pose

The camera pose computed cannot be taken as the UAV pose because in most of the cases, the camera is not located at the center of all propellers. In (5), (6), (7), and (8), it is shown that the UAV pose, $\boldsymbol{p}_{uav}$ is the concatenation of camera pose with the transformation from the camera to the center of UAV, $\boldsymbol{T}_{camera}^{uav}$ which depends on the UAV used.

$$\boldsymbol{p}_{uav} = \boldsymbol{p}_{marker}(\boldsymbol{T}_{marker}^{uav}) \tag{5}$$

$$\boldsymbol{p}_{uav} = \boldsymbol{p}_{marker}\left(\boldsymbol{T}_{marker}^{camera}\boldsymbol{T}_{camera}^{uav}\right) \tag{6}$$

$$\boldsymbol{p}_{uav} = \boldsymbol{p}_{marker}\left(\boldsymbol{T}^{-1marker}_{camera}\boldsymbol{T}_{camera}^{uav}\right) \tag{7}$$

$$\boldsymbol{p}_{uav} = \boldsymbol{p}_{camera}\boldsymbol{T}_{camera}^{uav} \tag{8}$$

C. Vision-based State Estimation

Having the pose of the drone alone is not sufficient for a stable control algorithms. The linear velocity, v and angular velocity, ω are required, and computed as the time, t derivative of linear displacement and angular displacement respectively from one instance to another. However, the displacements for this computation are with respect to the local coordinate frame of the drone, but not with respect to world coordinate as computed previously. Equations (9), (10) and (11) derive the calculation for local displacements from previous UAV pose, $\boldsymbol{p}_{uav,t_{i-1}}$ to current UAV pose, $\boldsymbol{p}_{uav,t_i}$. The linear and angular displacements are extracted from the transformation matrix in (11), $\boldsymbol{T}_{uav,t_{i-1}}^{uav,t_i}$ which is the transformation of UAV previous pose to current pose in UAV local coordinate frame.

$$\boldsymbol{p}_{uav,t_i} = \boldsymbol{p}_{uav,t_{i-1}}\boldsymbol{T}_{uav,t_{i-1}}^{uav,t_i} \tag{9}$$

$$\boldsymbol{p}^{-1}{}_{uav,t_{i-1}}\boldsymbol{p}_{uav,t_i} = \boldsymbol{p}^{-1}{}_{uav,t_{i-1}}\boldsymbol{p}_{uav,t_{i-1}}\boldsymbol{T}_{uav,t_{i-1}}^{uav,t_i} \tag{10}$$

$$T^{uav,t_i}_{uav,t_{i-1}} = p^{-1}{}_{uav,t_{i-1}} p_{uav,t_i} \qquad (11)$$

Equations (12) and (13) are used for computation of linear velocity and angular velocity respectively for x, y and z-axis. s and θ are the linear displacement and angular displacement respectively from previous pose to current pose in UAV local coordinate frame.

$$v = \dot{s} = \frac{\delta s}{\delta t} \qquad (12)$$

$$\omega = \dot{\theta} = \frac{\delta \theta}{\delta t} \qquad (13)$$

Equations (14) and (15) are used for computation of linear acceleration and angular acceleration respectively for x, y and z-axis.

$$a = \ddot{s} = \frac{\delta v}{\delta t} \qquad (14)$$

$$\alpha = \ddot{\theta} = \frac{\delta \omega}{\delta t} \qquad (15)$$

D. Control of UAV to Desired Waypoint

The pose (position and orientation) of the unmanned aerial vehicle, together with its linear and angular velocity, now serve as the input to UAV control signals computation algorithms. Four degrees of freedom control, i.e. roll, pitch, yaw and vertical acceleration are computed separately.

A PD-controller is employed for the UAV movement control. The control signals for pitch, u_x, roll, u_y, vertical acceleration, u_z and yaw, u_{Θ_z} are computed based on (16), (17), (18) and (19) respectively, where K_p is the proportional gain and K_d is the derivative gain.

Here, S and Θ are the linear displacement and angular displacement respectively with respect to the world coordinate frame. Local linear displacement, s and local angular displacement, θ should not be used because the UAV is to reach a waypoint in the world coordinates, ($S_{x,desired}$, $S_{y,desired}$, $S_{z,desired}$) and in the orientation, $\Theta_{z,desired}$ with respect to the world coordinate frame. S_x, S_y and S_z are the current linear displacements, whereas Θ_z is the current angular displacement with respect to the world coordinate frame.

v_x, v_y and v_z are the current local linear velocities, whereas ω_z is the current local angular velocities with respect to the UAV coordinate frame.

Also, $v_{desired}$ for x, y and z-axis and $\omega_{z,desired}$ at this stage are set to be zero so that the UAV will stop and hover around any specified world coordinates in specified orientation.

$$u_x = K_{p,x}\left(S_{x,desired} - S_x\right) + K_{d,x}\left(v_{x,desired} - v_x\right) \qquad (16)$$

$$u_y = K_{p,y}\left(S_{y,desired} - S_y\right) + K_{d,y}\left(v_{x,desired} - v_y\right) \qquad (17)$$

$$u_z = K_{p,z}\left(S_{z,desired} - S_z\right) + K_{d,z}\left(v_{z,desired} - v_z\right) \qquad (18)$$

$$u_{\Theta_z} = K_{p,\Theta_z}\left(\Theta_{z,desired} - \Theta_z\right) + K_{d,z}\left(\omega_{z,desired} - \omega_z\right) \qquad (19)$$

E. UAV Patrol Path Planning

After designing the controller for UAV to navigate to a desired waypoint, the next step is the path planning of UAV so that it can carry out the patrol of different locations autonomously. In order to achieve that, a series of waypoints has to be used as $S_{x,desired}$, $S_{y,desired}$ and $S_{z,desired}$ in (16), (17), and (18) respectively. Other than the waypoints, the orientations, $\Theta_{z,desired}$ have to be specified in (19), so that the unmanned aerial vehicle will fly to the waypoints in desired orientations to observe the desired views of the patrol areas.

To increase the efficiency of the patrol, desired linear and angular velocities can be set to non-zero values. This prevents the UAV from stopping at each waypoints reached before moving to the next.

Therefore, a series of waypoints, orientations, linear velocities and angular velocities ($S_{x,desired}$, $S_{y,desired}$, $S_{z,desired}$, $\Theta_{z,desired}$, $v_{x,desired}$, $v_{y,desired}$, $v_{z,desired}$, $\omega_{z,desired}$) are to be entered as two-dimensional array in the control program. Once all components of a desired state fall within their tolerance levels, the program will use the following desired state for control signals computation and repeat the sequence after the last defined state is achieved.

F. Assignment of Priority Hierarchy to Multiple Control Inputs

In the proposed autonomous patrol and surveillance system, the security personnel should be able to override the autonomous control of the UAV using a manual joystick when suspicious people or potential crimes are found. This allows the security personnel to have a closer look at the situation from different views. In this case, the autonomous controller program will always be sending control signals to achieve the next state. However, the master program should stop sending the commands from this autonomous program when joystick controller is providing control commands.

In a broad sense, surveillance applications should cater for different levels of management that may want to control the UAV. There might be more than one joystick control for higher management, control through web application or a different patrol path desired. Hence, a master control program that is capable of comparing the priority hierarchy assigned when multiple inputs are providing control commands is necessary.

The master program checks through the presence of control signals from highest assigned priority input to the lowest. When a control command exists, it is sent to the UAV and the current loop exits, skipping the control commands from the lower priority inputs. If the higher priority input stop sending control commands, after the defined delay time of 5 seconds, the program will no longer wait for its commands but it will send the lower priority control commands to the UAV. This prevents the UAV from immediately moving away when there is a slight pause in the control command.

IV. Results and Discussions

Experiments were conducted in a 10 m × 10 m room in Universiti Teknologi PETRONAS, Malaysia to evaluate the performance of the designed system.

A. Experimental Setup

Fiducial markers are printed on papers and pasted as shown in Fig. 4. Although the markers can be pasted on the ceiling to prevent occlusions, they are pasted on the wall because the UAV used in the experiments does not have an upward facing camera. The pose of markers are defined into the program.

The UAV used is a Parrot AR.Drone (Fig. 5) that comes with an onboard HD camera of 720p streaming at about 30fps. The lens covers a 92° field of view [27].

Fig. 4. Experimental setup

Fig. 5. Parrot AR.Drone (UAV used in the experiment)

B. Results and Discussions

The integrated system is first tested by programming it to hover at a same spot for 8 seconds. The UAV pose estimation output in terms of position and orientation in x, y, z-axis are shown in Fig 6 and Fig. 7 respectively. It is observed that the estimated pose is quite stable (less than 15% variation) without significant noise and spikes. The stable pose data computed at frequency of 30Hz warrants the control of drone movement using the proposed vision-based state estimation method. Fig. 8 represents the coordinate frames for all markers used, world coordinate and computed UAV pose using the proposed pose estimation method.

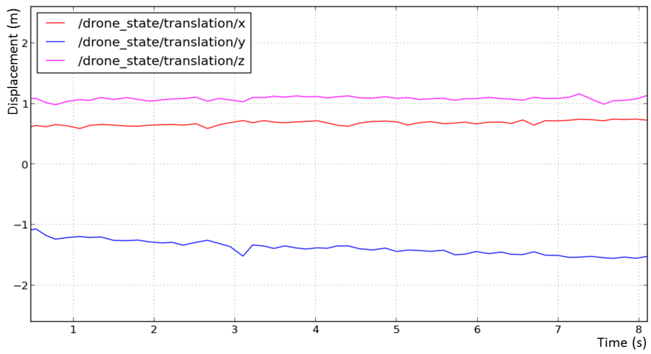

Fig. 6. Hovering UAV position data based on markers recognized

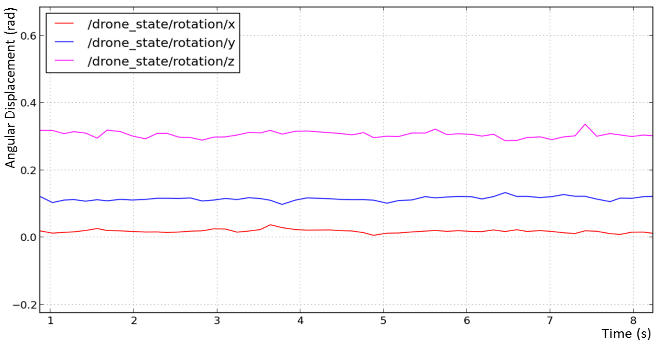

Fig. 7. Hovering UAV orientation data based on markers recognized

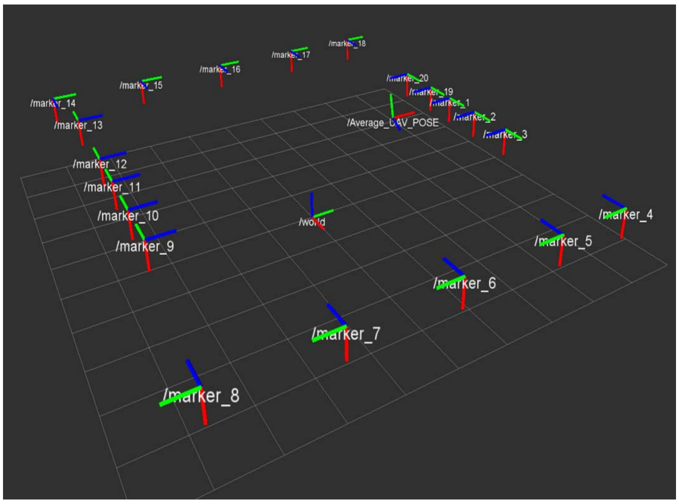

Fig. 8. Representation of the poses of markers, world coordinate and UAV

The computed state of the UAV is then used in the autonomous controller. After tuning the proportional and derivative gains for each degree of freedom, the drone is able to navigate to the desired waypoints with acceptable overshoot and response time. Fig. 9 plots the response of the UAV as it moves towards a target position 4 meters away. The overshoot is 13.8% with a settling time of 6.3s. The required percentage and settling time are subject to the requirements of the application. The main concern is to ensure the overshoot will not lead to the UAV crashing into the wall or any obstacles near the desired path. In this case, if the waypoints are not more than 4m from one to another, as long as the obstacles are 0.5m away from the path, then the drone will not likely hit any obstacles. For higher risk region like doors and narrow corridors, closer waypoints are defined so that the overshoot distance is less. Alternatively, the maximum velocity of the UAV can be reduced to control the overshoot. Besides, the time that the UAV takes to reach to the next waypoint will be less than the settling time mentioned. This is because in the path planning module, certain tolerance in pose is set. Once the UAV pose falls in the tolerance limits, it will not oscillate around the waypoint, because the following waypoint then becomes the new target pose.

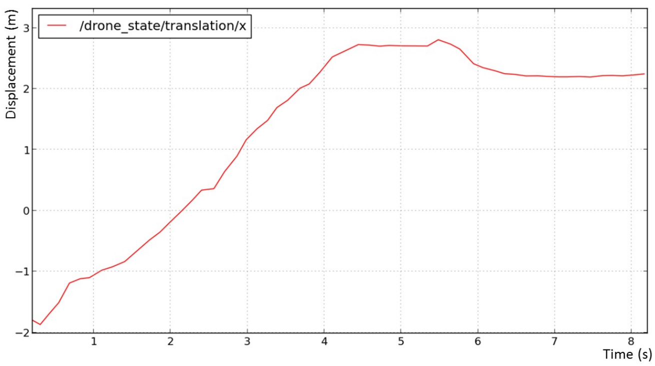

Fig. 9. Response of UAV towards a 4m target pose

Since the number of markers captured by camera and poses of the markers might affect the pose estimation, and hence, the state estimation, the UAV is programmed to fly to 6 positions (specified by world x, y and z coordinates) using the path planning module to assess the performance of the system. The UAV hovers for 5 seconds before moving to the next position so as to test the stability of the state estimation program and controller developed. The red line in Fig.10, depicts the path travelled by the UAV autonomously, whereas the blue line represents the ideal flight path. It is observed that the response of the UAV follows the pre-determined path closely with error of approximately less than 0.2 m. This proves the reliability of the designed autonomous patrol and surveillance system using UAV.

Experiments to test the entire system were done. The UAV is capable of navigating autonomously in and out of rooms and patrol different locations of the rooms repetitively while streaming live video from the camera. The joystick controller overrides the autonomous controller, allowing manual control of the UAV to desired places. The patrol path continues when the joystick is not used.

V. Conclusion

An autonomous patrol and surveillance system using unmanned aerial vehicle has been presented. In addition, path planning and priority hierarchy of multiple control inputs was achieved. The use of UAVs in the context of patrol and surveillance is a viable alternative to patrols by human security personnel who are subject to many limitations, for example, overlooking certain places, human memory limitation and fatigue. Experimental results shows that UAVs may be used in patrol and surveillance especially in indoor environment.

Acknowledgment

The authors gratefully acknowledge the contribution of Mechanical Engineering Department of Universiti Teknologi PETRONAS and Laboratoire Electronique, Informatique et Image, University of Burgundy for the continuous technical support and access to facilities.

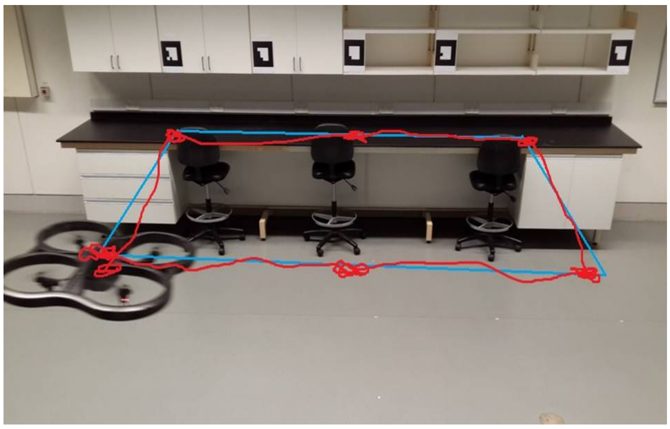

Fig. 10. UAV flight path to different positions

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