# System Integration of a Vision-Guided UAV for Autonomous Tracking on Moving Platform in Low Illumination Condition

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## BIOGRAPHY

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## ABSTRACT

This paper describes the development of a UAV to track and land on a moving platform in an environment with ultra-low illumination. Specifically, a customized marker illuminating with infrared (IR) LED (with 850 nm wavelength) is secured on the moving platform to be utilized as a landing pad, while the UAV installed with a monocular camera with IR filter is going to track the marker to follow and land on the moving platform. Sensor reading from an on-board LiDAR scanning range finder is fused with barometer to accurately and robustly determine the absolute height relatively to the marker and also to measure the descent velocity during the landing process. The developed algorithm is realized in a quadcopter UAV and the performance of UAV system is validated through actual flights in both day and night time.

## INTRODUCTION

In past decades, military and civilian sectors are widely adopting unmanned aerial vehicles (UAVs) for a variety of practical applications, such as agriculture, search, disaster rescue, surveillance and explorations. The development of electronic sensors and processors as well as advanced robotic technologies has created more autonomous UAV for many applications to improve job efficiency compared to traditional methods. Kendoul

(Kendoul, 2012) has done a comprehensive survey concentrating on the control, guidance and navigation of many commonly available UAVs.

One of the most critical and dangerous phases of autonomous flight is during landing. Even for the manned aircraft, landing is one of the most dangerous operations for pilots to handle. It could cause unwanted disaster if the aircraft is not properly controlled when touchdown (Benbassat & Abramson, 2002). In literature, global positioning system (GPS), LiDAR and radar sensors have been widely adopted for position estimation of the UAV. UAVs using GPS information for precise guidance and landing are presented in various literature (Belton, Betcher, Ffoulkes-Jones, & Blanda, 1999) (Wang, et al., 2015) (Pervan, Chan, & Colby, 2003) (Gold & Brown, 2004). Besides using GPS signals, many automatic recovery system uses millimetre-wave radar with transponders to send data onto the UAV on the platform for pose estimation between them. One disadvantage of such systems is that it usually requires extra devices on the landing pad. And the data link between the UAV and the landing platform needs to be guaranteed during flight. In some other works, a rotorcraft with visual tracking and LiDAR sensors is proposed, in which it is capable to provide both position and orientation information of the ship deck (Garratt, Pota, Lambert, Eckersley-Maslin, & Farabet, 2009) (Chen, Phang, Shan, & Chen , 2016).

To-date, vision based autonomous aerial systems is dominating due to rich information given by the images. Many mono and stereo vision based algorithms have been developed for autonomous landing of UAVs (Shakernia, Vidal, Sharp, Ma, & Sastry, 2002) (Hubbard, Morse, Theodore, Tischler, & Mclain, 2007) (Lange, Sunderhauf, & Protzel, 2009) (Laiacker, Kondak, Schwarzbach, & Muskardin, 2013). For these algorithm, pre-known markers are usually required to be attached on the landing pads. Many systems (Mahony, Russotto, Hamel, & Herisse, 2008) (Herisse, Hamel, Mahony, & Russotto, A nonlinear terrain-following controller for a VTOL unmanned aerial vehicle using translational optical flow, 2009) (Herisse, Hamel, Mahony, & Russotto, 2010) are using optical flow to estimate the velocity of the UAV with respect to the flat ground However, these algorithms could only work if the flat ground assumption condition is met and providing the ground target is not moving. In these systems, it is difficult for UAV to acquire accurate height estimation if the camera has no visual of pre-known marker or being too far away from the marker. To achieve smooth touchdown, it is vital to control descent speed based on a rate-based controller and measure the descent speed accurately. Furthermore, all these system are implemented based on good light condition and environment is always bright enough for the normal camera to capture useful images. For many modern applications, missions could sometimes executed at night, hence it is important for the UAV being able to land on moving platform in low illumination environment in case of such requirement.

In this paper, inspired by the aforementioned restrains, an autonomous UAV landing on moving platform in both day and night time solution is proposed. It is achieved by utilizing both mono camera with IR filter to filter out visible spectrum and LiDAR system. A monocular vision camera with IR filter is primarily used to estimate the relative horizontal position and vertical position of the target. Meanwhile, the LiDAR sensor can accurately extract the height information of the UAV with respect to the marker. Also, LiDAR measurement can be used to detect and filter outliers introduced by the vision algorithm effectively. An infrared LED based marker is mounted on the moving vehicle to indicate the landing location. The paper is divided into following sections: Section II will briefly introduce the sensor, processers and all the hardware used in this platform. Section III focus on the algorithms to measure states based on IR camera and LiDAR range finder. Furthermore, Section IV will mention the flight controller and control law used in this implementation while the real flight data and its comparison with ground truth will be shown in section V. In the end, conclusion remarks will be made.

## HARDWARE PLATFORM

The UAV platform to realize the autonomous landing on a moving vehicle is fully self-customized, as shown in Figure 1. This platform, codenamed T-Lion is developed by the Control Science Group of Temasek Laboratories at the National University of Singapore (TL@NUS). It was specially cater to carry high payload ($> 2$ kg) with the ability of flying at a longer endurance ($> 20$ mins). It has an optimal take-off weight of 5.5 kg, and a tip-to-tip dimension of 110 cm. Due to its suitable size and high payload, it is widely used in NUS for many indoor and outdoor research work.

*Figure 1: T-Lion UAV platform*

Electronics components and sensors that were installed in T-Lion specifically for this research work will be discussed in the following subsections.

**Flight Controller**

The T-Lion UAV is equipped with an in-house flight controller. The hardware consists of two inertial measurement units (IMU) of different model, with smart switching between the master sensor and the secondary sensor when needed (i.e. faulty detected on master sensor). It is mainly used for flight stabilization, where the raw measurement data of angular rates and accelerations will be fed into the flight controller's Kalman filter for further processing. The flight controller is also capable to receive GPS signals, which in our research project, however, is not used. Accompanied with the flight controller, a power splitter which can be powered directly using 4 to 6 cells Li-Po battery is included. The power splitter outputs 12v, 5v, and 3.3v for all sorts of electronics. Figure 2 and 3 show the flight controller and power splitter, respectively.

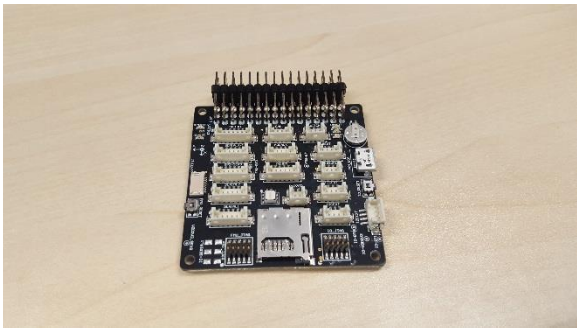

*Figure 2: Flight Controller*

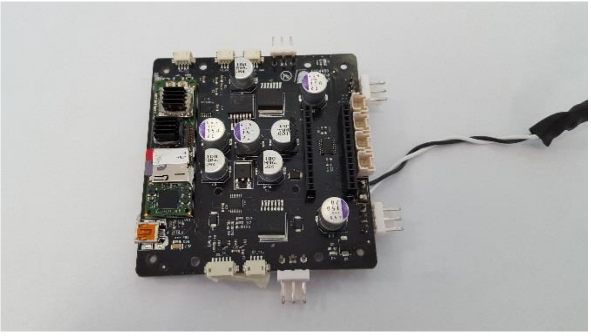

*Figure 3: Power Distribution Board*

**Laser Range Finder**

One particular challenge in visually aided navigation for UAVs is the depth measurement of the visual marker. In order to overcome this challenge effectively, an accurate height measurement is needed. A 270 degree wide angle laser range finder form Hokuyo with the range of 30 m is mounted and used to accurately estimate the UAV flying height. Hokuyo UTM-30LX is an industrial level laser range sensor, which provide distance measurement within mm accuracy. Algorithm to extract meaningful data from the span of laser range finder will be explained in detail in the next section.

**Gimbal Controlled Camera**

A monocular camera, PointGrey BlackFly is employed for visual image capturing during flight and landing. As the visual marker is placed facing up on the ground vehicle, the camera is needed to point directly downwards at all time. To handle the stabilization and direction of the camera, a 2-axis gimbal system is included. Arris Zhaoyun Brushless Gimbal is adopted for the work.

To effectively track the marker in ultra-low illumination environment, the marker will be lighted up with Infrared (IR) light. As a result, the BlackFly camera is modified as such that an IR filter lens is placed between the CMOS sensor and the camera lens. This enable the CMOS sensor to capture only the light with wavelength approximately 850 nm, which is in the IR range.

**Onboard Computer**

As a challenge in all computer vision research, it is well known that visual image processing is computational intensive. In literature, visual processing in UAV related applications can be solved by transmitting images to a powerful ground station for processing, then transmit the processed data (such as measurement or target reference) back to the UAVs for control and command. In our research, to avoid telecommunication issues such as interference or communication breakdown, we have included a powerful i7 processor on-board our UAV.

An Intel NUC mini-computer is selected and mounted on T-Lion. It is installed with Linux ROS system, where all image and laser processing algorithm are implemented and run in real-time in this computer during flight.

**Putting All Together**

The more important part of hardware integration is to properly connect each of the electronics components together, and to power up accordingly. Our power splitter is able to provide power supply to all mentioned components, which is mainly in 12v and 5v. In addition, the components are connected as shown in Figure 4. The peripheral components are all connected to Intel NUC via USB ports, while the NUC is connected to the flight controller via TTL serial port. Additional GPS receiver is included in the system for data comparison purpose.

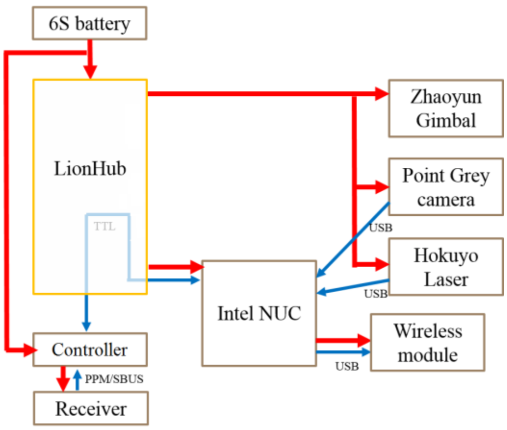


*Figure 4: Hardware Structure of UAV*

## STATE ESTIMATION

In this section, the on-board state estimation algorithm, which is responsible to provide relative position between the landing pad and the UAV, is investigated. In this implementation, we adopt vision system to measure the relative XY position between the marker and the UAV. The system uses a visual fiducial system – AprilTag as our visual marker attached onto the moving platform for the UAV to identify the landing spot. AprilTag system is introduced by Olson (Olson, 2011) to localize the system in full 6 degree-of-freedom (DOF). This is an improvement of the previous system to incorporate a robust and fast line detection algorithm and stronger coding style. It has a better robustness for the partial occluded marker, and estimate the position and orientation of the tag related to the camera. Hence, this information could be utilized by the drone to localize its position and orientation related the tag-carried coordinate system. Lee (Lee, Ryan, & Kim, 2012) has used AprilTag to achieve autonomous landing in the daytime environment which uses the on-board image-based visual servoing to vertically take-off and landing.

To enable our UAV to be capable of executing mission in the low-illumination conditions, we modified the landing platform and customized an IR light illuminating tag. The tag will be constantly illuminated near IR light of 850 mm wavelength. The camera is also equipped with 850 mm filter to exclude undesirable light in order to make the tag more distinguished shown on the captured image for the pose estimation algorithm. Figure 5 shows a capture image of the IR marker by the on-board camera.

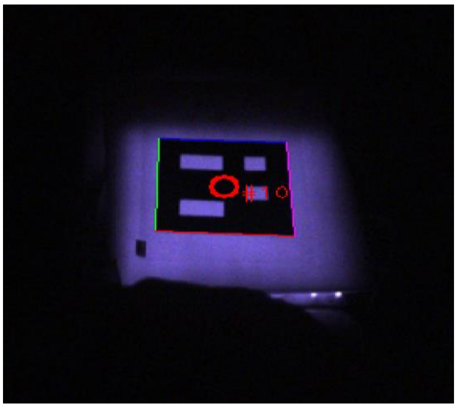

*Figure 5: Onboard Image of Infrared Marker*

It is crucial for the autonomous landing to have accurate measurement of height during the landing. Hence, in order to measure accurate height, a high-end Hokuyo laser range finder is installed on the UAV. A simple but reliable algorithm to estimate height from a series of laser scans is designed and the idea has been explained in our previous work (Chen, Phang, Shan, & Chen , 2016). The basic idea is to use split-and-merge algorithm to extract all the lines from 1081 single distances captured by the LiDAR sensor. Distance from the furthest line to the UAV is the true height of the drone. The height of the landing platform could also be extracted from the algorithm, hence the distance between the UAV and landing pad could also be acquired for a smooth landing. The sloped line which is beyond certain threshold will be rejected to avoid landing on the slope. The steps of the algorithm can be visualized in Figure 6 below.

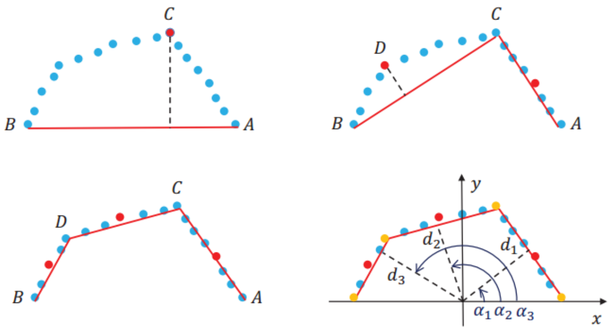


*Figure 6: Split and Merge Algorithm to Extract Height*

The flow chart of the height estimation algorithm from LiDAR is shown in Figure 7. As long as the true ground is projected by the laser beams from LiDAR, the accurate height measurement could always be acquired. Hence, moving vehicles underneath the UAV would not affect the height measurement.

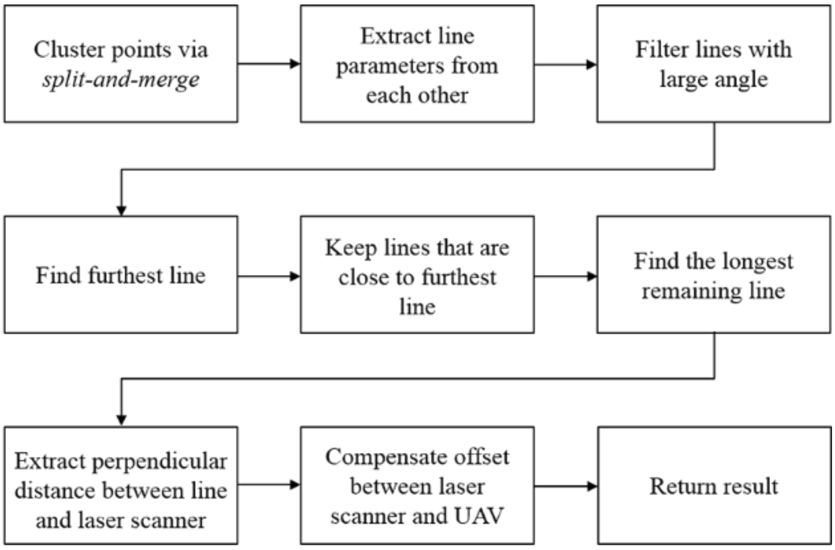


*Figure 7: Flow Chart of Height Measurement Algorithm*

## FLIGHT CONTROLLER DESIGN

The flight control of the quadcopter T-Lion UAV is separated into 2 cascaded loop, in which the inner-loop which runs in higher update rate (50 Hz) stabilized the UAV, while the outer-loop (20 Hz) controls the position of the UAV to the desired waypoint. Figure 8 shows the control structure of the UAV, where the inputs and outputs of the control loops are clearly shown.

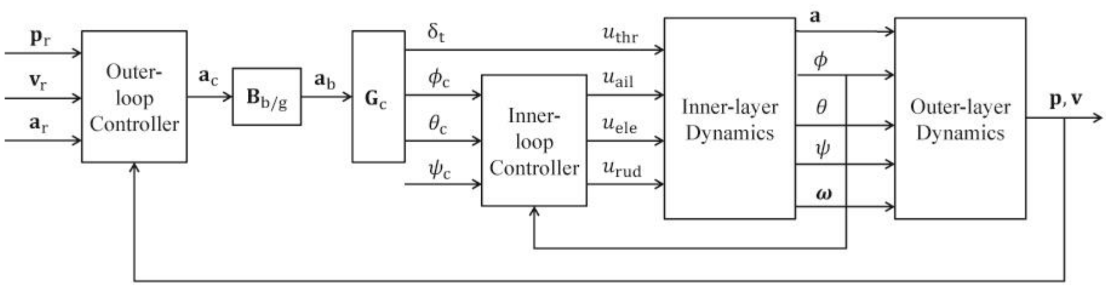


*Figure 8: Controller Structure*

### Model Identification of T-Lion

We are adopting first principle modelling approach to identify the mathematical model of the quadcopter T-Lion. More detail on the model identification methodology can be found in our previous work in (Chen, Phang, Shan, & Chen , 2016). The only difference between the previous work and the current work is the parameters of the UAV, where each of the parameter can be identify in a similar fashion, too.

### Position Control of T-Lion

The outer dynamics of the UAV in quadcopter configuration is differentially flat, which means that all its state variables and inputs can be expressed in terms of algebraic functions of flat outputs and their derivatives. An intuitive choice of flat outputs for quadcopter is

$$\sigma = [x, y, z, \psi]^T$$

It is obvious that the first three outputs, $x, y, z$ are totally independent. In other words, when designing its outer-loop control law and generating the position references, the UAV can be considered as a mass point with constrained velocity, acceleration and its higher derivatives in the individual axis of the 3-D global frame. Hence, a stand-alone controller based on multi-layer integrator model in each axis can be designed to track the corresponding reference in that axis. To achieve a good tracking performance, it is common to include an error integral to ensure zero steady-state error. This requires an augmented system to be formulated as

$$\dot{x}_{aug} = \begin{bmatrix} 0 & -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} x_{aug} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} u_{aug}$$
$$y_{aug} = x_{aug}$$
$$h_{aug} = [1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0] x_{aug}$$

where $x_{aug} = [\int p_e \quad p_r \quad v_r \quad a_r \quad p \quad v]^T$, $p_r, v_r, a_r$ are the position, velocity and acceleration references, $p, v$ are the actual position and velocity of the UAV, $p_e = p_r - p$ is the tracking error of the position.

In this control structure format, in order to track the moving marker, a robust and perfect tracking controller (RPT) is introduced. This controller takes in references not only on the position, but also on velocity and acceleration, in which our case, is the movement of the moving marker, which can be estimated with our visual tracking algorithm. The controller fits perfectly well in our research for tracking moving object. Interested reader can refer to [cite some paper here] for the implementation of RPT controller on quadcopter UAVs. As a result of this controller, a linear feedback control law of the following form can be acquired as

$$u_{aug} = F_{aug} x_{aug}$$

where

$$F_{aug} = \left[ \frac{k_i \omega_n^2}{\varepsilon^3} \quad \frac{\omega_n^2 + 2\zeta\omega_n k_i}{\varepsilon^2} \quad \frac{2\zeta\omega_n + k_i}{\varepsilon} \quad 1 \quad -\frac{\omega_n^2 + 2\zeta\omega_n k_i}{\varepsilon^2} \quad -\frac{2\zeta\omega_n + k_i}{\varepsilon} \right]$$

Here, $\varepsilon$ is a design parameter to adjust the settling time of the closed-loop system. The rest of the parameters are standard second order with integral gain parameters. Theoretically, when the design parameter $\varepsilon$ is small enough, the RPT controller can give arbitrarily fast responses. Nevertheless, it is safer practically to limit the bandwidth of the outer-loop to be much smaller than that of the inner-loop dynamics, because of the constraints of the UAV physical dynamics and its inner-loop bandwidth.

## FLIGHT EXPRIMENT

Experiment was carried out in the indoor and outdoor environment to verify the accuracy of pose estimation algorithm using AprilTag. Indoor flight test using Vicon system as ground truth to compare the position estimation from on-board algorithms. The on-board position was estimated by an extended Kalman filter (EKF) with input and measurements from IMU data and AprilTag algorithm.

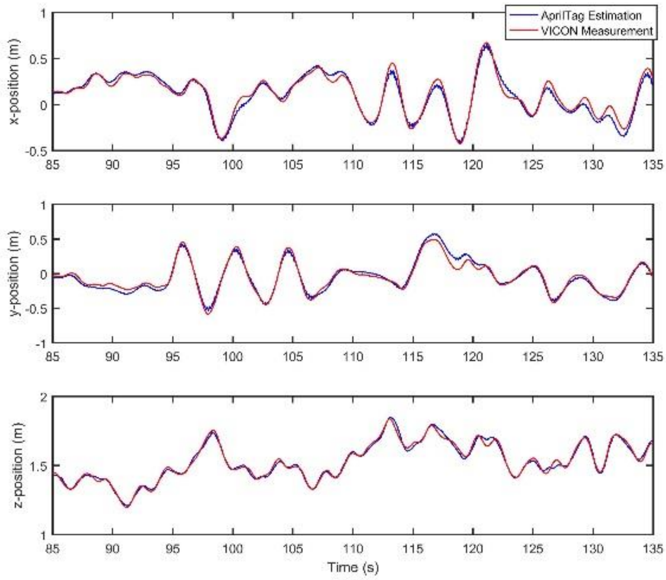


*Figure 9: Position Estimation Comparison between AprilTag Fused Data and Vicon*

First experiment, shown in Figure 9, shows the X, Y and Z position comparison when UAV is manually controlled by human pilot via Remote Controller. As observed from the results, the on-board position estimation is very close to the ground truth data.

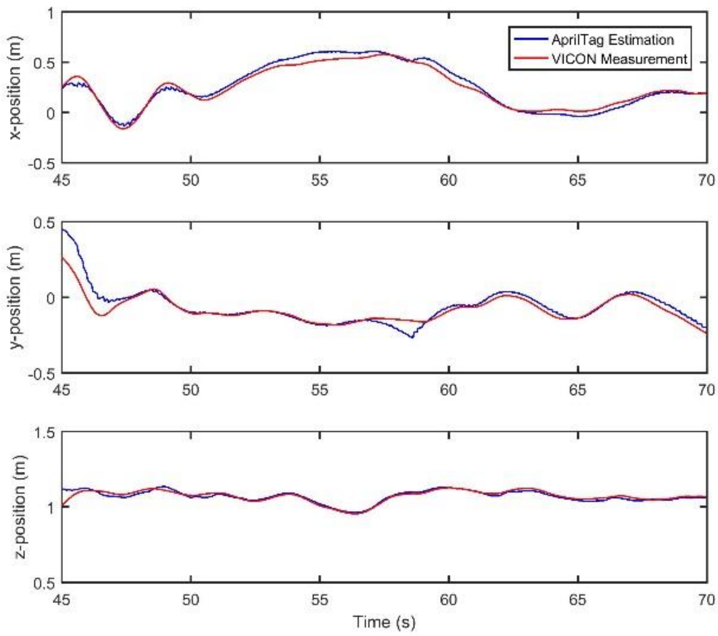


*Figure 10: Position Estimation Comparison during UAV Auto-Hover*

In the next experiment, the UAV is commanded to autonomously hover above the marker with on-board pose estimation from AprilTag and IMU. As shown in Figure 10, the UAV slightly loiter around the reference point due to disturbance caused by the wind effect bounced by the walls of the Vicon room. Generally, the hover performance is acceptable for further autonomous applications.

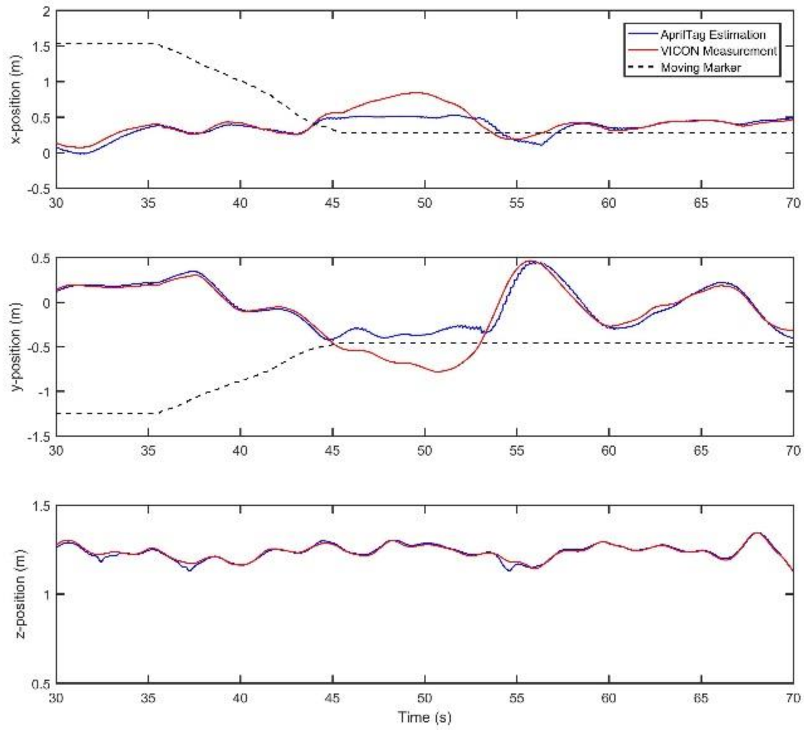


*Figure 11: Position Comparison during Auto-Hover and Target Moves*

In the last experiment, the UAV was commanded to track and follow the marker as the marker was moved smoothly in the Vicon room as shown in Figure 11. The black dotted line in the figure indicates the movement of the AprilTag marker. It could be observed from the figure that during the target moving phase, the UAV position estimation is accurate as compared to Vicon measurement. However, there is difference in X and Y position at the time when target abruptly stopped. The position estimation is slight diverse from the ground truth due to the Kalman Filter estimation. After about 10 s, the estimated position converges to the true position measured by Vicon system. Further effort needed to put onto fine tuning the parameters inside the filter to better track the moving target during all the period.

## CONCLUSION

The state estimation algorithm has been implemented to the actual UAV and it was tested with real flight experiments. Flight data from Vicon system and on-board flight controller has been compared to verify the accuracy of the algorithm. The integration of each part onto the system was validated by flight with successful tracking on the moving vehicle in both day and night time without GPS. However, a few limitations of current design should be solved. Firstly, in the GPS-denied environment, the system is not able to localize when the tag is not visualized. A visual odometry will be implemented in next version of the system. Then, the flight strategy and state machine should also be developed upon that to fly autonomously to handle special situations.

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