Trends in Bioinformatics

ISSN 1994-7941

OPEN ACCESS Trends in Bioinformatics

ISSN 1994-7941
DOI: 10.3923/tb.2017.11.19

Research Article
Vision-based State Estimation of an Unmanned Aerial Vehicle

[1]Lee Kian Seng, [1]Mark Ovinis, [1]Nagarajan, [2]Ralph Seulin and [2]Olivier Morel

[1]Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia
[2]University of Burgundy, 12 rue de la fonderie, 71200, Le Creusot, France

Abstract

Background and Objective: Unmanned Aerial Vehicles (UAVs) have found widespread use in many applications due to its mobility and maneuverability. An important aspect in controlling the movement of these vehicles is its state estimation. State estimation is especially challenging for indoor applications, where Global Positioning System (GPS) signals are weak and have low accuracy. **Methodology:** This research proposed a vision based state estimation that is applicable even for indoor use. It is a low cost, low power and reliable state estimation approach using a monocular camera with a series of fiducial markers. When a marker is captured by the camera, its position and orientation with respect to the camera's coordinate frame is determined based on its homography transformation. The pose of the camera and hence the vehicle, in world coordinate can then be inferred from known markers poses. **Results:** In this study experimental results showed that the proposed method is suitable for indoor navigation of unmanned aerial vehicles. The reliability of the state estimation was improved by increasing the number of markers captured. **Conclusion:** The experimental results verified that the vision based state estimation method for indoor UAV navigation a promising solution and had several advantages over traditional other methods.

Key words: State estimation, 3D pose, indoor localization, computer vision, monocular camera, fiducial markers, unmanned aerial vehicles

Received: September 01, 2016 Accepted: November 30, 2016 Published: December 15, 2016

Citation: Lee Kian Seng, Mark Ovinis, Nagarajan, Ralph Seulin and Olivier Morel, 2017. Vision-based state estimation of an unmanned aerial vehicle. Trends Bioinform., 10: 11-19.

Corresponding Author: Lee Kian Seng, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia

Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Unmanned Aerial Vehicles (UAV) are increasingly finding civilian applications such as public surveillance, transportation and visual inspection. With advances in control technology, accurate control algorithms have enabled precise and aggressive navigation of a UAV[1]. UAVs are capable of performing quick and complex maneuvers such as navigating through narrow window and performing multiple flips[2,3]. Researchers envisioned a swarm of UAVs cooperating to carry out tasks effectively, for example, building a cubic structure[4], even playing ping pong[5] and autonomously using advanced control algorithms. State estimation is a required feedback to the controller. The state of a UAV comprises its position, orientation, linear velocity, angular velocity, linear acceleration and angular acceleration.

In an indoor environment, the most commonly used approach; GPS is not feasible primarily due to weak signals. Other methods as discussed in the following section are costly, power consuming and inefficient with high payloads. This paper presents a low cost, low power and reliable state estimation approach using a monocular camera with a series of fiducial markers. A monocular camera is cheaper, consumes less power and is lighter compared to laser range finder. The markers used are printed patterns.

Control algorithms to manoeuver a UAV precisely require accurate state estimation. For the building of cubical structure example, a VICON motion tracking system is used. It gives the pose of the UAV at 150 Hz with millimeter accuracy. Of course, such system is very costly besides its limitation of requiring a properly calibrated cameras set up. However, the use of an external motion capture system restricts the system developed for use in a laboratory set up only[6].

Another common approach uses Global Positioning System (GPS) to location the robot[7] with a magnetometer to determine the direction that the robot is facing. Such a system is currently available as a commercial product[8]. However, GPS lacks precision and reliability[9]. It has an average accuracy of 3.5 m and is subject to atmospheric conditions, quality of receiver as well as any blockage of the signals[10]. This limits the usage of the UAV to relatively wide area. Indoor environments and corridors between buildings, for example, are not suitable for such technique.

To perform state estimation without external sensors, a few methods have been proposed. A popular idea is to use a laser range finder for localization in an indoor environment[11,12]. This, however, requires a heavy laser range sensor with high power consumption[13]. Also, the UAV can lose track of its position because of the limited range that the laser sensor can detect[14]. In contrast, a RGB (Red, Green, Blue) monocular camera provides rich information in addition to being low weight and small[15].

A monocular camera is utilized together with printed fiducial markers to estimate the state of UAV[16]. It consumes less power and comes at much lower cost besides being virtually unlimited in terms of sensing range. The advantage of using such markers is that it can be easily detected using standard pattern recognition algorithms and conventional classification methods[17]. A geometric approach is employed for pose estimation from the appearance of marker in perspective projection.

The objective of this research was to examine the state of the art in state estimation and developed a proposed framework with emphasis on the approach in obtaining the state of UAV. The proposed method was also compared with other methods.

METHODOLOGY

The proposed framework employed vision-based algorithms that recognized fiducial markers and computes their positions and orientations around the x, y and z-axis. In an environment where the markers size and poses were known, the pose of the camera and hence, the UAV with respect to the world coordinate can be determined. The accuracy and reliability increases when the number of markers captured increases. To reduce the noise and fluctuation of the pose data, average pose over small period of time is computed which results in lower frequency and smoother pose data.

Experiment were also performed for the validation of the proposed framework. For the conducting of the experiment 10×10 m room in UniversitiTeknologi PETRONAS was used as testing area.

Software platform: The state estimation program implemented in Robot Operating System (ROS) because of its exponential growth in popularity in recent years[18]. The 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[19]. The significance of using ROS in this research is that the vision-based state estimation program developed can then be easily integrated or utilized by a wide variety of robots especially UAVs supported by ROS.

Marker recognition: AR Toolkit was deployed for fiducial marker recognition. It is a well-known software library for creating Augmented Reality (AR) applications that normally involves the overlay of virtual imagery on the markers[20]. It is capable of recognizing and differentiating one marker to another and computing the pose of the markers in six degrees of freedom around three axes using homography transformation. This is the basis of the proposed state estimation algorithm. Figure 1 shows examples of these markers.

Data visualization: It is difficult to interpret the pose by looking at rapidly changing numbers. The axes orientations for world coordinate frame, markers, camera and UAV can be different, making it more confusing to verify the computation codes. Therefore, the pose information of the aforementioned components are represented in a graphical manner using RVIZ, a 3D visualization tool for displaying sensor data and state information in ROS (rviz). Figure 2 is a representation of the world coordinate frame, markers, camera of UAV and UAV in RVIZ. Each components is labeled clearly and the axes orientation is displayed by different colors for each axis. It provides an intuitive way of visualizing the relative position of one component to another. This greatly simplified the development and testing process for the state estimation program.

UAV state estimation: The state estimation involves the on-board camera pose computation from markers captured by the camera, computation of UAV pose from on-board camera pose and computation of the linear and angular velocity and acceleration.

Camera pose computation from a fixed marker: The AR Toolkit provides the transformation matrix from camera to marker. Hence, the pose of the marker computed from pose of the camera, using (1). However, since the state estimation algorithm employs fixed markers to determine the pose of moving camera and UAV, (2) and (3) shows the derivation of the equation needed to determine the pose of the onboard camera of UAV. The inverse of the transformation matrix from camera to marker is used to compute, given which is dependent on the placement of the marker in indoor setup:

$$p_{marker} = p_{camera} T_{camera}^{marker} \tag{1}$$

$$p_{marker} T_{camera}^{-1marker} = p_{camera} T_{camera}^{marker} T_{camera}^{-1marker} \tag{2}$$

$$p_{camera} = p_{marker} T_{camera}^{-1marker} \tag{3}$$

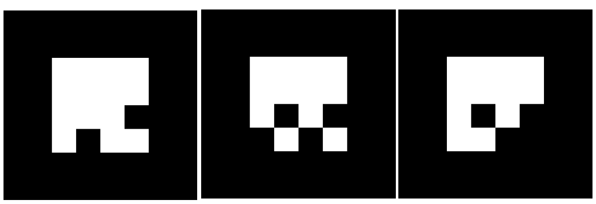

Fig. 1: Examples of fiducial markers recognizable by AR toolkit

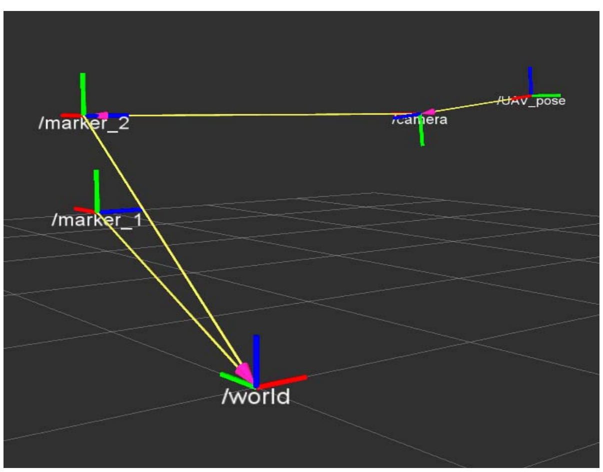

Fig. 2: Graphical representation of components poses in RVIZ

Camera pose from multiple fixed markers: To compute the UAV pose in any position and orientation in an indoor setup, a series of markers is required. The algorithm has to be able to compute the pose of the robot whenever a marker or markers are seen. The algorithm is further developed to detect different markers. 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 using (3). Since multiple markers can be seen in the same image, the program will check all markers and return the results with respect to each marker.

Computation of a stable camera pose: The use of multiple markers in a single image captured increases the accuracy of the camera pose. This is because the resulting pose can be calculated using the average of camera poses computed from a few poses of different markers. To add more flexibility to the program, a user can specify a time interval corresponding to the frequency of pose data desired for the average pose computation. For example, the average will be computed every 0.0667 second if a 15 Hz pose data is desired. For fast maneuvering, a higher frequency pose data may be preferred whereas for lower speed movement, lower frequency data can reduce the noise and fluctuation of the results and hence, reduce power consumption of rapidly changing control signals. Equation 4 is used for the average pose computation, where is the number of camera pose added in the time interval.

$$p_{camera,\ average} = \frac{\sum p_{camera}}{n} \tag{4}$$

Computation of UAV pose: Thus far, only the camera pose is computed. In most of the cases, the camera pose is not the same as the UAV pose because the camera is not located at the center of all the rotors. Equations 5, 6 and 7 show the computation of UAV pose. The transformation from marker coordinate frame to UAV coordinate frame is the concatenation of transformation from marker to camera and transformation from camera to center of UAV, which depends on the UAV used is already computed for camera pose computation discussed.

$$p_{uav} = p_{marker}(T_{marker}^{uav}) \tag{5}$$

$$p_{uav} = p_{marker}\left(T_{marker}^{camera} T_{camera}^{uav}\right) \tag{6}$$

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

Computation of velocity and acceleration: With the position and orientation of UAV at any time instance, the linear velocity and angular velocity, can be calculated as the time, derivative of linear displacement and angular displacement respectively from one instance to another. However, it is important to note that the displacements for the calculations are based on the local coordinate frame of the UAV. Equations 8, 9 and 10 derive the calculation for local displacements from previous UAV pose, to current UAV pose. The linear and angular displacements are extracted from in (10), which is the transformation of UAV previous pose to current pose in UAV local coordinate frame.

$$p_{uav,t_i} = p_{uav,t_{i-1}} T_{uav,t_{i-1}}^{uav,t_i} \tag{8}$$

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

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

Equations 11 and 12 are used for computation of linear velocity and angular velocity, respectively for x, y, z-axis and are the linear displacement and angular displacement, respectively from previous pose to current pose in UAV local coordinate frame.

$$v = \dot{s} = \frac{\delta s}{\delta t} \tag{11}$$

$$\omega = \dot{\theta} = \frac{\delta \theta}{\delta t} \tag{12}$$

Equations 13 and 14 are used for computation of linear acceleration and angular acceleration, respectively for x, y and z-axis.

$$a = \ddot{s} = \frac{\delta v}{\delta t} \tag{13}$$

$$\alpha = \ddot{\theta} = \frac{\delta \omega}{\delta t} \tag{14}$$

RESULTS

For the validation of proposed framework and evaluation of its performance the proposed techniques had been tested on UAV. For experimental Setup, Fiducial markers wrer printed on A4 papers and pasted as shown in Fig. 3. Although such markers can be pasted on the ceiling to prevent occlusions, they were pasted on the wall because the UAV used in the experiments does not had an upward facing camera. The pose of markers is defined into the program.

The UAV used was a Parrot ARDrone shown in Fig. 4, that comes with an onboard HD camera of 720 p streaming at about 30fps. The lens covers a 92° field of view[21]. The 640×360 pixel video resolution is used to demonstrate the ability of the program to function with a lower resolution camera.

When one marker is detected, the program provides the state of the UAV at about 30 fps, which is limited by the rate of image stream of the UAV camera. When two markers are detected, the state of UAV given by the program is about 60 fps. The rate is proportional to the number of markers seen by the camera. This is because the program checks the markers one after another. As long as one is detected, the UAV pose is directly computed and reported. Therefore, the computation of average pose should be done over the period corresponding to the frequency of state estimation specified. Figure 5 represents the UAV pose data while it is held stationary without computing the average pose at lower frequency whereas Fig. 6 shows the results computed by accumulated pose data at 15 Hz under the same condition. In comparison, the data at lower frequency is less noisy with lower amplitude and frequency of fluctuation. This is desired because it reduces the computational power of the UAV control and extends the limited flight time.

While changing the position and orientation of the UAV, the pose of the robot is reported and presented in real time. Figure 7 shows the poses of the UAV and markers in real world, whereas Fig. 8 is the representation of the poses of the

Fig. 3: Experimental setup

Fig. 4: ParrotAR.Drone (UAV used for experiment)

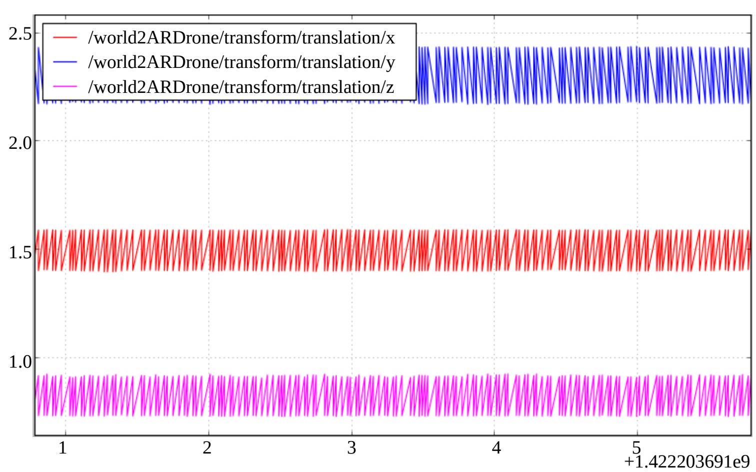

Fig. 5: UAV pose data based on markers recognized

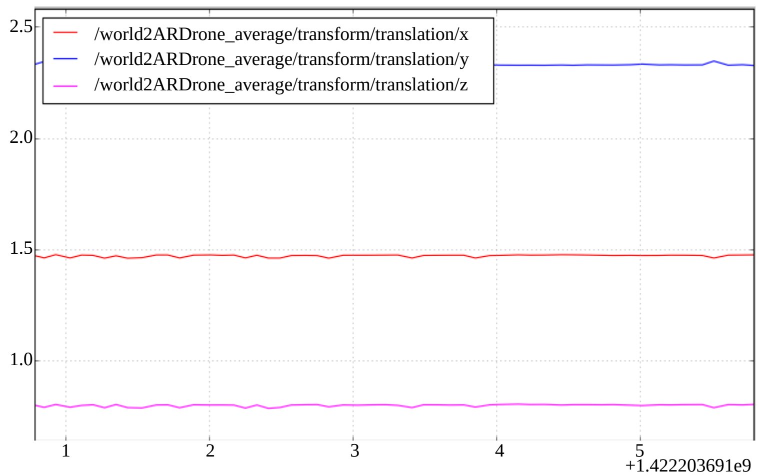

Fig. 6: Average UAV pose data computed by the accumulated pose data at 15 Hz

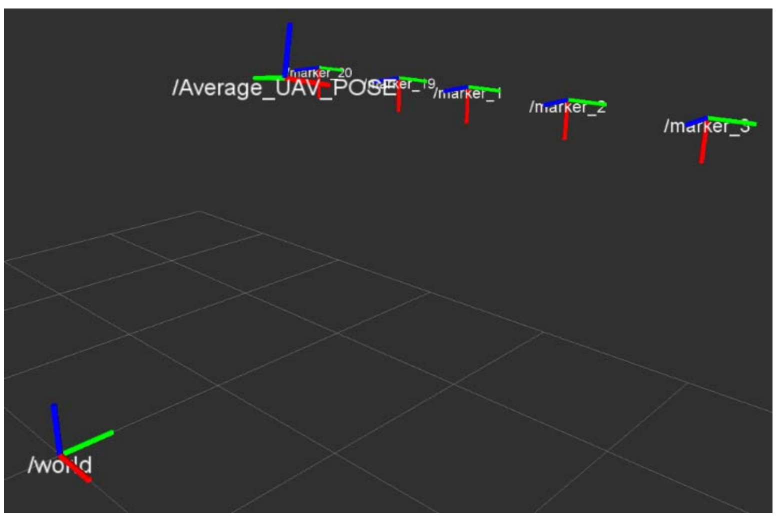

Fig. 7: Poses of UAV and markers in real world

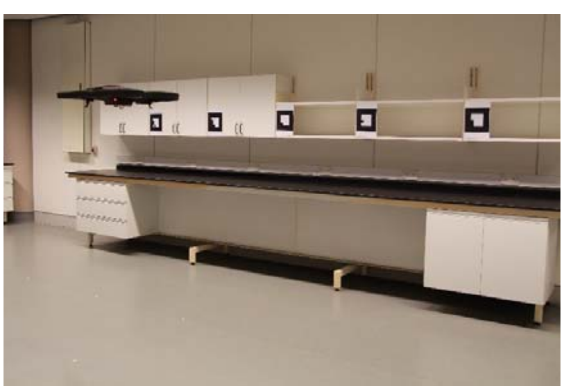

Fig. 8: Representation of the poses of the UAV, markers and world coordinate

UAV, markers and world coordinate frame based on the data of the program at the same time instance. In an indoor environment where all the markers poses are entered to the program, the pose of UAV is obtained smoothly without noticeable, sudden change in pose as the UAV navigates around the environment Fig. 9.

Figure 10 depicts the mean error of each axis as the distance in x, y and z-axis changes from 1-4 m. Figure 11 shows the standard deviation of the errors. It is noticeable that the error increases as the distance increases. This is because the further the UAV is from the markers, the less clear the markers appear in the camera view, which reduces the accuracy of the pose estimation. The standard deviation of the data is rather low, indicating consistent results. These data

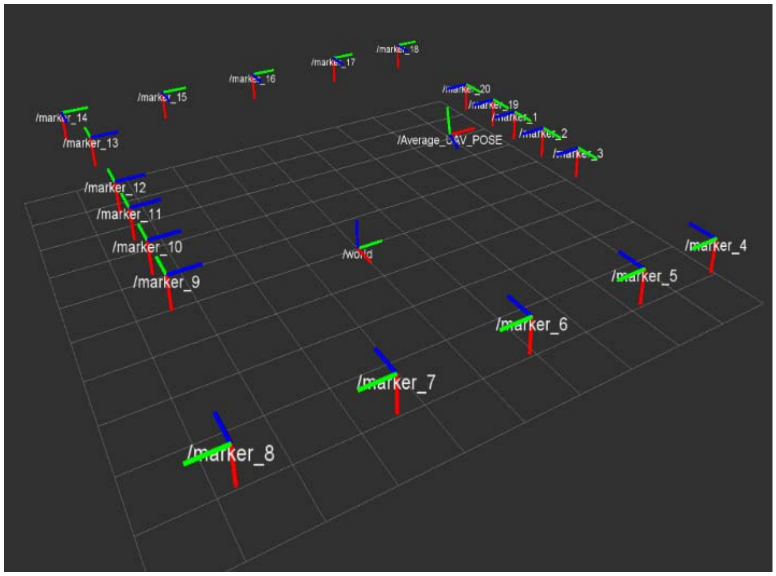

Fig. 9: Application of the state estimation program in an indoor environment setup

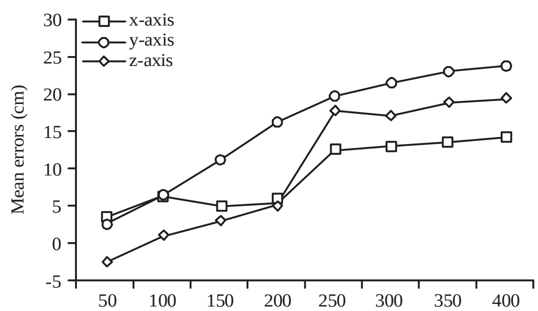

Fig. 10: Graph of mean error of each axis against the distance from the markers

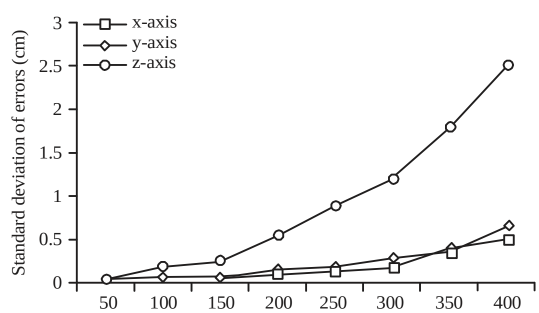

Fig. 11: Graph of standard deviation of errors of each axis against the distance from the markers

serve as a guideline for path planning and markers placement decisions for indoor navigation system. For example, to pass through a narrow door or corridor, markers have to be less than 2.5 m away from the UAV along the path to be travelled by the UAV so that the error of 0.2 m will not cause the UAV to crash to the wall.

The directional sense for both linear and angular velocity and acceleration are verified to be in x, y and z-axis of UAV local coordinate frame. These data can be used as feedback for UAV control signal computation algorithms.

DISCUSSION

The proposed framework had been implemented and validated. The experimental results it is revealed that the main advantages of this approach, it consumed low power consumption since the only sensor required was a camera compared to other methods explained by Ahmed *et al.*[22] and Sapkota *et al.*[23] in year 2015 and 2016, respectively. During experiment described in results section, AR Toolkit was used for marker detection and pose estimation which give great results. Computer program that processes the image captured by camera and outputs the state of the UAV is written in C++ and Python programming language. It includes a series of calculations using transformation matrices to ultimately obtain the pose of the unmanned aerial vehicle. Computation of average pose from multiple outputs, publication of UAV pose at user specified frequency with the accumulation of pose data to reduce the fluctuation of the output pose as well as the computation of UAV linear, angular velocity and acceleration. Other method also presented[24] but proposed techniques worked quite optimal and feasible by using indoor state estimation method for carrying out navigation of UAV in indoor environments.

CONCLUSION

An indoor state estimation of unmanned aerial vehicle using monocular camera and fiducial markers has been presented. Results from experiments showed that this method is viable and reliable as an indoor state estimation approach to be utilized for carrying out UAV navigation in indoor environments.

SIGNIFICANT STATEMENT

This research work provided a new method for indoor navigation of UAV system, which consume less power and it is more reliable method. Besides that this techniques is also cost effective solution because it use only one camera for navigation use.

ACKNOWLEDGMENT

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

REFERENCES

1. Mellinger, D. and V. Kumar, 2011. Minimum snap trajectory generation and control for quadrotors. Proceedings of the IEEE International Conference on Robotics and Automation, May 9-13, 2011, IEEE., pp: 2520-2525.
2. Mellinger, D., N. Michael and V. Kumar, 2014. Trajectory Generation and Control for Precise Aggressive Maneuvers with Quadrotors. In: Experimental Robotics, Khatib, O., V. Kumar and G. Sukhatme (Eds.)., Vol. 16, Springer, Berlin, Heidelberg, pp: 361-373.
3. Lupashin, S., A. Schollig, M. Sherback and R. D'Andrea, 2010. A simple learning strategy for high-speed quadrocopter multi-flips. Proceedings of the IEEE International Conference on Robotics and Automation, May 3-7, 2010, IEEE., pp: 1642-1648.
4. Lindsey, Q., D. Mellinger and V. Kumar, 2012. Construction with quadrotor teams. Autonomous Robots, 33: 323-336.
5. Muller, M., S. Lupashin and R. D'Andrea, 2011. Quadrocopter ball juggling. Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, September 25-30, 2011, IEEE., pp: 5113-5120.
6. Engel, J., J. Sturm and D. Cremers, 2012. Camera-based navigation of a low-cost quadrocopter. Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Ocotber 7-12, 2012, IEEE., pp: 2815-2821.
7. Krajnik, T., M. Nitsche, S. Pedre, L. Preucil and M.E. Mejail, 2012. A simple visual navigation system for an UAV. Proceedings of the 9th International Multi-Conference on Systems, Signals and Devices, March 20-23, 2012, IEEE., pp: 1-6.
8. Anonymous, 2014. Ascending technologies. October 17, 2014. http://www.asctec.de/en/.
9. Saska, M., V. Vonasek, T. Krajnik and L. Preucil, 2012. Coordination and navigation of heterogeneous UAVs-UGVs teams localized by a hawk-eye approach. Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, October 7-12, 2012, IEEE., pp: 2166-2171.
10. GPS,, 2017. GPS accuracy. GPS., USA. http://www.gps.gov/systems/gps/performance/accuracy/.
11. Pravitra, C., G. Chowdhary and E. Johnson, 2011. A compact exploration strategy for indoor flight vehicles. Proceedings of the 50th IEEE Conference on Decision and Control and European Control Conference December 12-15, 2011, IEEE., pp: 3572-3577.
12. Grzonka, S., G. Grisetti and W. Burgard, 2009. Towards a navigation system for autonomous indoor flying. Proceedings of the IEEE International Conference on Robotics and Automation, May 12-17, 2009, IEEE., pp: 2878-2883.
13. Bills, C., J. Chen and A. Saxena, 2011. Autonomous MAV flight in indoor environments using single image perspective cues. Proceedings of the IEEE International Conference on Robotics and Automation, May 9-13, 2011, IEEE., pp: 5776-5783.
14. Mustafah, Y.M., A.W. Azman and F. Akbar, 2012. Indoor UAV positioning using stereo vision sensor. Procedia Eng., 41: 575-579.
15. Engel, J., J. Sturm and D. Cremers, 2014. Scale-aware navigation of a low-cost quadrocopter with a monocular camera. Robotics Autonomous Syst., 62: 1646-1656.
16. Eberli, D., D. Scaramuzza, S. Weiss and R. Siegwart, 2011. Vision based position control for MAVs using one single circular landmark. J. Intelli. Rob. Syst., 61: 495-512.
17. Busch, J., F. Sagar, T. Wagner, P.F. Tehrani, 2013. Indoor localization using augmented reality markers. Department of Telecommunication Systems, Telecommunication Networks Group. https://www.tkn.tu-berlin.de/tknteaching/student_projects/project_summaries/indoor_localization_using_augmented_reality_markers/.
18. Boren, J. and S. Cousins, 2011. Exponential growth of ros [ros topics]. IEEE Rob. Autom. Mag., 18: 19-20.
19. Cousins, S., B. Gerkey, K. Conley and W. Garage, 2010. Sharing software with ros (ros topics). IEEE Rob. Autom. Mag., 17: 12-14.
20. Anonymous, 2014. AR toolkit. December 31, 2014. http://www.hitl.washington.edu/artoolkit/.
21. Anderson, C., 2010. Parrot AR. drones specs: ARM9, Linux, 6DoF IMU, ultrasonics sensor, WiFi....WOW! January 6, 2010. http://diydrones.com/profiles/blogs/parrot-ardrones-specs-arm9.

22. Ahmed, S.F., K. Kushsairy, M.I.A. Bakar, D. Hazry and M.K. Joyo, 2015. Attitude stabilization of Quad-rotor (UAV) system using fuzzy PID controller (an experimental test). Proceedings of the 2nd International Conference on Computing Technology and Information Management, April 21-23, 2015, IEEE., pp: 99-104.
23. Sapkota, K.R., S. Roelofsen, A. Rozantsev, V. Lepetit, D. Gillet, P. Fua and A. Martinoli, 2016. Vision-based unmanned aerial vehicle detection and tracking for sense and avoid systems. Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, October 9-14, 2016, IEEE., pp: 1556-1561.
24. Medeiros, V.S., R.E. Vale, Y.C. Gouveia, W.T. Souza and A.V. Brito, 2016. An independent control system for testing and analysis of UAVs in indoor environments. Proceedings of the 13th Latin American Robotics Symposium and 4th Brazilian Robotics Symposium, October 8-12, 2016, IEEE., pp: 55-60.