Journal of Engineering and Applied Sciences 12 (16): 4138-4143, 2017
ISSN: 1816-949X

A Survey of Onboard Sensors for Quadrotor's Collision Avoidance System

[1]Sulaiman Sabikan, [2]Sophan Wahyudi Nawawi and [2]Shahdan Sudin
[1]Department of Electrical Engineering Technology, Fakulti Teknologi Kejuruteraan,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[2]Department of Control and Mechatronic Engineering, Faculty of Electrical Engineering,
Universiti Teknologi Malaysia UTM, Johor Bahru, 81300 Johor, Malaysia

Abstract: The quadrotor control system with the reactive Collision Avoidance System (CAS) function always require environmental information acquired directly from the onboard sensors. Without the input instruments, quadrotor system may not function to its full potential. In some cases, sensor capability is undermining the quadcopter collision avoidance algorithm and reduces the overall system performance. However, an appropriate sensor selection for a quadrotor requires special consideration such as processor capability, CAS algorithm execution and payload constrains. Motivated by that phenomena, this study presents a survey of onboard sensor for quadrotor CAS that has been developed and implemented. Fundamental collision avoidance system frameworks, some important issues in quadrotors CAS design requirements, several collision avoidance algorithms from previous works and sensor selection considerations are reviewed. Furthermore, three different practical sensors that were used in quadrotors system are nominated in this study including ultrasonic sensor, vision sensor and LIDAR. The advantages of each onboard sensors for collision avoidance are summarized in the conclusion.

Key words: Obstacle detection, collision avoidance, quadrotor, UAV, appropriate, reactive

INTRODUCTION

Quadrotor is a kind of small Unmanned Aerial Vehicles (UAVs), powered by four high speed electricalrotors that can manoeuvre in three-dimensional spaces within tight space and relatively low altitude. Furthermore, it can navigate autonomously or controlled manually by an operator who can manoeuvre the vehicle to avoid collision. Dealing with unexpected environment and to realize autonomous flight mission, safe navigation capabilities remains a research challenge which is accomplished by a combination of online environmental sensing, path planning and collision avoidance strategies (Scherer *et al*., 2008). These combination of functions are called Collision Avoidance System (CAS) that has been applied in robotics such as in arm robotic manipulators, wheeled mobile robots, Autonomous Underwater Vehicles (AUVs) as well as in an UAV (Cruz and Encarnacao, 2011). However, CAS development strategies for quadrotors platform differ because of their manoeuvrability characteristics, operational conditions, limitations in onboard processing power (Fraundorfer *et al*., 2012) and the load carrying capacity. As so, not all sensors that are used in ground mobile robot system can be used in an UAV system. Therefore, selection of appropriate onboard sensor technology is one of the most elementary part in the development stages of a practical CAS of quadrotors system.

The purpose of using onboard sensors for quadrotos can be categorized into three; stabilization control, navigation control and obstacle detection. For instance, the Inertial Measurement Unit (IMU) and magnetometer serves as a prerequisite for the attitude and altitude control and navigation control. The Global Positioning System (GPS) receiver module provides position estimation used in the autonomous navigation control, while ultrasonic sensors, infrared sensors, vision based sensors and LIDAR sensors provide measurements for obstacle detection. Besides the onboard sensors, some external sensors has also been used to control the quadrotors operations, especially for indoor applications. Inpreviously proposed methods, the commersial VICON or OptiTrack motion positioning system have been among the most favorable external sensors in order to provide the pose (ground position, ground velocity and attitude) of an autonomous quadrotor (Ducard and Andrea, 2009; Davis *et al*., 2013; Kendall *et al*., 2014; Israelsen *et al*.,

Corresponding Author: Sulaiman Sabikan, Electrical Engineering Technology Department, Fakulti Teknologi Kejuruteraan, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

2014; Mellinger and Kumar, 2011). The implementation of the first two categories of sensors that has been used for stabilization and navigation control will not be discussed further in this survey. Stability control is the basic controller to control a quadrotor in the air. IMU, magnetometers and barometers are common sensors in the stabilization control system and it has performed well by adopting various proposed control system strategies. While, for navigation control, the positioning is easily done by utilizing a GPS coordinate system. On the other hand, in GPS-denied environments, the motion positioning system will facilitate quadrotor localization. These two functions are prerequisites for obstacle avoidance controller.

The third objective of using onboard sensors is interesting to be discussed as it would make a worthwhile contribution to the research community. Now a days, advancement in sensor technology offers more options of sensors that can be integrated into the quadrotors platform to develop acollision avoidance system with obstacle sensors being one of the few. Each obstacle sensor has a different working principle, provides different amounts of information, time sampling rate, latency, reliability and cost. Up to this point, many researchers have been working on the development of control strategies for collision avoidance algorithm by applying different obstacle sensor types and configuration. These diversity of obstacle sensors were can be used UAV system is our motivation in this survey paper. Without denying the importance of other sensors, this survey paper focused on the reviews written on obstacle sensors for CAS.

Several review papers focusing on quadrotors have been previously presented such as by Ghazbi *et al*. (2016) general overview of >160 different quadcopters research projects (Pham *et al*., 2015) (major collision avoidance systems approach) (Alexopoulos *et al*., 2013) (comparison of three collision avoidance methods for an UAV) and Albaker and Rahim (2009) key functions on the unmanned aircraft's CAS system. Based on these previous reviews, a survey or review paper was not found that was specifically dedicated to the obstacle sensor implementation for the quadrotors collision avoidance system.

MATERIALS AND METHODS

Cas design requirements: The main objective of the collision avoidance controller is to avoid collisions with any objects within their predefined trajectory and to generate collision-free navigation if at all any obstruction is encountered. Obstacle sensors are used to sense and

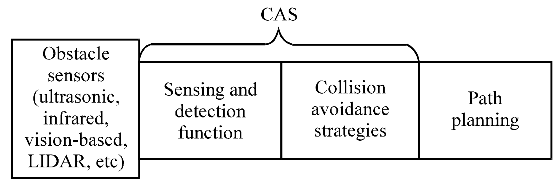

Fig. 1: Collision avoidance system framework

provide obstacle information to the controller. As shown in Fig. 1, function of CAS can be categorized into two main functions; sensing and detection and collision avoidance strategies (Pham *et al*., 2015). Both of these systems are fundamental requirements in path planning function. Static obstacles and dynamic obstacles are two types of obstacles that are normally taken into account while planning the design. Static obstacles may comprise of articulated obstacles, natural landmarks, physical objects (flagpole) or any constructed structures (walls) while dynamic obstacles may comprise of cooperative aircrafts in multi-vehicle scenarios, humans or any moving objects. The difference in physical appearance, sizes and surface of an obstacle would be a big challenge in sensing and detection functions. Hence, a multi sensor approach should be considered.

The sensing function is a process of acquiring useful information about its surrounding environment. This function is carried out by a physical sensor that is integrated to the main controller circuits. There are several types of obstacle sensors currently available that can be considered to be used in into quadrotors such as ultrasonic-based, infrared-based, vision-based and laser-based sensor. Once a UAV receives information of the obstacles, obstacle detection process occurs where the UAV determines if there are any imminent collisions. There are several obstacle detection approaches; trajectory calculation and distance estimation, worst case, probabilistic and act as seen.

Many methods have been proposed to perform collision avoidance in aerial vehicle such as by Samir (2014) (collision avoidance layer), Mendes and Ventura (2012) (teleoperated obstacle avoidance) (bug algorithm), Davis *et al*. (2013) (Artificial Potential Field algorithms) (Vector Field Histogram algorithm) and Susnea *et al*. (2009) (Bubble Band Technique). In CAS design consideration, it is always related to these two problems (Navajas and Prada, 2014; Benito *et al*., 2014) which are how to detect the obstacle and how to generate obstacle free navigation.

Sensor selection is essential in the design and development of a quadcopter system to achieve closed-loop control. Without obstacle sensors added-on into the quadcopter system their autonomous mission looks like blind and deaf human walking alone straight to the destination without any assistive equipment. Our quadrotor trajectory or behaviours will be unchangeable, even if the obstruction exists in the flying routes.

Sensor measurement capability must be considered before determining the other factors in our proposed control algorithm. It is because, successful collision avoidance algorithm depends on the quality of sensor data measurement. Sensor measurement capability that needs to be considered include real-time measurement capability, operational environment, payload and cost. Comparison with ground vehicles, obstacle sensor selection for a quadrotor is more additional considerations such as processor capability, sizes of sensor and weight ratio should be relatively acceptable with a total weight of our quadrotor.

The processing power of onboard controller is still the main restriction for an advanced quadrotor CAS implementation. For example, camera sensors need high computer processing to perform rapid mathematical calculations, image processing and data acquisitions. To overcome this limitation, computer algorithm processing is executed on the ground stations and the algorithm output is then sent to the on-board quadcopter via wireless communication (Saha *et al*., 2014). However, this approach will affect system's latency and would make our controllers lag. In addition, although high power consumption will reduce flying time, it may require bigger battery capacity. Therefore, it is necessary to find a balance between on-board electronic sensors and power consumption besides carefully considering the number of sensors and sensor-fusion tecniques used to design CAS.

The other constraint for small unmanned vehicle is the payload requirements. Any additional onboard sensor will increase the total robot weight consequently decreasing its operation time.

RESULTS AND DISCUSSION

Sensors for CAS: In this study, three different types of sensors that were used in previous research for quadrotor CAS are discussed.

Ultrasonic: Ultrasonic based sensor is the earliest sensor that was applied for obstacle avoidance dedicated to quadrotor system as it has a simple configuration. Ultrasonic sensors use sound responses to function. The response of ultrasonic sensors is linear with distance to surface colour or optical reflectivity of the object. For example as it was demonstrated in a previous study (Bouabdallah and Siegwart, 2007) three miniature ultrasonic sensors are arranged in a cross configuration of OS4 quadrotor platform and it was claimed to be the first successful collision avoidance experiment on a quadcopter system. The main target is to avoid collision with walls or person in an indoor laboratory environment in low altitude. The collision avoidance algorithm is quite simple whereby it is designed to fly away from the obstacle around 40~50 cm once an obstacle is detected. Ultrasonic sensors are the cheapest in comparison with other sensors. In some of the other publications (Gageik *et al*., 2015; Salaskar *et al*., 2014) an innovative and simple solution for quadroto CAS was demonstrated.

Furthermore, another study (Vedder *et al*., 2015) has proposed an indoor localization system based on ultrasound grid system for multi quadcopter supported with IMU that avoids collisions with static objects and other copters. In order to do so, they need to determine localization of quadcopters and every static obstacle and then define the obstacle zones. This approach uses a low cost hardware setup and is useful for accuracy positioning in GNSS-denied areas. The quadcopters avoids collisions by placing contours that represents risk around static and dynamic objects.

One of the disadvantage of using ultrasonic sensor is the difficulties that occur in measuring sharp changes in environment such as corners besides decreasing the reaction time of the system due to the latency between transmitting and receiving ultrasonic waves. However, implementation into the real system would require manual tuning. Some imlementation problems that are highlighted include sonar sensor precision, propeller sound interference and wave overlapping among the sonar sensors.

However, instead of using sound-based ranging sensors, infrared-based sensors also can provide ranging detection and some researchers have combined it together as demonstrated in one of the publications (Rambabu *et al*., 2015).

Vision-based: The earliest vision based sensor used for quadcopter system was presented by Lenz *et al*. (2012) which involved usage of a single camera as an input to generate obstacle map and applied classification model approach for their obstacle detection method by implementing Markov random field. The library of paired motionsand visual-space masks in order to generate obstacle avoidance trajectories are used. If less than some thresholds of pixels within a masked area are labelled as obstacles, the corresponding motion is considered to be safe. This research has been implemented in autonomous miniature aerial vehicles with low power parallel neuromorphic hardware to perform offline outdoor experiment. A remote camera with wireless communication with the ground station has been presented by Kong *et al*. (2014). All image processing such as image segmentation, edge detection, optical flow is done on the ground and command is sent back to the drone via Wi-Fi. The Parrot AR platform was used in this project to evaluate the proposed algorithm from the real experimental results without undergoing simulation stages. An OpenCV Image Processing Software and JAVA 1.7 Programming Softwas was used for image processing purposes. From this project, it was seen that vision processing power and test bed performances are still major issues for quadcopter system and image processing still cannot be done onboard. As a result of this limitation, this project was limited in indoor environment and had a slow flying time at a slower speed to avoid capturing blurred images.

In another publication, Saha *et al*. (2014) on-board monocular vision-based sensor for obstacle detection in indoor environment which used distance estimation for detection strategies has been presented. In order to estimate a safe distance for the vehicle from an obstacle, a mathematical model translation is used to calculate image plane coordinate to the real object coordinate. Image processing is also done from ground stations which then sends UAV command via Wi-Fi communication. However, this approach also has issues for real implementation due to the computational load and camera calibration process which are time consuming.

An onboard vision sensor has been used as a main obstacle sensor by Lyu *et al*. (2015). The Sense and Avoid (SAA) method was implemented in their CAS design. The SAA function is accomplished through two sub-functions, namely sense, detecting and tracking of potential collision aircraft and Avoid, avoidance manoeuvre to resolve the collision. Similarly, identical onboard camera sensors and image processing techniques to detect the obstacle were also presented in. However, this project implemented potential field method for their real-time collision free path planning and several special ground patterns marking for UAV localization were provided. Some improvements have been made to the PFM including introduction of relative distance between the agent and the target repulsive potential formula and also introduction of term, agent velocity in the attractive potential formula.

An RGB camera with depth image sensor is presented for the use in teleoperated quadcopter by Albaker and Rahim (2009). Depth image processing model and Predictive Control (MPC) was applied in this system. The MPC method uses information from the depth image, roll and pitch angles which then estimates the obstacle's distance as an input to the second control module. Two experiments with rectangular shape obstacles, vertical and horizontal obstacle were performed. The USB camera was also implemented by Sato *et al*. (2016) to measure the position and posture of quadrotor helicopter.

Some of the major limitations of camera-based solutions sensor that can be observed from these previous studies include the computational power and lightin conditions.

LIDAR: One of the many advantages of Light Detection and Ranging (LIDAR) is that it can measure distances with high precision and resolution. The scanning Laser Range Finder (LIDAR) URG-04LX was used by Luo *et al*. (2012) to detect any obstacles around the quadrotor with detection angle area of 240° and 4 m of distance. Three flight modes including hovering turn, forward flight and gate exploration was proposed. According to the analysis of SLRF measurements, the UAV can switch from one mode to another in the presence of obstacles. It has an installed mirror for altitude measurement purposes. This has been implemented indoors for miniature coaxial platform (FeiLion) and it generated high level flight command and flight path in real-time. The navigation trajectory options included turning right or left. However, no options were presented for taking over the obstacle after considering the height of obstacle. Similar, LIDAR concept was utilized in another publication (Zohaib *et al*., 2013).

Autonomous navigation of a rotary wing MAV where a single laser range finder is used for both position estimation and map generation are presented by Gurdan *et al*. (2007) and Mac *et al*. (2016). No external postion sensor was used to determine the current vehicle position. The main reason for choosing the laser scanner was due to its accuracy, response speed and beam width. However, one of the disadvantage of using laser sensor is its weight which is approximately 200 g. Its considered heavy to be mounted on a typical small scale MAV.

CONCLUSION

The purpose of onboard sensors for quadrotor is for stabilization control, navigation control and obstacle detection. This study presents a survey of onboard sensors for obstacle detection in order to develop a CAS for quadrotor. Collision avoidance requirements and review of several types of onboard obstacle sensors are presented. From this survey, we obtain these following conclusions. Ultrasonic sonar sensors are the most suitable sensors for wall detection or flat surfaces. Vision based sensors provides a lot of information about obstacles however the onboard controller power is needed for image processing. Ground processing limits the outdoor application because of wireless communication signal strength. Instead of using multiple ultrasonic sensors, LIDAR with 360° scanning area is the most efficient and accurate for omnidirectional obstacle detection as well as for indoor environment mapping.

Therefore, our interest in futureis to design and develop a practical solution in CAS development by considering a larger set of CAS design consideration factors that meets mission target requirements. The 360 LIDAR sensors and ultrasonic sensorsare considered the best option for omnidirectional obstacle detection and altitude control in the same time.

ACKNOWLEDGEMENT

This research was performed under financial support from the Universiti Teknologi Malaysia (Q.J130000.2623.12J52), Ministry of Higher Education Malaysia and Universiti Teknikal Malaysia Melaka.

REFERENCES

Albaker, B.M. and N.A. Rahim, 2009. A survey of collision avoidance approaches for unmanned aerial vehicles. Proceedings of the 2009 International Conference on Technical Postgraduates, December 14-15, 2009, IEEE, Kuala Lumpur, Malaysia, ISBN:978-1-4244-5223-1, pp: 1-7.

Alexopoulos, A., A. Kandil, P. Orzechowski and E. Badreddin, 2013. A comparative study of collision avoidance techniques for unmanned aerial vehicles. Proceedings of the 2013 IEEE International Conference on Systems, Man and Cybernetics, October 13-16, 2013, IEEE, Manchester, UK., ISBN:978-1-4799-0652-9, pp: 1969-1974.

Benito, J.A., D.R.G. Glez, J. Garrido and R. Ponticelli, 2014. Design considerations of a small UAV platform carrying medium payloads. Proceedings of the 2014 International Conference on Design of Circuits and Integrated Circuits, November 26-28, 2014, IEEE, Madrid, Spain, ISBN:978-1-4799-5743-9, pp: 1-6.

Bouabdallah, S. and R. Siegwart, 2007. Full control of a quadrotor. Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, October 29-November2, 2007, IEEE, San Diego, California, USA., ISBN:978-1-4244-0911-2, pp: 153-158.

Cruz, G.C.S. and P.M.M. Encarnacao, 2012. Obstacle avoidance for unmanned aerial vehicles. J. Intell. Rob. Syst., 65: 203-217.

Davis, E., B.E. Nizette and C. Yu, 2013. Development of a low cost quadrotor platform for swarm experiments. Proceedings of the 2013 32nd International Conference on Control Chinese, July 26-28, 2013, IEEE, Xi'an, China, ISBN:978-9-8815-6383-5, pp: 7072-7077.

Ducard, G. and D.R. Andrea, 2009. Autonomous quadrotor flight using a vision system and accommodating frames misalignment. Proceedings of the IEEE International Symposium on Industrial Embedded Systems, July 8-10, 2009, IEEE, Lausanne, Switzerland, ISBN:978-1-4244-4109-9, pp: 261-264.

Fraundorfer, F., L. Heng, D. Honegger, G.H. Lee and L. Meier *et al*., 2012. Vision-based autonomous mapping and exploration using a quadrotor MAV. Proceedings of the 2012 IEEE-RSJ International Conference on Intelligent Robots and Systems, October 7-12, 2012, IEEE, Vilamoura, Portugal, ISBN:978-1-4673-1736-8, pp: 4557-4564.

Gageik, N., P. Benz and S. Montenegro, 2015. Obstacle detection and collision avoidance for a UAV with complementary low-cost sensors. IEEE. Access, 3: 599-609.

Ghazbi, N.S., Y. Aghli, M. Alimohammadi and A.A. Akbari, 2016. Quadrotors unmanned aerial vehicles: A review. Intl. J. Smart Sens. Intell. Syst., 9: 309-333.

Gurdan, D., J. Stumpf, M. Achtelik, K.M. Doth and G. Hirzinger *et al*., 2007. Energy-efficient autonomous four-rotor flying robot controlled at 1 kHz. Proceedings of the 2007 IEEE International Conference on Robotics and Automation, April 10-14, 2007, IEEE, Roma, Italy, ISBN:1-4244-0601-3, pp: 361-366.

Israelsen, J., M. Beall, D. Bareiss, D. Stuart and E. Keeney *et al*., 2014. Automatic collision avoidance for manually tele-operated unmanned aerial vehicles. Proceedings of the 2014 IEEE International Conference on Robotics and Automation, May 31-June 7, 2014, IEEE, Hong Kong, China, ISBN: 978-1-4799-3685-4, pp: 6638-6643.

Kendall, A.G., N.N. Salvapantula and K.A. Stol, 2014. On-board object tracking control of a quadcopter with monocular vision. Proceedings of the 2014 International Conference on Unmanned Aircraft Systems, May 27-30, 2014, IEEE, Orlando, Florida, ISBN:978-1-4799-2376-2, pp: 404-411.

Kong, L.K., J. Sheng and A. Teredesai, 2014. Basic micro-aerial vehicles (MAVs) obstacles avoidance using monocular computer vision. Proceedings of the 2014 13th International Conference on Control Automation Robotics and Vision, December 10-12, 2014, IEEE, Singapore, Singapore, ISBN:978-1-4799-5199-4, pp: 1051-1056.

Lenz, I., M. Gemici and A. Saxena, 2012. Low-power parallel algorithms for single image based obstacle avoidance in aerial robots. Proceedings of the 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, October 7-12, 2012, IEEE, Vilamoura, Portugal, ISBN:978-1-4673-1736-8, pp: 772-779.

Luo, D., F. Wang, B. Wang and B.M. Chen, 2012. Implementation of obstacle avoidance technique for indoor coaxial rotorcraft with scanning laser range finder. Proceedings of the 2012 31st International Conference on Chinese Control, July 25-27, 2012, IEEE, Hefei, China, ISBN:978-1-4673-2581-3, pp: 5135-5140.

Lyu, Y., Q. Pan, C. Zhao, H. Zhu and T. Tang *et al*., 2015. A vision based sense and avoid system for small unmanned helicopter. Proceedings of the 2015 International Conference on Unmanned Aircraft Systems (ICUAS), June 9-12, 2015, IEEE, Enver, Colorado, ISBN:978-1-4799-6010-1, pp: 586-592.

Mac, T.T., C. Copot, A. Hernandez and D.R. Keyser, 2016. Improved potential field method for unknown obstacle avoidance using UAV in indoor environment. Proceedings of the 2016 IEEE 14th International Symposium on Applied Machine Intelligence and Informatics, January 21-23, 2016, IEEE, Herlany, Slovakia, ISBN:978-1-4673-8740-8, pp: 345-350.

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.

Mendes, J. and R. Ventura, 2012. Safe teleoperation of a quadrotor using FastSLAM. Proceedings of the 2012 IEEE International Symposium on Safety, Security and Rescue Robotics, November 5-8, 2012, IEEE, College Station, Texas, ISBN:978-1-4799-0165-4, pp: 1-6.

Navajas, G.T. and S.R. Prada, 2014. Building your own quadrotor: A mechatronics system design case study. Proceedings of the 2014 III International Congress on Engineering Mechatronics and Automation, October 22-24, 2014, IEEE, Cartagena, Colombia, ISBN:978-1-4799-7932-5, pp: 1-5.

Pham, H., S.A. Smolka, S.D. Stoller, D. Phan and J. Yang, 2015. A survey on unmanned aerial vehicle collision avoidance systems. Cornell University, Ithaca, New York. https://arxiv.org/ftp/arxiv/papers/1508/1508. 07723.pdf.

Rambabu, R., M.R. Bahiki and S.A.M. Ali, 2015. Relative position-based collision avoidance system for swarming UAVS using multi-sensor fusion. ARPN. J. Eng. Appl. Sci., 10: 10012-10017.

Saha, S., A. Natraj and S. Waharte, 2014. A real-time monocular vision-based frontal obstacle detection and avoidance for low cost UAVs in GPS denied environment. Proceedings of the 2014 IEEE International Conference on Aerospace Electronics and Remote Sensing Technology, November 13-14, 2014, IEEE, Yogyakarta, Indonesia, ISBN: 978-1-4799-6187-0, pp: 189-195.

Salaskar, P., S. Paranjpe, J. Reddy and A. Shah, 2014. Quadcopter-Obstacle detection and collision avoidance. Intl. J. Eng. Trends Technol., 17: 84-87.

Samir, N., 2014. Collision avoidance and simple path planning for autonomous robotic exploration. Master Thesis, Lulea University of Technology, Lulea, Sweden.

Sato, K., T. Kasahara and T. Izu, 2016. A simple autonomous flight control method of quadrotor helicopter using only single Web camera. Proceedings of the 2016 International Conference on Unmanned Aircraft Systems, June 7-10, 2016, IEEE, Arlington, Virginia, ISBN:978-1-4673-9334-8, pp: 671-678.

Scherer, S., S. Singh, L. Chamberlain and M. Elgersma, 2008. Flying fast and low among obstacles: Methodology and experiments. Intl. J. Rob. Res., 27: 549-574.

Susnea, I., V. Minzu and G. Vasiliu, 2009. Simple, real-time obstacle avoidance algorithm for mobile robots. Procedings of the 8th WSEAS International Conference on Computational Intelligence, Man-Machine Systems and Cybernetics, December 14-16, 2009, WSEAS, Stevens Point, Wisconsin, USA., ISBN:978-960-474-144-1, pp: 24-29.

Vedder, B., H. Eriksson, D. Skarin, J. Vinter and M. Jonsson, 2015. Towards collision avoidance for commodity hardware quadcopters with ultrasound localization. Proceedings of the 2015 International Conference on Unmanned Aircraft Systems, June 9-12, 2015, IEEE, Denver, Colorado, ISBN:978-1-4799-6010-1, pp: 193-203.

Zohaib, M., M. Pasha, R.A. Riaz, N. Javaid and M. Ilahi *et al*., 2013. Control strategies for mobile robot with obstacle avoidance. J. Basic. Appl. Sci. Res., 3: 1027-1036.