Mechatronic Design of a Delivery Octarotor Drone

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***Abstract*—This article describes the mechatronic design of a delivery octarotor drone equipped with safety features including protective bumpers for its propellers, parachute, and retractable gear. A GNSS-RTK unit provides extensive pose-refinement for trajectory tracking, while an RGB-Depth Camera provides distance measurements from any present obstacles. A deep learning algorithm classifies any objects into certain categories (i.e., balloons, drones) followed by a trajectory avoidance algorithm. An onboard computer handles these sensor measurements and communicates with the autopilot for adjusting the trajectory. At the same time, it provides HD-live video feed to the base station and runs any onboard ROS-services. The resulting drone can safely land within a circular area of radius 1.5 m, while flying over, under and around obstacles or buildings. The carried payload is handled by a dual linear actuator gripper that releases it upon the drone's precise landing.**

***Index Terms*—delivery drone, drone safety features, obstacle classification**

I. Introduction

Delivery drones made their experimental debut in 2014 for food [1] and drink [2], while similar efforts have been reported for postal services [3], followed by recent commercial services for e-commerce [4] and retailing [5]. A recent survey on load transportation [6] shows an intensified research and commercial area. Hybrid schemes using drones and trucks [7] or trains [8] have been reported, while issues such as stationary recharging stations [9], [10] demand attention. Recent appeared theoretical approaches rely mostly on the Traveling Salesman Problem which has been properly modified to account the drones' peculiarities [11], [12] while future advances in the area of drone delivery appear in [13], [14].

Ensuring safety to humans and property while operating these drones is of paramount importance [15], [16] and the governments are expected to regulate this market. Inhere, a commercial octarotor is used as a delivery drone with enhanced safety issues. The article describes these enhancements including the classical parachutes, propeller protective bumpers, alternative autopilots relying on local coordinates, GNSS-RTK for additional accuracy on the progressed path, RGB-D cameras for SLAM, obstacle avoidance while running deep learning algorithms for obstacle classifications as stationary (buildings) or moving (neighboring drones and balloons).

II. Octarotor Drone Description

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A. Octarotor Design

Figure 1. Octarotor delivery drone

The developed octarotor delivery drone relies on the frame of Vulcan's Mini 8 [17]. This has been equipped with a parachute, protective bumpers for the propellers, an RGB-D camera, GNSS-RTK for precision trajectory and a gripper with two parallel moving jaws for grasping and releasing the payload, as shown in Figure 1. The drone has a detachable gear can carry a payload of 3Kgr (excluding

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its dual 16Ah 5S Lipo batteries). The flying envelope of this drone is over 15~mins with a 1.8Kgr payload. The octarotor configuration offers increased robustness in flight against one or two motor failures.

Furthermore, the onboard depth sensors (x3 optional) have a Field of View (FoV) 87ºx58º and measure the distance from 1280x720 points (obstacles) at distances 0.2 up to 10m. At the same time, a deep learning algorithm operating on the HD-RGB video from this camera, identifies balloons and other drones and sends this information to the autopilot for obstacle avoidance. An onboard Intel i7 NUC [18] running Ubuntu 18.04 [19] and the Robot Operating System [20] implements the Mavlink protocol [21] and can assist the drone's autopilot in case of emergency.

In the sequel, the aforementioned drone's enhancements that primarily address the safety issues associated with the flight of such devices are presented.

B. CUBE Autopilot & On-Board Computer

The adopted Flight Control Unit (FCU) is the CUBE FCU [22] owing to its triple Inertial Measurement Unit (IMU) configuration for redundancy and open-source hardware implementation. On the software side, the open-source ArduCopter [23] flight stack was flashed onto the FCU.

Amongst the safety features implemented using the ArduCopter firmware are geofencing, emergency motor stop, retractable landing gear and parachute deployment for safety, as well as GNSS-RTK integration for enhanced precision and gripper integration readiness. Another feature of the ArduCopter firmware is the integration with the Mavlink Protocol [24] for mission planning and communication with aerial vehicles.

The Here+ RTK GNSS [25] receiver has been employed for reducing the positioning measurement error in 3 to 4cm [26].

The attached Intel i7 enabled board allows the end-user to plan missions on-the-fly using geographic coordinates. The companion computer can be used for any visual-servoing; a custom casing for the NUC computer is designed for direct mounting on the underside mounting rail of the octarotor, as shown in Figure 2 with a 450g weight.

Figure 2. Intel NUC mounting assembly

C. GNSS-RTK

The Global Navigation Satellite System (GNSS) - Real-time kinematic positioning (RTK) is a technique used to enhance the position's precision of satellite-based positioning systems. This can be acheived with a combination of a fixed or moving base GNSS receiver (Base) used for reference, and one or more moving GNSS receivers (UAV). The Base and UAV are communicating with each other in real time, through a communication link. The Base re-broadcasts the phase of the carrier that it observes, and the octarotor compares its own phase measurements. This allows the octarotor to calculate its relative position within centimeters. The GNSS receivers that have been chosen for the delivery drone are the u-blox NEO-M8P with typical nominal accuracy of 2.5cm when the RTK is used [27].

III. SAFETY FEATURE ENHANCEMENTS

The enhancements include a protective bumper for the four coaxial pairs of propellers, a parachute and an Automatic Dependent Surveillance-Broadcast (ADS-B) transponder that enables the tracking of the delivery drone.

A. Protective Propeller Bumper Design

The 3D-printed plastic protective propeller bumpers have a 200g weight (per coaxial pair of rotors), shown in Figure 3. The cover consists of lightweight (white colored) flexible plastic parts on the extremities so as to absorb energy from side impacts, as well as 10mm in diameter carbon tubes to enhance rigidity and stability during flight. Each bumper is mounted at the mounting plates of the coaxial motors. A lower crash structure can be visualized for absorbing energy in case of underside impacts with humans.

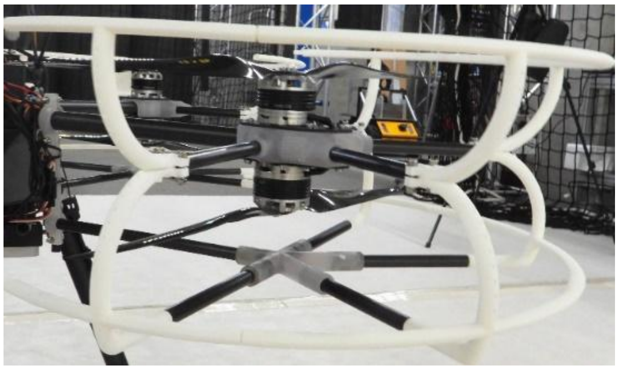

Figure 3. Protective bumper

B. Parachute Mechanism

A 48 inch parachute [28] with an ejection mechanism of the shroud lines and its extension cord followed by the parachute is used. This parachute for a 7Kgr drone offers a descent speed of 6.7m/sec and an impact energy of 157Joules (equivalent to a free fall from 2.26m). An extra RC receiver is used to activate the trigger through an externally supplied PWM signal. The weight of the parachute is 250g (excluding the additional 4S 1300~mAh LiPo battery), shown in Figure 4.

Figure 4. Parachute & Video Transmitter

IV. ENVIRONMENT PERCEPTION

A. RGB-Depth Camera and Video Transmission

The drone is equipped with an Intel D435i RGB-D camera [29], [30] acquiring depth and RGB images at 30FpS. From the depth mosaic, an obstacle classifier provides a rectangular Bounding Box (BB) around the detected object, while a histogram-based inlier pixel classifier provides an averaging of the pixels' depth within this BB. Consecutive triplets of bins are summed up, and the triplet with maximum number of summed counts is selected as the object location.

Inlier pixels that are known to fall into the selected triplet are averaged to calculate distance to the object. Since the BB is also known, the relative location of the obstacle can be estimated using the camera intrinsics and the estimated distance to the object. A demonstration of the proposed pipeline is provided in Figure 5-Figure 7 with the identified BB of the balloon.

Figure 5. Acquired RGB-image

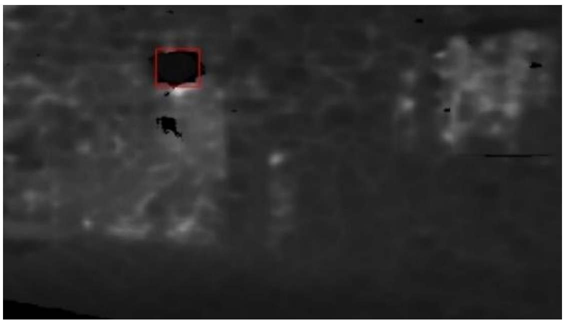

Figure 6. Acquired depth-image

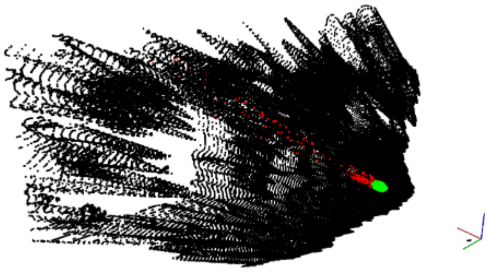

Figure 7. Computed background rendering (black), outlier (red), and inlier (green) measurements

B. Deep Learning for Obstacle Classification

A real-time deep learning based object detector is employed to visually detect obstacles similar to drones or balloons during the flight. This detector relies on the YOLOV4 tiny detector [31] optimized for the Intel NUC. Since it is difficult to obtain training datasets which include balloons and/or drones, a simulated dataset was employed that blends these objects with background images, as shown in Figure 8. In the `collected' images, random augmentation (translation, scaling, rotation and distortion) is applied to enrich their divergence, followed by the Poisson Image Blending method for generating synthetic datasets.

Figure 8: Synthetic training image

The Yolo-detector shown in Figure 9 consists of: a) the extractor of the pyramid feature maps from images and b) the object classification and regression head. The pyramid feature maps with various scales are designed to detect objects of different sizes. These feature maps are further fused with each other to increase the detection performance. The final object classification and regression head outputs the location and BB size of the objects of interest.

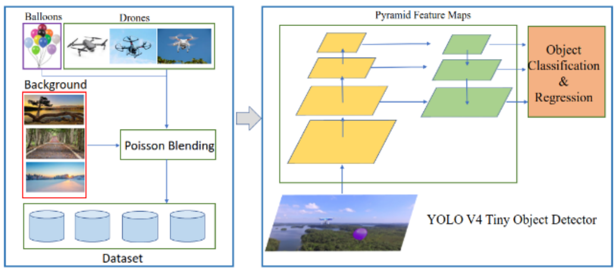

Figure 9. Dataset synthesis and object detection framework

C. Waypoint Trajectory

The navigation of the delivery drone, relies on the Arducopter's flight controller algorithm [32] which is assigned with a series of waypoints to pass through. The flight controller algorithm receives the set position commands from the onboard companion computer through a serial wired or wireless UART port using the Mavlink protocol format [21].

D. Obstacle Avoidance

The object avoidance [33] "Bendy ruler" code implemented within the Ardupilot is selected, where intermediate path waypoints are calculated around the obstacle; the depth to this obstacle is measured using the RGB-D sensor.

V. Payload Gripper Mechanism

The designed gripper, shown in Fig. 10, can hold a maximum payload of 2Kgr with an automated drop-off. The final design used a dual linear actuator relying on the Actuonix L-16 linear servo [34], with 63:1 gear ratio and a 100mm stroke, being capable of grasping objects from 8cm up to 30cm. The power (6V, up to 650mA) is provided by the the drone's power supply, while the maximum exerted force is 50N. These PWM-controlled actuators can be controlled from a pre-programmed autopilot port for opening the gripper jaws during package drop-off.

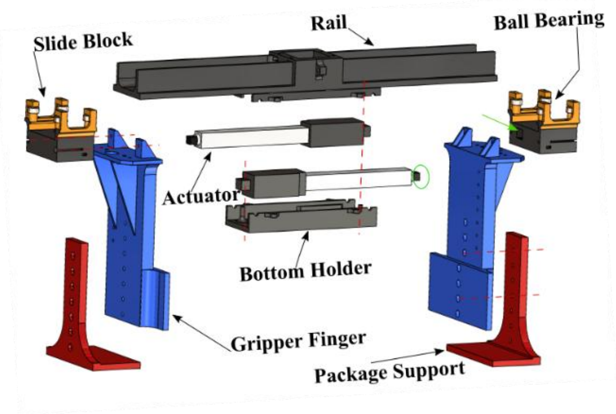

Figure 10. Gripper Mechanism

VI. Experimental Studies

NYUAD's delivery drone was awarded the first place in the Dubai World Challenge for Self-Driving Support at the Drone Category. The objective was to follow a 150~m path while carrying an unknown payload at minimum time. The payload was 20x10x5cm with a 750g weight. There were balloons acting as obstacles and the drone had to avoid them by passing around them.

At the same time, the drone's path was constrained to reside within a certain height and a narrow corridor and had to move under a building overpass. The trajectory consisted of 18-waypoints, shown in Figure 11, and the drone landed in a circle with radius 1.5m; the overall time needed for our octarotor was 62sec to complete the mission. Flying and landing photos appear at Figure 13 and Figure 13.

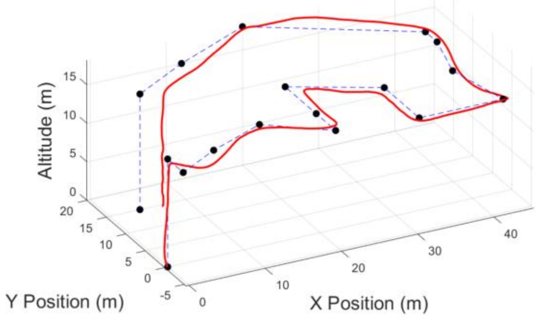

Figure 11. Drone 3D-Trajectory

Figure 12: Octarotor delivery drone flying snapshot

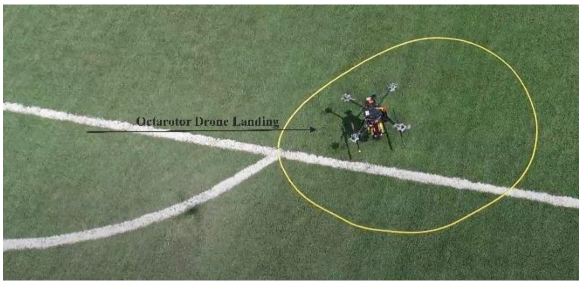

Figure 13. Octarotot delivery drone landing snapshot

VII. Conclusions

The safety enhancements and the environment perception augmentation in a delivery drone was considered in this article. This drone participated and won the Dubai World Challenge for Self-Driving Support in the Drone Category.

Conflict of Interest

The authors declare no conflict of interest in obtaining and presenting the results in this research effort.

Author Contributions

NE, NG and DC worked on the autopilot and trajectory planning. NE designed the protective covers and DC designed the gripper mechanism. ATs and HUU worked on the safe landing, DX and HUU worked on the obstacle avoidance, ATz wrote the paper; all authors have approved the final version.

References

[1] B. M. Murphy, *The Future is Here: Drones are Delivering Domino's Pizzas to Customers*, 2014.

[2] Journey Australia Staff, *Happiness from the Skies: Watch Coke Drones Refresh Guest Workers in Singapore,* 2014.

[3] S. Perez and L. Kolodny, *UPS Tests Show Delivery Drones Still Need Work,* 2017.

[4] Amazon Prime Air, *Amazon's Future Delivery System,* 2016.

[5] A. Frangoul, *Tech Giant Alphabet Launches Drone Delivery Service in Australia,* 2019.

[6] D. K. D. Villa, A. S. Brandao, and M. Sarcinelli-Filho, "A survey on load transportation using multirotor UAVs," *Journal of Intelligent & Robotic Systems,* vol. 98, pp. 267–296, 2020.

[7] M. Moshref-Javadi, S. Lee, and M. Winkenbach, "Design and evaluation of a multi-trip delivery model with truck and drones," *Transportation Research Part E: Logistics and Transportation Review,* vol. 136, p. 101887, 2020.

[8] H. Huang, A. V. Savkin, and C. Huang, "A new parcel delivery system with drones and a public train," *Journal of Intelligent & Robotic Systems,* vol. 100, pp. 1341–1354, 2020.

[9] I. Hong, M. Kuby, and A. T. Murray, "A range-restricted recharging station coverage model for drone delivery service planning," *Transportation Research Part C: Emerging Technologies,* vol. 90, pp. 198–212, 2018.

[10] A. Tsoukalas, A. Tzes, S. Papatheodorou, and F. Khorrami, "UAV-deployment for city-wide area coverage and computation of optimal response trajectories," in *Proc. 2020 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2020.

[11] Q. M. Ha, Y. Deville, Q. D. Pham, and M. H. Hà, "On the min-cost traveling salesman problem with drone," *Transportation Research Part C: Emerging Technologies,* vol. 86, p. 597–621, 2018.

[12] E. E. Yurek and H. C. Ozmutlu, "A decomposition-based iterative optimization algorithm for traveling salesman problem with drone," *Transportation Research Part C: Emerging Technologies,* vol. 91, pp. 249–262, 2018.

[13] A. Gupta, T. Afrin, E. Scully, and N. Yodo, "Advances of UAVs toward future transportation: The state-of-the-art, challenges, and opportunities," *Future Transportation,* vol. 1, pp. 326–350, 2021.

[14] M. Moshref-Javadi and M. Winkenbach, "Applications and research avenues for drone-based models in logistics: A classification and review," *Expert Systems with Applications,* vol. 177, p. 114854, 2021.

[15] E. Frachtenberg, "Practical drone delivery," *Computer,* vol. 52, pp. 53–57, 2019.

[16] F. Schenkelberg, "How reliable does a delivery drone have to be?," in *Proc. 2016 Annual Reliability and Maintainability Symposium (RAMS),* 2016.

[17] UAV Vulcan, *Vulcan UAV Mini8,* 2017.

[18] Intel Products, *Intel NUC Mini PCs,* 2021.

[19] Ubuntu, *Ubuntu 18.04.6 LTS,* 2020.

[20] A. Koubâa and others, Robot Operating System (ROS)., vol. 1, Springer, 2017.

[21] A. Koubâa, A. Allouch, M. Alajlan, Y. Javed, A. Belghith, and M. Khalgui, "Micro air vehicle link (Mavlink) in a nutshell: A survey," *IEEE Access,* vol. 7, pp. 87658–87680, 2019.

[22] ArduPilot Dev Team, *The Cube Overview,* 2021.

[23] ArduPilot Dev. Team, *Copter Home,* 2021.

[24] D. Foundation, *MAVLink Developer Guide,* 2017.

[25] ArduPilot Dev Team, *Here+ RTK GPS,* 2021.

[26] T. Baybura, İ. Tiryakioğlu, M. A. Uğur, H. İ. Solak, and Ş. Şafak, "Examining the accuracy of network RTK and long base RTK methods with repetitive measurements," *Journal of Sensors,* vol. 2019, 2019.

[27] ublox, *NEO-M8P series,* 2021.

[28] Skycat, *x48 Pro Series for 2-9 Kg SUAV,* 2021.

[29] Intel, *RealSense Depth Camera D435i,* 2021.

[30] B. Nenchoo and S. Tantrairatn, "Real-Time 3D UAV pose estimation by visualization," in *Multidisciplinary Digital Publishing Institute Proceedings,* 2020.

[31] A. Bochkovskiy, C. Y. Wang, and H. Y. M. Liao, "Yolov4: optimal speed and accuracy of object detection," *arXiv preprint arXiv:2004.10934,* 2020.

[32] ArduPilot Dev Team, *Planning a Mission with Waypoints and Events,* 2021.

[33] ArduPilot Dev Team, *Object Avoidance with Bendy Ruler,* 2021.

[34] Actuonix, *L16 Series Mini Linear Actuators,* 2021.

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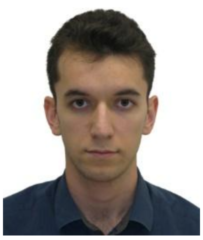

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