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Development of an Autonomous Flying Excavator

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Abstract: In the construction industry, excavation is a difficult task that requires to be automated to save the resources like cost, time, and labor. In this paper, a prototype of an excavating drone has been presented which can operate totally autonomously without human interaction. The navigation control has been achieved with Pixhawk flight controller and ARDUPILOT Mission Planner has been used for the path planning purpose. A drone platform has been integrated with an excavating arm that can exert 42 N of force to dig and lift the soil. A sensing algorithm has also been developed by using the 3D depth camera integrated into the platform for a fully autonomous operation.

Keywords: autonomous excavators; pixhawk controller; Autopilot; drones

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1. Introduction

The construction industry is one of the most focused industrial sectors that require autonomous technology to operate in harsh environments and excavation is the key stage of any construction process. For this task, an excavator is an indispensable tool that can handle duties that other machines cannot. By realizing the innovative idea that excavations can be carried out using a drone platform, many construction sites can speed up the related work in any environmental conditions and expand their working areas to any height levels using drones. In this study, an autonomous flying excavator platform has been proposed in which a 3D printed excavator assembly has been mounted on the drone. The platform ensures to withstand all the counter forces during the excavation in flight mode. The flight of the drone is autonomous using the prescribed mission uploaded on the controller. A Pixhawk cube orange has been used with the latest Here 3 GPS and RTK technology to achieve accurate position control in the air. For the detection of soil piles, a sensing algorithm has also been developed under ROS architecture which uses 3D point cloud mapping techniques to properly place the tip of the bucket for excavation. The whole focus of this study is to give an idea of an autonomous flying excavator which can be very effective and beneficial in the construction industry from a different perspective. Section 2 provides a literature review on existing aerial manipulators and uses of drones in different construction applications. In Section 3, the working methodology is presented, and the sensing algorithm in Section 4. Experimental results are given in Section 5 and finally, in the last section concluding marks and future works are presented.

2. Literature Review

Several different types of aerial manipulators have been used in the past. Some of these devices address sensor placement, gripping items in the air, and exerting force on various objects. In [1], a 2 DOF manipulator with a revolute joint and a prismatic joint for sensor placement was utilized to overcome this challenge. To make sure that none of the assembly pieces is close to the motors or their blades [2], a cable has been used in tethered drones to connect the drone platform to the manipulator. In this way, it is possible to control all the components of the drone from the ground, where the battery status can be monitored, and the base station laptop can receive data about the drone's real-time position so that it can send the correct coordinates to the controller for position control. In [3], a cable-suspended load has been lifted from the ground by an unmanned aerial robot when the load mass is unknown. However, strong external forces cannot be applied to these systems since the drone may become unstable. Various types of airborne platforms have been discussed in [4] to deal with the challenges of gripping an object, securing a sensor, and applying some force to a surface to execute the required duties. Dual manipulators have been employed to handle any object that a single manipulator could grasp. These dual manipulators help provide extra rigidity to any parts, sensors, or platforms in architecture. However, there has been no method of attaching the manipulator to the drone for excavating activities, which encourages us to create an excavator drone platform that would be a very innovative contribution to the construction and drone industries.

In recent years drone has been widely used in many different construction activities which mainly includes building and land surveys, topographical mapping, and inspection of construction sites. A small drone has been utilized to eliminate safety risks associated with roof surveying and to gain access to difficult or complex roof sections [5]. The creation of topographic maps can be expensive and time-consuming, but they are of great value for all construction projects. In this situation, drones are an appropriate solution since they are capable of collecting a vast amount of data in a short period of time and thus can save cost, time, and other resources [6]. In [7], the support system's geometry has been captured using a smartphone-controlled multirotor drone during the excavation phase. Then, the 2D imaging data has been converted into 3D construction staging models to obtain a detailed record of construction activities, including the site geometry change and geotechnical engineering evaluation, which can help builders to take future steps in the projects more effectively. The use of drones in the construction industry is limited to mapping, surveying, and image collection only. This motivates us to devise an idea for a flying excavator prototype that can utilize drones extensively for autonomous excavation.

3. Working Methodology

The proposed excavating drone platform has a three-component structure. First, we have the F450 mm frame size drone equipped with an orange cube Pixhawk controller and the Here 3 GPS system that is responsible for the drone's flight, stability under diverse load situations, and maneuverability with robust control. The open-source Ardupilot platform has been used to configure the Pixhawk controller, allowing various sensor modules, such as the IMU, magnetometer, and internal GPS data, to be utilized for the smooth operation of the flight. The second part is the manipulator which has been first designed using the CAD tool Solid works 2018. Each part has been 3D printed and after assembling all the components it got rigidly fixed with the drone using nuts and bolts. The platform design process ensured that none of the components would contact the drone's blades during flight and excavation operations. Especially, the interference of manipulator components with the blades was carefully cross-checked through the CAD model and simulations to prevent it before final assembly. The stability of the platform was also taken into account in the design process. In the initial design, all three components of the excavator boom, arm, and bucket were assembled. However, this design caused an instability issue, i.e., whenever the manipulator operates in flight mode, its center of mass shifts significantly, making the platform unbalanced and fall over. To resolve the above issue, the actuator and link for the boom were eliminated, leaving only two actuators for the arm and bucket. As a result, the total length of the manipulator has been shortened from 410 mm to 374 mm.

This design change has allowed us to balance the platform by moving the center of gravity to the lower center of the platform. Using inverse kinematics equations, the controller determines the length of each actuator and then sends the suitable amount of PWM signals for positioning the bucket's tip at the correct location. The third component is the sensing algorithm which uses depth to detect the excavated ground and generate its 3D point cloud map. A cropping technique has been employed to filter out unnecessary points and only the points within the region of interest (i.e., the area of excavated ground) have been transmitted to the controller for processing, which then commands the excavator to begin excavation from the correct location.

3.1. Path Planning and Control

For successful drone navigation, it is a prerequisite to calibrate the radio transmitter and the motor ESCs through the mission planning platform that allows them to communicate with each other. To control the drone's pitch, yaw, roll, and throttle, the transmitter has been configured by adjusting the flying modes and channel and model settings. It is important to make sure that the "Failsafe" feature is always on during the drone flight so that it can return and land in the same spot where it first took off when flying out of the transmitter's range. The flight modes used in this study are Loiter, Auto, and Autotune, which are available on the Ardupilot mission planner platform. The PID control parameters for the copter have been fine-tuned using Autotune prior to the experiment in which the copter has executed yaw, pitch, and roll movements. At the beginning of the experiment, the copter has been armed in the Loiter mode, which can lock the GPS position, and after being given a small amount of throttle, it switched to the Auto mode to carry out the mission entirely autonomously. The EMAX 2826 motors and a Hobby King 70-amp ESC have been utilized with 10 inches diameter propellers with two rotating in the clockwise direction and two in the anticlockwise direction [8]. Autonomous navigation control has been achieved using GPS, RTK, and a mission planner. The user-given location has been converted into longitude and latitude coordinates for the GPS module mounted on the drone using the mission planner. Positional accuracy can be enhanced up to a centimeter level using the RTK system. Then, the drone precisely can follow the coordinates and land at a target location for excavation. Autonomous navigation is terminated when the sensor begins scanning soil piles and it is resumed to dump the excavated soil to the designated area.

3.2. Excavator Modelling and Working Principles

The assembly of the excavator has been designed using SOLIDWORKS 2018 and 3D printed with PLA material. We have chosen the PLA because it can be printed quickly and withstand the required digging force during excavation. Figure 1 shows the CAD model for the components that require 3D printing.

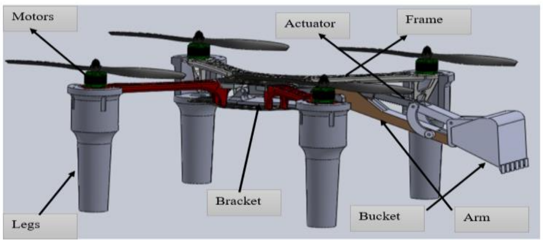

Figure 1. SolidWorks CAD model of drone components.

The Atuonix L12 I series actuators with a gearing choice of 1:100 have been employed in our platform. In full retraction and extension, their lengths are 102 mm and 152 mm, respectively. Each actuator weighs about 40 grams and can handle a load of 42 N. The actuators can be actuated by sending PWM signals to Arduino which was selected as a microcontroller in this study. The following figures show the platform created after assembling all the required hardware components.

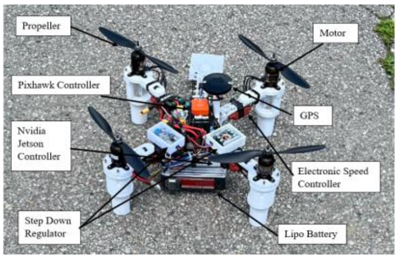

Figure 2. Top view of the assembled point platform.

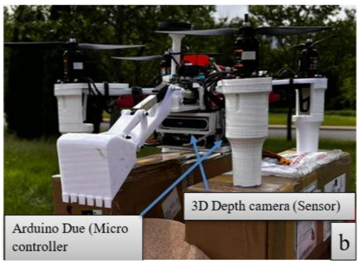

Figure 3. Isometric view of the assembled platform.

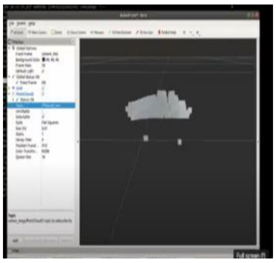

Figure 4. Sensing of the cloud data.

4. Sensing Algorithm

For the fully autonomous excavation with the prototype platform, a sensing algorithm has been developed by using the Intel Real sense D415 depth camera. This algorithm has been used to detect the surface of the excavated soil with sensing data. Also, the sensing info can be used for the controller to generate the required commands to execute excavating operations and stabilize the drone. For the autonomous operation, we have used the Nvidia Jetson Nano as an onboard computer, and the software architecture has been based on the ROS platform. The packages utilized in our application are Intel real sense depth camera, pcl ros, move it, and mavros. As shown in Figure 4, the Intel real sense camera and PCL ROS package allow us to detect the terrain and publish point cloud information that can be visualized in RVIZ. After sensing the ground surface, the filtering technique (i.e., cropping point cloud) has been applied to reduce the number of points along the x and z axes that do not belong to the region of interest (area of excavated ground).

5. Experimentation

To validate the performance of the developed platform, the test scenario has been considered as seen in Fig 5, which outlines each step-by-step moment during one cycle of autonomous excavation. The drone has taken off from the initial home position and then landed at the targeted location. Based on the processed sensory info about the target ground for excavation, the platform has started digging and loading the soil into the bucket. Then, the drone has flown again to dump the soil in the prescribed area and finally landed at the original location after completing the required mission. The entire operation, position accuracy, and stability of the drone need to be guaranteed. For position control, RTK system data has been fused with the GPS to get the most accurate location info. For stability, all the ESCs have been finely tuned to deliver the appropriate amount of PWM signals to each motor. During the experiment, the platform navigated along the trajectory shown in Figure 6. The developed platform has successfully completed autonomous excavation by handling the position accuracy and stability in the given scenario. The used RTK system and GPS provide centimeter-level positional accuracy for the platform. In the experiment, the target landing point and actual landing point for excavation are (0.000, 3.000) m and (0.004, 2.992) m, respectively. During the flight to reach this target point, the RMSE value between the desired trajectory (blue line in Figure 6) and the actual flight path (red line) is 0.00894 m. After that, the platform completed the dumping process in the air and landed at the final destination whose desired and landed points are (1.500, 2.992) m and (1.492, 2.995) m. Finally, the RMSE value between the desired trajectory (green line) and the actual path (black line) to the final destination is 0.00854 m. Table 1 provides a summary of these results. For stability, the maximum lean angle allowable for the loiter mode in which the excavation was conducted is 30 degrees, and the average lean angle of our copter during the entire experiment is 20 degrees. Therefore, a stable flight was maintained during the operation.

Figure 5. Drone taking off from the initial point (**a**), drone en route to be landed landmark (**b**), drone landmark doing excavation autonomously (**c**), Dumping the excavated soil (**d**), and the drone arrived back after the excavation operation (**e**).

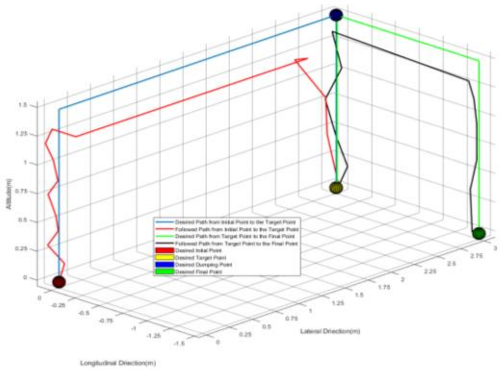

Figure 6. Navigation trajectory of the platform experiment.

Table 1. Experiment Results.

<table>
<tr><th rowspan="3">For excavation</th><th>Desired landing position</th><th>Actual Position</th><th rowspan="3">For Dumping</th><th>Desired landing position</th><th>Actual Position</th></tr>
<tr><td>(0.000, 3.000) m</td><td>(0.004, 2.992) m</td><td>(1.500, 2.992) m</td><td>(1.492, 2.995) m</td></tr>
<tr><td colspan="2">Root Mean Square Error (RMSE): 0.00894 m</td><td colspan="2">Root Mean Square Error (RMSE): 0.00854 m</td></tr>
</table>

6. Conclusions

The construction industry is one of the fields where drones are in use for various purposes to save time and costs. In this paper, a flying excavator prototype has been presented using a drone equipped with the Pixhawk controller and ARDUPILOT mission planner interface. In addition, a sensing algorithm has been developed to detect the excavated ground at the construction site. By using the detected ground information, the developed flying excavator platform was able to conduct the required digging task autonomously in the considered test scenario. To improve the control of the drone during excavation, a high-precision 1D LiDAR can be added to the platform for accurate height control. In addition, a more advanced GPS technology or flight mode control could be considered to lock the lateral and longitudinal directions of the platform, which is effective for maintaining the drone's position under dynamic weather conditions such as wind.

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