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Fire-fighting UAV with shooting mechanism of fire extinguishing ball for smart city

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ABSTRACT

With the growth of technology and massive city development, firefighting services have become more challenging to cope with a smart-city concept. One of the challenges that firefighters are facing is reaching the top floors of high-raised buildings. Firefighters need heavy and oversized pieces of equipment to reach top floors, which they sometimes fail to deliver on time due to big cities' traffic. The proposed solution to this global problem is using firefighting unmanned aerial vehicle (UAV) to reach the top floors fast and efficiently; It can also provide a better vision for the firefighting team and slow down the spread of fire using fire extinguishing ball. In this paper, a noble design for a Firefighting UAV with shooting and dropping mechanism of fire extinguishing ball has been developed and successfully tested. A Camera with night vision has been integrated into the UAV to provide a helpful aid for firefighters. The UAV has a controller with a 2.4 GHz radio frequency (RF) signal and video surveillance to regulate the UAV's movement. The controller is also for activating the shooting and dropping mechanism. The researchers examined the behavior of the drone in terms of its stability and functionality.

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1. INTRODUCTION

Firefighters play a critical role in providing safety to both commercial and residential buildings [1]. Firefighting operations in the Philippines take too much time to finish due to the minimal resources and low upgrades in technologies in the bureau of fire protection (BFP); the poor performance results to increase the damage that makes it close to impossible to save all of the lives affected by the fire flames [2], [3]. One of the reasons firefighters arrive late is the severe traffic after a fire-spread starts. High-rise buildings are also a significant problem for the firefighters during operations [4], [5]. Since they cannot reach the top floors with their firefighting equipment, they are bound to use the building's installed firefighting equipment before reaching the highest floor affected by the fire [6]. They also need to take the stairs since elevators may be inaccessible, and after they reach their target floor, the flames might spread everywhere and cause a disaster.

With the vast technology upgrades, from robots to machines, small businesses to corporates, there is a demand for improvement in firefighting services to adjust with the smart city concepts. Unmanned aerial vehicles' (UAVs') applications, from both technical and non-technical perspectives, have been increased in the past few years [7]. UAVs play a critical role in this century, from traffic and crowd management systems to inspect the solar installation. With the development of smart cities, UAVs are used in a wide range of applications. They are flexible in performing vital tasks that are difficult or dangerous for humans to do [8].

Several studies about the UAS (Unmanned Aircraft System) in fire departments for exploration and saving on decreasing fire burden. The firefighter drones (UAVs) mainly focus on monitoring the site with a camera and do not have a standalone mechanism for fire extinguishing purposes [9]. Other researchers came up with the solution of connecting the drone to the ground by a hose to gain access to the vast container. So the tank of the drone can be filled from the container [10]. One of the problems encountered with the solution is the drone's movements' limitations due to the water container's connection to the ground.

Fire distinguisher balls can be used to limit the spread of flames and address the mentioned problem. In the 19th-century glass ball containing fire suppressant liquids was used to fight the fire [11]. In the long run, the design "glass ball" became less trendy to many customers. The fire extinguisher balls are not made of glass anymore, but it is built-in with foam casing and is covered in poly-vinyl chloride (PVC). It counters and reacts to heat or flame quickly, which causes the triggers implanted in the unit to respond immediately and disperse the dry chemical fire suppressant built inside. The fire distinguisher ball must be rolled forward or thrown into the flames to activate. Then it triggers and spreads a dry-powder fire extinguishing agent [12]. Mono-ammonium phosphate is commonly used as a non-toxic alternative that extinguishes class A, B, or C fires [13].

This paper proposes a noble design for an unmanned aerial vehicle with a shooting and dropping mechanism. In which it releases the fire extinguishing ball that helps firefighters decrease the spread of fire. The study's significance is to help the firefighter suppress the fire and provide a real-time monitoring system of an area. The general objectives are designing and developing an unmanned aerial vehicle (UAV) to support firefighters and individuals in exterminating fire. The specific objectives of this study are: i) design and develop an unmanned aerial vehicle (UAV) with eight propellers (octocopter) to carry up to five kilograms' load; ii) integrate a night vision high-definition (HD) camera that improves the user's perception, with a 5.8 GHz radio frequency (RF) signal to communicate with the video streaming; iii) design a remote control with a 2.4 GHz radio frequency (RF) signal to regulate the drone's movement; iv) design and develop an efficient shooting and dropping mechanism; and v) integrate the gyroscope and GPS module to stabilize the flight of the drone.

The UAV uses a gyroscope to stabilize the drone's flight right after shooting the fire extinguishing ball. It can automatically turn into a steady flight if the signal is disconnected from the remote-control connection range. Real-time video streaming can be accessed through the controller's liquid crystal display (LCD) in a designated area or building. The flying time of the UAV is up to fifteen minutes. It can carry up to five kilograms of load with a flight range of one kilometer from the controller without interference. The drone's speed during the flight is up to fifty miles per hour, and the prototype can only carry two fire distinguisher balls at a time due to the limited resources.

2. RESEARCH METHOD

The conceptual framework of the system can be found in Figure 1. The conceptual framework explains the system's flow in terms of input-process-output, where the user controls the UAV's flight and monitors the area with a controller. The communication between the UAV and the controller is based on the radio frequency transmitter [14]. A radio frequency receiver is integrated into the microcontroller to receive the signals. The controller's LCD screen is connected wirelessly to the microcontroller, which is integrated into the UAV. An embedded microcontroller controls the servo motor's adjustment and triggers activation for the shooting and dropping system.

The project uses the concept of octocopter, in which it had eight rotating arms [15]. One significant factor is the direction in which the propellers of the rotors' craft rotate. In general, each rotor should rotate in the opposite direction; one should rotate clockwise while the other should rotate counterclockwise.

2.1. UAV concepts

A unique servo mechanism is integrated into the arm rotor to control the copter's movement's direction. It has been marked with yellow tape to indicate the front side of the arm. The movement entirely works with the applied thrust and the direction of the motor movement in which it should be considered that the two arms (the leading arm and the arm diagonal to it) would depend on the roll, pitch, and yaw [16]. As the rotating arm increases, the payload capacity also increases because more rotors carry heavy equipment. A gyroscope is integrated, giving aerial stability to the UAV; it also measures the number of rotations around the three axes, namely x, y, and z. When the gyro is rotated, a small proof mass shifts as the angular velocity changes. Another integrated sensor is the barometric pressure sensor [17] that shows aerial robots' altitude data during the flight.

A GPS sensor is used to stabilize the UAV. The UAV works based on the available GPS satellite deployed to orbit the earth 20,180 km above (called MEO) [18], [19]. The copter's navigation was often hampered in the waypoint navigation due to the GPS location's erroneous information. This concept is called a GPS glitch [20]-[23]. The GPS glitch's primary cause was the unavailability of the GPS signals, which results in insufficient GPS data. If the glitch is very long, then the location value gets rejected subsequently [24]. See Figure 2 for the 3-D design of the UAV's prototype.

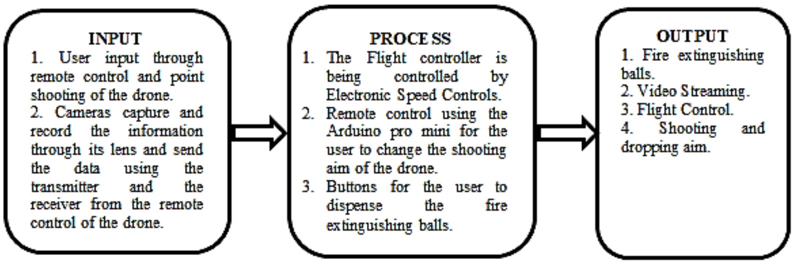
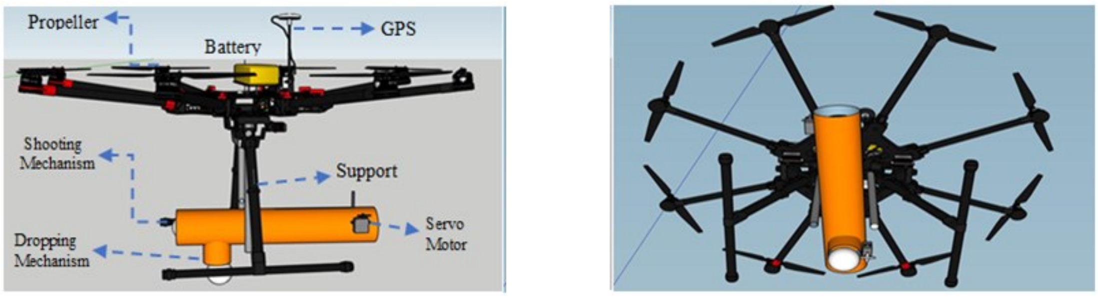


Figure 1. Conceptual framework



(a) (b)

Figure 2. 3-D design of the UAV: (a) side view of the UAV and (b) bottom view

2.2. Shooting and dropping mechanism

For the shooting and dropping mechanism, the NRF24L01 Transceiver is used to send and receive activation signals [25]. By clicking on the designed push button in the controller, the received data would activate the trigger. The SPI library of Arduino is the most important library for communicating with two or more microcontrollers. The researchers made computations based on research-based formulations regarding the shooting mechanism's force of the pressure to the ball. Getting the soring constant (spring stiffness) of a spring using hooke's law,

$$F = -kx \tag{1}$$

where:
F = force exerted by the spring
k = spring stiffness based on its material
x = displacement of the spring's end from its equilibrium position

Given: 1.5 kg of payload → 14.71 N; eight inches' length of displacement of the spring's end → 0.203 m (Note: The displacement is measured when the payload is on the other side of the fixed spring's end position). Calculating for k,

$$k = |{}^{F}/_{x}| \quad \text{(Rearranging (1) and (2))}$$

$$k = |{}^{14.71N}/_{0.203m}| \quad \text{(Substitute the given)}$$

$$k = 72.463\, N/M \quad \text{(Spring's constant result)}$$

Assuming that the air resistance is not present, the spring's displacement will be 31.7 cm once the spring trigger is pulled. Given: x = 31.7 cm displacement from the spring's end equilibrium,

$F = -kx$ (Using (1) to get the spring's force)

$F = -(72.463\, N/m) \times (-0.317m)$ (Substitute the given)

$F = 23.007N$ (spring's force in Shooting mechanism)

Since the spring force is calculated, the ball's acceleration and velocity as it exits the end of the barrel can be measured, given that the mass of the ball is 0.06 kg. The ball exits at the end of the barrel with a length of 0.356 m. Given: 0.06g-mass of the test ball and 0.356 m-length of the barrel where the ball travels before it exits; Solution,

$$a = F/m \quad (3)$$

where:
a = acceleration of the ball
F = force exerted by the spring m = mass of the ball

$a = (23.007N)/(0.06kg)$ (Substitute the given)

$a = 383.45\, m/s^2$a= 383.45 m/s² (Acceleration of the ball as it exits the barrel)

there for we can calculate,

$$v^2 = 2ax \quad (4)$$

$v^2 = 2 \times (383.45\, m/s^2) \times (0.356m)$ (Substitute the given)

$v^2 = 273.016\, m/s^2$v² = 273.016 m/s² (Square root both side)

$v = 16.523m/s$ (Velocity of the ball)

the obtained result of the ball's velocity is used to measure the ball's distance as it exits the barrel. This data also helps future researchers with a related topic using spring as a reference. Since the ball's velocity is calculated, the projectile range can now be obtained. The shooting mechanism is on a one-meter altitude and assumes that the air pressure is not present and the position directly hits the ball's center. In Figure 3, the velocity of the fire distinguisher ball when the drone is one meter above the target is illustrated where the V_x and V_y are representing the horizontal and vertical velocity of the ball with 0° angle of elevation (an angle of elevation is formed between the line of sight and horizontal line). Here we present the line of sight with. See (5) to (8) for details.

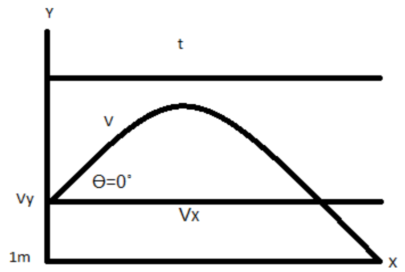


Figure 3. The velocity of the ball

Given: 0°-the angle of elevation
16.523m/-velocity of the ball as it exits the barrel
1m-the height of elevation
9.81m/s²-gravity constant

$V_x = V \cos\theta$ (5)
$V_x = 16.523 \cos 0^\circ$ (Substitute the given)

$V_x = 16.523\, m/s$ (Horizontal Velocity of the ball)

$V_y = V \sin\theta$ (6)

$V_y = 16.523 \sin 0°$ (Substitute the given)

$V_y = 0$ (Vertical Velocity of the ball)

$t = V_y + \sqrt{V_{y^2} + 2gh}$ (7)

$t = 0 + \sqrt{0 + 2(9.81\, m/s^2)(1m)}$ (Substitute the given)

$g = 9.81\, m/s^2$

$t = 0.45s$ (Time taken by the ball before it hits the ground)

$R = V_x(t)$ (8)

where,
R is the distance traveled by the ball as it hits the ground.

$R = (16.523\, m/s)(0.45s) = 7.435m$ (Distance traveled by the ball)

The result obtained is the distance traveled by the ball from the shooting mechanism. These calculations have assumed that the air resistance is not present, and the shooting barrel's piston directly hits the ball's center.

3. RESULTS AND DISCUSSION

3.1. Components design

A firefighting UAV with shooting and dropping mechanism has been designed and developed in this study where it can carry up to two fire-distinguisher balls and act as the surveillance to help firefighters monitor the area. There are several components used for this project. The list of components and their utilization in this project is presented in Table 1.

Table 1. Components of the UAV

Component:	Description:
Hardware Components of the Drone	
Naza V2 Flight Controller (Gyroscope)	It is used to measure angular acceleration on an x, y, or z-axis. It is responsible for UAV's stabilization
High Definition Camera with night vision	It helps capture and record the information or data through the lens and save it to an SD card.
IOSD Mini	It can display multiple flight information specifications such as power voltage, height, distance, horizontal attitude, GPS satellite number, and more.
Propellers Type 1045	It is used to transmit power by converting rotational motion into thrust.
Rotors (EMAX MT4114)	Used to move the component of an electromagnetic system in the electric motor, electric generator, or alternator
7" LCD	It is used for displays that the HD camera will produce
Batteries	They are used to make the drone, and every function has to work.
Power Distribution Board	It is a PCB design that gives an easy and neat overall distribution of power from the LiPo Battery into a multiple ESC used in the multi-rotor RC systems.
DJI Naza GPS	This helps with the navigation to determine the position of the drone.
Controller Parts	
Arduino Nano	It is used as a microcontroller to manage the components mounted or connected to it.
2.4 GHz NRF24L01 Module with PA LNA SMA Antenna	Used to transmit and receive the signals
Receiver Parts	
NRF24L01 Module	Act as a Wireless transceiver
250Kv Servo Motor with Max Thrust of 10KG	The max thrust of the motor should be doubled than the drone's capacity payload. A low KV should be considered for higher torque.
Materials for Fixed Shooting and Dropping Mechanism	
Orange PVC pipe	It is a pipe that is usually used in water piping or electrical connections
Spring	It is an elastic feature and is made from spring steel.
Servo Motor	Used to receive a control signal that represents a desired output position of the barrel and apply power to its DC motor until its barrel turns to that position

3.2. Performance evaluation

In the performance evaluation, the hardware and software were tested in the UAV and shooting mechanism functionality. The functionality test results can be found in Table 2, where the hardware and software components were tested. Upon the computation of the result, the average passing rate is 97.22%. During these tests, the researchers identified that controlling the UAV is challenging, and weather conditions can affect the drone's performance; It explains the failure to shoot the target while flying.

The shooting distance from the UAV and battery life has been recorded in Table 3. The battery's duration on the ground was longer than when the drone was flying because the components required the battery's full support. The actual pictures of the prototype can be found in Figure 4 that was taken during the functionality tests from ideal mode (on the ground) and flying mode.

Table 2. Tasks, functions, and components testing result

Tasks/Functions/ Components	Passed Trials	Failed Trials	Ave. Passing Rate (%)
The functionality of the Drone			
LCD: Battery Indicator & RF signal	3	0	100%
HD Camera	3	0	100%
HD Camera in Night Mode	3	0	100%
The functionality of the Shooting Mechanism			
Dropping	4	0	100%
Shooting	4	0	100%
FLIGHT TEST			
Flying while carrying Shooting Barrel	4	0	100%
Flying while Shooting	3	1	75%
Flying while Dropping	4	0	100%
FLIGHT TEST			
Reach 30 meters high and/or above	3	0	100%
Total:	30	2	97.22%

(a) (b)

Figure 4. Prototype of UAV; (a) during the tests on the ground and (b) flying mode

Table 3. Shooting test by average measurement

Height of the Drone Shooting Mechanism test	The horizontal distance from a drone to the target			
	Trial 1	Trial 2	Trial 3	Ave. Rate (%)
10 m	4.2 m	3.6 m	3.8 m	3.8 m
1.5 m	3.2 m	3.5 m	3.0 m	3.23 m
2 m	3.6 m	3.2 m	3.4 m	3.4 m

4. CONCLUSION

As the completion of this project, an octocopter Unmanned Aerial Vehicle is successfully designed and implemented. This UAV has a unique design for shooting and dropping mechanisms (using PVC materials) of fire distinguisher balls class A to C. An HD camera with night vision interfaced with real-time video streaming and a 5.8 GHz radio frequency (RF) signal is used to help the firefighting team target and shoot the fire extinguishing balls. During this study, the remote controller with 2.4 GHz RF signals is used to manipulate the shooting and dropping mechanism; it can also trigger and control the UAV's movements. A gyroscope and GPS module have been integrated to stabilize the flight of the drone. In this experiment, the UAV's functionalities in terms of hardware components, shooting, and dropping mechanism during the flight were tested with an overall 97.22% passing rate. One of the challenges accrued during the test was the UAV's sensitivity to the weather condition, which can affect shooting accuracy to the target point. Therefore, it requires a skilled person to take over the UAV's controller. Moreover, these fire-extinguisher balls can only be used to aid firefighting challenges in smart cities and not recommended as a standalone solution. For future works and to improve this study, researchers may use 3D printing for the shooting mechanism to carry more fire distinguisher balls during each flight attempt. The battery life can also be improved by adding an extra battery.

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