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ORIGINAL RESEARCH ARTICLE

DEVELOPMENT AND DEPLOYMENT OF QUADCOPTER IN SILOS' INSPECTION AND SURVEILLANCE

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ABSTRACT

Efficient and routine inspection/surveillance of agricultural installations is a panacea that guarantees structural integrity and healthy storage of grains. Conventional methods of silo inspection are tedious, time-consuming, costly, disruptive and with attendant safety concerns. A quad copter comprising four Electronic Speed Controller (ESC), four Brushless DC motors, a motion camera, a flight controller unit, a battery and an off board remote controller was designed, developed and evaluated for silos' facility inspections. The system is powered by 11.4V LiPo (Lithium polymer) fitted on-board of the quad copter, a digital camera and a 12V remote controller for off-board control (yaw, pitch and roll), with an entire system weight of 3.62kg. Apt deployment of such unmanned aerial vehicle in routine facility integrity inspection eliminated the high risk and loss of man hour associated with contemporary techniques. The result of its performance test indicated that the system has maximum attainable speed of 10km/h and maximum height/range of 150 m for over all 10 minutes of flight time. Also, the threshold speed for each rotor was found to be 1030 rpm and an average speed of 0.5km/h needed during inspection of silos to avoid blurred images from the camera was achieved. Comparative analysis of the design with the conventional method revealed that the developed quad copter was cost and time effective, convenient, risk free thus recommended for full scale deployment for inspection/surveillance in silo installations.

1.0 Introduction

Storage is an important aspect of post-harvest technology in commercial agriculture with the target of storing agricultural produce; provide food between harvest seasons and to provide seed for subsequent planting season (Adejumo, 2013). In Nigeria, grains are traditionally stored in calabashes, rhombus, gourds, and drums. These structures are usually adapted to the socio-economic and prevailing weather conditions of the environment where they are deployed while requiring locally available materials like clay, straw, woven twigs or wood for their construction. Improved structures such as local stores and metallic drums (with shelter) also feature at the traditional level of storage (Adejumo and Raji, 2007). Notably, modern storage of grains in Nigeria is often made in metallic silos usually located in every State and the Federal Capital Territory (Talabi, 1996). Traditional method for storage includes Domestic structures, Rhombus, Traditional Crib, Barn, Shelf, Pit/Underground storage while modernized method for storage uses Improved crib, Ware house, Silo/ Bin, Controlled atmosphere storage system, Refrigeration, Cold storage, Evaporative coolant system (ECS), and Hermetic and nitrogen storage systems.

Silo structures are used for storing bulk materials. They are used mainly in agriculture for grain and silage (fermented feed) storage. They also play very important role in storage of things like industrial materials (calcite, minerals), petrochemical supplies, medical supplies (pills, capsules), and perfumery chemicals, among others. The storage of such materials is dependent on duration, size or scale of storage, and the type of material used in the silo construction.

Consequently, silos designs are primarily determined by the properties and type of the materials to be stored. As the density, flow and friction properties of grains, cement, coal, carbon black, and other bulk materials vary widely, the loads applied on a silo structure and the associated load carrying system are different from the traditional building type structures (Adem *et al.,* 2009), which makes silos special structures.

The silos' walls have been found to be subjected to both normal pressure and shear imposed by traction of the stored material in them. Their magnitude and distribution over the height of the wall largely depend on the stored material properties and operations (whether loading or discharging). Also considered during the design of silos are other potential loads such as wind and seismic loads, thermal stresses (between the silo's wall and the stored bulk solids), stored material expansivity and structural mechanics of the supports. As a result of these and to forestall integrity issues, silos are designed and evaluated as special structures. (Adem *et al.,* 2009).

Silos fail with frequency much higher than the rate of failure of other industrial structures (Carson, 2000). Although with scanty statistics, it has been speculated that hundreds of industrial and farm silos (bins, and hoppers) experience some degree of failure each year. The signs of deterioration and the failures observed during a thorough silo inspection are different for concrete and metal silos. Deterioration in concrete silos manifests as wall delamination, cracks, spalling and rebar corrosion while metal silos deteriorate by heavy rust and corrosion, thinning metal, visible holes, wall deformations and cracks. (Susong, 2018). Other signs of degradation according to John and Tracy (2003) include buckling, bending, denting of steel or aluminium silo wall and failure of screw feeder or reclaimer in flat-bottomed silo. Furthermore, silo can fail due to explosion by bursting, asymmetrical loads created during filling or discharging, corrosion (for metal silos), fluctuating soil pressure, silage acids deterioration (for concrete silos), internal structural collapse, thermal ratcheting and earthquakes (Adem *et al.,* (2009)

Without periodic inspections to uncover potential structural integrity issues, silos can collapse with little or no warning. A catastrophic failure is always costly in terms of damage to facilities and potential downtime. They have also resulted in loss of life for personnel in the path of a collapse. Such failures could result from design error, construction error, usage, and improper maintenance (John and Tracy, 2003).

Maintenance of a silo must not be neglected since it falls within the domain of the owner or the user. When proactive response to facility integrity issues is ignored to the extent of the use of common instinct of lowering the silo fill level, failure becomes imminent at greater speed and severity. Common reaction to signs of silo distress is to overlook them, usually due to the personnel reckless ignorance of the dare consequences of such reaction. Cracks in a concrete wall, or dents in a steel shell, though they may seem insignificant, are danger signals which indicate that corrective measures are probably required. Even if danger signs are understood, it is common for inappropriate action to be taken in an attempt to reduce the chance of failure. In some severe cases, where damage could have been relatively minor with appropriate action, catastrophic failure has been induced. To mitigate such failures, there is need for safe but cost/labour effective routine inspection technique for silos.

According to Mole Master Inspection procedure, the process of inspection involves a Structural Engineer, sometimes accompanied by an Agricultural Engineer, visits to the site to conduct field observations. Thereafter, the engineer using binoculars (and occasionally with infrared and corona detection cameras as a tool and method) conducts visual observation of the silo exterior walls for deterioration. Cracks, bulges, or material leakages constitute these visual cues. Usually cranes, scaffolds, rope-access, and people are used to inspect both the storage tanks and the overall structure. These inspections can be effective, but is only accurate for surfaces that can be seen from the ground. In remote regions, this can be even more tedious, as the pylons and very tall silos are not easily accessible, and the terrain between the pylons makes movement difficult.

Susong (2018) indicated that scaffolding could be used as a method and tool for silo inspection but with less safety and cost advantage when compared to rope access and other conventional methods. Rope access method involves setting up the ropes and rigging equipment for the specialist to climb and carry out inspection and maintenance. However, its availability, mobilization and training requirement of this method is exuberant. It was generally discovered that the conventional methods are tedious, time-consuming, costly, disruptive and with attendant safety concerns hence maintenance and inspection of silos are costly, risky and time consuming for those who carry out the inspection.

The solution to this is to deploy autonomous drones for inspection as suggested by Eschmann *et al*., (2012). The use of Aerial Drones has now become a massive innovation in inspection allowing visual analysis of areas usually off limits due to inaccessibility (CATEC, UAV news, 2017). Over the years, Aerial Vehicle inspection technique has provided structural inspections of high or difficult to reach structures which are faster and safer than conventional access methods.

Glez-de-Rivera *et al*. (2014), Myeong *et al*. (2015), Prem *et al.* (2015) and Young *et al.* (2017) developed Unmanned Aerial Vehicles (UAV) which were controlled to survey/inspect the desired location and the information of the location.

In addition, Usama and Nauman (2015) in their research work designed parameters of indigenously developed quad copter for area surveillance. According to their research and in agreement with work of Samir *et al*. (2009), the optimum performance of any quad copter depends on the design features, as it affects the weight, agility and manoeuvrability.

There were sketchy studies of drones' utilization in the inspection of structures, and even limited to visual inspections only (Vaibhav *et al*., 2018). Ellenberg *et al.* (2015) conducted an investigation on remote sensing capabilities of a commercialized drone (Parrot AR 2.0) for crack detection from various distances. An algorithm was developed for post-image processing of the conducted field test on a bridge for the drone performance evaluation.

Jennifer and Baritte (2015) developed a prototype quad copter and observed that the common challenge was that quad copter finds it difficult balancing itself while hovering and thus could not produce a stable data image for analysis. Omijeh *et al.* (2017) designed a quad copter for real-time inspection and surveillance actions in a pipeline facility using a quad copter design profile. At the end of the design, the UAV was capable of attaining autonomous flight at a height of 20 meters and a range of 30 meters. This system still has room for improvement and to expand the usefulness and flexibility of the quad copter designs. In lieu of these desirable features, a portable quad copter with expanded capabilities in altitude, range, flight time and control, was conceived to be deployable in silo inspection so as to reduce drastically the high attendant risk and man hour incurred in the existing routine facility inspection techniques.

2. Materials and Method

2.1 Materials

The main materials of the UAV frame are carbon fibre plates. The selection of motors was based on the frame size, propeller size, battery capacity, and system drive.

The quad copter was developed using components and hardware such as flight controller board (housing the barometer and compass), brushless DC motor, electronic speed controller (ESC), RF remote, receiver and LI-PO battery. Also a DIC camera was attached to this quad copter for on board surveillance.

The system is divided into five main parts to include the structural unit, the input unit, control unit, output unit and power supply.

2.2 Design Constraints

In the design of the quad copter, the following constrains were considered and implemented:

1. The quad copter can only operate in a sunny or dry condition/weather.
2. The quad copter can operate only at a range of 150 meters away from the operator
3. The quad copter is controlled by a KK-2 based microcontroller which has no auto pilot mode or beginner's option and an RF controller.
4. The quad copter has a flight time of 10-12 minutes

2.3 Design Analysis

The design requirements for the flight system development influence the selection of components for the design.

2.3.1 Lift and Weight

In lift and weight analysis; the interest was actually to reduce weight thereby increasing the lifting ability of the flight system in the design.

From weight to RPM ratios; it is near certain for the relations in Equations (1) and (2) (Usama and Nauman, 2015);

$$M = \frac{S_{RPM}}{S_{Rf}} \times W_{Rf} \qquad (1)$$

$$L = \frac{W_{Rq}}{W_{Rf}} \times PL_{Rf} \qquad (2)$$

Where:

M = Mass of propeller, kg
L = Length of propeller, cm
S_{RPM} = Required speed, RPM
S_{Rf} = Referenced speed, RPM
W_{Rf}= Referenced weight, kg
W_{Rq}= Required Weight, kg
PL_{Rf}= Referenced propeller length, cm

Thus from ratio analysis; 1.0 kg weight of quad copter would demand;

- 2 pairs of 283 rpm brushless motors.
- 2 pairs of 20cm clockwise and counter clockwise length propellers.

The relationship governing the lift capabilities of this flight system is given in Equation 3;

$$\text{Lift (thrust; kg cm s}^{-2}) = \frac{W_q(Kg) \times S^2 \times D^4{}_q \times (D_{air} \times 24) \times 29.9 \times C_f}{2.2} \qquad (3)$$

Where;

W_q = Weight of quad copter (kg).

D_q = Rotation diameter of propeller blades (cm).

D_{air} = Density of air (kg/cm^3). (varies with altitude)

C_f = Lift coefficient = 1.

S = Speed in rpm

From the Equation 3;

Prospected weight of quad copter, Wq = 3.62kg = 3620g.

For four blades, D_q= (25cm x 4) = 100cm.

From the weight to rpm ratios; a prospected weight of 3.62kg will be used to determine the threshold speed (s);

S = (weight to rpm ratio) kg x (Reference rpm value/kg of weight) (4)

S= (3.62/1)kg x (283)rpm/kg = 1030rpm.

Thus; 2 pairs of 1030rpm brushless motors will lift a 3.62kg quad copter.

2.4. Development Procedure

The method of research was done by reviewing UAVs, multicopters, and especially quad copter. By using gathered knowledge and information, an approximation of the quad copter weight is made based on some of the main components needed.

A 3D model conceptual design was then made with the help of CAD software Solid Works 2015. A comparison of different materials for quad copter was done with weight, strength and cost taken into consideration and ABS Plastic based on the initial weight approximation, main components such as motors, propellers, high resolution digital image correlation (DIC) camera, ESC and other electrical components were selected. With reference from the components selected, a prototype was designed.

The manufactured parts and all electrical components were then assembled, plastic adhesive was used to hold the wire harness at fixed position on the frame to avoid interruption during operation, calibration and synchronization of the remote control and the on-board flight controller was carried out.

Finally the flight test was carried out to determine the performance of the quad copter. Testing was done on the battery performance of the quad copter and also the ability of the quad copter to stabilize itself when hovering. Any offset in the individual speed of the rotors of the quad copter was calibrated through the flight controller by changing the proportional, integral, and derivative value.

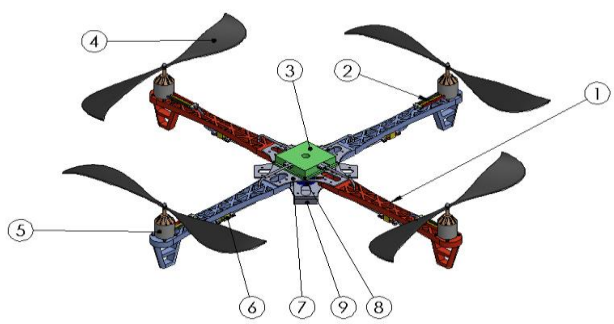

Figure 1: Quadcopter

Table 1: Components of the Quadcopter

S/N	Item	Description/Specification
1	Propeller Arm	HJ- FRP
2	Connecting wires	-
3	Flight controller	FS- R6B
4	Propeller	4 N0s: 9443 R
5	Brushless motor	4 N0s: 31.2A
6	ESC (Electronic speed controller)	Simonk 30A
7	Carbon fiber base.	-
8	LIPOBattery(Lithium Polymer Battery)	3-cell: 4200mAh
9	Camera stand	High Resolution DIC Camera was used

2.4.1 Stress Analysis of the Quadcopter Arm

The arm of the quad copter was analysed on Solid works CAD simulation software. The Von Misses stress analysis was used for this analysis. The maximum result of the arm was discovered to be 2.732 $\times 10^7$ N/m^2 when a force of 4.5N (weight of the motor) was applied as shown in Figure 2. Figure 3 also displays the maximum displacement of the arm. This result indicates that the arm is capable of carrying the total weight of the quad copter without failing.

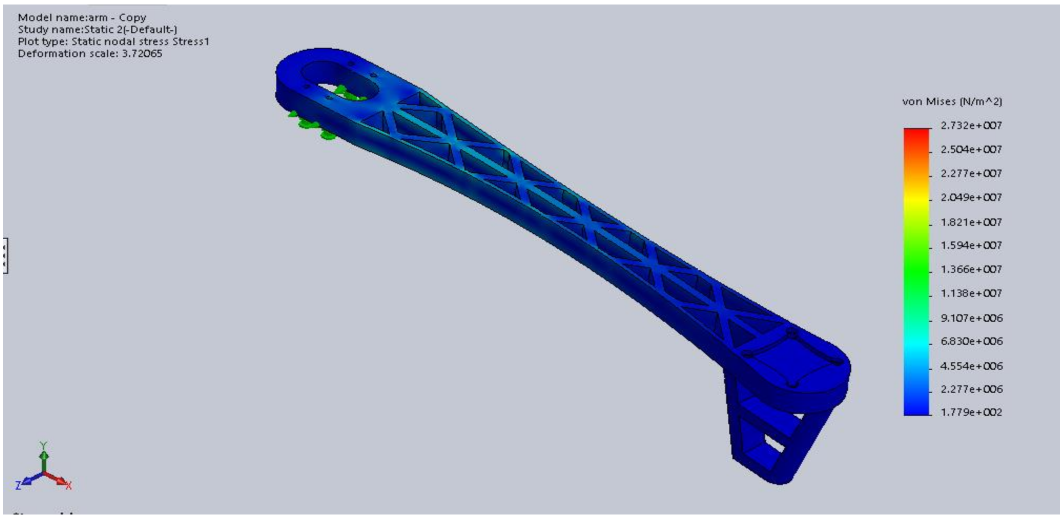

Figure 2: Maximum stress analysis of the arm.

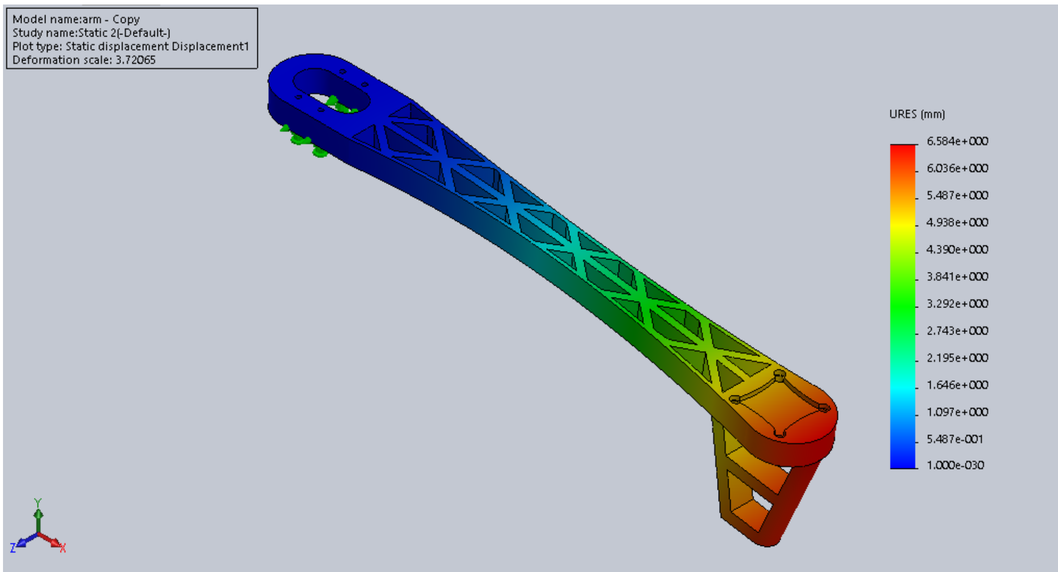

Figure 3: Maximum displacement of the quadcopter arm

2.5. Performance Test Procedures

To safely fly the quad copter; various tests were carried out on the individual components and the assembled quad copter, to ensure everything is functioning properly before flight. Two test stages were carried out on the quad copter; these tests were unit and flight tests.

2.5.1 Unit Test

While the basic flight control of the KK2 was tested simply by PID (proportional-integral-derivative) tuning and flying the quad copter; units' sensors were tested since they were used for the tracking algorithms. The barometer and the compass on-board the flight controller were units tested to ensure optimal performance. The units tested include the motors, barometer and battery.

The motors were tested to lift the quad copter and its components (3.62kg) successfully. The quad copter was able to fly at a speed of 10 km/hr., meeting the requirements needed; but the maximum speed was not tested since it will be out of sight at such speed.

The first sensor to be tested was the BMP085 (barometer). This sensor uses atmospheric pressure to estimate the altitude of the quad copter in meters. This sensor was needed to implement altitude-hold; a flight mode that attempts to keep the quad copter at the same altitude. Three methods to improve the accuracy and precision of the barometer; control (no action); adding foam sponge cover; and adding a mesh cover. The mesh cover proved ineffective as it made the altitude-hold worse by inspection. The remaining two options were tested in a number of different ways. One test was flying the quad copter up to two meters and seeing which method provided better altitude-hold.

Several LIPO battery sizes were tested on the quad copter, to determine the duration of the battery used. The quad copter accessories had an average current draw of 20.2A, and a battery with higher capacity meets the requirement.

2.5.2. Flight Test

Pre-flight test was conducted. The remote control was first switched on before the flight controller. The remote control was to be armed ready for further flight control action from it with a beep preceding the arming action. The speed controller controls the speed of the fan according to preassigned values on the accelerometer memory. Speed of the fan increases as the atmospheric wind speed decreased. Increment in speed was achieved by gradual increase in acceleration from the left joystick on the remote control. So the speed controller, remote controller, and the on-board flight controller performed as per the design. Table 2 shows the flight check list that precedes the flight test.

Table 2: Pre-flight check list

S/N	Units	Check Actions
1	Airframe and Landing arm ready	Ensure the airframe and landing arm are intact.
2	Propellers secured; undamaged and in correct flying orientation?	Ensure that the propellers are secured; undamaged and in correct flying orientation.
3	Motors secured and undamaged?	Ensure motors are secured and undamaged.
4	ESCs secured and undamaged?	Ensure that ESCs are secured and undamaged.
5	RF receiver and connections secured and undamaged?	Ensure that that RF receiver and connections are secured and undamaged.
6	RF remote undamaged?	Ensure that the RF remote is secured and undamaged.
7	KK-2 flight controller secured and undamaged?	Ensure that KK-2 flight controller is secured and undamaged.
8	Battery fully charged?	Ensure that the battery is fully charged.
9	Battery correctly installed and connected on the quad copter?	Ensure that battery is correctly installed and connected on the quad copter.
10	Battery correctly strapped and secured?	Ensure that the battery is correctly strapped and secured.

2.6. Program for Operation

The program for the operation of the quad copter was developed with Assembly Language. The code block for this operation is shown below:

```
ORG 0000H
MOV P1, #0FFH
MOV P2, #0FFH
MOV P3, #0FFH

MAIN:
ACALL serial port
CLR P1.0        ;TURN OFF MOTORS
CLR P1.1        ;TURN OFF MOTORS
CLR P1.2        ;TURN OFF MOTORS
CLR P1.3        ;TURN OFF MOTORS
SETB P2.7

MONITOR:
JNB P2.7, $
ACALL RECIEVE ; RECIEVE COMMAND FROM TRANSMITTER AND SENSORS
MOV R5, A
ACALL DELAY
SETB P1.0       ;TURN ON MOTORS
MOV R5, A
ACALL DELAY
SETB P1.1       ;TURN ON MOTORS
MOV R5, A
ACALL DELAY
SETB P1.2       ;TURN ON MOTORS
MOV R5, A
ACALL DELAY
SETB P1.3       ;TURN ON MOTORS
MOV R5, A
ACALL DELAY
CLR P1.0        ;TURN OFF MOTORS
MOV R5, A
ACALL DELAY
CLR P1.1        ;TURN OFF MOTORS
MOV R5, A
ACALL DELAY
CLR P1.2        ;TURN OFF MOTORS
```

```
MOV R5, A
ACALL DELAY
CLR P1.3          ;TURN OFF MOTORS
MOV R5, A
ACALL DELAY
SJMP MAIN

DELAY:

H1:     MOV R2, #100
H2:     MOV R3, #255
H3:     DJNZ R3, $
        DJNZ R2, H2
        DJNZ R5, H1
        RET

serial_port:    MOV TMOD, #20H      ;SERIAL PORT INITIALIZATION
                MOV TH1, #-3                 ;9600 BUADRATE (-3)
                MOV SCON, #50H
                SETB TR1
                RET

RECIEVE:        MOV  A, SBUF
HERE:           JNB RI, HERE
                CLR RI
                RET

        END
```

3. Results and Discussion

The following are the results of the test that were carried out.

3.1.1. Motor Test

While testing the brushless DC motor, the speed was compared with the duration of the battery. Figure 4 shows that an increased speed reduces the duration of the battery. However, inspection operation targets accuracy and precision rather than speed, hence the quad copter was designed for inspection and not for speed operation thus prolonged battery life.

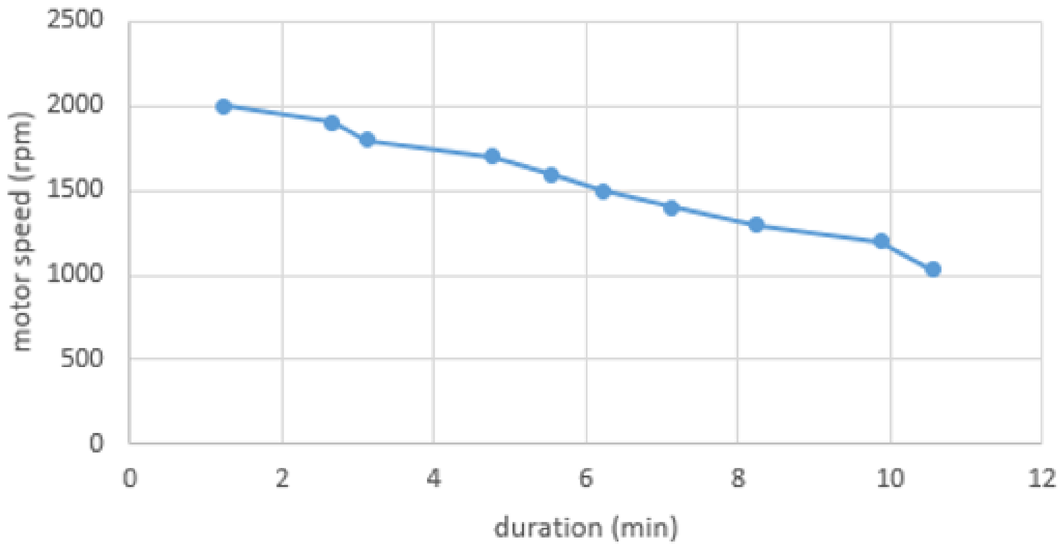

Figure 4: Variation of motor speed with time

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3.1.2. Battery test

Table 3 displayed flight durations for several batteries tested. With the 4200 mAh battery; the quad copter was able to attain a maximum flight time of 10 minutes projected for facility inspection. The result shows that higher capacity battery will increase the duration of the flight though with likely increase in cost.

Table 3: Comparison of battery capacity and flight time

Capacity (mAh)	Flight time (min)
2450	6.34
3000	7.62
4200	10.8

3.1.3. Barometer test

In the barometer test that was conducted, it was observed that the foam sponge was able to provide a better altitude holding. Table 4 shows the result of this control when tested upon 2 meters height.

Table 4: Foam and Control of Quadcopter

	Control	Foam
Average	0.79	1.84
Medium	0.72	1.90
Standard Bev.	0.40	0.27

3.1.4. Flight tests

After carrying out proper pre-flight and flight checks; the various units were checked and the systems powered as recommended by the safety guideline to ensure safety of the quad copter and the personnel operating it. After conducting the flight test, the system was capable of attaining a maximum height/range of 150m from the operator at a hovering speed of 0.5km/hr. which is to be maintained for a quality picture during flight. This showed system extended capabilities compared to Omijeh *et al*., (2017) design.

3.2 Comparative Analysis of Inspection Techniques

A comparison between a commonly used traditional method for inspection of silo structure (use of scaffoldings) and the use of quad copter was carried out in order to estimate the effectiveness of the quad copter in terms of cost and working time. The silo structure has a diameter of 6m and a height of 12.5m located in Michael Okpara University of Agriculture, Umudike (Figure 5). Four silos were inspected, and Table 5 shows the result of the comparison done.

Figure 5: Field test of the developed quad copter on silos

Table 5: Comparative analysis of Traditional techniques and Quadcopter inspection

	Traditional Method (use of scaffolding)	Use of Quadcopter
Number of silos	4	4
Number of technical workers	4	2
Time of inspection (hours)	0.83×4= 3.5	0.16×4=0.66
Wages (₦)	35000×4=140000	25000×2=50000

From Table 5, the inspection done by four (4) workers using traditional means was done effectively at lesser cost and time using a quad copter.

4.1. Conclusion

Based on design, simulation and prototyping, a quad copter of overall weight as 3620g, with ABS Plastics material of hollow cross-section was developed. The arms were subjected to maximum stress of 27.32 MPa and maximum deflection of 0.006 mm well below yield strength of the arm material. The results obtained in this study showed that the quad copter was capable of attaining maximum height/range of 150m, hovering and taking the desired pictures at a speed of 0.5km/hr. if the speed is altered, blurred images are obtained.

4.2. Recommendation

This quad copter can still be upgraded with additional sensors (IR sensors, wireless technology and 3D mapping tools) to expand the overall usefulness and flexibility of the quad copter. In addition to this, an autopilot flight controller or beginner's mode configuration should be incorporated in the flight controller to assist the station pilot when controlling the quad copter.

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