

# DEVELOPMENT OF A QUADCOPTER FOR POWER LINE INSPECTION

**N.J. Wilken and R. Gouws**

*North West University, School of Electrical and Computer Engineering, Potchefstroom South-Africa, njwilken@gmail.com*

**Abstract.** The inspection of transmission lines is to be done annually. It is proposed that a quadcopter is used to do the inspection of these transmission lines. The modelling of the quadcopter was done by studying its physical characteristics and ultimately a mathematical model could be presented with the use of the Newton equations. The control strategy suitable of this project is the use of PD control, which will consist of four control loops combined as one. The prototype quadcopter is able to do transmission line inspections, is equipped with a monitoring system, move smoothly and have special features like stabilizing mode and altitude hold.

**Key Words.** Quadcopter; PD Controller; Altitude Controller; Arduino and Controller simulation.

## 1. INTRODUCTION

A constant supply of energy is a necessity for a country that wants an ever growing economy. To meet this demand, reliable electrical networks that consist of power lines are essential.

Eskom is a power supplying company that have generated and sold over 225 000 Giga-Watt-hour in the year of 2011 and 2012, providing 45% of all the electricity used in Africa and 95% of all the electricity used in South-Africa [1]. In order to supply these enormous amounts of electricity thousands of kilometres of transmission lines is needed and is found all over Africa.

### 1.1 Problem Background

The inspection of transmission lines are done annually in the form of line patrol, this is when a team from Eskom walk the line with the help of a motor vehicle to do a visual inspection on the condition of the transmission lines. Due to the vast amount of time needed to do this and the accessibility constrains due to rough terrain and obstacles, some of the inspections are done by a helicopter. According to an Eskom financial report of 2010 the expenses for these inspections run up to R36 million per year [2]. The use of a helicopter is a costly method to inspect transmission lines and thus an alternative solution to this problem needs to be found.

It is proposed that a transmission line inspecting quadcopter needs to be developed that is more effective than the conventional methods of inspecting power transmission lines, in terms of time, safety and the costs involved.

### 1.2 Existing Solutions to the Problem

Transmission lines are not an unfamiliar sight and ever since these lines made their appearance it was needed to be monitor by means of inspection. Over the years different solutions have been found to do this task.

Transmission lines have been inspected on foot for a very long time as there was no better method available to perform this task. Power networks consist of thousands of kilometres of transmission lines and take a vast amount of time to inspect on foot if inspection is done thoroughly. Furthermore power lines are sometimes built in rough terrain that

is difficult to access due to mountains, new development and height constrains.

A method used with more success is to inspect the power lines with the help from a helicopter. This technique is very accurate because it can overcome the height constrains involved with power lines. Using a robot is the most recent solution and method of inspecting power transmission lines. This robot is developed to run on the earth wire of the line and with a camera in attached to the frame of the robot, photos and even videos can be recorded of the transmission line [3].

## 2. PROPOSED SOLUTION

In order to obtain a general feel and knowledge of what to expect during the design of this project, proper research had to be done on similar projects with roughly the same scope. The research revealed some important aspects that need more planning and time than other, stumbling stones to avoid, crucial approaches for success and risks involved in completing this project.

The quadcopter needs to be able to fly along a power line for inspection purposes and should consist of an autopilot function. This function should provide the ability that the quadcopter can hover, do auto take-off and landing on command of the operator. The physical construction should be able to house and supply power to a monitoring system for the inspection purpose. The following key components were acknowledged to guarantee that the project is a success:

- Custom development of a controller to achieve the desired features that the quadcopter should consist of.
- Construction/Assembling of an appropriate frame/chassis.
- Achieving lift-off, flying and movement of the quadcopter, by means of motors, propellers and speed control.
- Design a monitoring system to do a visual inspection on the power lines.
- Establish a remote communication system between quadcopter and operator.
- Supplying power to all the components on the quadcopter.

These components listed are only high level and require a lot more detail to incorporate correctly into the quadcopter for complete success.

### 3. DYNAMIC QUADCOPTER MODEL

In order to design a controller for the quadcopter it is first of all necessary to develop a dynamic model that accurately describes the quadcopter in terms of its movements and principal characteristics.

#### 3.1 Physical and Mathematical Model

The axis and structure orientation of the quadcopter that will be used to do the modelling is in Fig. 1 [4], where  $x$ ,  $y$  and  $z$  is the coordinates of the quadcopters centre of gravity. The  $\Phi$  represents the roll angle;  $\theta$  represents the pitch angle and  $\Psi$  the yaw angle.

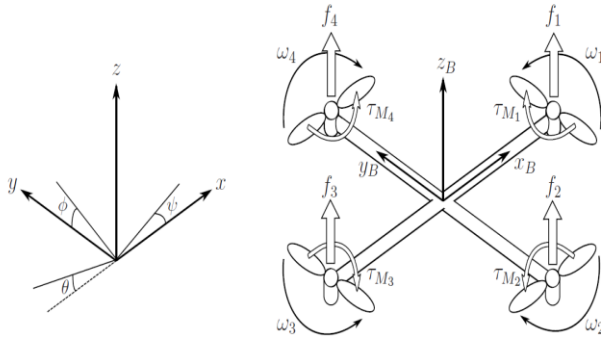


Fig. 1: Quadcopter body and inertia frames used for modeling.

From Fig. 1 it can be seen that the rolling moment takes places around the  $y$ -axis, the pitching moment around the  $x$ -axis and the yawing moment around the  $z$ -axis. The linear position ( $\xi$ ) and the Euler angles ( $\eta$ ) are defined as

$$\xi = \begin{bmatrix} x \\ y \\ z \end{bmatrix}, \eta = \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix}$$

A transformation matrix is required to switch between the body and inertial frames. This matrix, denoted by  $R$ , is called the rotation matrix [4].

$$\bar{R} = \begin{bmatrix} C_\psi C_\theta & C_\psi S_\theta S_\phi - S_\psi C_\phi & C_\psi S_\theta C_\phi + S_\psi S_\phi \\ S_\psi C_\theta & S_\psi S_\theta S_\phi + C_\psi C_\phi & S_\psi S_\theta C_\phi - C_\psi S_\phi \\ -S_\theta & C_\theta S_\phi & C_\theta C_\phi \end{bmatrix}$$

In the rotation matrix  $C_\psi$  represents  $\cos(\Psi)$ ,  $S_\theta$  represents  $\sin(\theta)$  and so forward. The assumption is made that the body of the quadcopter is rigid and symmetrical, and in an X configuration in the  $x$ -axis and  $y$ -axis as seen in Fig. 1. The inertia matrix is then given by

$$\bar{I} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix}$$

The fact that the structure is symmetrical yields the result that  $I_{xx} = I_{yy}$  for the diagonal matrix of the inertia. The next step is to conceptualize the force from each motor ( $f_i$ ) that is created by its angular velocity ( $\dot{\omega}_i$ ).

$$f_i = k\omega_i^2$$

The  $i$  denote the motor number and  $k$  is a certain lift constant of that motor. Similarly a torque ( $\tau_{M_i}$ ) is created around the axis of that motor and is given by

$$\tau_{M_i} = b\omega_i + I_M$$

where  $I_M$  is the moment of inertia and  $b$  is the drag constant. A thrust ( $T$ ) is created as a result of the collective forces of all four motor that will act in the direction of the  $z$ -axis [4].

$$T = \sum_{i=1}^4 f_i = k(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2)$$

The torques ( $\tau$ ) that corresponds with roll, pitch and yaw in the body frame is then given as

$$\bar{\tau}_B = \begin{bmatrix} k(-\omega_2^2 + \omega_4^2)l \\ k(-\omega_1^2 + \omega_3^2)l \\ k(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2) \end{bmatrix} = \begin{bmatrix} \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix}$$

provided that the rotation of the motors is chosen as in Fig. 1 and that the length ( $l$ ) from the motor to the centre of gravity is the same for all the motors. The Newton-Euler equations can now be used to describe the dynamics of the quadcopter from the equations obtained already. This then yields

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = -g \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} + \frac{T}{m} \begin{bmatrix} C_\psi S_\theta C_\phi + S_\psi S_\phi \\ S_\psi S_\theta C_\phi - C_\psi S_\phi \\ C_\theta C_\phi \end{bmatrix}$$

which can be used to get the expressions for acceleration in the  $x$ -axis,  $y$ -axis and  $z$ -axis. In the equation above, the  $g$  denote gravitation and  $m$  the mass of the entire quadcopter. The Euler-Lagrange equations can now be used to get a matrix system in terms of the acceleration in the Euler angles [4].

$$\begin{bmatrix} \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} \tau_\phi / I_{xx} \\ \tau_\theta / I_{yy} \\ \tau_\psi / I_{zz} \end{bmatrix}$$

This equation for the acceleration in the Euler angles is only valid if the Coriolis Effect is ignored. Since this is a small scale project and will not be traveling fast over long distances, this effect can be ignored in the dynamic model.

#### 3.2 Simulation of Dynamic Model

The matrix systems and equations from the previous section should now be rearranged in such a way that a state space model can be determined, which will aid the student when trying to simulate the model. The following equations are obtained

$$\begin{aligned}\ddot{x} &= T/m (C_\psi S_\theta C_\phi + S_\psi S_\phi) \\ \ddot{y} &= T/m (S_\psi S_\theta C_\phi - C_\psi S_\phi) \\ \ddot{z} &= T/m (C_\theta C_\phi) - g \\ \ddot{\phi} &= \tau_\phi / I_{xx} \\ \ddot{\theta} &= \tau_\theta / I_{yy} \\ \ddot{\psi} &= \tau_\psi / I_{zz}\end{aligned}$$

From these equations [4] it can easily be seen that all of the movement is as a consequence of the lifting force from the rotating motors. It can also be seen that the thrust is responsible for the displacement in position and torque is responsible for the acceleration in the Euler angles.

It was found that the easiest way to model the system is to decouple the inputs, thus the quadcopter will be modelled with three different models. When the three models have been developed they can just be added together to form the overall model of the quadcopter. The three models are one for the altitude and yaw, the second for the roll and the third for the pitch angle.

The state space model for each of these models has been generated using manipulation of the equations and then the three models were combined once again to produce the entire model required. The model simplification technique used in [5] has been implemented on the model. The state space model is presented in the form of

$$\begin{aligned}\dot{X} &= AX + BU \\ Y &= CX + DU\end{aligned}$$

where the X is the state matrix, U is the input matrix and Y is output matrix.

$$X = [x \ y \ z \ \phi \ \theta \ \psi \ \dot{x} \ \dot{y} \ \dot{z} \ \dot{\phi} \ \dot{\theta} \ \dot{\psi}]^T$$

$$U = [T \ \tau_\phi \ \tau_\theta \ \tau_\psi]^T$$

$$Y = [x \ y \ z \ \phi \ \theta \ \psi]^T$$

The A, B, C and D matrix were obtained by using the unique equations formulated earlier. The resultant state space model has been simulated in MATLAB® Simulink®.

The aim of this simulation is to verify that the dynamic quadcopter model acts in a similar manner to a real life quadcopter. To test this behaviour a step input was used to simulate a change the total thrust, roll angle, pitch angle and yaw angle. The output of the model is then measured on oscilloscopes, to see what effect each input has on the position of x, y and z and the Euler angles roll, pitch and yaw.

#### 4. DETAIL CONTROL

During the simulation of the derived model of the quadcopter it was seen that some effects of the quadcopter model in not desirable. Since this model proved to be accurate the only method to get rid of these effects is by means of proper control.

The derived state space model of the quadcopter that has been simulated in Simulink® was used to obtain equations for each of the inputs to the model. From the MATLAB® equations a controller can be devolved that would control the quadcopter to make it useful.

#### 4.1 Controller Design

The controller of the quadcopter will consist of four major control loops that would ultimately be combined to create the controller. The controller type that will be used for all four of the control loops is PD controllers. The control loops will be designed to control the thrust provide by the motors, the rolling moment around the x-axis, the pitching moment around the y-axis and the yawing moment around the z-axis.

The PD control loop for the total thrust provided from the four motors will have the following balance

$$\frac{z}{T} = \frac{K_A}{s^2}$$

where z is the output position, T is the total thrust of the motors and  $K_A$  a certain constant determine by the quadcopter characteristics. Since thrust is the input, for a PD controller, it can be written as

$$T = (k_{P,z}(z_d - z) + k_{D,z}(z_d - z)s) \frac{m}{C_\phi C_\theta}$$

where  $k_{P,z}$  and  $k_{D,z}$  are the PD constants and  $z_d$  is the input to the thrust control loop, indicating the desired altitude. Using the equations above the transfer function can be obtained

$$T_z(s) = \frac{z}{z_d} = \frac{\frac{m}{C_\phi C_\theta} (K_A k_{D,z} s + K_A k_{P,z})}{s^2 + \frac{m}{C_\phi C_\theta} (K_A k_{D,z} s + K_A k_{P,z})}$$

The transfer function can now be used to implement the control loop to control the thrust, given that the constants of the quadcopter are known. The propagation and derivative constants of the altitude control loop can now be calculated for a certain settling time and percentage overshoot. After careful consideration and reviewing literature a suitable settling time would be less than one second while any percentage less than 5% would be an acceptable overshoot for the controllers.

A similar approach has been followed to calculate the transfer functions of the rolling moment around the x-axis control loop, the pitching moment around the y-axis control loop and the yawing moment around the z-axis control loop. The transfer function for the rolling moment around the x-axis is

$$T_\phi(s) = \frac{\phi}{\phi_d} = \frac{I_{xx} (K_B k_{D,\phi} s + K_B k_{P,\phi})}{s^2 + I_{xx} (K_B k_{D,\phi} s + K_B k_{P,\phi})}$$

where  $\phi$  is the output roll angle,  $\phi_d$  is the desired roll angle and  $K_B, k_{P,\phi}$  and  $k_{D,\phi}$  is constants associated with the roll control loop. The propagation and derivative constants of the roll moment control loop can now be calculated for the specified settling

time and percentage overshoot. The transfer function for the pitching moment around the y-axis is

$$T_{\theta}(s) = \frac{\theta}{\theta_d} = \frac{I_{yy}(K_C k_{D,\theta} s + K_C k_{P,\theta})}{s^2 + I_{yy}(K_C k_{D,\theta} s + K_C k_{P,\theta})}$$

where  $\theta$  is the output pitch angle,  $\theta_d$  is the desired pitch angle and  $K_C, k_{P,\theta}$  and  $k_{D,\theta}$  is constants associated with the pitch control loop. The transfer function for the yawing moment around the z-axis is

$$T_{\psi}(s) = \frac{\psi}{\psi_d} = \frac{I_{zz}(K_D k_{D,\psi} s + K_D k_{P,\psi})}{s^2 + I_{zz}(K_D k_{D,\psi} s + K_D k_{P,\psi})}$$

where  $\psi$  is the output yaw angle,  $\psi_d$  is the desired yaw angle and  $K_D, k_{P,\psi}$  and  $k_{D,\psi}$  is constants associated with the yaw control loop. The four control loops designed above should yield the required controller, once they are combined and all the constants are known and calculated, to control the quadcopter. The control scheme of the quadcopter will be in the form of Fig. 2.

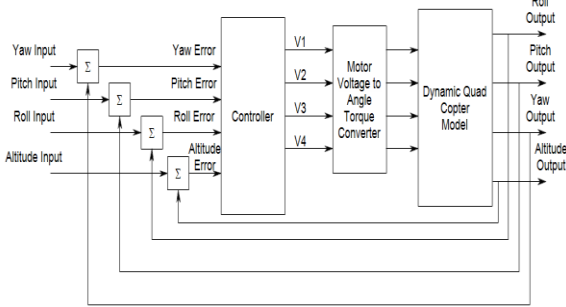


Fig.2: Quadcopter Control Scheme.

The controller of the quadcopter is only able to change one thing in order to control it and that is the voltage of the four motors ( $V_1, V_2, V_3, V_4$ ). As the motor voltage varies the speed and direction of the angular velocity will also vary. It is for this reason that a converter is added to calculate the voltages required at each motor to achieve the thrust and torques needed at the output. The controller in Fig. 2 is the combination of the four control loop designed above.

#### 4.2 Controller Simulation

In order to verify that the controllers designed in the previous section yield the required response with the calculated values for the propagation and derivative constants, it must first be simulated in Simulink®. The four controllers have been constructed and simulations could begin using the known and calculated constants. The resultant altitude controller can be seen in Fig. 3.

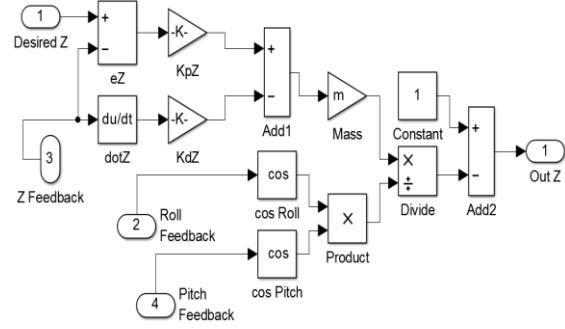


Fig.3: Altitude control loop.

The controller makes use of three summing nodes, a multiplication and division function to present the control of a desired altitude as input to the actual altitude. To be able to deliver the desired altitude the controller makes use of the feedback from the actual altitude, roll angle and pitch angle. This feedback is used to compute an error to continuously check that the desired movement is achieved. The step response yield the requirement in terms of the settling time and maximum overshoot.

The control loop for the roll controller can be seen in Fig. 4, where a desired roll angle is given as input and the output is the actual roll angle. The controller uses only the actual roll angle as feedback to compute the error and stabilize the quadcopter.

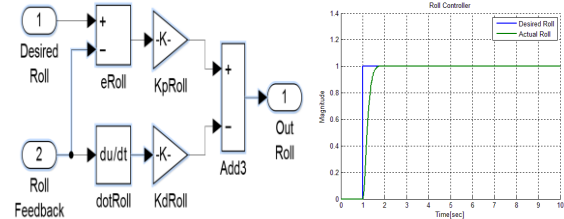


Fig.4: Roll control loop and step response result.

The results of the step response of the roll controller is shown in the right of Fig. 4 where it can be seen that its delivers a stable response with minimal overshoot in an acceptable settling time. From the simulation it is also seen that the coordinate of x is change while the rolling moment occurs. The pitch control loop is almost identical to the roll controller, the only difference being the input desired pitch angle and the output of the actual pitching angle. The pitch control loop is shown in the left side of Fig. 5 with its step response on the right.

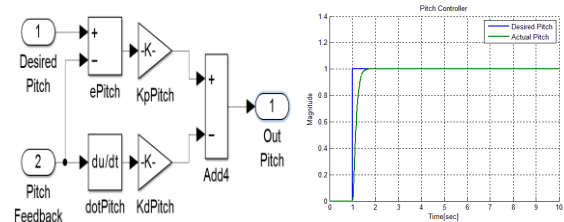


Fig.5: Pitch control loop and step response result.

When the controller is connected to the derived quadcopter model and given a step input the result can be seen in the right half of Fig. 5. The output of this response deliver all the required objectives stated in the beginning of this section. From the simulation it is also seen that the coordinate of y is change while

the pitching moment occurs. The yaw controller was designed and simulate in a similar manner and the control loop is shown is the left side of Fig. 6.

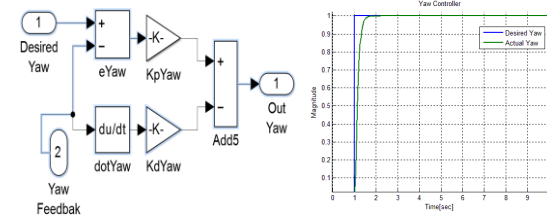


Fig.6: Yaw control loop and step response results.

The right side of Fig. 6 show the result of when a step input is given to the desired yaw vs. the output of the controller. The overshoot and the settling time are easily adjusted to the desired maximums by tweaking the gains of the propagation and derivative constants of the controller. This tuning action will ensure for a quadcopter that is stable and delivers excellent results in terms of inspection quality.

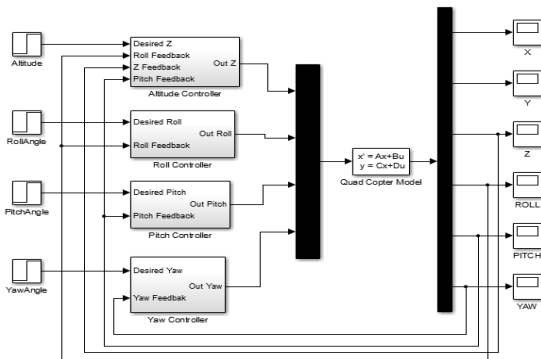


Fig.7: Simulate quadcopter model and controllers.

The four controllers designed and simulated in this section can now be joined together to form the quadcopter controller. The quadcopter controller is then joined to the derived dynamical model of the quadcopter to simulate the entire movement of the quadcopter. This simulated quadcopter model with its controllers can be seen in Fig. 7. The results of the entire quadcopter system remain the same as already mentioned in this section.

## 5. RESULTS

During the results section all the findings obtained from various tests will be stated and the do's as well as the don'ts will be discussed. The results will be compared with the simulations done in the previous chapter and will be the indication whether the project is successful in delivering the required objectives.

### 5.1 Motor and Battery Test

A motor test was done to determine the current it would draw when the motor is in different states. Measurements were taken while the motor had no load and then again with load connected to the shaft of the motor. The load used for this test was two different propellers sizes namely a 12X4.5 and 10X4.5 propeller. The results of the motor test can be seen in Fig. 8.

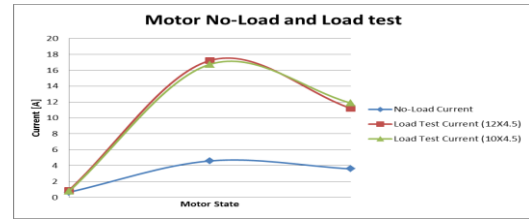


Fig.8: Motor Current curves under various loads.

The power needed to keep the motor rotating is then calculate as 166W for the 12X4.5 propeller and 175.8W for the 10X4.5 propeller. From the power results one can see that the bigger propeller will be more effective to use, given that it can lift the entire weight of the quadcopter. These power consumptions can now be used to calculate how much power will be used when flying.

Although a low voltage Li-Po alarm will be used to warn the operator when the battery is nearing its end to give power to the quadcopter, it is essential that one has a predetermined figure of what operating time would be available. The motor running current, as determined above, is used to calculate the total operating time the battery would be able to supply power to the quadcopter. The results can be seen in Fig. 9.

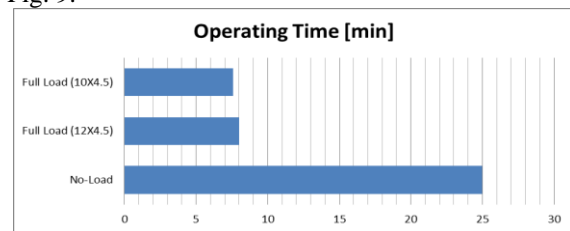


Fig.9: Results for battery discharge test.

The results in terms of operating time, in minutes, give the same figure as the operating currents of the motor under certain loads. As the operating current of the motor increases the time that the battery will be able to supply power will decrease. With propellers connected to the motors shaft the best operating time a single battery would deliver is about 9 minutes.

### 5.2 Quadcopter controller results

In order to ensure safe operation the roll and pitch controllers of the quadcopter where given saturation values. The values used are a lower limit of -45° and an upper limit of +45°. The impact of this is that the quadcopter is only allowed to rotate 45° around the x- and y-axis in both directions.

The roll, pitch, yaw and altitude controller has been tested individually by means of data logging using the flight controller board, while the quadcopter were in flight. The result for both the roll and pitch controller revealed that the required change in roll and pitch angle, given by the operator, could be achieved by the controllers while compensating for external interferences like the changing wind speed. From the data obtain, the yaw controller appeared to be extremely sensitive. When given a small required change in the yaw angle, as an input, the actual change in the yaw angle were considerable larger. The reason for this is due to the fact that the motors

provide twice as much thrust that the actually needed for the specific quadcopter. When the altitude controller was tested the observation has been made that the altitude proved to very difficult to be maintained, varying about 5 to 6 meters. It is for this precise reason that the student implemented a special altitude hold function that keeps the altitude within a range of less than one meter when activated.

### 5.3 Integrated system line inspection

The goal of this project is deliver a product or method that Eskom can use to do their line inspection with, while reducing the costs and improving the quality of the inspection results. Thus the quadcopter without the monitoring system are merely a toy and of no use to Eskom. The monitoring system were attached to the quadcopter and the result can be seen in Fig. 10.



Fig.10: Final quadcopter with monitoring system.

The integrated quadcopter executed all required movements smoothly while remaining completely stable. To verify that the quadcopter could indeed deliver the required performance to do a power transmission line inspection and yield the results as needed to declare the project a success, the quadcopter has been tested on such an inspection. The image in Fig. 11 shows the quadcopter while flying close to a transmission line.

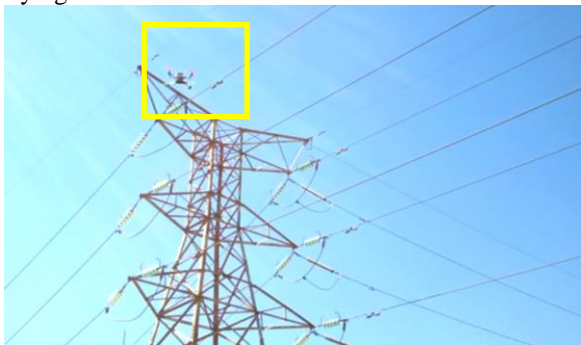


Fig.11: Quadcopter doing a transmission line inspection.

The integrated transmission line test was done while there was a breeze at an altitude of about 16 to 18 meters. All of the controllers together with the altitude hold function were used during this field test with great success. The quadcopter could be flown at a distance of about 4 meters from the transmission line. The on-board inspection results can be seen in Fig. 12.

On the left hand side of Fig. 12 a snapshot using the normal camera were taken with the quadcopter about 4 meters from the transmission line and on the right hand side is a snapshot using the concept thermal imaging camera.



Fig.12: On-board inspection results from quadcopter

The images are good enough to identify faults on the line. This means that the quadcopter provides the required stability to obtain the inspection results as required by Eskom.

## 6. CONCLUSION

The modelling of the quadcopter was done by studying its physical characteristics and ultimately a mathematical model could be presented with the use of the Newton equations of motion. The state space model had to be extracted to simulate the derived model in Simulink®.

The control strategy suitable of this project is the use of PD control, which will consist of four control loops combined as one. The overshoot and the settling time are easily adjusted to the desired maximums by tweaking the gains of the propagation and derivative constants of the controller. This tuning action ensures for a quadcopter that is stable and delivers excellent results in terms of inspection quality.

The simulated PD constants were programmed onto the controller. These constants proved to be an excellent starting point and only required a small amount of alteration to deliver a smooth and stable response. The altitude hold function delivered extremely accurate results varying by less than a meter while maintaining a constant altitude. This feature proved to be very useful when the transmission line inspection test was done to obtain good quality inspection results.

## REFERENCES

- [1] Eskom, "Eskom: Our business," Eskom, [Online]. Available: <http://www.eskom.co.za/c/40/company-information/>. [Accessed 15 01 2013].
- [2] Eskom, "financialresults," 2010. [Online]. Available: [http://financialresults.co.za/2010/eskom\\_ar2010/eskom\\_abridged-ar2010/flippingbook.swf?pageNumber=](http://financialresults.co.za/2010/eskom_ar2010/eskom_abridged-ar2010/flippingbook.swf?pageNumber=). [Accessed 15 01 2013].
- [3] A. Burger, "Chapter 3: Overhead line inspections," in *The fundamentals and practice of overhead line maintenance*, Johannesburg, Crown Publications, 2006, pp. 34-49.
- [4] L. Teppo, "Modelling and control of quadpoter," Aalto University, Espoo, 2011.
- [5] P. Castillo, R. Lozano and A. E. Dzul, "The Quad-rotor Rotorcraft," in *Modelling and Control of Mini-Flying Machines*, Compiegne, France, Springer, 2004, pp. 39-60.