Development of an UAV for Search & Rescue Applications

Mechatronic Integration for a Quadrotor Helicopter

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Abstract—**In the event of a disaster, there is an impending need for robotic assistance in order to conduct an effective search and rescue operation, due to their immediate permissible deployment. In this paper, the development of an unmanned aerial vehicle (UAV) intended for search and rescue applications is presented. The platform for the UAV is a quad-rotor type helicopter, simply referred to as a quadrotor. A plan for the mechatronic system integration was devised to combine the mechanical, electronic and software elements of the research. Once the system was modelled mathematically, a control strategy was implemented to achieve stability. This was investigated by creating a MATLAB® Simulink® numerical model, which was used to run simulations of the system.**

Keywords-Quadrotor, UAV, Field Robotics, Mechatronics, Search & Rescue

I. INTRODUCTION

With increasing occurrences of tragic events in recent times, the development of field robots to be utilised in search and rescue operations has become more relevant. Even though the tsunami and earthquakes that have occurred in Japan and New Zealand this year would be the most obvious situation where these robots can be utilised, there also exist scenarios in industry where they can be functional [1]. The apparent industries would be the hazardous chemical industry and mining industry. The main advantage that a search and rescue robot has over its human counterpart is the relative speed at which they can enter a disaster site and begin to collect information. Robots can be deployed into a disaster site almost immediately because they are expendable in relation to human life [2]. The search and rescue division of the Mechatronics and Robotics Research Group (MR^{2}G) at the University of KwaZulu Natal have embarked on numerous research projects. This includes an unmanned ground vehicle (UGV) called the CAESAR [3] and an autonomous boat for sea rescue operations [4]. Research on the development of a UAV to be used as a search and rescue drone is the latest undertaking by the department, of which will be discussed in this paper. Other research groups have also embarked on similar endeavours with great success. The Centre for Robot-Assisted Search and Rescue (CRASAR) assisted in Haiti with two robots called the iSENSYS, a conventional helicopter drone, and AirRobot which is a quadrotor drone [5]. There are also other commercially and academically developed platforms that have the capability of being utilised in search and rescue situations. Examples of these are the STARMAC II autonomous quadrotor helicopter developed at Stanford University and the X-4 Flyer Mark III developed at the Australian National University [6; 7].

A virtual concept of the UAV is depicted in Figure 1. The quad-rotor type helicopter, otherwise simply known as the quadrotor, was selected as the platform for the UAV as it possesses the characteristics required for an airborne search and rescue robot. The most advantageous characteristic of the rotorcraft is the ability to hover, allowing for localised inspection and a thorough reconnaissance of a disaster site. It is also preferred over its conventional counterpart due to the greater degree of safety that it possesses because of the considerably smaller rotor diameters. Large rotors found on conventional helicopters would be far too dangerous to be introduced into confined spaces. A dynamic system was modelled and a control strategy implemented. A plan for the mechatronic system integration was also devised to combine the mechanical, electronic and computer elements of the research.

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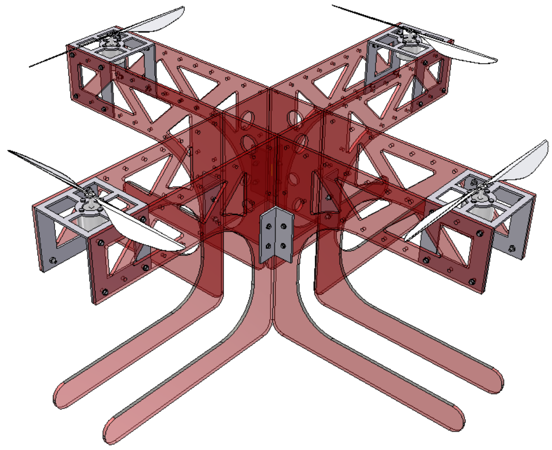

Figure 1: Proposed quad-rotor helicopter structure

II. DYNAMICS

Similar to a conventional helicopter, a quad-rotor helicopter is a six-degree-of-freedom, multivariable, strongly coupled, and under-actuated system. The main forces and moments acting on a quad-rotor helicopter are produced by its rotors [8]. It is arguably a simpler setup from conventional helicopters, as quad-rotor helicopters can be controlled exclusively by variation in motor speed and do not require any complicated actuators. Two pairs of rotors rotate in opposite directions to balance the total torque of the system. Figure 2, shows a free body diagram of a typical quad-rotor type helicopter [8].

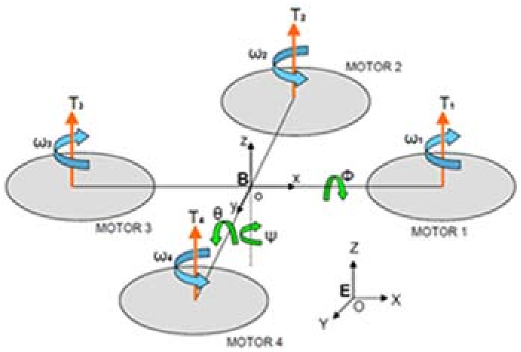

Figure 2: Free body diagram of a quad-rotor helicopter

As shown, only two reference frames are used (the earth fixed frame E, and the body frame B), unlike that of a conventional helicopter which has three. The reason for this is that the rotors of a quad-rotor helicopter are fixed; whereas the main rotor of a conventional helicopter has actuators to control the roll and pitch angles, which moves independent of the fuselage.

A quad-rotor setup is controlled by manipulating thrust forces from individual rotors as well as balancing drag torque. For hovering, all rotors apply a constant thrust force as illustrated in Figure 3(c), thus keeping the aircraft balanced. To control vertical movement, the motor speed is simultaneously increased or decreased, thus having a lower or higher total thrust but still maintaining balance. For attitude control, the yaw angle (ψ) may be controlled by manipulating the torque balance, depending on which direction the aircraft should rotate. The total thrust force still remains balanced, and therefore no altitude change occurs. This can be shown in Figures 3(a) and 3(b). In a similar way, the roll angle (ϕ) and pitch angle (θ) can be manipulated applying differential thrust forces on opposite rotors, as illustrated in Figure 3(d) [9; 10].

Although this may seem simple in theory, practically, there will be many factors which need to be taken into account. One of the greatest challenges will be to achieve stability in an outdoor environment. Especially a disaster area where there will be many obstacles and possibly harsh winds.

III. ROTOR AERODYNAMICS

As with conventional helicopters, most of the aerodynamic significance of quad-rotor helicopters lies within their rotors. The rotors, motors and batteries determine the payload and flight time performance of the aircraft. The rotors, especially, influence the natural dynamics and power efficiency. Research at the Australian National University has shown that an approximate understanding of helicopter rotor performance can be obtained from the momentum theory of rotors [7]. This performance is very important as a search and rescue robot, the rotorcraft will be exposed to harsh environments where it must be able to produce enough thrust force to counter any bursts of external forces applied to it in order for it to stabilise itself. It should also be able to carry the payload of equipment such as cameras, sensors, etc.

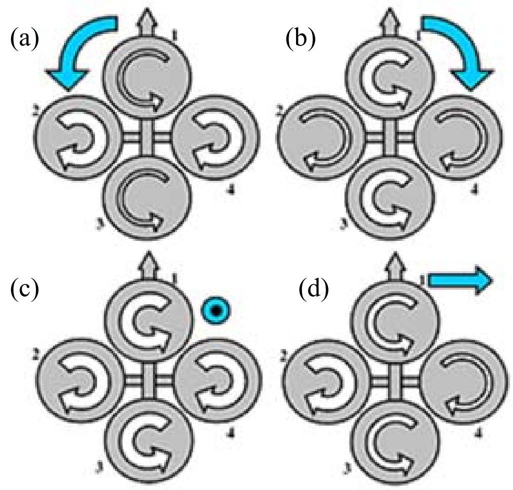

Figure 3: Quad-rotor dynamics, (a) and (b) difference in torque to manipulate the yaw angle (ψ); (c) hovering motion and vertical propulsion due to balanced torques; and (d) difference in thrust to manipulate the pitch angle (θ) the roll angle (ϕ).

Blade element theory is particularly useful for rotor performance. The forces and drag moment developed on a uniform wing are modelled by,

$$F_i = b\omega_i^2 \quad (1)$$

$$\tau_i = d\omega_i^2 \quad (2)$$

Where, F_i is the thrust force produced, τ_i is the drag moment and ω_i is the rotational speed of rotor *i*. The constants

b and d are the thrust and torque constants respectively and can be defined as,

$$b = C_T \rho A R^2 \tag{3}$$

$$d = C_Q \rho A R^3 \tag{4}$$

Where R is the rotor radius, ρ is the density of air and A is the rotor disc area. C_T and C_Q are dimensionless thrust and drag moment coefficients respectively. Smaller rotors require higher speeds and more power than larger rotors for the same thrust [7; 11]. The total thrust of the system is,

$$f = \sum_{i=1}^{4} F_i \tag{5}$$

It is also evident from equation (1) and equation (2) that the thrust force and rotor torque have a direct quadratic dependancy to the angular velocity of the rotor. This is a useful relationship, as the rotor angular velocity can be controlled by the motor and consequently, the thrust force and drag moment are controlled by the motors. Besides the thrust force and the drag moment, which are the predominant aerodynamic forces and moments created by a rotor, there exist three other external aerodynamic influences which act on a propeller [12]. These may be illustrated in Figure 4. The first is called ground effect F_{IGE}. This refers to the variation of the thrust co-efficient when the rotor is in close proximity to the ground. The second influential aerodynamic force occurs as a result of horizontal forces acting on all the blade elements, known as the hub force H, and the third influence, referred to as rolling moment R_M, is the combined moment due to the lift at each point along the radius of the rotor.

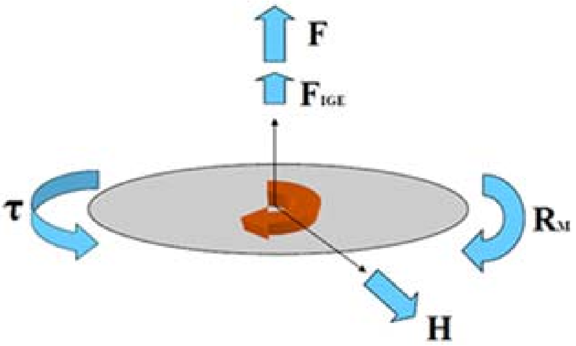

Figure 4: Aerodynamic forces and moments on a rotor

IV. Quad-Rotor Dynamics Modelling

The Euler-Lagrange method was used to model the flight dynamics of the rotorcraft [13; 14]. The model stands under the assumptions that the motor dynamics are relatively fast and may therefore be neglected. Also, the rotor blades are assumed to be perfectly rigid and no blade flapping occurs. External wind forces are also not considered at this stage. The equations of motion are developed in terms of the translational and rotational parameters of the six-degree-of-freedom system, using generalised co-ordinates in a vector q,

$$q = [x \quad y \quad z \quad \phi \quad \theta \quad \psi]^T \tag{6}$$

A Lagrangian was obtained by modelling the energy of the system, where the difference between kinetic and potential energy is taken. Kinetic energy of the system was modelled for both translational and rotational motion. The potential energy of the system was related only to the altitude of the rotorcraft. The Lagrangian, L, can be expressed as,

$$L(q,\dot{q}) = \frac{1}{2} m\left(\dot{x}^2 + \dot{y}^2 + \dot{z}^2\right) + \frac{1}{2}\left(I_{xx}\dot{\phi}^2 + I_{yy}\dot{\theta}^2 + I_{zz}\dot{\psi}^2\right) - mgz \tag{7}$$

Where, m is the total mass of the rotorcraft and g is the acceleration due to gravity. I_{xx}, I_{yy} and I_{zz} represent the mass moment of inertia about the x, y and z axes respectively. For this analysis, the Euler-Lagrange equation with an external generalised force [7] is used.

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}} - \frac{\partial L}{\partial q} = F \tag{8}$$

Where, the force F represents all the external forces acting on the body of the rotorcraft. The only forces acting on the body are those from the rotor. The translational forces are the thrust forces resulting from each rotor, and the rotational forces are due to the drag moment as well as the moment caused by thrust forces from opposite rotors about the centre of gravity. It must be noted that hub force, ground effect and gyro effects were not taken into account, as the model was developed for the purpose of designing a control system around it, and thus should be kept as simple as possible, with only the main effects being considered. Therefore the force is,

$$F = \begin{bmatrix} -f\sin\theta \\ f\sin\phi\cos\theta \\ f\cos\phi\cos\theta \\ (F_{M3} - F_{M1})l \\ (F_{M2} - F_{M4})l \\ \sum_{i=1}^{4}\tau_{Mi} \end{bmatrix} \tag{9}$$

The first three components of the vector F represent the external translational force acting on the rotorcraft in the x, y, and z directions respectively with regards to the earth fixed reference frame, while the last three components of the vector represent the external moments acting on the rotorcraft. This was obtained by translating the body fixed reference frame components into earth fixed reference frame components using the rotation matrix R,

$$R = \begin{bmatrix} \cos\theta\cos\psi & \cos\theta\sin\psi & -\sin\theta \\ \sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi & \sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi & \sin\phi\cos\theta \\ \cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi & \cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi & \cos\phi\cos\theta \end{bmatrix} \tag{10}$$

Thus, the Euler-Lagrange equation, together with equation (9) yields,

$$\begin{bmatrix} m\ddot{x} \\ m\ddot{y} \\ m\ddot{z} \\ I_{xx}\ddot{\phi} + \dot{I}_{xx}\dot{\phi} \\ I_{yy}\ddot{\theta} + \dot{I}_{yy}\dot{\theta} \\ I_{zz}\ddot{\psi} + \dot{I}_{zz}\dot{\psi} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ mg \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} -f\sin\theta \\ f\sin\phi\cos\theta \\ f\cos\phi\cos\theta \\ (F_{M3} - F_{M1})l \\ (F_{M2} - F_{M4})l \\ \sum_{i=1}^{4}\tau_{Mi} \end{bmatrix} \tag{11}$$

Therefore the equations of motion was determined in the form of the acceleration vector,

$$\ddot{q} = \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \\ \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} -\dfrac{f}{m}\sin\theta \\ \dfrac{f}{m}\sin\phi\cos\theta \\ \dfrac{f}{m}\cos\phi\cos\theta - g \\ \dfrac{1}{I_{xx}}\left((F_{M3} - F_{M1})l - \dot{I}_{xx}\dot{\phi}\right) \\ \dfrac{1}{I_{yy}}\left((F_{M2} - F_{M4})l - \dot{I}_{yy}\dot{\theta}\right) \\ \dfrac{1}{I_{zz}}\left(\sum_{i=1}^{4}\tau_{Mi} - \dot{I}_{zz}\dot{\psi}\right) \end{bmatrix}. \qquad (12)$$

V. QUAD-ROTOR CONTROL

Attitude (ϕ, θ and ψ) and altitude (z) had to be taken into account in order to stabilise the rotorcraft. Position (x and y) is dependent on the roll and pitch angle orientation. Thus, the position can be controlled via attitude control. Therefore, the system is an under actuated one, having six degrees of freedom and only four control inputs.

These parameters are related using the relationship described in equation (1) and equation (2). As discussed above, by controlling the rotational speed of the motors, one can in actual fact control the rotorcraft. Therefore, the following are chosen for control inputs based on works conducted at Lausanne and Stanford University,

$$u_1 = b\left(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2\right) \qquad (13)$$

$$u_2 = b\left(\omega_3^2 - \omega_1^2\right)l \qquad (14)$$

$$u_3 = b\left(\omega_2^2 - \omega_4^2\right)l \qquad (15)$$

$$u_4 = d\left(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2\right) \qquad (16)$$

Where, u_1, u_2, u_3 and u_4 are control inputs for altitude, roll, pitch and yaw respectively [15; 6]. By taking into account the motion in the hovering state the system can be simplified to a linear and uncoupled state. This was facilitated by utilising a linear PD controller. The control inputs described in equation (13) to equation (16) may be represented in vector form,

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = \begin{bmatrix} b & b & b & b \\ -bL & 0 & bL & 0 \\ 0 & bL & 0 & -bL \\ d & -d & d & -d \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix} \qquad (17)$$

From rearranging equation (17), the desired motor speed may be computed so that it can then be sent to the motor controllers. Where,

$$\begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix} = \begin{bmatrix} \dfrac{1}{4b} & -\dfrac{1}{2bL} & 0 & \dfrac{1}{4d} \\ \dfrac{1}{4b} & 0 & \dfrac{1}{2bL} & -\dfrac{1}{4d} \\ \dfrac{1}{4b} & \dfrac{1}{2bL} & 0 & \dfrac{1}{4d} \\ \dfrac{1}{4b} & 0 & -\dfrac{1}{2bL} & -\dfrac{1}{4d} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} \qquad (18)$$

The columns of the matrix in equation (18) correspond to each control input, and the rows correspond to the square of the rotational speed of each motor. The computation of the square root of each row must be executed before the values can be sent to the controller. There are four feedback control loops (Figure 5) which must be implemented simultaneously, which for a PD controller, takes the form,

$$U = k_p(\text{proportional error}) + k_d(\text{derivative error})$$

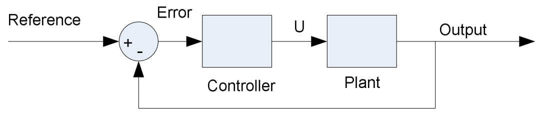

Figure 5: Feedback control loop

The PD controllers for altitude, roll, pitch and yaw respectively are [16],

$$U_1 = k_{p_{ALT}}\left(y_{ref} - y\right) + k_{d_{ALT}}\left(\dot{y}_{ref} - \dot{y}\right) \qquad (19)$$

$$U_2 = k_{p_{ROLL}}\left(\phi_{ref} - \phi\right) + k_{d_{ROLL}}\left(\dot{\phi}_{ref} - \dot{\phi}\right) \qquad (20)$$

$$U_3 = k_{p_{PITCH}}\left(\theta_{ref} - \theta\right) + k_{d_{PITCH}}\left(\dot{\theta}_{ref} - \dot{\theta}\right) \qquad (21)$$

$$U_4 = k_{p_{YAW}}\left(\psi_{ref} - \psi\right) + k_{d_{YAW}}\left(\dot{\psi}_{ref} - \dot{\psi}\right). \qquad (22)$$

Where, k_p and k_d are the proportional and differential controller gains respectively. The values were manually tuned for optimal controller performance. These were different for altitude, roll, pitch and yaw. The components with subscript *ref* are user defined reference values which were compared to feedback output values to determine the error. These feedback control loops will be implemented using a microcontroller.

VI. ELECTRONIC SYSTEM INTEGRATION

The electronic system integration is presented in Figure 6 [17]. The key components are a microcontroller, electronic speed controllers (ESC's), an attitude and heading reference system (AHRS), a communication interface between the UAV and the user, a vision system and suitable power distribution.

The microcontroller receives data from the AHRS, vision system and communication interface, which is then processed so that orders can be executed to the ESC's to control the motors. The AHRS measures the inertial movements of the UAV. It comprises of an inertial measurement unit (IMU) and a global positioning system (GPS).

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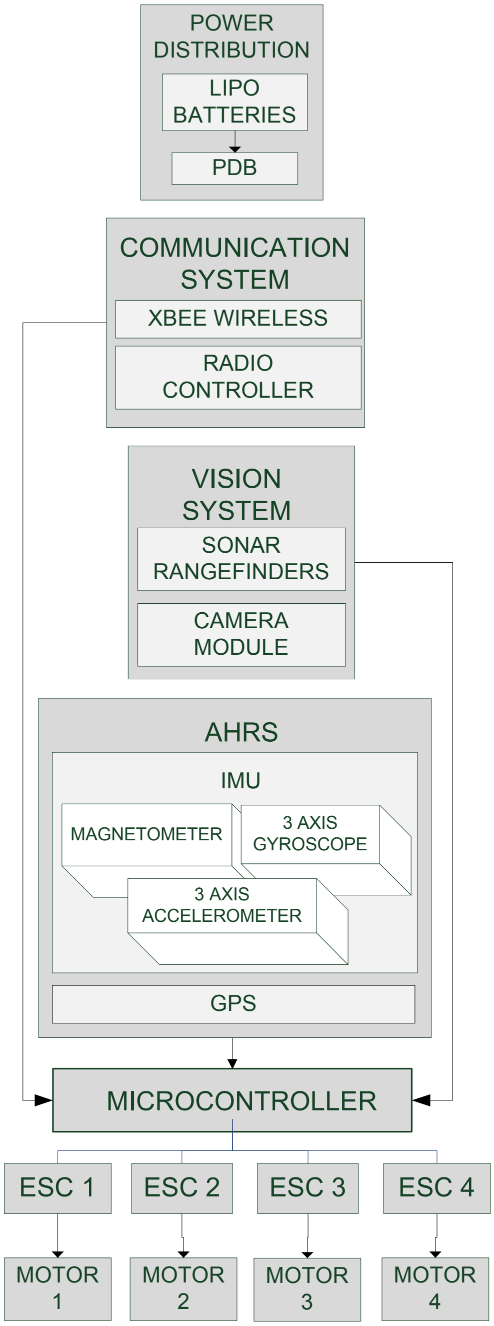

Figure 6: Electronic system integration

The IMU contains 3-axis accelerometers and gyroscopes to measure translational and rotational body motion respectively. It also consists of a magnetometer, which acts as a digital compass and determines the heading of the UAV. The GPS is used to determine the location of the rotorcraft. Another component which could be added to the AHRS is a pressure sensor to measure altitude. However, these sensors are only suitable for high altitude applications and therefore, it would be more appropriate to use rangefinder to determine the altitude of the UAV. These rangefinders could be either sonar or laser and form as part of the vision system. The vision system is used to detect possible obstacles in the path of the rotorcraft, as well as transfer visual data to the user via the communication interface. Lithium Polymer (LiPo) batteries are the most suitable power source in such applications due to their lightweight properties. Power is distributed to all the electronics in the system via a power distribution board (PDB).

VII. MECHANICAL STRUCTURE

The structure of a quad-rotor helicopter is a simple one, basically comprising of four rotors attached at the ends of a symmetric cross. A proposed structure is presented in figure 1. The key features that should be taken into account in such a structure are symmetry and rigidity. To avoid unstable flight, the structure should be as rigid as possible, while maintaining the lightest possible weight. The best way to achieve this is through lightweight alloys or composites [7]. Symmetry is also of great importance for stability. The centre of gravity (COG) should be kept as close to the middle of the rotorcraft as possible, as depicted in figure 3.

VIII. NUMERICAL MODEL SIMULATION

The mathematical model described by equation (12) was simulated on MATLAB® Simulink®. The simulation comprised of several inputs and outputs parameters which were obtained from the physical model. The inputs are motor speed and basic system parameters (listed in Table I). The outputs are the thrust, torque, q , $\dot{q}$ and $\ddot{q}$. The thrust forces and rotor torques were modelled around equation (1) and equation (2).

TABLE I. CONSTANT MODEL PARAMETERS

$\boldsymbol{m}$	kg	4
$\boldsymbol{l}$	m	0.3
$\boldsymbol{R}$	m	0.15
$\boldsymbol{\rho}$	kg/m^3	1.204
$\boldsymbol{C_T}$	-	0.5
$\boldsymbol{C_Q}$	-	0.08

Sample input data for the simulation is specified in Table II. These simulations were strategically chosen to investigate lift, yawing, pitching and rolling motion respectively. First, they were conducted with no control systems implemented, and then the effects of the control system were investigated, using the same input data. Figure 7 depicts the type of results that were obtained, where the projectile of the UAV was plotted.

TABLE II. SAMPLE INPUT DATA

Simulation Number	**Motor Speed (rad/s)**			
	Motor 1 (CW)	**Motor 2 (CCW)**	**Motor 3 (CW)**	**Motor 4 (CCW)**
1	230	229	230	231

It can be seen that the miniscule difference in motor speed, still makes a considerable difference in translational deviation. The simulation was run for a time of 60 seconds without the implementation of control and then set to hold. From this observation, one can really perceive the importance of motor control in such applications.

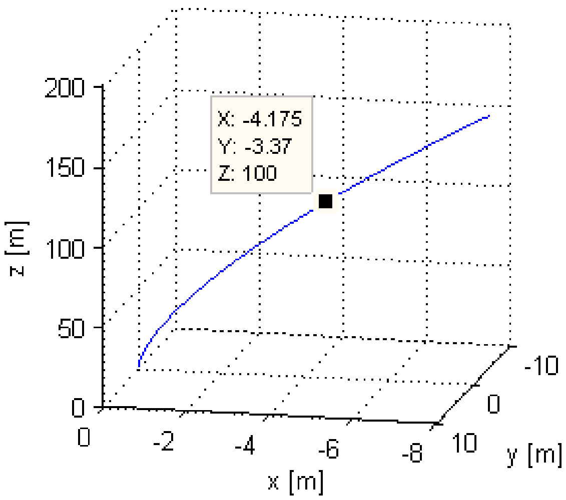

Figure 7: Plot of the translational projectile path of the quadrotor

IX. CONCLUSION

It is clear that the quad-rotor helicopter is a dynamically complex system, which requires a great amount of control in order for it to function as a search and rescue UAV. However, as shown, this is not an impossible feat, as there are methods in which this can be accomplished. The detailed approach taken, presented a system that was simplified drastically to accommodate the implementation of a linear feedback control system. This was ideal, as it allows for simple computing. Therefore, all data processing can be implemented via the onboard microprocessor. Using the simulated mathematical model obtained, the microchip can be coded for numerous stability applications.

The mechanical efficiency of the rotorcraft is of equal importance. The performance of the UAV is dependent on both effective and highly responsive motor control as well as aerodynamic efficiency. This relationship, which requires the seamless combination of mechanical efficiency, electronic implementation and computing, makes the quadrotor UAV a dynamic mechatronic system.

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