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Design and Dynamic Modeling of a Rotary Wing Aircraft with Morphing Capabilities

Christoph Hintz, Cody Torno†, and Luis Rodolfo García Carrillo

Abstract— **The aim of this paper is to introduce a multi-rotorcraft with morphing capabilities. Unlike conventional multicopters whose body fly in a horizontal configuration, the proposed platform is be able to rotate its body into a vertical flying mode configuration. The research presented considers an 8-engine vehicle that is able to fly with 4-engines in case of rotor failure. The vertical flight mode is also intended for enabling navigation through narrow areas where conventional helicopter are too big to operate properly. Also, the convertible flight functionality allows saving battery if necessary. The dynamic model of the vehicle while performing in horizontal and vertical configurations is presented. An animated model shows the functionality of the vehicle while performing the transition maneuver.**

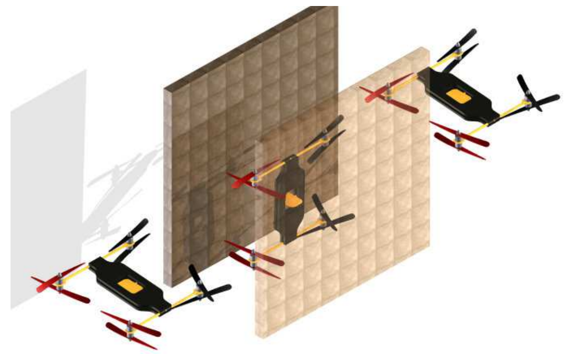

Fig. 1. The rotary wing multicopter morphing vehicle going through a narrow space.

I. Introduction

Unmanned Aircraft System (UAS) development represents a fast growing research area, because of its widely field of applications. These systems are used, among others in sport events video and photography, especially extreme sports. Highway monitoring is another area where UAS have found application, since this activity is important to secure roads, bridges and alerting of traffic jams or crashes. In addition, disaster relief has a wide range of applications for UAS. There are many more applications in the civil domain, such as atmospheric research, wildlife research, environmental compliances, etc. [1]. On the other hand, military is a field were UAS are used in diverse tasks such as impact and disaster effects management, aerial reconnaissance, search and rescue operations, etc.

Rotary wing multi-rotorcraft research represents a very important area of study. Rotary wing multicopters are able to hover, and their design is very simple in comparison to other fixed wing or conventional helicopters UAS. Rotary wings are able to change their attitude angles by changing speed of the rotors, this eliminates the necessity of a swashplate. There are also a lot of platforms like the ARDrone® that are very user-friendly [2]. The 3DRobotics® UAS platforms are very appropriate for creating user defined configurations [3], so that every owner has the chance to remove or add software and components as required. On of the drawbacks of these UAS platforms is that they suffer from the possibility of rotor failures. A non conventional multi-rotorcraft UAS with enhanced capabilities, on the other hand, could enable the possibility to operate properly even in cases where some of the engines fail [4].

The convertible or morphing multi-rotorcraft vehicle proposed in this paper is a very flexible platform which aims at overcoming these challenge. The platform can fly with: (i) 8 rotors under normal working conditions, (ii) 4 rotors if engine failure occurs, (iii) 2 rotors, enabling only a limited flight mode that can be used for sending the vehicle back to the ground control station in case of numerous engine damage. The proposed vehicle is a very powerful platform when working with a total of 8 engines, however, if energy is a main concern the vehicle can change its shape into a vertical flying mode, in order to fly or hover with 4 engines only. Furthermore, the vertical flight mode gives the vehicle the possibility to evolve in narrow places, therefore, this characteristic makes the vehicle more useful in, for example, search and rescue operations in urban areas or indoors.

The multi-rotorcraft rotary wing vehicle with morphing capabilities is similar to a quad rotorcraft platform equipped with a pair of counter-rotating engines at the end of each arm, making a total of 8 engines. As can be seen in Figure 2, the body of the multicopter presents an "H" shape, i.e., it has 2 main arms. At the end of each arm the vehicle has a rotary system that connects the rotors, making it possible to put the multirotor's body in a vertical or horizontal position. This configuration of just 2 arms instead of 4 makes the setup, configuration, and programming of the rotary function easier and reduces the possibility of failure or mistakes. The rotation movent converting the vehicle from a conventional miltirotor to a vertical flyer is controlled by only one servo located in the rotorcraft body, which is connected to the

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C. Hintz, C. Torno, and L.R. García Carrillo are with the Unmanned Systems Laboratory, School of Engineering and Computing Sciences, Texas A&M University - Corpus Christi, Corpus Christi, TX 78412 USA. e-mail: {chintz, ctorno}@islander.tamucc.edu, L.R. García Carrillo e-mail: luis.garcia@tamucc.edu

rotary engine connectors by means a gear system. The gear system is used because an ordinary servo has a maximum rotation of 135°. Therefore, to enable a "two sided" (clockwise or counterclockwise) convertible capability possible, a gear system of a 1:2 ratio is required in order to obtain a movement of 180° and more. The proposed vehicle has a group of inertial sensors placed on top of a rotary base, which is located exactly at the vehicle's center of gravity. The base is connected with the rotorcraft's body through a rotor's shaft, with the main objective of holding the base in a horizontal position the whole time. This characteristic is required because the group of inertial sensors could be confused during the morphing procedure.

The morphing characteristics of the vehicle supports the objective of making the multicopter robust against rotor failures. In fact, it is not important which rotor fails; the UAS is able to rotate its body to clockwise or counterclockwise, leaving the the group of working rotors on top. Furthermore, the convertible characteristic also ensures that the proposed platform is able to fly through narrow spaces. These previously mentioned functionalities enable the UAS to operate with 4 engines in the vertical mode, making it possible to save energy during hover and enabling longer flights. In addition, in case of extreme rotor failure it would be possible to operate the system with only two upper rotors, making a return to home maneuver possible.

The organization of this paper is as follows. Section II describes some of the related work. Section III the dynamic model of the morphing platform is described. Section V provides more details about the design of the vehicle and presents some animated models. Details about the vehicle's functionality are provided in Section IV. Some simulations and a link to a video showing the vehicle functionality under a simulated environment are provided in Section VI. The paper conclusions are in Section VII.

II. Related work

Several research and development has been devoted to the development of UAS that can change its flying configuration. In general, these works have presented vehicles equipped with fixed wings and tilting rotors, vehicles equipped with wings that rotate, and multicopters with tilting rotors.

The work of Kendoul, et al [6], which developed an autonomous aircraft with tilting rotors and fixed wings. The proposed vehicle is a small tiltrotor aircraft with reduced number of rotors that can go from vertical flight mode in airplane mode. It has two propellers that are able to redirect laterally and longitudinally. Notarstefano and Hauser [7] on the other hand presented a tilting rotor aircraft with only one propeller and fixed wings that enables vertical to horizontal flight. The authors provide details concerning the relationships between speed, angle of rotor, and flight path of the vehicle. The proposed vehicle uses gimbal motors to rotate the propeller about the two axes in the horizontal plane. An interesting model is presented by Russo et al [8], describing the entire range of operation of their Longitudinal Vectored Thrust (VTOL) aircraft. The authors presented a full transition from hover to forward flight. Partovi et al [9] presented a vehicle that hast 3 fixed propellers and one rotary propeller in its back. This hybrid aircraft uses its 3 horizontal propellers to control the altitude, while the fourth rotary back propeller is implemented to control the airplane flight. During the helicopter flying mode mode the rear motor is horizontal, supporting and stabilizing the vertical flight. A more conventional design is presented by Amiri et al [10], who created a helicopter-looking vehicle with 2 rotary propellers. The authors designed a Lift-Fan Oblique Active Tilting control mechanism to ensure a high speed cruise flight combined with a vertical takeoff/landing capability.

Oner et al. [11] presented a UAS with a tilt wing and rotor mechanism. The vehicle has both a horizontal and a vertical flight mode. The platform has four rotors that are mounted on four wings that rotate. The authors reported a flight time of 20 minutes in vertical flight mode, and a 1.5 to 2 hours in horizontal flight mode at a speed of 40 to 70 km/h. The authors further improved their results in [12], presenting linear and nonlinear controllers. The authors built their vehicle with carbon composite material to make it strong and light, enabling a successful experimental tests. The authors continued their work and tested the vehicle in wind tunnels to perfect the aerodynamic design [13]. They presented experimental results of their developed platform in [14].

Vargas-Clara and Redkar [15] designed a fixed rotor vehicle with rotary wings that has its propellers on the top of the wings. To go in horizontal flight mode, the vehicle drops its hight, rotate its wings, and flies with the propeller in the back.

A. Multicopters with Tilting Rotors

Recently, several research studies have been devoted to improve multicopter by changing the design of conventional platforms. Ryll et al [16] designed a quad rotorcraft with 8 control inputs with 6 degrees of freedom, instead of 4 control inputs with 6 degrees of freedom like a conventional quadcopter. They designed a multicopter with 4 engines, where every rotor is able to tilt about its the pitch and roll axis of the platform. This gives the quad rotorcraft additional functionality, so that the flexibility of the vehicle increases. This also allows optimizing energy, increasing the vehicle's efficiency. Segui-Gasco et al. [5] designed a model to improve the performance and fault-tolerance of conventional quad rotors. This design offers a wider range of control torques by combining gyroscopic torques, thrust vectoring and differential thrusting using dual axes tilting. Their paper describes a way to make it possible to fly with one rotor failure. They also present a prototype and a mathematical model of the platform.

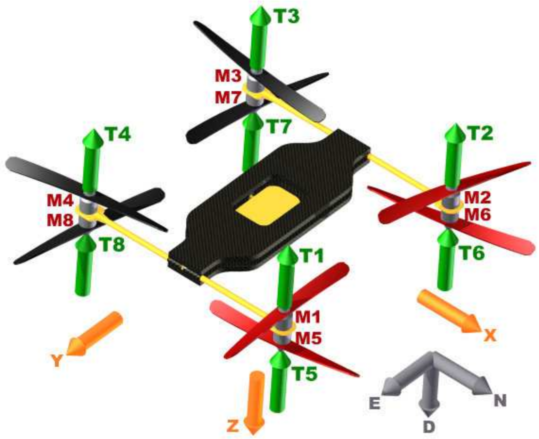

Fig. 2. Representation of the proposed multicopter vehicle in a North-East-Down (NED) frame. The gray arrows represent the NED frame, while the orange arrows represent the (X,Y,Z) body fixed frame. Rotors are labeled from 1 to 8, and have associated thrusts represented by green arrows.

III. DYNAMIC MODEL OF THE MORPHING PLATFORM

Research has also been done concerning the dynamic model of multi-rotorcraft flying machines [17], which is mostly related to the conventional flight, or horizontal body position flying mode. In this section a dynamic model of the a "H-type" flying configuration is presented. This configuration considers two frontal motor and two rear motors, ans is similar to the similar to the "X-type" flying configuration presented in [18].

A. Dynamic Model of the Vehicle under a Conventional Horizontal Configuration

This paper assumes that the nonlinear dynamics are obtained in North-East-Down NED. The inertial reference of the body frame is represented by X,Y,Z, see Figure 2. We assume that, while evolving in a conventional horizontal flight, the multicopter will have the same characteristics that the vehilce presented in [18].

The platform dynamical model can be represented by the following state equations

$$m\ddot{x} = -u(\cos(\psi)\sin(\theta)\cos(\phi) + \sin(\psi)\sin(\phi)) \quad (1)$$

$$m\ddot{y} = -u(\sin(\psi)\sin(\theta)\cos(\phi) - \cos(\psi)\sin(\phi)) \quad (2)$$

$$m\ddot{z} = -u(\cos(\theta)\cos(\phi) + mg) \quad (3)$$

$$\ddot{\psi} = \tilde{\tau}_\psi \quad (4)$$

$$\ddot{\theta} = \tilde{\tau}_\theta \quad (5)$$

$$\ddot{\phi} = \tilde{\tau}_\phi \quad (6)$$

where m is the vehicle's mass, u a control variable, g is gravity, and (ϕ, θ, ψ) represent the roll, pitch, and yaw states of the platform [18].

The dynamic model of the proposed 8-rotors multicopter has 4 front rotors and 4 rear rotors. M_1, M_3, M_6, and M_8 will rotate counterclockwise while M_2, M_4, M_5, and M_7 will rotate clockwise. Each thrust can be modeled as $\tau_i = C_M m_i^2$. In this case C_M is a constant value, depending on each rotor characteristic an w_i denotes the speed of the rotor i [19]. It is also assumed that the generated torque τ_i for each rotor is proportional to its lift force, so that $\tau_i = C_M T_i$. Taking all this assumptions into account, the general torques can be represented as

$$\begin{bmatrix} \tau_\psi \\ \tau_\theta \\ \tau_\phi \end{bmatrix} = \mathrm{C}_{M_1} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ T_7 \\ T_8 \end{bmatrix} \quad (7)$$

where C_{M_1} is a 3×8 matrix having the following form

$$\mathrm{C}_{M_1} = \begin{bmatrix} -C_M & C_M & -C_M & C_M & C_M & -C_M & C_M & -C_M \\ -l & -l & l & l & -l & -l & l & l \\ -l & l & l & -l & -l & l & l & -l \end{bmatrix} \quad (8)$$

In this previous matrix, l represents the distance between the mass and the center of the rotor to and the vehicle's center of gravity.

B. Vehicle's Torques under a Vertical Flight Configuration

For the vertical flight configuration, two different two different situations can occur. The first configuration occurs when T_1, T_2, T_5, and T_6 are the only motors operating. This happens when the vehicle's body has been rotated clockwise (when seeing the vehicle from the front). On the other hand, the second configuration occurs when T_3, T_4, T_7, and T_8 are the only motors operating. This happens when the vehicle's body has been rotated counterclockwise (when seeing the vehicle from the front).

From the vehicle's dynamic model under a conventional horizontal flight configuration, the general torques during the first configuration of vertical flight mode are represented as

$$\begin{bmatrix} \tau_\psi \\ \tau_\theta \end{bmatrix} = \begin{bmatrix} -C_M & C_M & C_M & -C_M \\ -l & l & -l & l \end{bmatrix} \begin{bmatrix} T_1 \\ T_4 \\ T_5 \\ T_8 \end{bmatrix} \quad (9)$$

For the second vertical flight configuration, i.e. the vehicle has rotated counterclockwise, the general torques are represented as

$$\begin{bmatrix} \tau_\psi \\ \tau_\theta \end{bmatrix} = \begin{bmatrix} -C_M & C_M & C_M & -C_M \\ -l & l & -l & l \end{bmatrix} \begin{bmatrix} T_2 \\ T_3 \\ T_6 \\ T_7 \end{bmatrix} \quad (10)$$

From equations (9) and (10), it is possible to observe that, during the vertical flight configuration, there is no control of the roll angle ϕ, making it impossible to directly displace the vehicle in the lateral direction. However, if a motion in the inertial East direction is required, the vehicle can stabilize first its heading angle in order to decide a direction to go, and then, a forward motion by means of a pitch angle torque will produce the desired displacement. In order to make the vehicle more maneuverable, sidewards flight could be enabled if an additional servo motor is added to the upward rotors. This additional servo has to be rotated about the roll angle, enabling a lateral motion directly.

C. Vehicle's Torques during the Transition Part

For the transition part, i.e. when the vehicle changes from horizontal flight to vertical flight, the torques of the dynamic model are similar to the horizontal flight part; all 8 rotors will be used. During this procedure, the three torques will be represented as

$$\begin{bmatrix} \tau_\psi \\ \tau_\theta \\ \tau_\phi \end{bmatrix} = \mathrm{C}_{M_2} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ T_7 \\ T_8 \end{bmatrix} \tag{11}$$

where C_{M_2} is a 3×8 matrix with the following form

$$\mathrm{C}_{M_2} = \begin{bmatrix} -C_M & C_M & -C_M & C_M & C_M & -C_M & C_M & -C_M \\ -l & -l & l & l & -l & -l & l & l \\ -l\mathrm{C}_\gamma & l\mathrm{C}_\gamma & l\mathrm{C}_\gamma & -l\mathrm{C}_\gamma & -l\mathrm{C}_\gamma & l\mathrm{C}_\gamma & l\mathrm{C}_\gamma & -l\mathrm{C}_\gamma \end{bmatrix}$$

where C_* stands for cos(*), and γ represents the angle the platform rotates in order to achieve a vertical flight configuration.

IV. Generalities about the Vehicle's Functionality

The proposed platform is designed to fly in a conventional horizontal flight configuration, but also is designed to be able to convert into a vertical flight configuration. As an example of the potential applications where this funcionality might be useful, Figure 1 shows the platform going through a narrow corridor. In order to accomplish such task, the vehicle has to rotate its body 90° clockwise or counterclockwise, which reduces its horizontal dimension and enables accessing narrow spaces.

The multi-rotorcraft performing a conventional horizontal body flight is shown in Figure 3. The front axis is identified by means of the location of the four red propellers. In this configuration the angle between the inertial sensors base (the yellow central base shown in the picture) and the platform body will be zero.

The morphing or conversion stage is shown in Figure 4. The image shows that the middle yellow base is always horizontal during this process. The motors are also moving at unison with the yellow base, therefore, they are always pointing upwards in such a way that all the forces generated will be downward. The system that makes it possible to have the motors upwards is shown in Figure 5. It can be seen that the gear system is used to control the motion of the rotors by means of a single servo. The servo will be placed in the middle part of the multicopter body. The gear system will have a ratio from 1:2.

Fig. 3. A model of the morphing multicopter performing in a conventional horizontal body flight mode.

Fig. 4. A model of the morphing multicopter platform during the conversion or morphing stage. Notice that the middle yellow base is always horizontal during the morphing stage. The motors are also upwards during this process.

Figure 6 shows the vehicle evolving in the vertical flight mode. In this configuration, the 4 rotors located at the bottom will be turned off, so that the vehicle will remain as stable as possible in its position. Notice that the middle base is perpendicular to the body, keeping the inertial sensors in the appropriate position for operation.

V. DESIGN OF THE MORPHING PLATFORM

The proposed convertible vehicle has a "H-type" shape. The rotorcraft has a hollow body composed by two man plates separated by a distance of 5 cm. This hollow body will provide enough space for hosting sensors, electric and electronic parts, and the servo motor with its corresponding gear system. The reason to put all these components inside the body is to protect them from damage if a crash occurs. The middle yellow base carrying the inertial sensors will have a similar hollow body characteristic. The servo motor will keep this plate in a horizontal direction during horizontal, vertical, and transition stage flights. This is important since it is required to place different sensors and inertial systems on the plate, so that they are not getting wrong or misleading readings during the morphing maneuver.

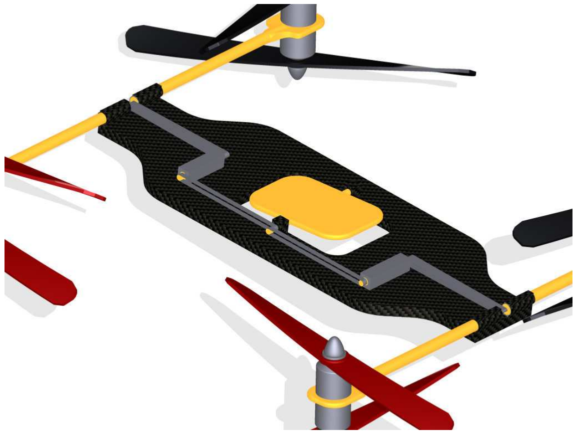

Fig. 5. A closer model of the servo and gearsystem of the Morphing Quad Rotorcraft .

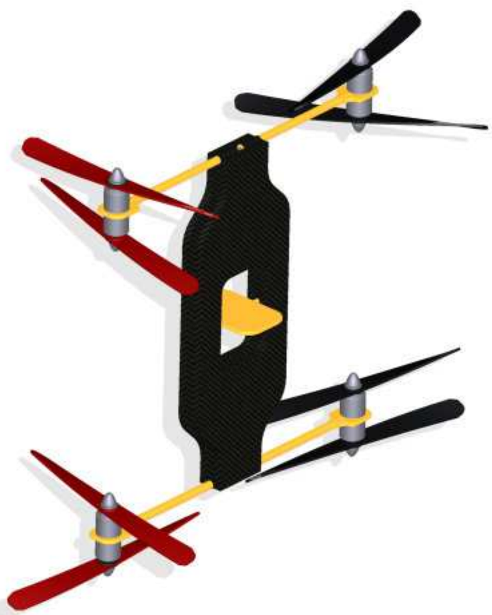

Fig. 6. The morphing multicopter during vertical flight mode. In order to keep the vehicle as stable as possible, the 4 rotors located at the bottom are turned off. The middle yellow base is perpendicular to the body, keeping the inertial sensors in the appropriate position for operation.

The morphing multi-rotorcraft vehicle has four engine pairs located at the end of each arm, therefore, the total number of engines is 8. Each engine pair rotates contrariwise. This makes the vehicle very powerful and stable. During operation, the vehicle's propellers are always aligned with the central plate, as can be seen in Figure 3 through Figure 6. The propellers' titling is controlled by a servo that is placed inside the hollow body of the vehicle. The servo system is shown in Figure 5. This servo is connected to the rotary wing connectors by means of a gear system whose ratio is 1:2. This ratio is important for the vehicle functionality because it enables an enhanced degree of freedom of 270°. In fact, it is required, at least, 180° of rotational motion in order to have the possibility to turn the vehicle clockwise and counterclockwise from its horizontal body position to

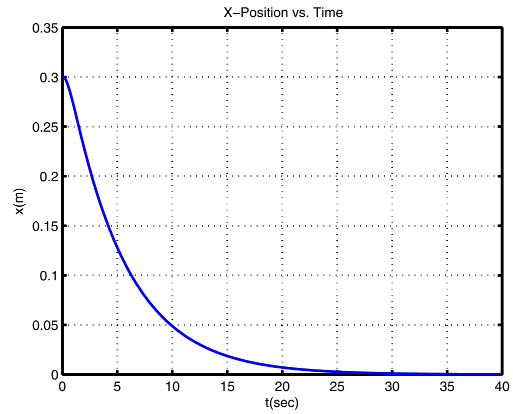

Fig. 7. x-Position vs. time Graph.

its vertical body position. There will be only one servo that is going to be connected with both rotary wing connectors to reduce the possibility of failure.

The vehicle H shape and size is planned to be of around 55 cm from rotor to rotor. The body will be constructed out of carbon fiber in order to reduce the weight of the multicopter platform. The hollow body will be made out of two parts separated by spacers. The yellow middle base is a hollow part of carbon fiber too. The hardware parts and connections between the middle base and the body are currently being designed in Inventor [20] with the purpose of generating proprietary 3D-printed parts. The eight propellers has been chosen of 11X4.7 type, made of carbon fiber to make them more robust than the conventional plastic propellers. The rotary connections between the body and the engines will be aluminum parts, since this material is relatively light and easy to manufacture. The engines will be placed at the end of the platform's arms on a carbon plate. The motors will be 850Kv brushless.

VI. Simulations

Simulations of the proposed vehicle dynamics i.e. equations (1) through (3) has been obtained from models created in Matlab/Simulink. The simulations presented here correspond to the stabilization of the vehicle during the horizontal body flight configuration, by means of a PID-controller. The initial conditions that used for the simulation are x=0.3m, y=0.5m and z=0m. Desired values correspond to x=0m, y=0m and z=1m. The system is simulated for 40 seconds. Figure 7 shows that the x-position approaches zero. The same behaviour is observed for the y dynamic in Figure 8. Figure 9 shows the altitude dynamic approaching the reference value of one. Figure 10, Figure 11 and Figure 12 show the attitude behaviour of the vehicle while going from the initial conditions to the reference.

A synthetic environment showing the platform functionality is provided at http://youtu.be/TKai7brjUuk

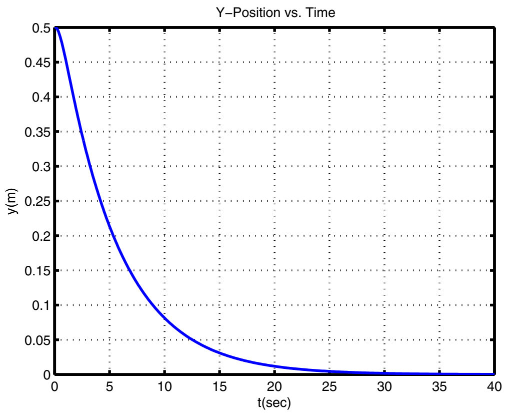

Fig. 8. y-Position vs. time Graph.

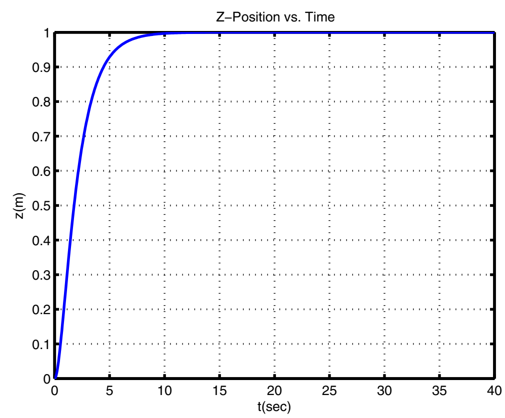

Fig. 9. z-Position vs. time Graph.

VII. Conclusions

This paper introduced a new rotary wing multicopter aircraft configuration enhanced with morphing capabilities. The proposed multicopter platform has a “H-type” shape, and is be able to rotate its body into a vertical flight configuration. The multicopter presented represents an 8-engine vehicle that is able to fly with 4-engines in case of rotor failure. The vertical flight mode is also intended for enabling navigation through narrow areas unaccessible for conventional multicopter platforms flying in a horizontal configuration. This functionality also allows saving battery if necessary. The dynamic model of the vehicle while performing in horizontal and vertical configurations was presented. An animated model showing the functionality of the vehicle while performing the morphing task was also included.

Future work will consider detailed dynamic models of the vehicle during its vertical and morphing configurations. A unified controller for the vertical, transition, and horizontal body flight modes will also be designed. The construction of the vehicle is currently under development, and experimental applications will be performed once the platform is ready.

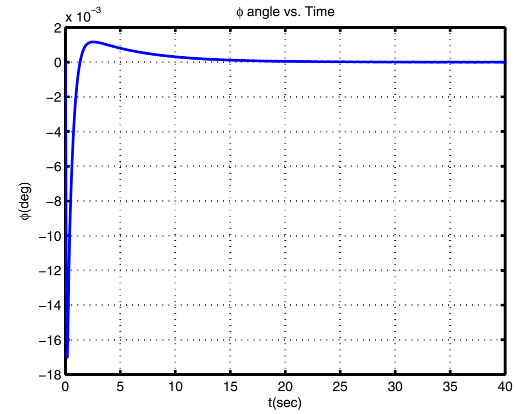

Fig. 10. Roll-Position vs. time Graph.

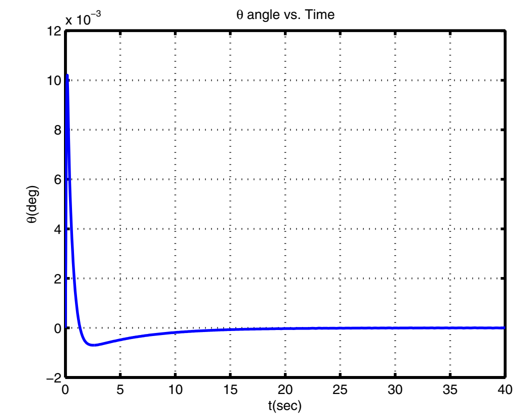

Fig. 11. Pitch-Position vs. time Graph.

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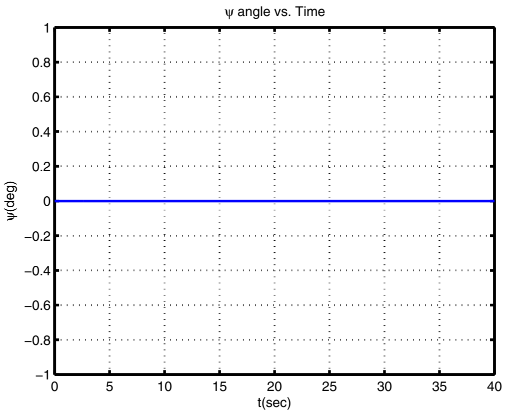

Fig. 12. Yaw-Position vs. time Graph.

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