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Simulation of motions of a 6DoF unmanned aerial vehicle from the mathematical model in free space

Kelechi Kingsley Igbokwe [1], James Eke [2] and Patrick Uche Okafor [2,*]

[1] *Department of Physics/Electronics, Abia State Polytechnic, Aba, Abia State, Nigeria.*
[2] *Department of Electrical/Electronics, Enugu State University of Science and Technology, Enugu State, Nigeria.*

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Abstract

This work prepares a smooth playing ground to modeling and simulation of a Collision Avoidance for Cooperative UAVs with Rolling Optimization Algorithm (ROA) Based on Predictive State Space (PSS) technique using Matlab, Simulink and Aerospace toolboxes of MathsWork. The methodological approach adopted is Computer Aided Software Engineering and to have handle collisions and maneuvers in a mathematical way, normal simulation of the trajectory of both the UAV and obstacles is defined by geometric approach. The goal of the work is to develop a mathematical model of a six degree of freedom (6DoF) of unmanned aerial vehicle (UAV) in free space for further modeling and simulation of a collision avoidance for cooperative UAVs with the required specifications. The motion (modeling of mathematical parameters like velocity, position, body rotational rate and Euler angles) of the 6DoF aircraft was determined by coordinate systems which allow the aircraft's position and orientation in spaceto be kept tracked. The discrete form of the developed model for simulation was achieved using appropriate transfer functions. The development of the mathematical model will enable the development of an artificial NN model predictive controller (MPC) that can handle the nonlinearities associated with the UAV based on PSS technique.

Keywords: UAV; Mathematical Model; Simulation; Coordinate System; Motion Platform

1. Introduction

Unmanned aerial vehicles (UAV) is simply and coincidely regarded as an automated aircraft or an aircraft with no pilot onboard to control it. In numerous conditions, it is identical to Unmanned aerial system (UAS). Although clarifications have been made from lots of aviation bodies to specify that clear the differences between the two. According to [1], a UAV is considered a device used for flight that has no pilot, including all classes of airplanes, helicopters, airships, and translational balloons. The classification of a UAS is comprised of an unmanned vehicle, as well as encompassing the ground control station, communication links, and launch retrieval systems [1] [2]. Six degree of freedom (6DoF) refers to the freedom of movement of rigid body in three-dimensional space.

The need for unmanned aerial vehicles (UAV) is increasing exponentially by the day due to their increasing application in the aerospace industries for civilian and military operations. The choice of UAVs for these operations is as a result of their ability to complete dangerous tasks in unfriendly environments [2].

On the other hand, unmanned aerial vehicles have the potential to offer various capabilities for military and civilian applications because of their low-cost, high-autonomy, super-flexibility, and especially absence of human risk[10]. With technological developments in dynamics [3], navigation [4], and sensors [5], many more civilian applications have been realized for unmanned aerial vehicles, such as aerial photography, search and rescue,surveillanceetc.Among these

*Corresponding author: Okafor Patrick Uche

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applications with multiple UAVs, collision with each other is the most critical envisaged technical problem in the increasingly dense airspace as reported by Tianyuan and co-authors [6].

The goal of this research is to develop mathematical model of a six degree of freedom (6DoF) unmanned aerial vehicle using computer aided software engineering approach in developing mathematical model of the UAV in free space and, hence, typical collisions and maneuvers in a mathematical way and normal simulation of the trajectory of both the UAV and obstacles is defined by geometric approach.

2. Challenge of UAVs

The general opinion for cooperative UAVs is the arising speculation that more than a few unmanned aerial vehicles are flying from different locations to their targetted destinations. Each UAV tends to apply the shortest route. Apparently, there are chances that collisions might occur if all of them choose the shortest route. Operations of these UAVs in civil airspace are restricted by aviation laws which required absolute compliance with rules and obligations that apply for manned aircraft [7].

3. The Modelling Approach

This articulated research employed a computer aided software engineering approach in developing mathematical model of the UAV in free space. From the specification of study requirement, the first step which is to realize an effective characterization/development of UAV in free space is to develop a mathematical model. The mathematical model assists in the enterprise of transfer function of the system. To create collisions and maneuvers in a mathematical way, normal simulation of the trajectory of both the UAV and obstacles are defined by geometric approach. The geometric approach exploits information of the location, speed and heading of both UAV and obstacles. Hence, the sensing system most associated with this type of approach is the Automatic Dependent Surveillance-Broadcast(ADS-B), which makes it unapplicable to non-aircraft obstacles. This technology is of huge help to the UAVs to identify other friendly aircraft in the region and precisely get information of their locations, speeds and headings. Howevr, this sensing method provide not information about other types of obstacles [8].

4. Material(s)

The materials used for achieving this work were based on the research requirement specification.

The software requirements in considering the UAV specification, typically the lightweight aircraft include MathsWorkMatlab, Simulink and Aerospace toolboxes (2018 version). Other software requirements needed before real-time communication can be achieved comprises of Microsoft Windows Software Development Kits (SDKs) 7 compiler and NET Framework 4. The Windows 7 SDK is used to provide the latest headers, libraries, metadata, and tools for building Windows 7 applications [6]. When Windows 7 SDK is applied in conjunction with Visual Studio 2010 offers the most favorable knowledge for accomplishment of different applications. Also, a hardware requirement such as laptop Computer was used.The laptop computer is an Intel core i7 CPU running on Windows 8 operating system. A major requirement here is that the computer system should have a good video graphics array (VGA) for enabling enlarged visual display because of the expected animation and other expressions (mathematical) outputs from the proposed system.

5. Aircraft Coordinate Systems

The coordinate systems of an aircraft are indispensably considered when modelling an aircraft are the *body coordinates* and *wind coordinates*.

5.1. Body coordinates

The no inertial body coordinate system is fixed in both origin and orientation to the moving vehicle. The vehicle is assumed to be rigid with the parameters defined as: the x-axis points through the nose of the vehicle as shown in Figure 1; the y-axis points to the right of the x-axis (facing in the pilot's direction of view) being perpendicular to the x-axis and the z-axis points down through the bottom the vehicle which is perpendicular to the x-y plane and satisfying the Right Hand (RH) rule. [9]

In translational degree of freedom, translations are defined by moving along these axes by distances *x*, *y*, and *z* from the origin while in rotational degrees of freedom rotations are defined by the Euler angles *P*, *Q*, *R* or Φ, Θ, Ψ as shown in Table 1.

Table 1 Euler angle parameters [10]

S/N	Euler angles	Definition
1	*P* or Φ	Roll about the *x*-axis
2	*Q* or Θ	Pitch about the *y*-axis
3	*R* or Ψ	Yaw about the *z*-axis

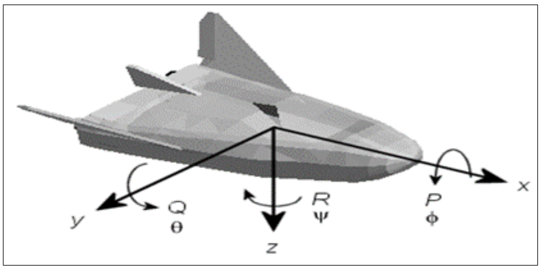

Figure 1 Body Coordinates of UAV [10]

5.2. Wind coordinates

The no inertial wind coordinate system has its origin fixed in the rigid aircraft. The coordinate system orientation is defined relative to the vehicle's velocity ***V***. The orientation of the wind coordinate axes is fixed by the velocity ***V***. The coordinate system is defined as follows using Figure 2: the *x*-axis points in the direction of ***V***, the *y*-axis points to the right of the *x*-axis (facing in the direction of ***V***) perpendicular to the *x*-axis and the *z*-axis points perpendicular to the *x*-*y* plane in whatever way needed to satisfy the RH rule with respect to the *x*- and *y*-axes [11].

The translational degrees of freedom havetranslations that are defined by moving along these axes by distances *x*, *y*, and *z* from the origin while rotational degrees of freedom have rotations that are defined by the Euler angles Φ, γ, χ as show in Table 2.

Table 2 Euler angle parameters [10]

S/N	Euler angles	Definition
1	Φ	Bank angle about the *x*-axis
2	Γ	Flight path about the *y*-axis
3	X	Heading angle about the *z*-axis

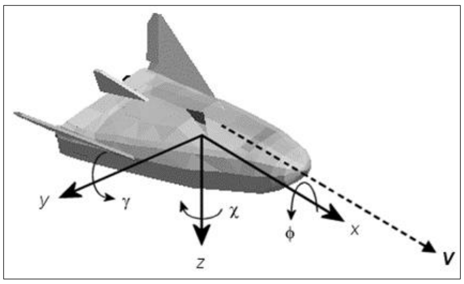

Figure 2 Wind Coordinates of UAV [10]

6. Methodology

The coordinate systems permit an individual to stay put in an aircraft or spacecraft's position and direction (orientation) in space. The modeling space vehicles are easily made when the vehicles are seen as coordinate system fastened to the body itself. If aircraft is considered, then the forward direction is modified by the presence of wind. It is relevant to note that the aircraft motion through the air is not the same as its motion relative to the ground.Mathematical model is the first step in understanding the mathematical principles and corporal laws applicable to the coordinate systems [6].

7. Aerodynamics of UAV

This basically computes the aerodynamic forces and moments using aerodynamic coefficients, dynamic pressure, center of gravity, center of pressure. This was done using the Aerodynamic Forces and Moments block to compute the aerodynamic forces and moments about the center of gravity. Here, the inputs and outputs are represented in the body axes by default [6].

The$\alpha$is represented as the angle of attack and β the sideslip. The rotation from body to stability axes is given by Equation 1:

$$C_{s \leftarrow b} = \begin{bmatrix} \cos(\alpha) & 0 & \sin(\alpha) \\ 0 & 1 & 0 \\ -\sin(\alpha) & 0 & \cos(\alpha) \end{bmatrix} \text{-----------------------} \ (1)$$

The above equation can be combined with the rotation from stability to wind axes as stated in Equation 2:

$$C_{w \leftarrow s} = \begin{bmatrix} \cos(\beta) & \sin(\beta) & 0 \\ -\sin(\beta) & \cos(\beta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{---------------------} \ (2)$$

According to Stevens and Lewins [9], the net rotation from body to wind axes can be computed as follows:

$$C_{w \leftarrow b} = \begin{bmatrix} \cos(\alpha)\cos(\beta) & \sin(\beta) & \sin(\alpha)\cos(\beta) \\ -\cos(\alpha)\sin(\beta) & \cos(\beta) & -\sin(\alpha)\sin(\beta) \\ -\sin(\alpha) & 0 & \cos(\alpha) \end{bmatrix} \text{--------} \ (3)$$

Generally, the Moment coefficients have the same notation in all systems. Force coefficients are given in Equation (4). It is important to note that there are no specific symbols for stability-axes force components in aerospace blocksets. However, the stability axes have two components that are unchanged from other axes as shown in Table 1.

$$F_A^w \equiv \begin{bmatrix} -D \\ -C \\ -L \end{bmatrix} = C_{w \leftarrow b} \begin{bmatrix} -X_A \\ -Y_A \\ -Z_A \end{bmatrix} \equiv C_{w \leftarrow b} . F_A^b \quad \text{---------------} \ (4)$$

Table 3 Description of Aerodynamic coefficients

Components	Axes		
	X	Y	Z
Wind	C_D	C_C	C_L
Stability	-	C_Y	C_L
Body	C_X	C_Y	$C_Z(-C_N)$

8. Simulation of the Vehicle (6DoF) Motion Platform

The motion of the 6DoF aircraft is determined by coordinate systems which allow one to keep track of an aircraft or spacecraft's position and orientation in space. So to run simulation to ascertain the performance of the 6DoF aircraft as shown in Figure 3, the input parameters are considered to be the Roll moment, Pitch moment and Yaw moment.

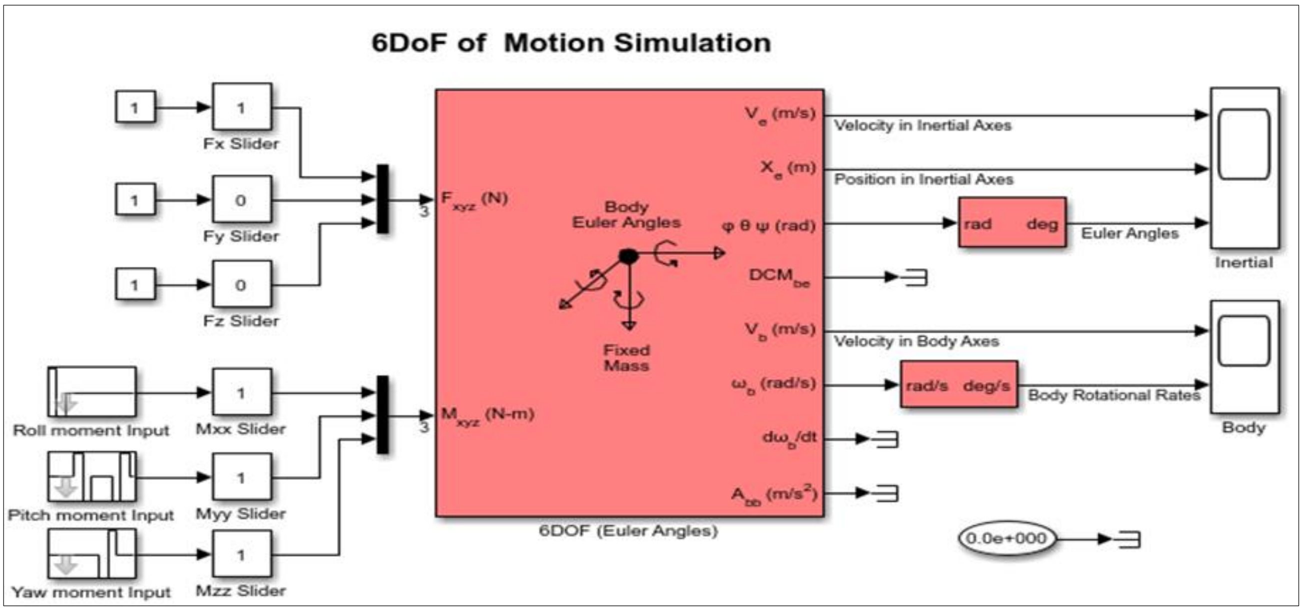

Figure 3 6DoF aircraft Motion Platform

The simulation time is set for 10sec. The output of the 6DoF aircraft is in terms of speed and position in inertial axes, and the Euler angles (converted from radians to degree) which are the main focus of this work, is presented in Figure 4.

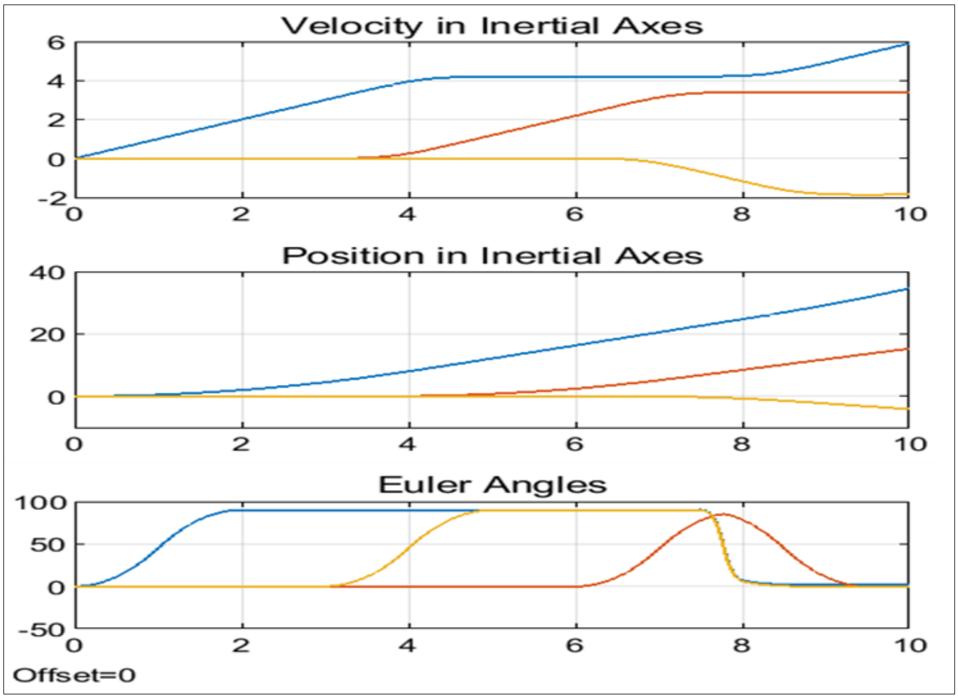

Figure 4 Simulation Result (output) of 6DoF showing the Speed and Position in Inertial Axis and the Euler Angle at 10sec

As observed in Figures 4 to 5 above, the vehicle is having a corresponding output at a simulation time not more than 30sec. This is because, as the simulation time increases, speed and position error tends to increase. The reason for the increment in the error is because, there is no nonlinear controller incorporated at this stage that can monitor the trajectory of the vehicle. This can be substantiated from Figures 6 to 7 where it could be clearly seen that the output of the aircraft is not correspondent to the input.

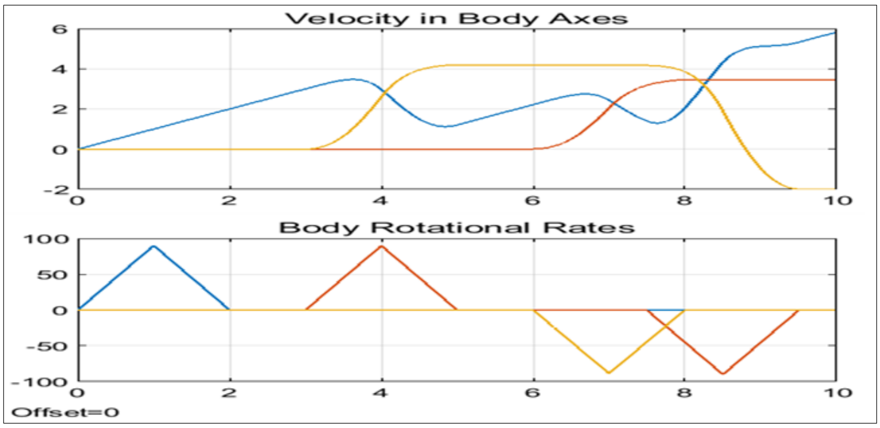

Figure 5 Simulation Result (output) of 6DoF showing the Speed in Body Axis and Body Rotational Rates at 10sec

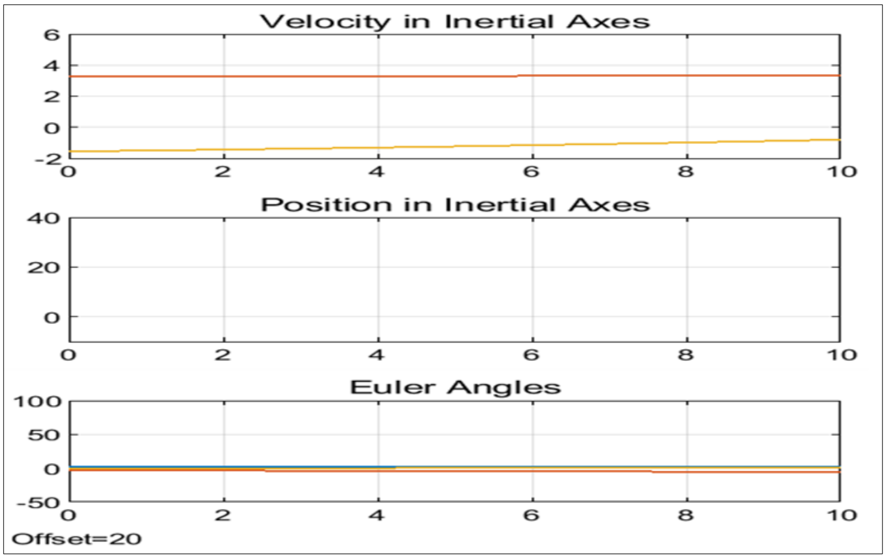

Figure 6 Simulation Result of 6DoF showing the Speed and Position in Inertial Axis and the Euler Angle at 30sec

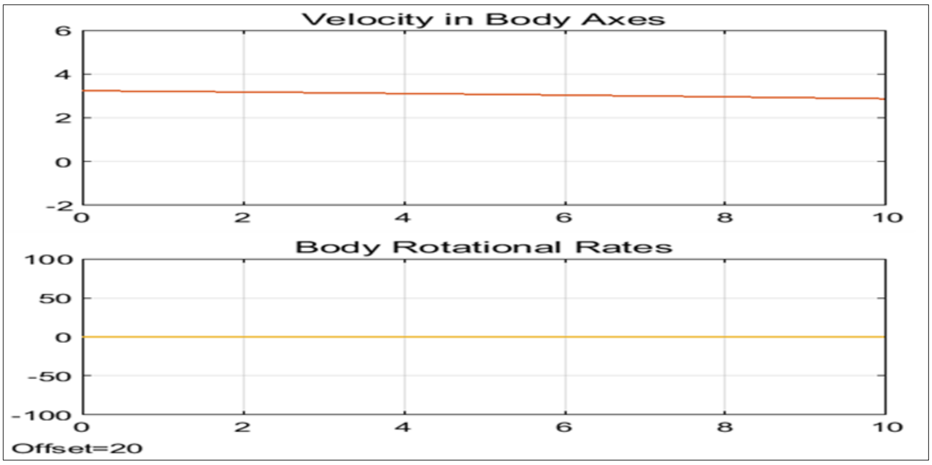

Figure 7 Simulation Result of 6DoF showing the Speed in Body Axis and Body Rotational Rates at 30sec

This result shows that there is need to incorporate a nonlinear controller to mitigate the effect of error accumulation in the system as time increases. Thus, this work has proposed a model predictive controller in this effect.

9. Conclusion

The researchers' intentions were to model and simulate collision avoidance for cooperative UAVs with Rolling Optimization Algorithm Based on Predictive State Space technique using Simulink and Aerospace toolboxes. It was realized that for the work to be successful, simulation of motions of 6DoF UAV was achieved considering the mathematical model of 6DoF UAV in free space first. The motion (mathematical model) of the 6DoF aircraft was determined by coordinate systems which allow an aircraft's position and orientation in space to be kept tracked. During modeling the translational degrees of freedom of the aircraft were defined by moving along these axes by distances x, y, and z from the origin, while the rotational degrees of freedom were defined by the Euler angles P, Q, R or Φ, Θ, Ψ. The input parameters were considered to be the Roll moment, Pitch moment and Yaw moment. Then, the discrete form of the developed model for simulation in Simulink was achieved using appropriate transfer functions. From the resulting equations and simulation data, it could be inferred that mathematical modeling serves as a hub to modeling and simulation as the gates (logic) are the hub of the digital electronics.

Recommendation

It is recommended that during the model and simulation of a Collision Avoidance for Cooperative UAVs, a Matlab executable programme be written in C^{++} to animate the cooperative collision avoidance of the designed and simulated work, to visualize the extent of the safety distance of the aircraft in real time.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

There is no conflict of interest between the authors.

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