Dynamic Modeling and Control System Design for a Passenger Coaxial Dodecacopter

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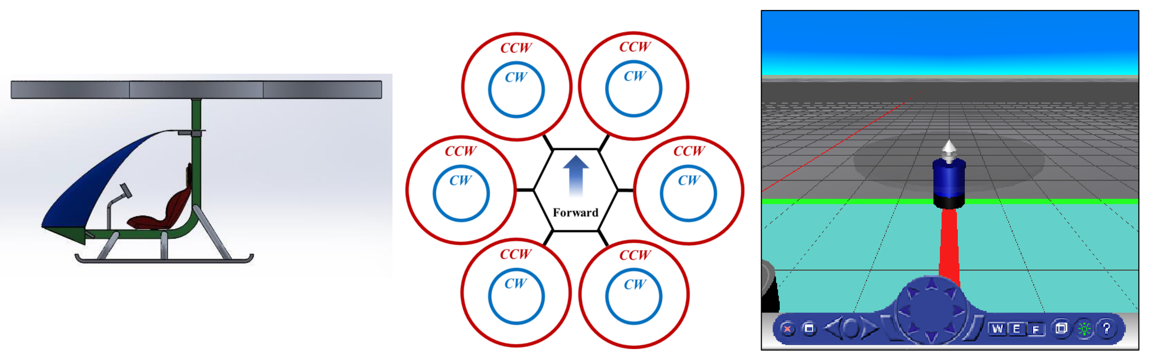
Abstract

Personal Aerial Vehicles (PAVs) are drones that provide transportation to passengers. The airframe and propulsion systems of a manned dodecacopter, or Personal VTOL Vehicle, were previously developed by Capstone students from Polytechnic University of Puerto Rico. This paper explores the dynamic model and control system based on this design. The modeled airframe is a coaxial dodecacopter with six arms. It has 12 motors, one pair in each arm: the upper motor rotating in opposite direction from the lower motor. The plant model and PID controller were developed in Simulink. The results confirms that the Personal VTOL Vehicle has sufficient robustness to be further developed into a real-life model, and therefore, is a viable alternative for urban mobility, capable of transporting a person with minimal flight control experience.

Introduction

There has been a rapid increase of much smaller Unmanned Aerial Vehicles (UAVs) in the market over the past decade. However, the viability for passenger aerial vehicles is yet to be discovered.



(a) (b) (c)

Figure 1. Development stages: (a) Extract data available from the VTOL Capstone Design Project, (b) Develop aerodynamic model, (c) Test aerodynamic model and control system.

Background

1. **Aerodynamics Theory**: Newton-Euler equations are used to describe the vehicle dynamic model with the total forces **ΣF** and moments **ΣM** [1]:

$$\begin{bmatrix}\Sigma\mathbf{F}\\ \Sigma\mathbf{M}\end{bmatrix}=\begin{bmatrix}mI_3 & 0_3\\ 0_3 & \mathbf{I}_3\end{bmatrix}\begin{bmatrix}\dot{\mathbf{v}}\\ \dot{\omega}\end{bmatrix}+\begin{bmatrix}\omega\wedge m\mathbf{v}\\ \omega\wedge\mathbf{I}_3\omega\end{bmatrix}$$

2. **Controls Theory**: The closed loop control system monitors the observed state against the desired state, and adjusts the variables to reach a set point.

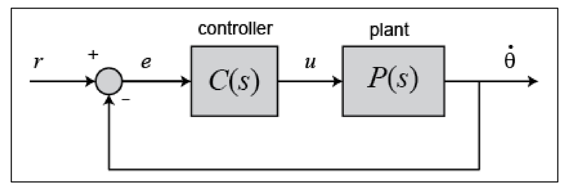


Figure 2. Typical structure of a feedback loop control system.

Problem

This design project focuses on building the dynamic model and control system of the Personal VTOL Vehicle Capstone developed by José Noel Caraballo, John M. Agosto Burgos, and Bilal M. Smaili Abounassif. The objective of this design is to explore the practicability of this type of vehicle and areas of opportunity for optimizing the technology and aerodynamics.

Methodology

CONFIGURATION MODEL:

- **Inputs**: 12 Motors provide Vertical Force and Moments
- **Outputs**: Cartesian Coordinates, Rotational Angles

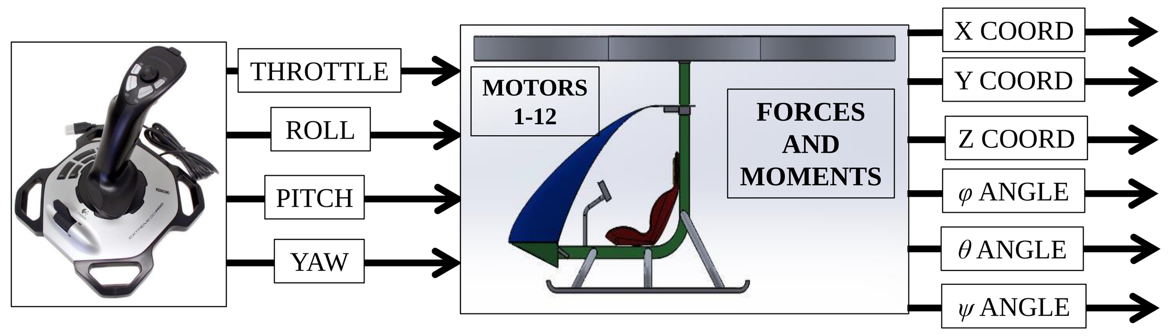


Figure 3. VTOL Configuration Model.

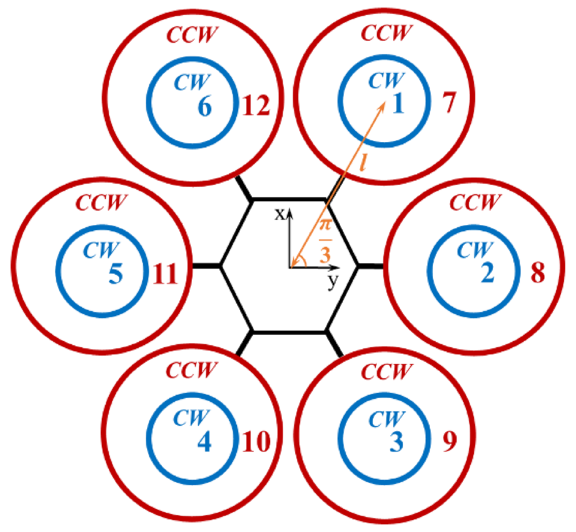


Figure 4. Configuration for the Dodecacopter's Forces and Moments (CW = clockwise rotation, CCW = counterclockwise rotation).

ACTUATORS:

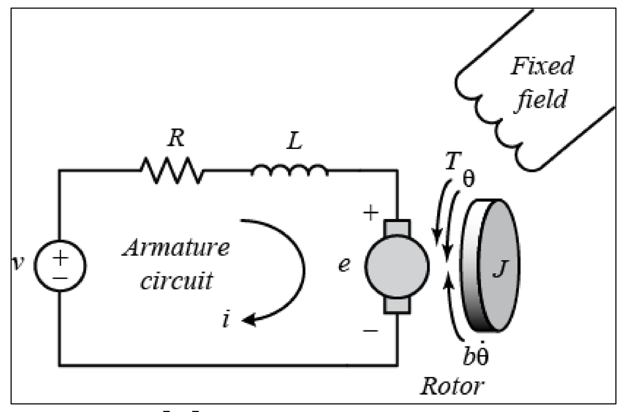


Figure 5. DC Motor model.

Motor model dynamic equation in Laplace domain [2]:

$$P(s)=\frac{\dot{\Theta}(s)}{V(s)}=\frac{K}{(Js+b)(Ls+R)+K^2}$$

Table 1. Parameters for the motor model:

Constant	Name	Assumed Value
J	Rotor moment of inertia	0.0406 (kg*m²)
K	Motor Torque Constant and Back Emf Constant	0.00275 (Vs/rad) (Nm/A)
L	Motor Inductance	1.5e-6 (H)
R	Motor Resistance	1.0e-5 (Ω)
b	Damping coefficient	0.273

CONTROLLER:

- **Motors**: Open-loop transfer function for each motor:

$$\boxed{\frac{0.00275}{6.09e-08s^2+8.155e-07s+1.029e-05}}$$

- **Controller:** A Proportional-Integral-Derivative controller configuration was used for this system:

$$C(s)=K_p+\frac{K_i}{s}+K_d s$$

Results and Discussion

Simulink Model:

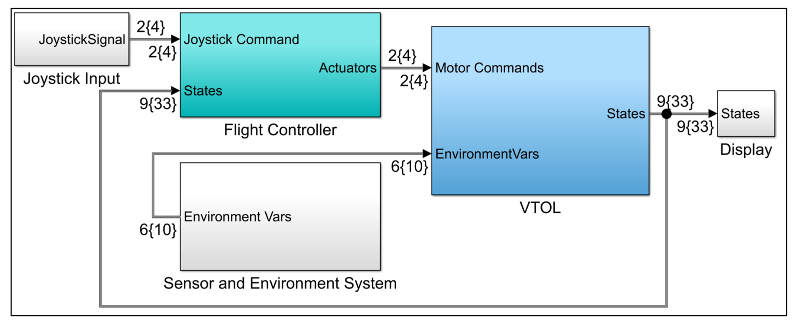


Figure 6. Simulink model for the designed VTOL Configuration. The mathematical representation of this project was baselined from the Simulink model for the Parrot Minidrone example [3]

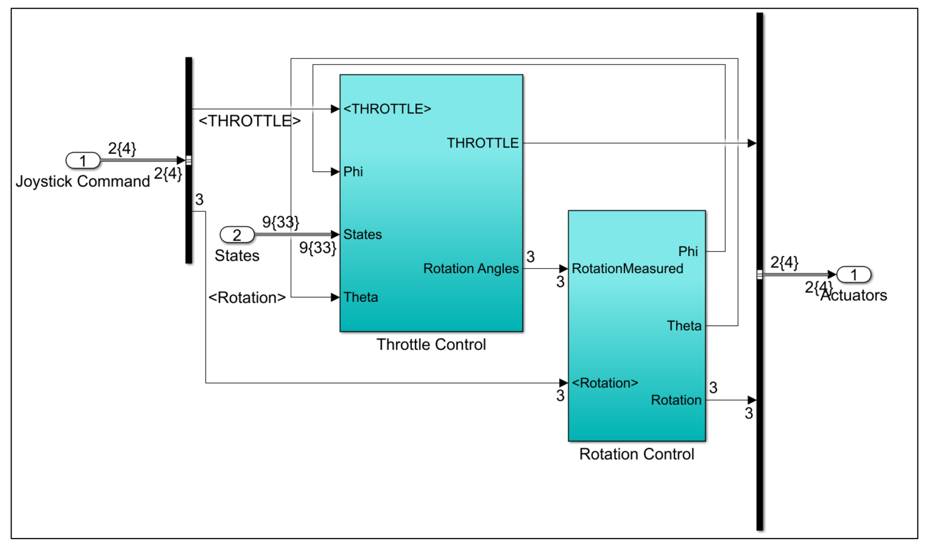


Figure 7. Flight Controller Configuration for Throttle and Rotation.

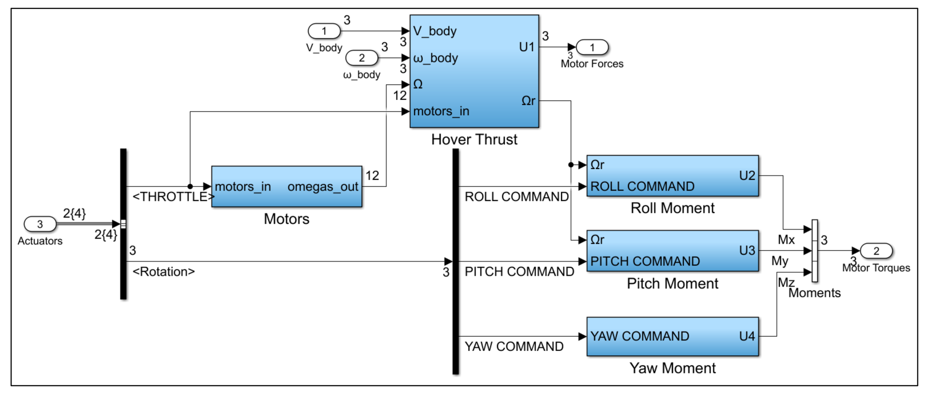


Figure 8. VTOL Model. Equations for motor forces and moments are part of this subsystem.

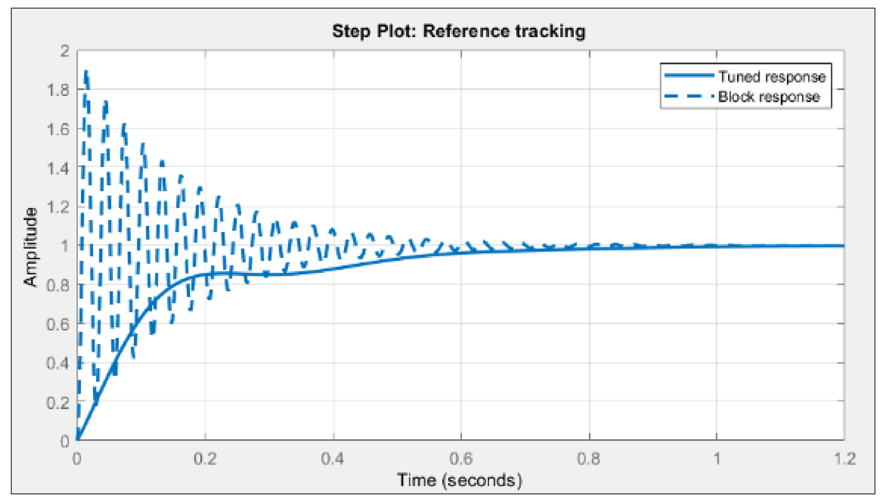
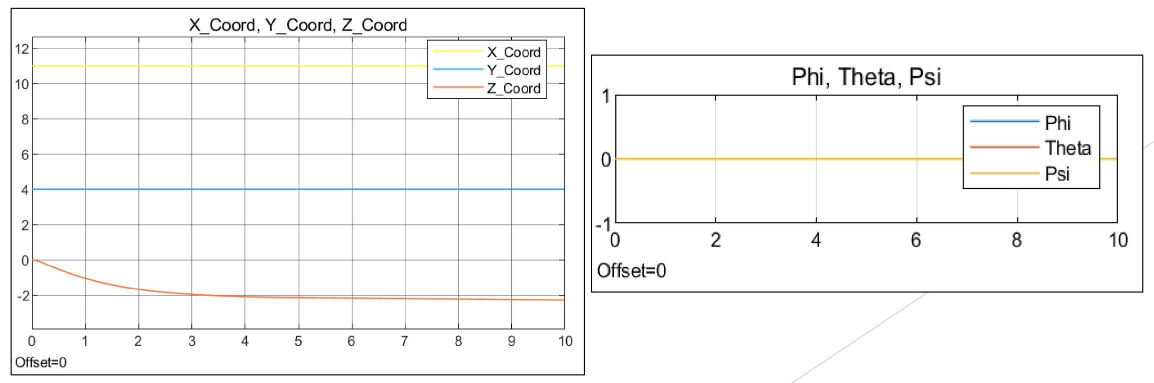


Figure 9. Motor PID Step Response. Tuned controller removed the overshoot and the oscillations.



(a) (b)

Figure 10. Output of the System with the Flight Controller: (a) Cartesian Coordinates, (b) Rotation Angles

Conclusions

- **Safety**: Despite the known stability of remotely piloted aerial vehicles with primarily four motors, the drones' fast mobility is something that cannot be implemented if it carries human passengers.
- **Innovation**: The 12-rotor passenger vehicle is an innovative design. The forces, moments, as well as the vehicle's moments of inertia, are much larger.
- **Robustness**: The dynamic model, as well as its control system, were designed to not only optimize its maneuverability, but also to maintain stability.
- **Economic Value and Utility**: Passenger aerial vehicles have a similar range of utility as unmanned aerial vehicles. This model can be further developed into a real-life model, capable of transporting a person with minimal flight control experience.

Future Work

- Extract motor constants
- Enhancements to Rotation Angle Controller
- Power subsystem model
- Sensor subsystem model
- Transfer CAD model design of the VTOL to adapt to Simulink 3D VR animation

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[2] D. Tilbury and B. Messner, "Control Tutorials for MATLAB and Simulink - DC Motor Speed: System Modeling," 2011. [Online]. Available: https://ctms.engin.umich.edu/CTMS/index.php?example=MotorSpeed&section=SystemModeling. [Accessed April 2022].

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