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Dynamic Performance Analysis of Hybrid-Electric Propulsion Systems for an Urban Air Mobility

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Abstract

As the urban air mobility of interest has been growing, the hybrid propulsion system has been studied to overcome the limitations that the lithium battery has low specific energy density. And, designing the hybrid propulsion system is difficult because hybrid components are closely intertwined and affected the environment in real-time. Therefore, this paper suggests the dynamic performance analysis of a hybrid-electric propulsion system for urban air mobility. In this research, we propose a framework including a 6-DOF model, a hybrid propulsion model, and a guidance and control law. And, we derive the mathematical and simplified data-based model to construct the series and parallel hybrid-electric propulsion system model. We focus on the mission profile from airport to city in Korea, and the proposed method confirms the feasibility of designing a hybrid propulsion concept considering the metrics such as the battery of state of charge, and remaining fuel mass.

1. Introduction

In the last two decades, Urban Air Mobility (UAM) has obtained a lot of interest because UAM can reduce travel time by expanding the operation path in three dimensions. According to the regulation about the emission of carbon dioxide,[1] many aerospace companies and institutions have developed the full-electric UAM system to make a difference from conventional aircraft, which is used the Internal Combustion Engine (ICE). For example, Airbus Vahana, Ehang 184, Kitty Hawk Cora, Lilium Jet and Volocopter are a popular UAM that uses electricity as the power source.[2] However, lithium-ion battery, mainly used as a source in the full-electric system, has low energy density and a long recharging time. This property makes it impossible for UAM to operate the long-endurance mission. Therefore, it is essential to use additional power sources such as gasoline,[3] fuel cell,[4] photovoltaic cell[5] to solve this problem. In particular, the gasoline-battery hybrid system is widely used because the response of fuel cell to the instant required power is slower than gasoline-battery hybrid propulsion system[6] and the photovoltaic cell can not produce enough power to sustain the UAM.[7]

Hybrid propulsion systems generally consist of motors, engines, generators, power management unit, and batteries. Although a lot of literature about the powertrain design for UAM exists, determining the appropriate component is still difficult because each property of component for UAM is unknown and unpredictable due to a shortage of commercial platforms and components. Furthermore, it is complicated to analyze how each component affects the entire hybrid system because hybrid parts are closely intertwined. And, most hybrid system design method is based on the required power equation, not a dynamic simulation analysis. Osita N. Ugwueze proposed the eVTOL design approach based on the power required for mission phases.[8] The sizing of the engine pack for a distributed series hybrid-electric propulsion system is addressed to choose the engine in five options using the requirement power profile in flight scenario.[9] Voskuijl et al. proposed the design and analysis approach of hybrid electric aircraft considering required power in flight mode such as climb, cruise, descent, and loiter.[10] And, the existing literature used the simplified model and can not consider the guidance and control law effect. McQueen et al. proposed the theory-based aerodynamic model to study the feasibility of implementing the fully electric and hybrid electric system into light aircraft.[11] Dehesa et al. presented the dynamic simulations of an unmanned aerial system (UAS) with different powertrain control logic approaches to evaluate the performance of a series hybridâelectric powertrain.[12]

Therefore, we propose the dynamic analysis framework based on mathematical modeling to confirm the feasibility of the designed hybrid propulsion system considering the transient response. First, the mission profile is designed to

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decide the propulsion component. Second, the mathematical and simplified data-based model including the motor and electric signal controller is proposed to make the series and parallel hybrid-electric propulsion system model. Third, the carrot-chasing guidance law and feedback linearization controller is used to implement the framework to consider the fuel mass reduction and transient required power in simulation. Finally, the state of charge (SOC) and the remaining fuel mass, called a performance metric, are used to evaluate the validity of the hybrid-electric propulsion system through the integrated dynamic simulation.

2. Mission Profile

The mission profile is determined in this section to design the UAM propulsion system. The profile is consists of profile path and flight speed. And, the mission profile is composed of take-off, climb, cruise, descent and landing mode, and the tiltrotor and lift-cruise UAM has a transient mode to convert the operation mode. In this research, according to the Korea UAM technology roadmap,[13] we decide the mission profile from Gimhae international airport to Gangnam station in Figure 3. This mission profile for multirotor type UAM has a distance of 27.7 km and is operated at a cruising speed of 60 km/h, with an estimated flight time of approximately 25 minutes.

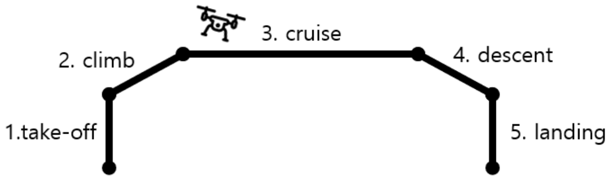

Figure 1: Profile for multirotor type UAM

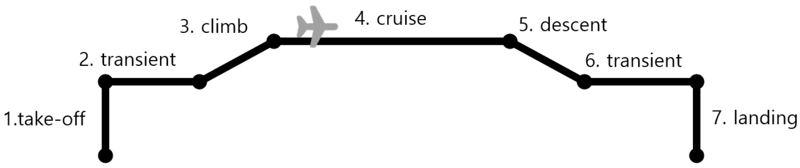

Figure 2: Profile for tiltrotor and lift-cruise type UAM

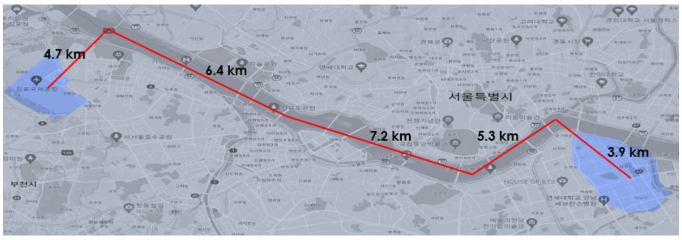

Figure 3: Proposed path at seoul city

Table 1: Mission profile requirement

Mode	**Altitude**	**Velocity**$_{multi}$	**Velocity**$_{tilt}$
Take-off	10 (m)	5 (m/s)	5 (m/s)
Transient	10 (m)	10(m/s)	15 (m/s)
Climb	500 (m)	10(m/s)	30 (m/s)
Cruise	500 (m)	15 (m/s)	45 (m/s)
Descent	150 (m)	10 (m/s)	15 (m/s)
Landing	10 (m)	5 (m/s)	5 (m/s)

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3. Hybrid-Propulsion System Model

The dynamic analysis of hybrid-electric propulsion system is proposed to obtain the power source result considering the mission profile, guidance, controller, and propulsion system. The existing method can be estimated the performance only in static environments that do not consider the guidance and controller algorithm and transient response. For example, when UAM system consumes the fuel as the power source, we can consider the fuel consumption effect because the required power for hover is decreased over time to obtain the exact simulation result. And, we check the state of charge and voltage of battery as a metric to guarantee the health of battery during the flight.

The hybrid propulsion approach is divided to the series hybrid and parallel hybrid. The series hybrid concept obtain the power by the electric motor directly. And, the gasoline engine of power transmits the generator to produce the electricity that will be used to the electric motor or battery. Therefore, this concept have structure: engine-generator-battery in Figure 4. This concept is useful to keep the optimal power for the gasoline engine by producing the power in the highest efficiency region. And, the transient required power is obtained by the battery. The parallel hybrid concept is used the power by gasoline engine and battery at the same time. The gear-box can make to allow power flow to enhance the power efficiency and redundancy of system. However, the gear box increases the system weight that limits the payload capacity. And, this concept does not allow to operate the internal combustion engine at most efficient point. Therefore, this parallel approach needs the optimal path to obtain the required power. This concept of structure as follow in Figure 5.

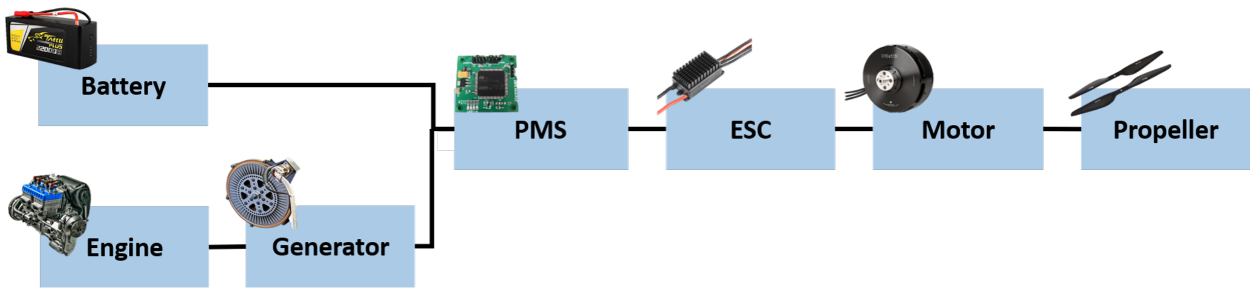

Figure 4: Series-hybrid propulsion

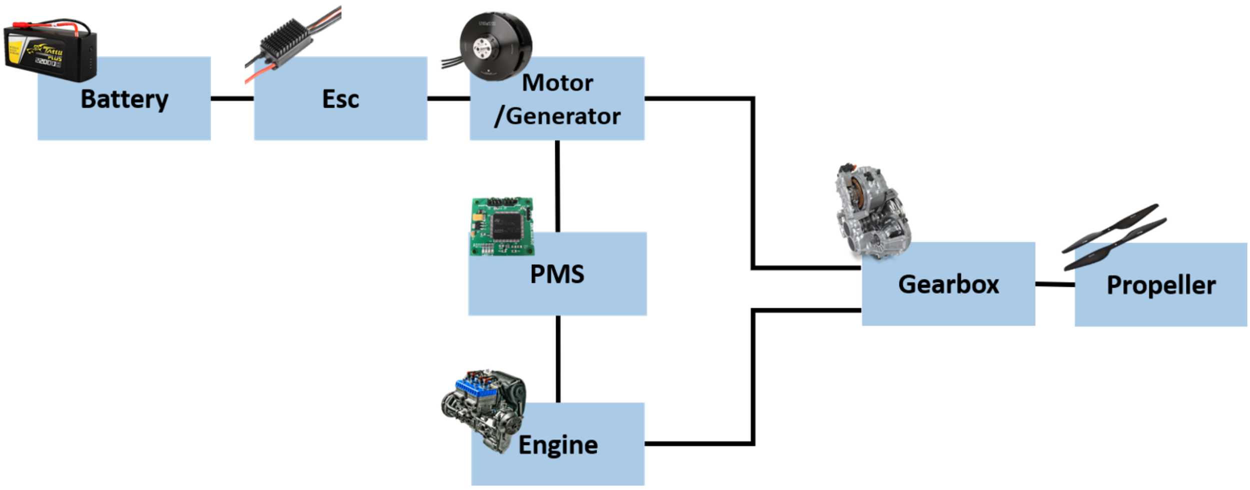

Figure 5: Parallel-hybrid propulsion

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3.1 Internal Combustion Engine Model

The gasoline engine modeling is replaced to the lookup table (LUT). In other literature, the internal combustion engine is modeled by the mechanical and chemical part. However, this structure is very complex and we can not obtain the exact model parameter that is essential for the simulation. Therefore, we use the LUT that is derived by the experiment. The LUT is divided to the Power to RPM and fuel-consumption to RPM. The Power to RPM LUT of input is required power and output is desired RPM. The fuel consumption to RPM LUT of input is RPM and output is the fuel-consumption value. For example, we obtain the LUT of DLE 40 twin gasoline engine whose have the maximum output power is 7.4KW with electric ignition. The obtained LUT is Figure 6 in below. If this experiment is not possible, we can use the manufacture-supplied data to overcome the this problem.

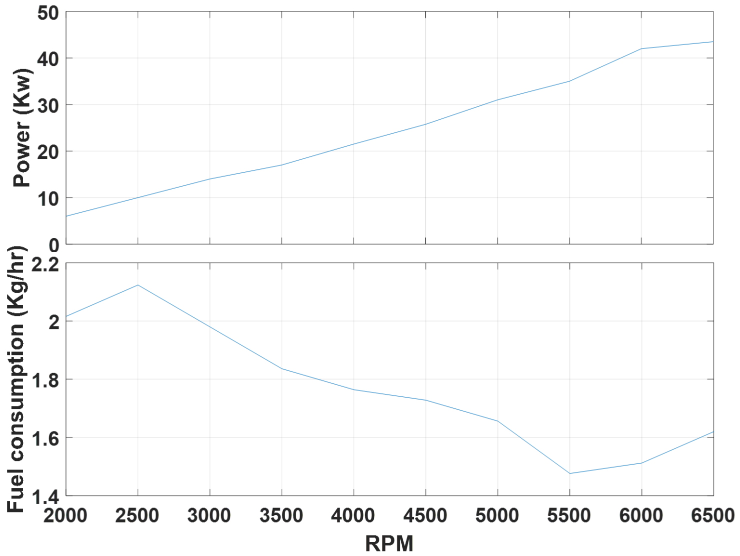

Figure 6: Performance experimental data for DLE 40

3.2 Battery Model

The battery is the main resource for electric motor and avionics. Unlike the gasoline engine, the battery can produce the limited energy during the flight. Therefore, we should predict the property of battery such as state-of-charge or voltage to check the health of battery. The modified Shepherd battery model[14] is used to represent the transient response and voltage drop effect in terminal phase.

$$
\begin{aligned}
E &= E_0 - R \cdot i - K \frac{Q}{Q-it} (i^* + it) + A \exp(-B \cdot it) \\
SOC &= SOC + \int_0^t \frac{i}{Q} dt
\end{aligned}
\tag{1}
$$

where E is battery voltage, E_0 is battery constant voltage, K is polarisation voltage, Q is battery capacity, A is exponential zone amplitude, B is exponential zone time constant inverse, R is internal resistance, i is battery current.

3.3 Electric Motor Model

The lumped parameter approach is mainly used for the motor model representing the equivalent circuit model. This approach needs accurate model parameters including the armature inductance, armature resistance, viscous damping friction, and back-EMF constant. However, identifying this parameter is also time-consuming and expensive work. To overcome this problem, we proposed a simplified model that decouples the mechanical part and electric part. Through the many experiments, we confirm that the producer-data sheet is very similar to the experimental result about the thrust and torque to the current. Therefore, we only use the look-up table to obtain the required current and mechanical model will be represented in the first order system in Figure 7.

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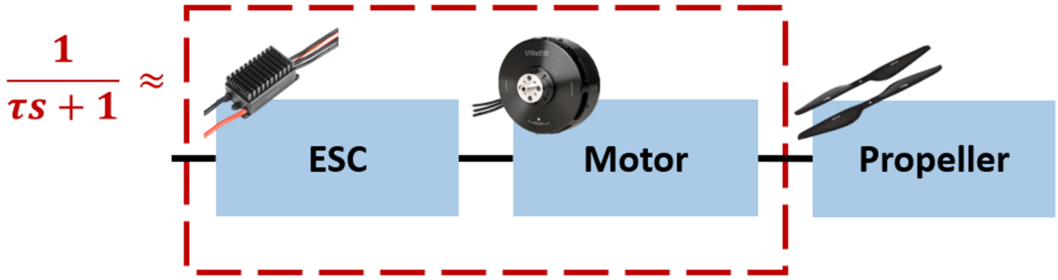

Figure 7: Simplified electric motor model

3.4 Generator Model

The generator model is similar to the motor model because generator operate inversely to the motor. Therfore, this system also is used to the look-up table and first order system. The generator model uses torque input and the rotational speed is the output.

3.5 Propeller Model

The propeller generates the force and moment to control the UAM system. Therefore, we need the exact parameter for the propeller system such as thrust and torque coefficient. This force and moment are affected by the air density that changes to the operating altitude.

$$\begin{aligned} T &= c_T \rho \omega^2 {D_p}^4 \\ M &= c_M \rho \omega^2 {D_p}^5 \end{aligned} \tag{2}$$

where c_T is the thrust coefficient, c_M is the torque coefficient, ω is the angular velocity of propeller, and D_p is the diameter of propeller.

$$\begin{aligned} \rho &= \frac{T_0 P_a}{P_0(273+T_t)}\rho_0 \\ P_a &= P_0(1-0.0065\frac{h}{(273+T_t)})^{5.255} \end{aligned} \tag{3}$$

where P_0, T_0, ρ_0 are the pressure, temperature, and air-density in the mean sea level, P, T, ρ are the pressure, temperature, and air-density in the current altitude.

3.6 Power Manage System

The power manage system determines the engine and battery of the weight of power in parallel hybrid propulsion system as follow:

$$\begin{aligned} P_{ICE} &= K_{ICE} P_{re} \\ P_{bat} &= (1-K_{ICE})P_{re} \end{aligned} \tag{4}$$

where P_{re} is the required power, P_{ICE} is the produced power from internal combustion engine, P_{Bat} is the produced power from battery, K_{ICE} is the weight of internal combustion engine.

3.7 Gear Box Model

The gear box model is used to consider power loss when the power from engine and motor is transmitted. We assume that the power transmitted from the engine and the motor has a constant efficiency as follows:

$$P_{total} = \eta_{ICE} P_{ICE} + \eta_{motor} P_{motor} \tag{5}$$

where η_{ICE} is the efficiency of engine and η_{motor} is the efficiency of motor.

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4. 6-DOF UAM Modeling

4.1 Kinematics of UAM

The inertial frame I is defined as North-East-Down frame (NED). And, body-fixed frame B is located at geometric center of UAM. $\eta = [x, y, z]^T$ and $\Omega = [\phi, \theta, \psi]^T$ represent the position and Euler angle measured in the inertial frame $\{I\}$, $\nu = [u, v, w]^T$ and $\omega = [p, q, r]^T$ represent velocity vector an angular velocity both measured from the frame $\{B\}$. And, we use the notations to represent the variable simply as follows: $\sin(x) \to s_x,\ \cos(x) \to c_x,\ \tan(x) \to t_x$.

The relationship with velocity in the inertial frame and velocity measured in the body-fixed frame is presented as follow.

$$
\begin{aligned}
\dot{\eta} &= R_{B\to I}\, \nu \ , where \\
R_{I\to B} &= \begin{bmatrix} c_\psi c_\theta & c_\theta s_\psi & -s_\theta \\ c_\psi s_\phi s_\theta - c_\phi s_\psi & c_\phi c_\psi + s_\phi s_\psi s_\theta & c_\theta s_\psi \\ s_\phi s_\psi + c_\phi c_\psi s_\theta & c_\phi s_\psi s_\theta - c_\psi s_\phi & c_\phi c_\theta \end{bmatrix}
\end{aligned} \tag{6}
$$

And, the time derivative of Euler angle in the inertial frame and angular rate measured in body-fixed frame have the relationship.

$$
\begin{aligned}
\dot{\Omega} &= S(\Omega)\, \omega \ , where \\
S(\Omega) &= \begin{bmatrix} 1 & \mathrm{s}_\phi t_\theta & \mathrm{c}_\phi t_\theta \\ 0 & \mathrm{c}_\phi & -\mathrm{s}_\phi \\ 0 & \frac{\mathrm{s}_\phi}{\mathrm{c}_\theta} & \frac{\mathrm{c}_\phi}{\mathrm{c}_\theta} \end{bmatrix}
\end{aligned} \tag{7}
$$

4.2 Dynamics of UAM

The mathematical UAM model is derived by using the newton second law ($F = ma$). Using the linear momentum equation, the translation dynamic model is obtained such that

$$
\begin{aligned}
F &= \frac{d}{dt}(mV)_I \\
&= m\frac{d}{dt}V_B + m(w \times V_B) \\
\Rightarrow m &\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix}_B + \begin{bmatrix} qw - rv \\ ru - pw \\ pv - qu \end{bmatrix}
\end{aligned} \tag{8}
$$

where force F exerted at frame $\{B\}$ is $\left[F_x, F_y, F_z\right]$.

Through the angular momentum equation, the rotational dynamic model is derived as follow:

$$
\begin{aligned}
M &= \frac{d}{dt}(H)_I \\
&= \frac{dH}{dt}_B + \omega \times H \\
&= \frac{d(I\omega)}{dt}_B + \omega \times I\omega \\
\Rightarrow \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} &= \begin{bmatrix} \left(I_{zz} - I_{yy}\right) qr + I_{xx}\dot{p} - I_{xz}\dot{r} - I_{xz}pq \\ \left(I_{xx} - I_{zz}\right) rp + I_{yy}\dot{q} - I_{xz}\left(p^2 - r^2\right) \\ \left(I_{yy} - I_{xx}\right) pq + I_{zz}\dot{r} - I_{xz}\dot{p} + I_{xz}qr \end{bmatrix}
\end{aligned} \tag{9}
$$

where moment M exerted at frame $\{B\}$ is $\left[M_x, M_y, M_z\right]$.

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5. Guidance and Control Law

5.1 Guidance law

The Carrot Chasing algorithm is one of the classic guidance method for fixed wing aircraft. This method generates a virtual target point (VTP) on top of the path that connects each waypoints. And, the aircraft are maneuvering along a carrot (VTP) to follow the waypoint. When defining the vertical distance from a UAM to a path as d, VTP is defined as a point on a path from q, the point at which the path meets the vertical distance of the aircraft. The carrot chasing algorithm generate the yaw angle command to reduce the horizontal distance between VTP and waypoints.

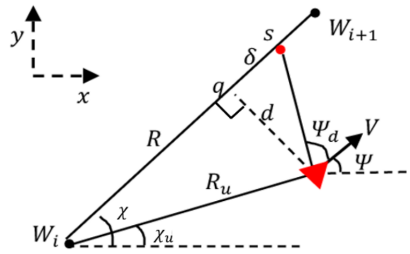

Figure 8: Carrot chasing algorithm variable

$$\psi_d = \tan^{-1}\left(\frac{d}{\delta}\right) \tag{10}$$

5.2 Control law

We use the feedback linearization as control law because this approach can be canceled the highly nonlinear term of UAM and designed as a linear control method by using the Nonlinear Dynamic Inversion (NDI). The nonlinear dynamic inversion of concept is as follows:

$$\begin{aligned} \dot{x} &= f(x) + g(x)u \\ u &= g(x)^{-1}\left(\tfrac{1}{\tau}(x_d - x) - \dot{x}_d - f(x)\right) \\ \dot{e} &= \tfrac{1}{\tau}(x_d - x) \end{aligned} \tag{11}$$

where τ is the time constatn of desired response.

The proposed controller consists of velocity controller, attitude controller, and angular rate controller. In tiltrotor UAM, we add the tilt angle controller to change the operation mode safely. At this time, we separate the system by selecting the time scale of each control-loop. Each controller was designed through a feedback linearization approach as mentioned above.

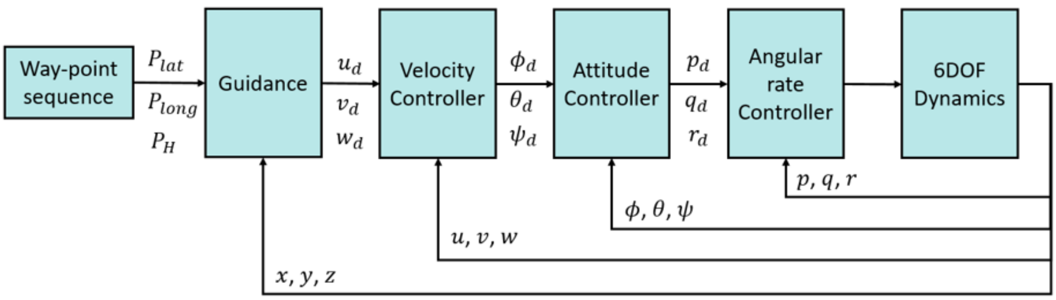

Figure 9: Proposed multirotor UAM controller of structure

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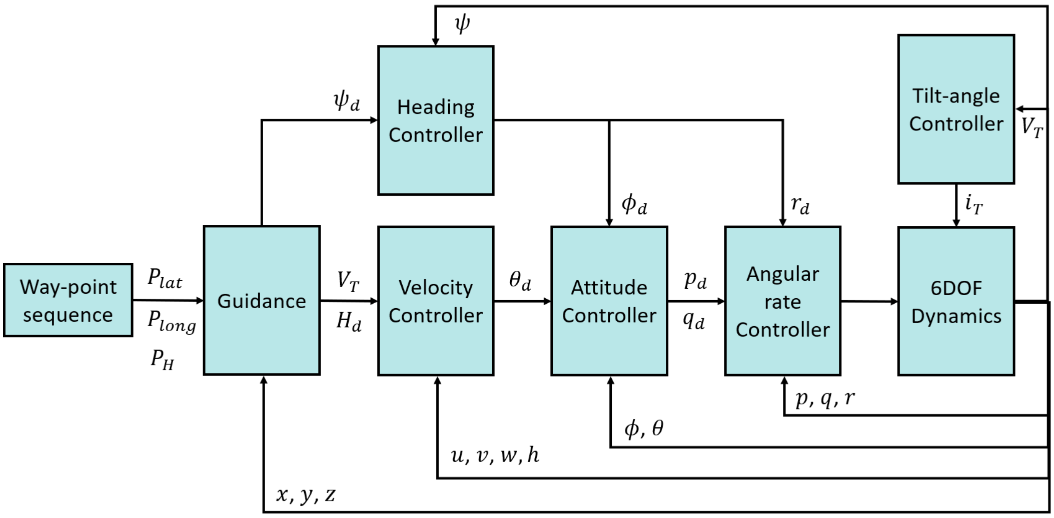

Figure 10: Proposed tiltrotor UAM controller of structure

6. Simulation Results

To verify the feasibility of the designed propulsion system, numerical simulation was performed by the MATLAB/Simulink in Figure 11. The structure of the simulation is divided into parameters, 6-DOF modeling, forces and moments, control and guidance, atmosphere model, propulsion, and graph blocks.

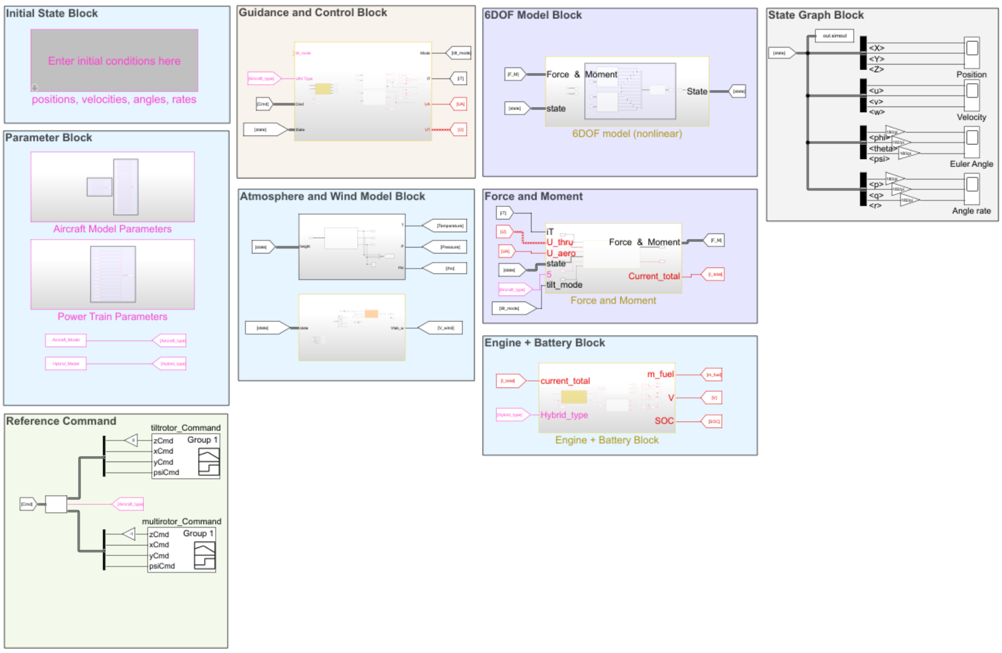

Figure 11: Dynamic performance analysis framework

The coaxial octocopter type UAM is used as a target platform in Figure 12. The UAM model parameters, control and guidance parameters, and hybrid propulsion model parameters are listed Table 2 and 3. And, we assumed that the hybrid propulsion system is designed as shown in Table 4. We performed the simulations on full-electric, serial hybrid, and parallel hybrid to obtain a propulsion system capable of performing missions. A suitable propulsion method can be selected based on the SOC and amount of fuel remaining after the mission. we assume that SOC must exceed 30 percent to satisfy the criteria.

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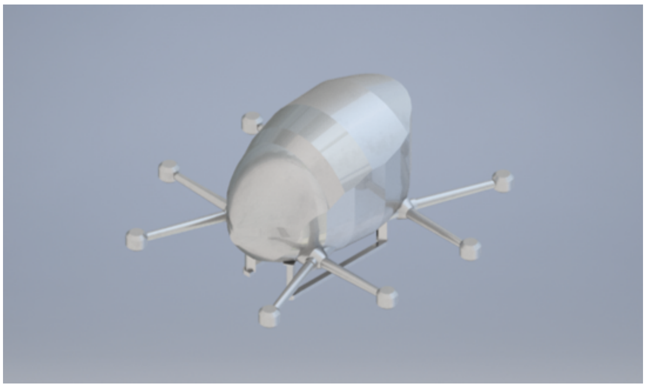

Figure 12: Coaxial octocopter type UAM

Table 2: UAM model parameter

parameters	Value	Units
m_{empty}	150	kg
I_{xx}	56.63	$kg \cdot m^2$
I_{yy}	56.16	$kg \cdot m^2$
I_{zz}	110.78	$kg \cdot m^2$
I_{xz}	10.23	$kg \cdot m^2$

Table 3: Controller parameter

parameters	Value	Units
τ_{v_x}	3	1/s
τ_{v_y}	3	1/s
τ_{ϕ}	0.3	1/s
τ_{θ}	0.3	1/s
τ_{ψ}	0.6	1/s
τ_{z}	0.666	1/s
τ_{p}	0.1	1/s
τ_{q}	0.1	1/s
τ_{r}	0.18	1/s
τ_{z}	0.18	1/s

Table 4: Hybrid propulsion system parameter

Component	Company	Product
Engine	Rotax	Rotax 582
Motor	T-motor	U15XL
ESC	T-motor	Flame 280a
Propeller	T-motor	52x20 cf
Generator	Launchpoint	Gensets

The path tracking results of UAM with hybrid propulsion are shown below. We can confirm that UAM maneuvers through each waypoint through the yaw angle command from the carrot chasing algorithm in Figure 13. And, the altitude tracking performance also accurately followed the command in Figure 14. The results of series hybrid and parallel including the voltage, SOC, and remaining fuel are presented in Figure 13 and 13. Through the dynamic performance analysis, we can obtain the possible hybrid propulsion system that can operate the prepared mission.

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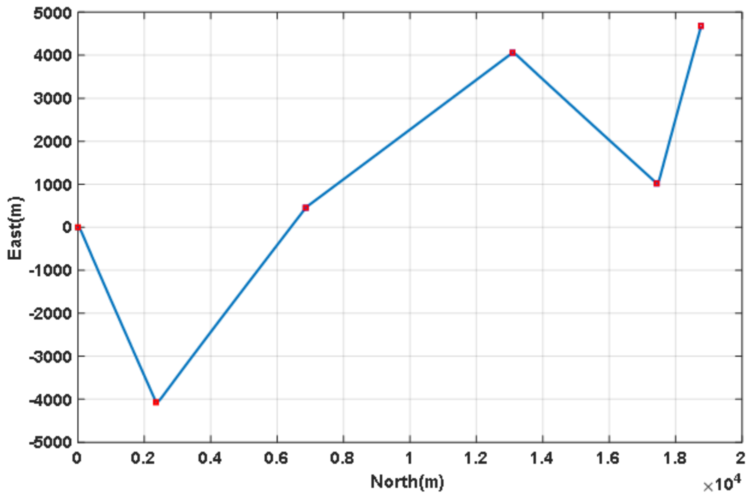

Figure 13: UAM position path graph

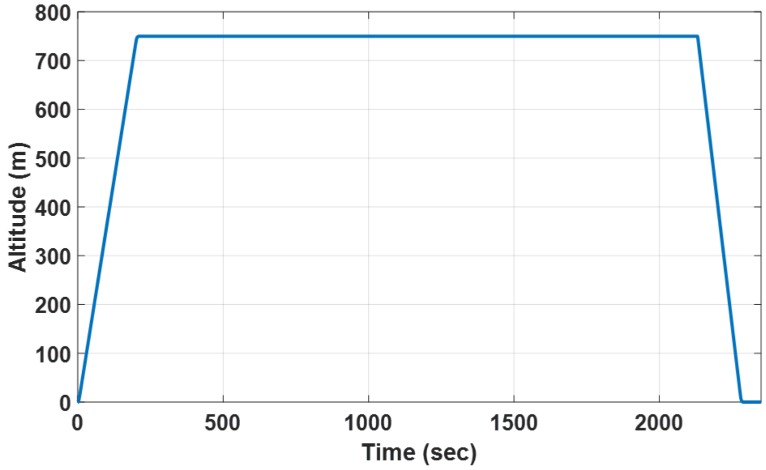

Figure 14: UAM altitude path graph

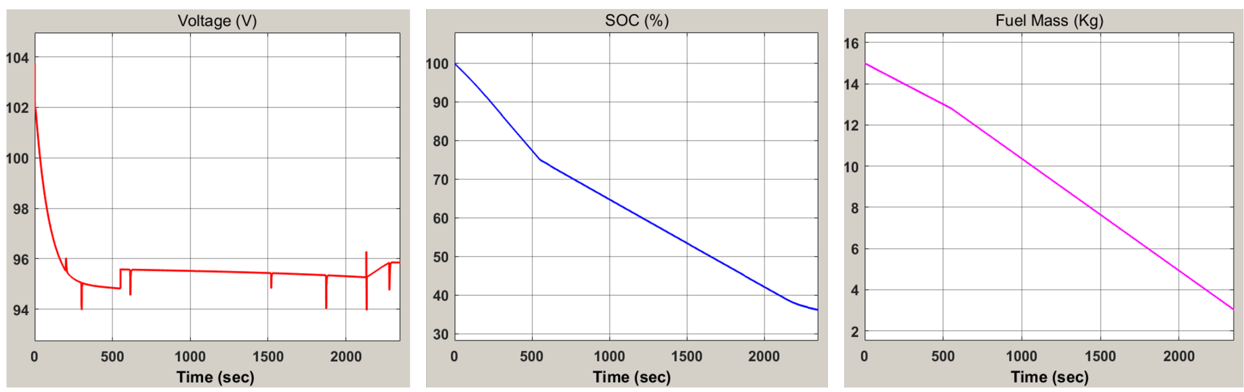

Figure 15: Results of series hybrid - voltage, SOC, fuel mass

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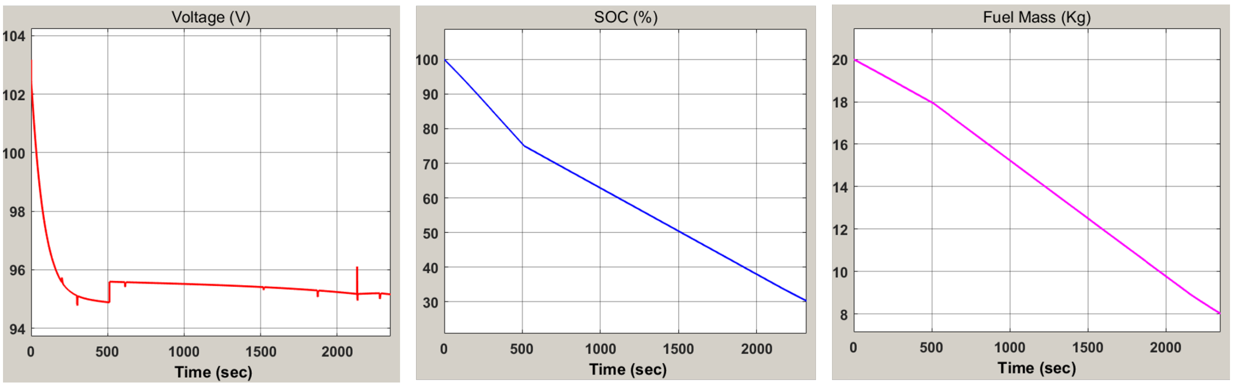

Figure 16: Results of parallel hybrid - voltage, SOC, fuel mass

Table 5: Hybrid propulsion system parameter

Metric	**Series Hybrid**	**Parallel Hybrid**
SOC (%)	34.78	30.5
Remaining fuel mass (kg)	2.21	8.05
Battery mass (kg)	53.23	48.23
Engine mass (kg)	59.1	59.1
Motor mass (kg)	53.0	53.0
Initial fuel mass (kg)	15	20
Total mass (kg)	330.33	330.33

7. Conclusion

We propose the dynamic analysis framework based on mathematical modeling to confirm the feasibility of the designed hybrid propulsion system considering the transient response in the mission profile. The mathematical and simplified data-based model for motor and electric signal controller are proposed to make the series and parallel hybrid system. The carrot-chasing guidance law and feedback linearization controller are used to consider the fuel mass reduction and transient required power in the simulation. Through the SOC and the remaining fuel mass, This method can evaluate the validity of the hybrid method. And, this simulator can be used for the developing the power management and engine control algorithm because this can generate the similar result to the real hybrid propulsion system.

8. Acknowledgments

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