To: Tony Stark, President

From: Ross Smyth, Student, Lead Test Engineer

Date: February 28, 2020

Subject: Bicopter Simulink Simulation

Introduction

I have carried out creating a Simulink simulation for the bicopter that I have been testing for the past few week and analyzed it under the conditions that you specified in your memo to me. Between each analysis the pulse width profile of the propellers was changed to match scenario that you requested. These profiles were developed by guess and check of an almost bang-bang control scheme in which instead of two states of a normal bang-bang control, on and off, three states are used: on, off, and hover. This resulted in easy to understand pulse profiles, and also easy to manipulate profiles to match the situations requested. The Simulink model remained the same between each situation, and it is shown below in Figure 1.

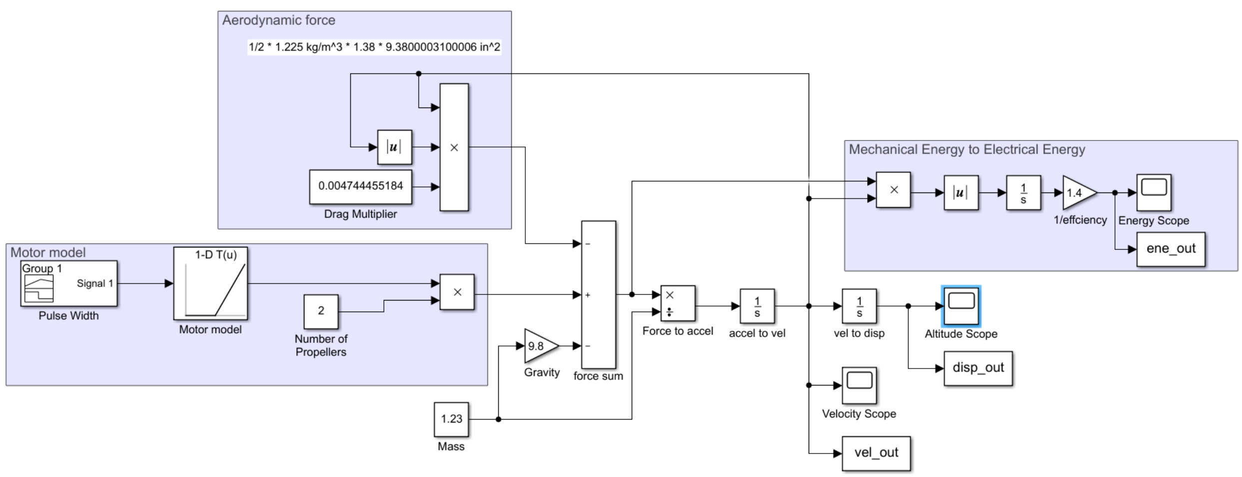

Figure 1: Simulink model of the bicopter system represented by differential equations, with energy, velocity, and displacement outputs.

Discussion

The Simulink model shown in *Figure 1* was developed by your guidance in the memo you sent me, but also along with my own assumptions and calculations made. These assumptions are primarily to due with the air resistance of the bicopter as that is difficult to characterize without a rigorous test campaign that has not been conduct of this bicopter, if it will be at all. I used the drag equation that you provided me, shown in Equation 1. The hover pulse width was determined by find the force in which zero net force is applied to the copter, the back-correlating it to the pulse width and it was calculated to be 1.67 milliseconds

$$\mathrm{F_{drag}} = \frac{1}{2}\rho \mathrm{C_d} A \|\mathrm{v}\|\vec{\mathrm{v}}$$

Equation 1: Drag force equation, dependent on the velocity vector of the bicopter

Where:

$$\mathrm{F_{drag}} = \textit{The drag force}$$
$$\rho = \textit{Atmospheric density}$$
$$\mathrm{C_d} = \textit{Bicopter drag coefficient}$$
$$A = \textit{Bicopter ram area}$$
$$v = \textit{Velocity}$$

For this equation several assumptions were made. Because the bicopter is thin but has a non-negligible ram area in the velocity direction, it was assumed be a thin plate which has a drag coefficient of 1.28 according to NASA Glenn Research Center. Also from NASA Glenn Research Center a set of equations (see Equation 2 and Equation 3) for estimating the atmospheric density at different altitudes was used to calculate the atmospheric density. This specific set is the set for estimating the density below 11 kilometers from sea level, as it is assumed that the copter will not be above that. The temperature in this set of equations is assumed to be 25°C, which is 298.15 K. Both of the equation are found on the same webpage from NASA Glenn Research Center here.

$$\mathrm{p} = 101.29 \times \left[\frac{\mathrm{T}}{288.08}\right]^{5.256}$$

Equation 2: Estimated atmospheric pressure at different altitudes below 11 km from sea level from temperature in Kelvin

$$\rho = \frac{\mathrm{p}}{0.2869 \times \mathrm{T}}$$

Equation 3: Estimated atmospheric density from the estimated temperature in Kelvin and pressure calculated above

Combining the above equations with the dimensions that you provided me of the bicopter, that the ram area is 6.7 inches by 7.2 inches, the drag multiplier, a combination of the constant terms in the drag equation, is estimated to be 0.0047, which is not very high and almost negligible at low speeds.

After setting up the Simulink simulation, the first situation analyzed is a situation where the bicopter starts at rest, flies up 1.5 meters, and hovers for one second all within 5 seconds. The propeller motor's pulse profile developed for this situation is shown in Figure 2. The bicopter's response in altitude is also shown below in Figure 3. This shows that with this pulse width profile the bicopter can hover at 1.5 meters in a minimum time frame of just below one second when starting from rest. The maximum velocity reached in this situation is 3.1 meters per second at 0.65 seconds after the start of the scenario, which can be seen in Figure 3. To estimate the lower bound of the electrical energy consumption the mechanical power of the bicopter was integrated to energy, and 17 Joules of energy are used in this situation. This is not a completely accurate number as using the mechanical energy shows that electrical energy consumption is zero when hovering, which is not true. Until a method to directly measure the electrical energy consumption of the motor model is developed this will work as a lower bound to just get the copter to the hovering position, but not to maintain that hover for the whole five seconds.

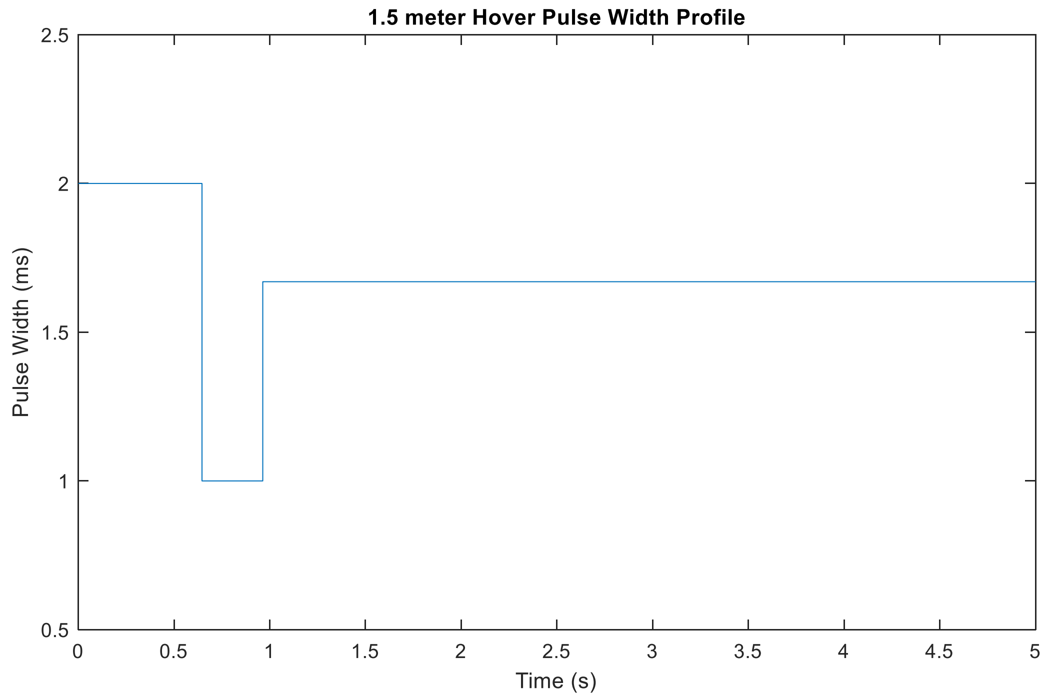

Figure 2: First scenario pulse width profile

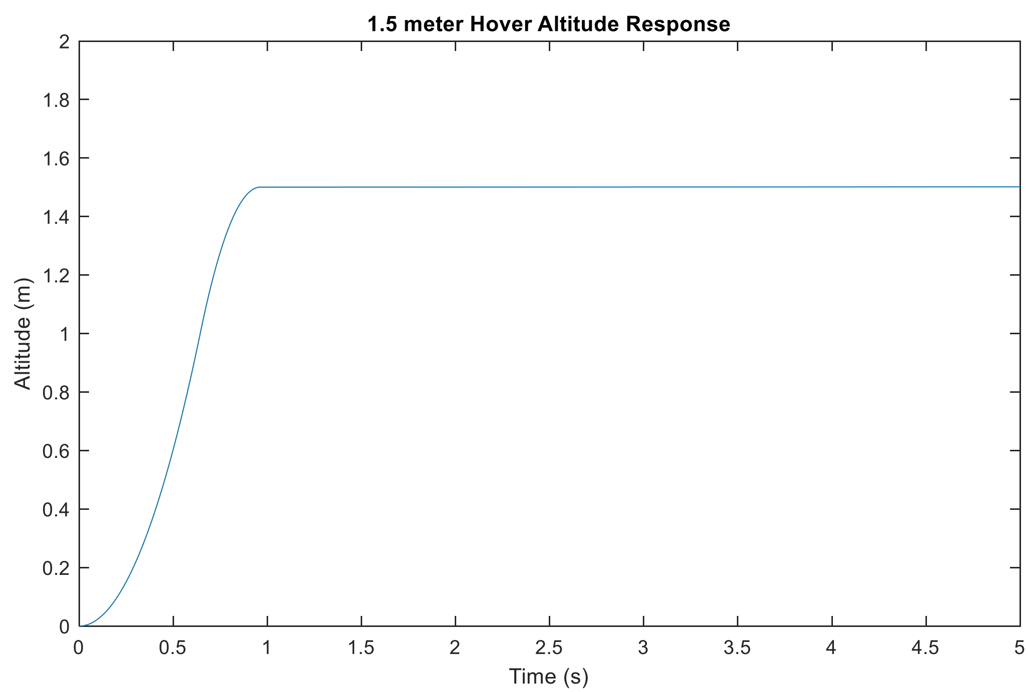

Figure 3: First scenario altitude response with 1.5 meter hover within 5 seconds

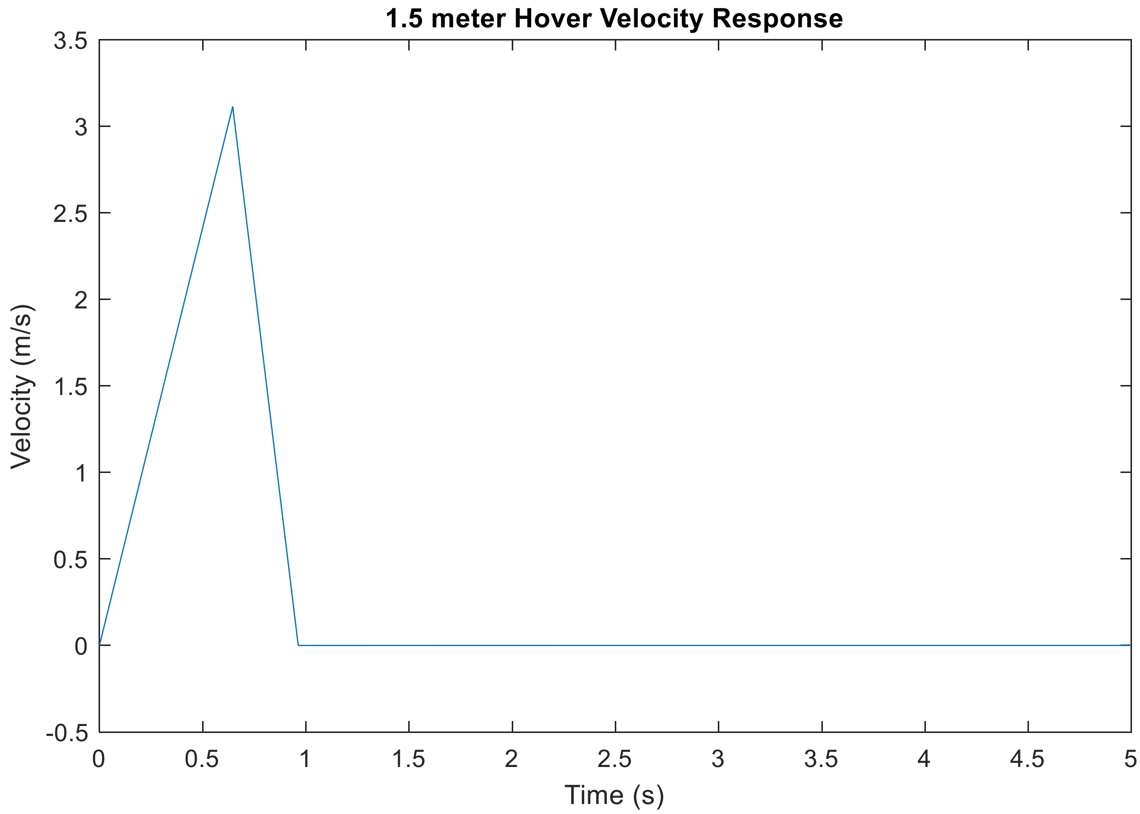

Figure 4: Velocity response of the bicopter in the first 1.5 meter hover scenario.

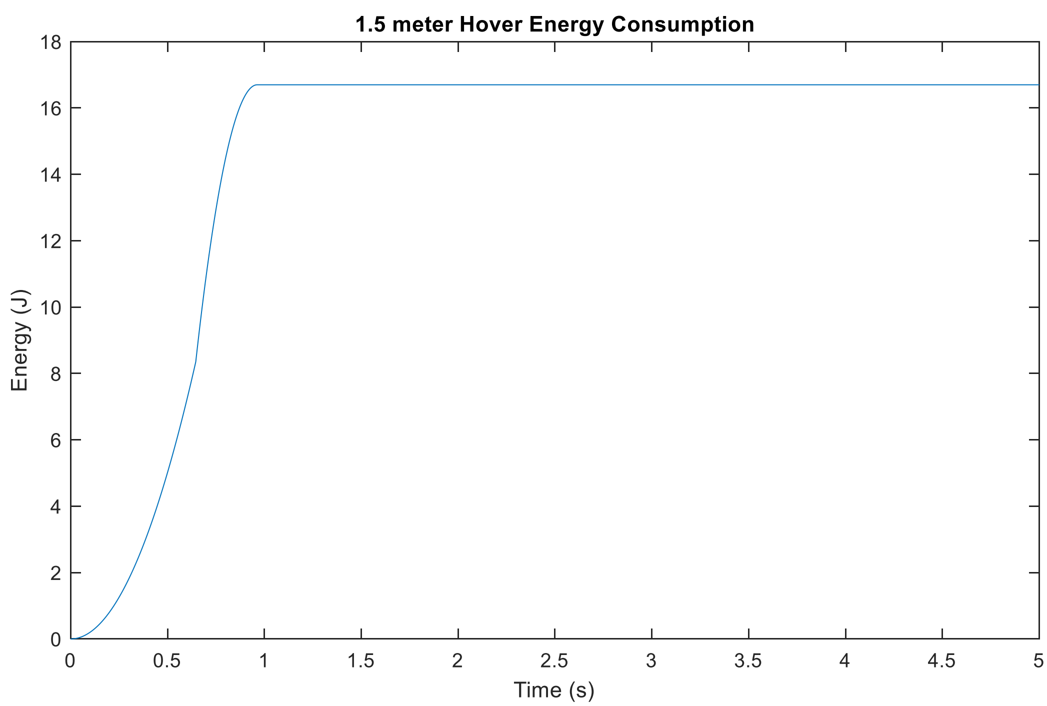

Figure 5: Energy consumption of the bicopter in the first 1.5 meter hover scenario

The next scenario analyzed in one in which the bicopter rises to an altitude of ninety meters within 15 seconds from rest, hovers between ninety and one hundred meters for five seconds, and then lands the bicopter. The pulse width profile developed for this situation is shown below in Figure 6. With this pulse width the copter is able to rise to the ninety-five meter hover altitude within eight seconds. The maximum upwards velocity experienced during this maneuver is twenty-three meters per second at 5.7 seconds after the start of the simulation. After five seconds it then descends to the ground, and lands shortly before 21 seconds after the start of the simulation at a speed of 0.014 meters per second, which should be plenty soft enough to not shock the system and break it, but to be sure shock analysis should be conducted on the bicopter system.

Over this entire hover and land scenario the copter consumes and estimated 2100 Joule of energy. As previously this is by adding an efficiency margin to the mechanical energy that the copter uses. This is not a very good assumption, and it cannot be said if this is even an upper or lower bound of energy consumption. This is because as previously the energy consumed while hovering is not accounted for, but also the energy that the copter gains while descending is taken into account, but this is energy added mostly due to the force of gravity while the motors are consuming little to no power, resulting it that maneuvering being vastly over estimated in the energy consumption. But regardless, this is the only way to estimate energy consumption developed currently. Considering batteries listed on the drone site genstattu.com on their battery page, the battery size with the most available is the 1550 milliAmp-hour rated batteries for the size of copter that is dealt with in this analysis. These batteries are rated to provide around eleven volts, which results in a total energy storage of approximately 60 kilojoules. With these batteries, this scenario could be repeated twenty-nine times before the battery was empty, assuming the energy estimation is correct.

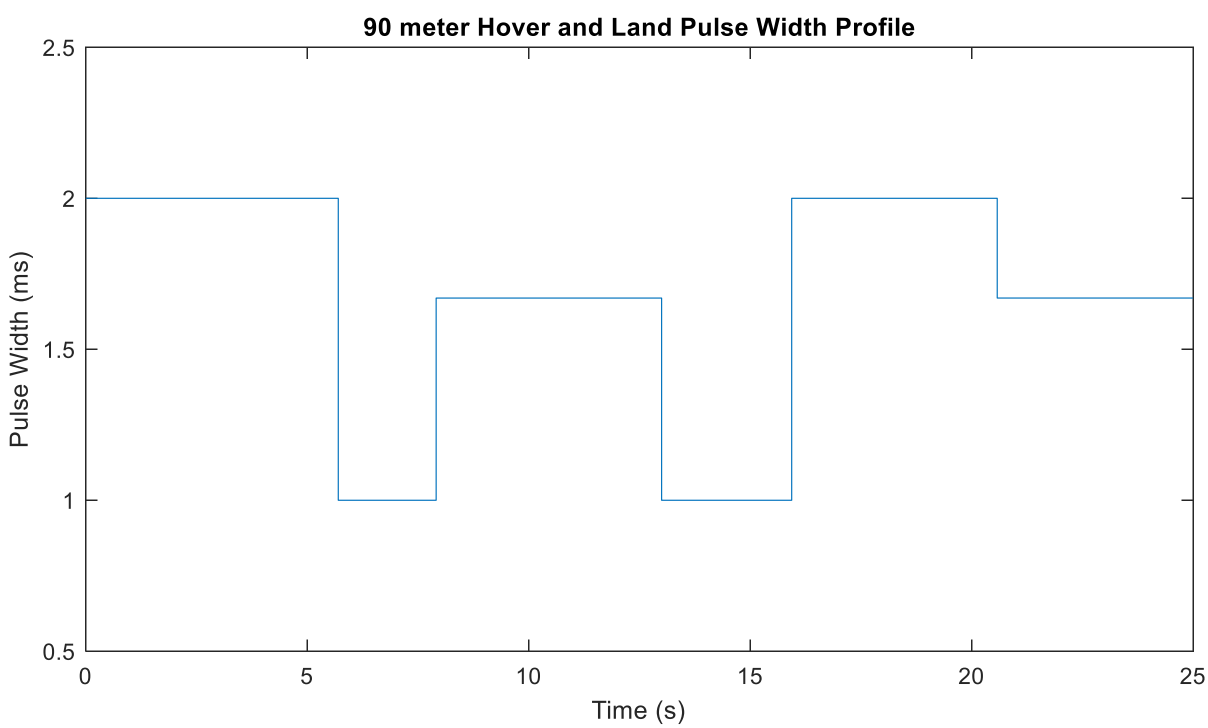

Figure 6: Bicopter motor's pulse width profile developed to rise the copter to 90 meters, hover, and then land without damage.

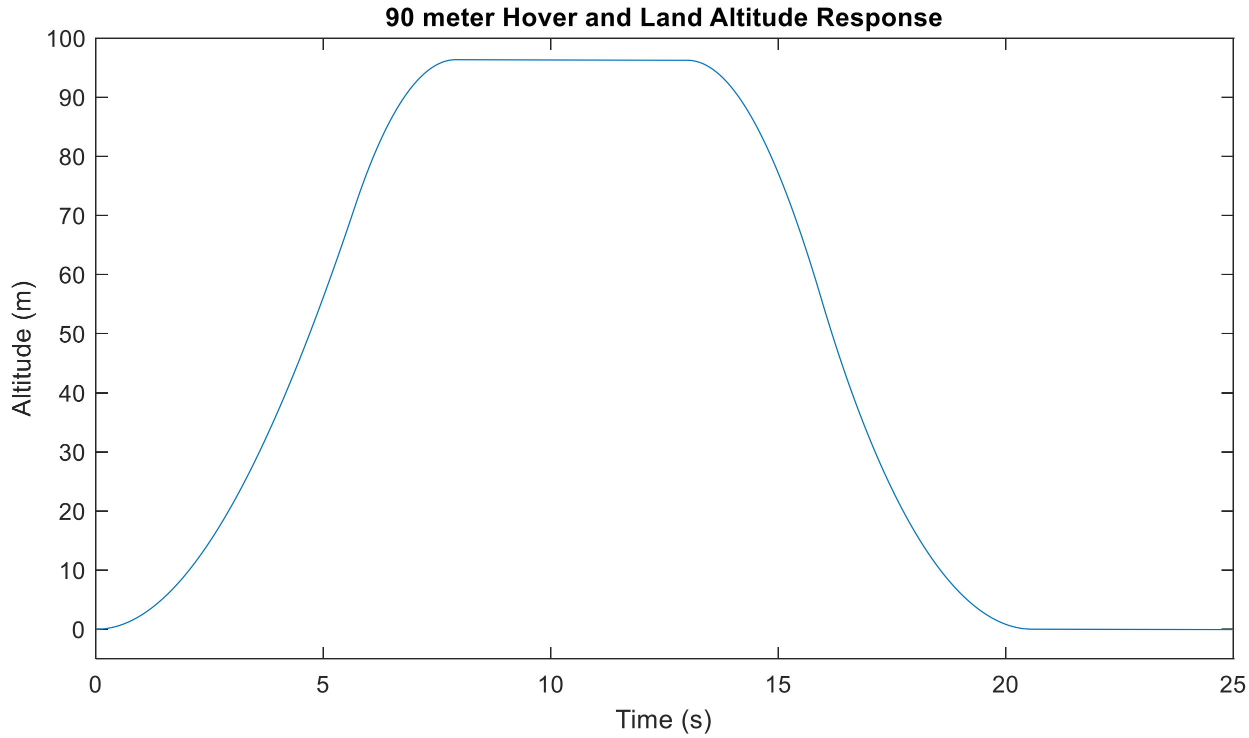

Figure 7: Altitude response of the pulse width profile shown above with hovering at 95 meters and landing done within 25 seconds.

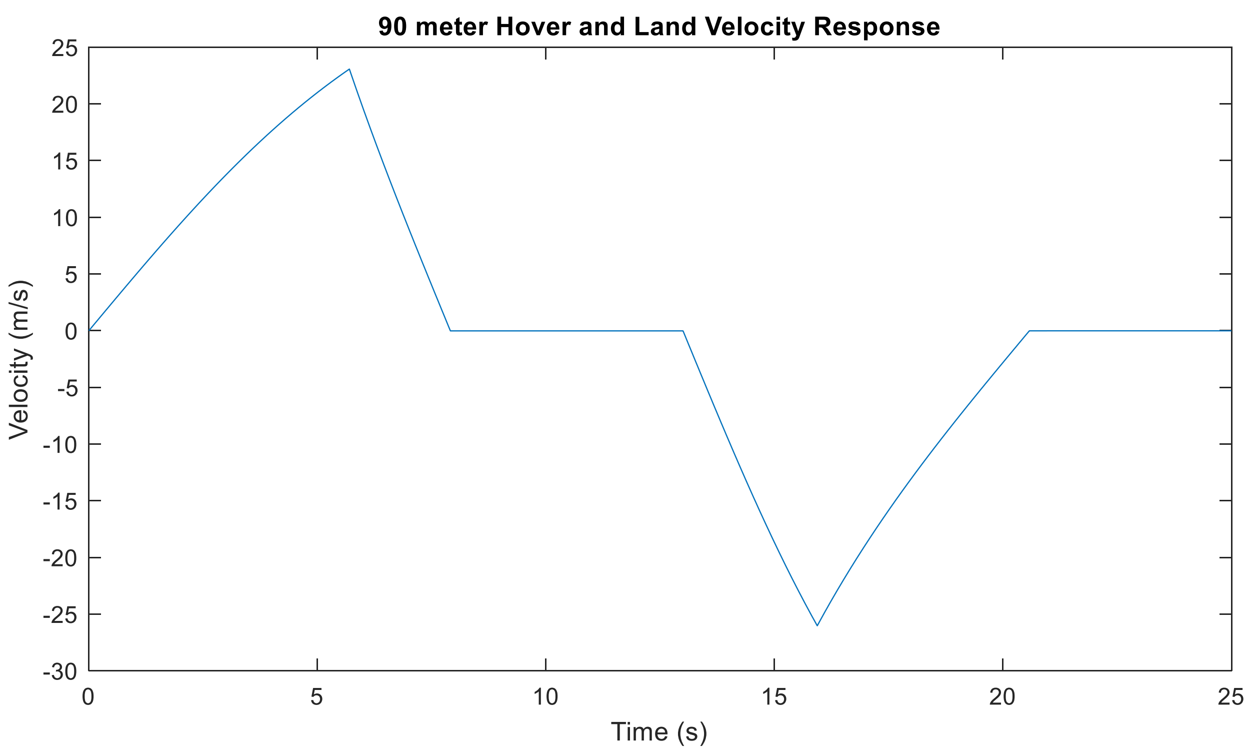

Figure 8: Velocity response of the bicopter in the 90 meter hover and land scenario.

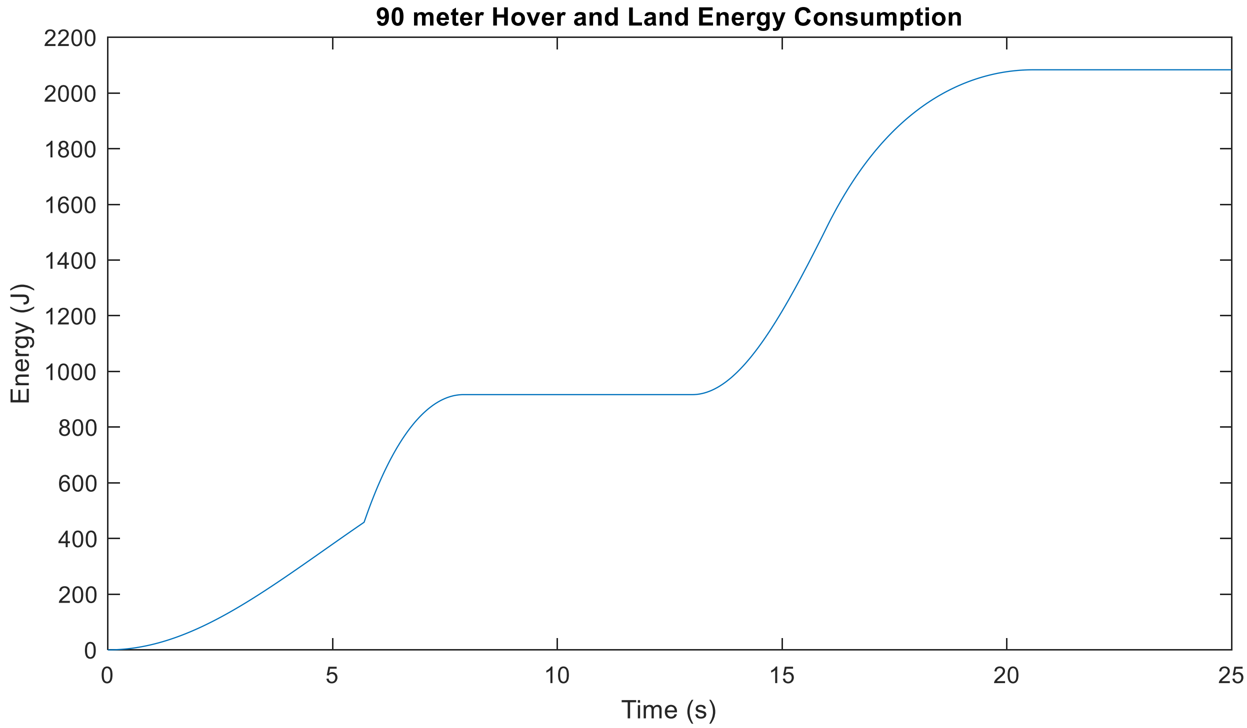

Figure 9: Energy consumption of the bicopter in the 90 meter hover and land scenario

Finally, the bicopter system was analyzed for its upwards terminal velocity, or the maximum velocity that the copter could reach going upwards. The terminal velocity is reached when the combination of the air resistance and bicopter system weight balances with the thrust from the rotors. This situation was simulated over fifty seconds, then the data inspected to see the terminal velocity. With this system and the assumption described above, the terminal velocity is slightly above 35.4 meters per seconds. 35.4 meters per second is reached at 40 seconds after the start of the scenario. The time constant, or the time to get to 63.2% of the steady state value is approximately 5.5 seconds, which using the commonly accepted value of four time constant durations to get to steady state results in a settling time of 21 seconds at a speed of 35.2 meters per second, which results in less than 0.5% error from the final speed value measured in the simulation.

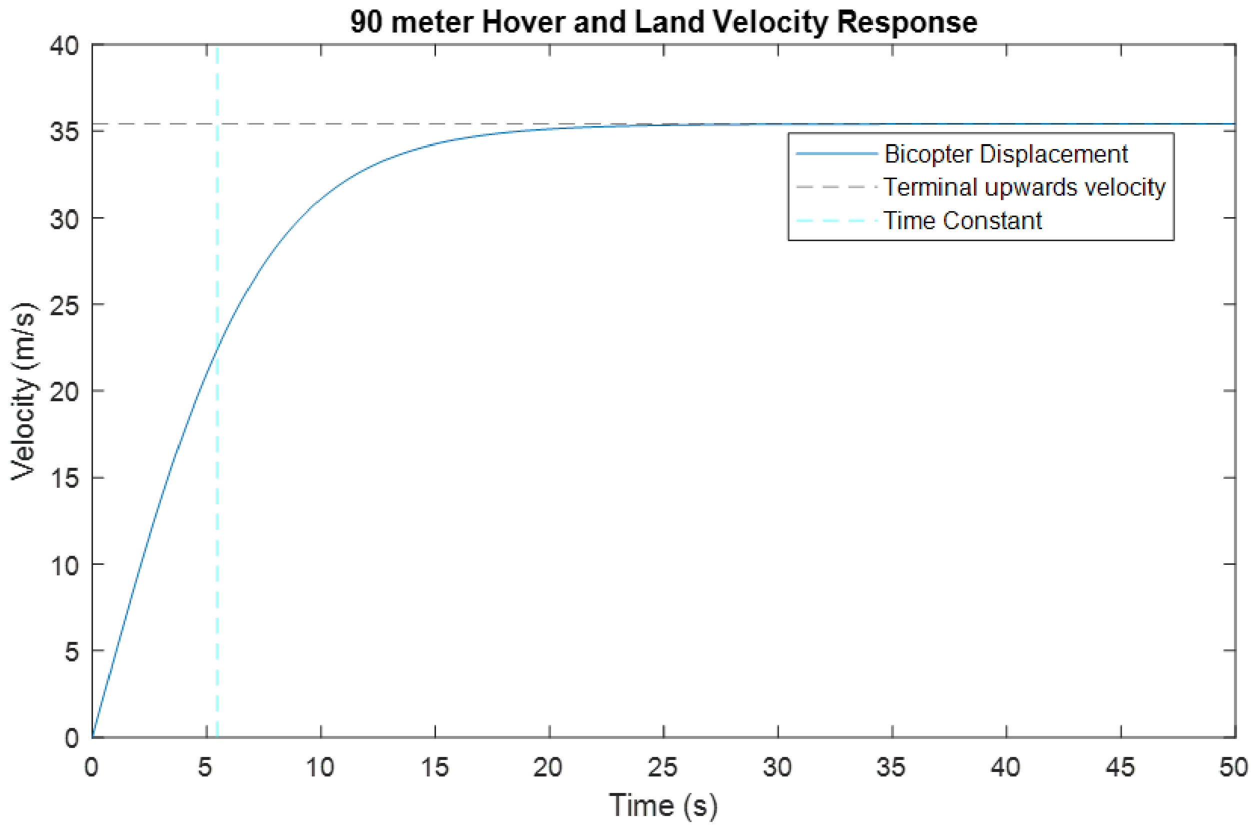

Figure 10: Bicopter velocity approaching terminal upwards velocity over 50 seconds with terminal velocity labeled.

Conclusion:

The bicopter system has been thoroughly analyzed in the scenarios that you assigned for me to consider, and the energy consumption as modeled has been characterized in the scenarios. For the 1.5 meter hover in 5 second scenario it is estimated that 17 Joules of energy is consumed by the copter. In the 90 meter hover and land scenario a total of 2100 Joules of energy is estimated to be consumed by the bicopter system. These are just estimates until a better method of measuring the energy consumed is developed, and are measures of the mechanical power with an efficiency margin multiplied to it. This is not that great of measurement of the electrical energy consumption as it doesn't account for the energy that is consumed during hovering, as mechanical energy doesn't change while hovering, and when the copter is descending with little or no electrical power being consumed by the motors the gravitational work is accounted for instead of the electrical energy which results in vast over-estimation of the electrical power during descents. But using these estimates, the 90 meter hover and land scenario can be repeated by a commonly sized drone battery approximately 29 times until the battery energy is depleted.

If you have any question about the process, the data, or if you would like specific data values please do not hesitate to contact me.

Respectfully,

Ross Smyth