Rocket Control Systems

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Contents

1 Introduction

For the first time since the U.S. space shuttle program was ended in August 2011, Americans will fly to the International Space Station on a U.S. built rocket later this year after the successful in-flight abort system demonstrated on the SpaceX Falcon 9 crew capsule demonstration on January 19, 2020[1]. This project is inspired by this turn of events.

In keeping with the theme of my courses for this quarter, I've continued to develop my understanding of the dynamics of rocket control systems. New features that were added to the model are a throttling capability to keep the rocket at just below Mach 1 speed during ascent, and the rocket is set to rendezvous with another object in orbit (say, a space station) and must match speed on approach. This project is a combination of the previously built *rocket propulsion* models that I made previously in the course, and the *guidance system* suggested model in the **Exercise 3 Instructions** (it was supposed to be).

2 Project Goal

The goal of this project is to demonstrate the speed regulation of a rocket as it approaches an object in earth orbit. The object in orbit will be at a set altitude and traveling at the orbital velocity associated with that altitude (see table of variables and calculations table below). With previous rocket propulsion models, we looked at the interplay between mass propellant, weight of the vehicle and propellant burn time with a given specific impulse, and how that impacted the vehicle's flight profile.

With this model, we've assumed that we can simplify those elements of the model. Here we will look at several given parameters for the stages of the SpaceX Falcon 9 rocket and Dragon crew capsule, and experiment with control mechanisms to regulate speed so that the crew capsule can rendezvous with the space station.

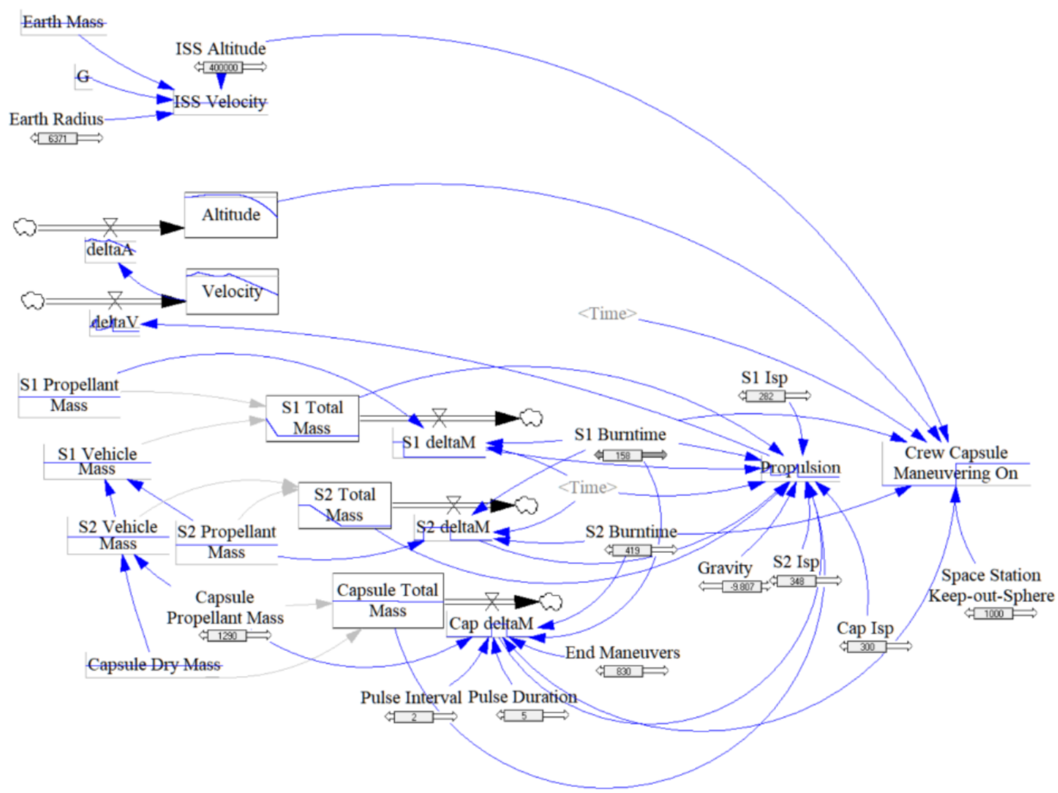
3 Reference Behavior Pattern

Figure 1: SpaceX Dragon Resupply vs Crew Missions. Provided by Everyday Astronaut and created by Declan Murphy at FLIGHTCLUB.IO[2].

With several successful space station resupply flights, there is plenty of information on the flight profiles of these missions, as shown in the above graphic. We will attempt to match the above flight profile and bring the capsule to match the space station. If successful, this will appear similar to the flight profile approaching the stable altitude of the space station.

4 Assumptions

In this model we are assuming that we can ignore most elements of the rocket flight and propulsion except for thrust, specific impulse and propellant burn time. We will also be ignoring all aspects of direction except for altitude, defined here as the distance from earth sea level. We are also assuming that given values of mass and specific impulse are sufficient for modeling purposes, and that figures for the ISS Resupply version of the capsule are similar enough to the crewed capsule parameters.



5 Model Development

This model began as an iteration on my model for Exercise 2, but with several key differences: This model utilizes a staged propulsion system in which the propellant burns out for the first stage, at which point the first stage mass is ejected from the launch vehicle, and then the process begins again after a set period of time with the second stage.

After the second stage we are left with the capsule, which will maneuver to 400 kilometers to rendezvous with the ISS. To accomplish this behavior, I replicated the mass and delta-mass components of the previous rocket model, using numbers gathered from various sources online[3,4,5]. The parameters used are based on the SpaceX Falcon 9 rocket and Dragon Crew Capsule are as follows:

Falcon 9 Specifications

Parameter	**Value**
Stage 1 Vehicle Mass	22,200 kg
Stage 1 Propellant Mass	410,900 kg
Stage 1 ISP	282 s
Stage 1 Burntime	158 s
Stage 2 Vehicle Mass	4,000 kg
Stage 2 Propellant Mass	107,500 kg
Stage 2 ISP	348 s
Stage 2 Burntime	419 s
Capsule Mass	8910 kg
Capsule Propellant Mass	1290 kg
Capsule ISP	300 s

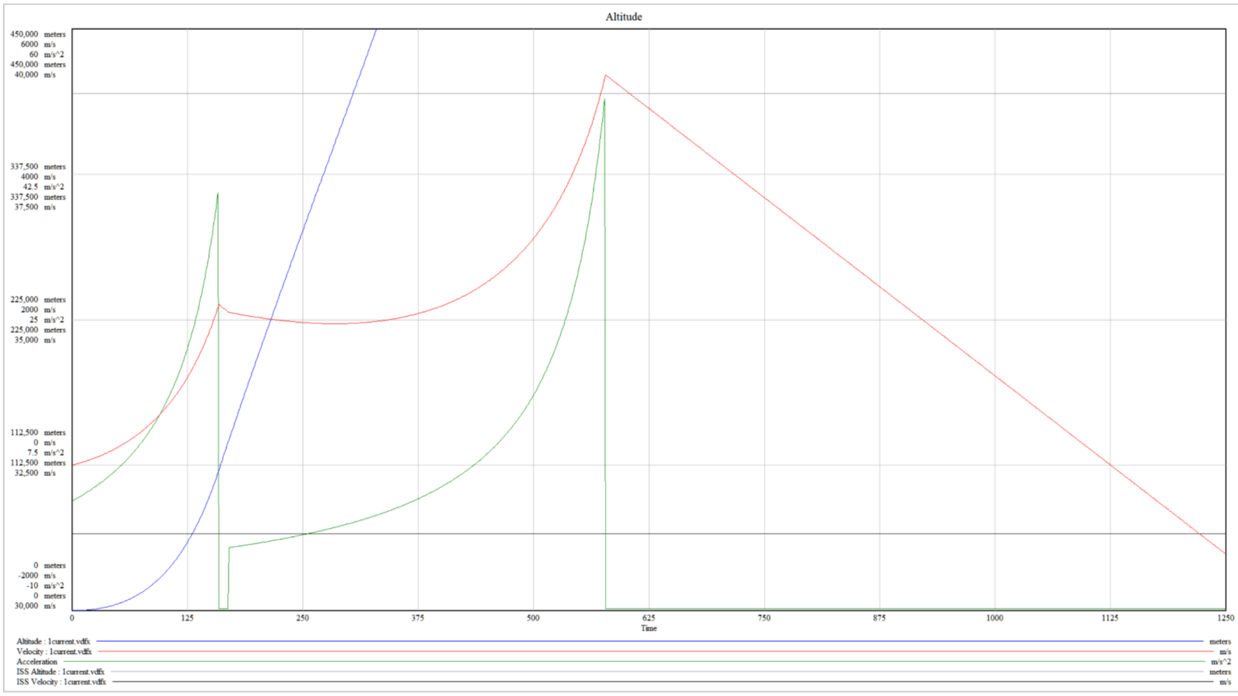
Note the lack of a given burntime for the capsule. This is because once the vehicle has been inserted into the proper stable orbit, it should only need fine adjustments to match the position and velocity of the space station. The model quickly grew to be very complex, with many feedback loops, especially between the three different stage mass flows and altitude to propulsion.

Key Equations

Propulsion	=	(Isp) * (-gravity) * (mass flow rate)/(total mass) + gravity
ISS Velocity	=	$\sqrt{\frac{G \cdot EarthMass}{EarthRadius + ISSAltitude}}$

Note that gravity is -9.806, hence the negative sign in front of it (negative * negative = positive).

5.1 Verification and Validation

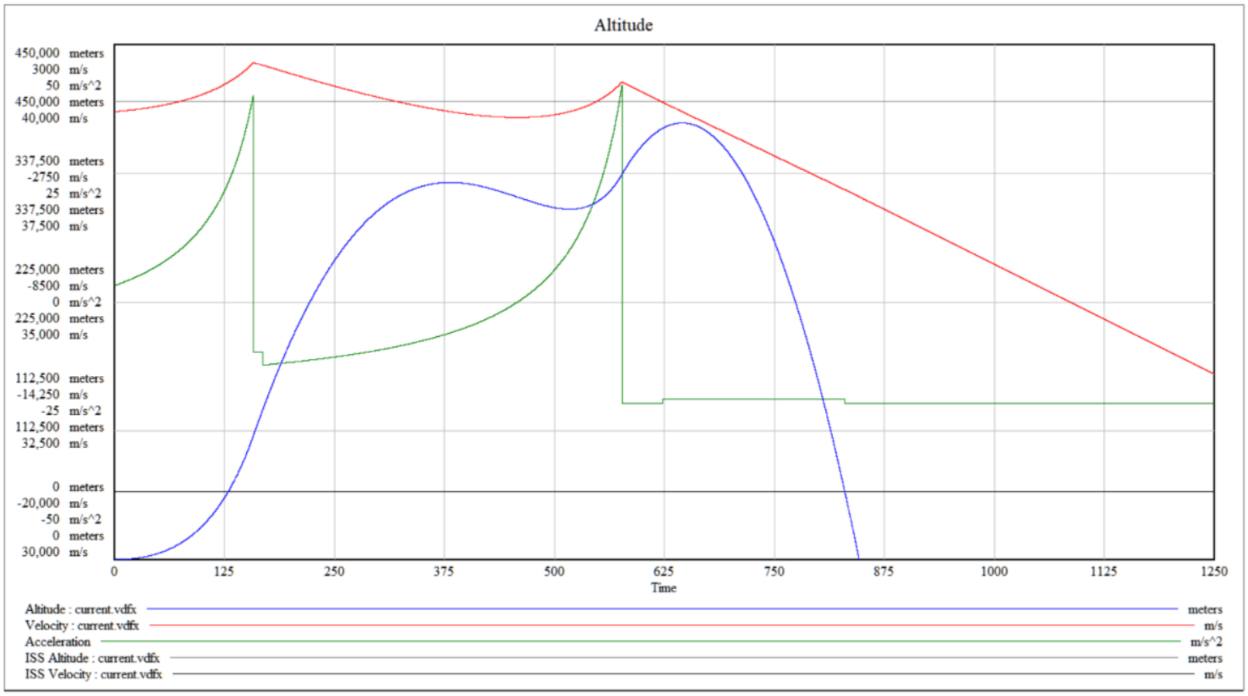


It was fairly straightforward to achieve the *type* of behavior desired from the model, but due to its complexity it took many steps to go through and make sure that the proper equations were being used with the right variables. This was especially true due to the several types of active control being forced on the model. For example, running through the propellant mass of the first stage, but remembering to reserve the propellant masses of later stages until after the burntime and an appropriate staging separation delay between engine burns. Not to mention removing the mass from prior stages from the propulsion equation.

Since I had the ideal flight profile in a graph right in front of me, I went through and frequently performed verification and validation jointly on the first and second stages of the the flight. In the graph above, we see that I had forgotten to add (subtract) gravity into the acceleration of the first stage, leading it to take off on a hyperbolic trajectory.

One key element still awaits validation as of the writing of this paper. The propulsive parameters of the dragon capsule were difficult to find, and with it now being at an orbital trajectory, it becomes clear that some elements of the model need to be changed to more appropriately model its dynamics. I didn't state the assumption that the earth is flat, as I might as well have at the beginning of this paper. Indeed it was simplest to model suborbital rockets on a "flat earth" where they simply fly up and then come back down. This was just fine for modeling both the first and second stages of the rocket here. However this did not work for the capsule, which when on its orbital trajectory, should have required more thrust to *change its orbit*, whether to increase OR decrease altitude. This is the point where Δv becomes critical in spaceflight.

6 Results



The most difficult part of the model has been the crew capsule maneuvering. At the point that the first and second stages have burned out and staged off from the capsule, the capsule is (or rather, should be) moving along an orbital trajectory. The same formulas used in the first two stages seem to work exceptionally well in getting the rocket up close to 400 kilometers (see the topmost grey line in the above graph) with the information given in the sources cited below and the expected rocket dynamics.

However, as the Acceleration curve shows (the green line), the assumed mass flow rate for the capsule was insufficient to have any meaningful effect on the altitude of the flight profile. Several attempts were made to build a control method similar to that of the thermostat model, but the capsule would run out of propellant before it could make the proper adjustments to altitude. For this reason, only the first two stages resemble the flight profile as displayed at the top of this report. I discuss why in the Verification and Validation section. Implementing the changes needed to fix the third stage will need to be future work as per time limitations.

7 Sensitivity Analysis

Actual values for the SpaceX Falcon 9 flight profile were not readily available in tabular form, only the graphs such as the one included in this report. However since the first two stages of the flight strongly resemble the actual flight profile, we can perform an analysis on the related parameters.

Parameter	Value		% Change	Max Altitude		% Change
S1 Burntime	150.1	-	5%	428918	+	9.36%
	158		Baseline	392195		
	165.9	+	5%	352209	-	10.20%
S2 Burntime	398.05	-	5%	497434	+	26.83%
	419		Baseline	392195		
	439.95	+	5%	319543	-	18.52%
S1 Isp	267.9	-	5%	271694	-	30.72%
	282		Baseline	392195		
	296.1	+	5%	390876	-	0.34%
S2 Isp	330.6	-	5%	312220	-	20.39%
	348		Baseline	392195		
	365.4	+	5%	363401	-	7.34%

Of particular interest are the values for specific impulse the burn time for each of the first two stages. We can see from the table that an interesting effect occurs with each one. With the burntime parameters, we see that the model is highly sensitive to changes of even 5%. By burning through the fuel faster, we are able to achieve a higher maximum altitude, going well above the space station (recall the goal was to reach 400 kilometers. Similarly, we see significant reductions in maximum altitude if the burntime is increased, so the burntime is inversely proportional to the maximum altitude.

We see a very different paradigm with the Specific Impulse (*Isp*) values. Here it is clear to see that the first and second stage were optimized for these specific impulse values to go along with the other given information about the Falcon 9. For those not familiar, Isp is the thrust per unit weight flow rate, and is used as an indicator of rocket performance, measured in seconds (but is NOT a time duration). So with this model, the parameters best used for tweaking to find better performances and flight profiles are the fuel burntimes.

8 Extending the Model and Future Work

Development of this model has been a challenge for every step of the way. There is a reason why "Rocket Science" is synonymous with "difficult". In this case we see it in several respects. Complexity of the control systems on multiple stages, complexity in the calculations (especially with regard to propulsion specifically), and a complete shift in dynamics when one gets too far away from the earth to treat it as the "flat center of the universe".

Future work on this model will implement the proper equations to account for the orbital dynamics (part of which include calculating gravity as a function of the gravitational constant, G, as opposed to the average acceleration due to gravity at earth sea level. To get this started, that is how I calculated the velocity of the ISS given G, the earth's mass, and its distance from the earth's center.

Extending this model further, it would be possible to calculate the full flight profile from launch to orbital insertion of a satellite, or to create hypothetical situations of more complex orbital rendezvous scenarios, such as orbital refueling of spacecraft. I have also already begun simplifying some parts of the model as I've grown familiar with its workings and relationships between parts, allowing me to trim back some of the many arrows curving across the stock and flow diagram.

9 Works Cited

[1] Clark, Stephen. "*SpaceX aces final major test before first crew mission*," Spaceflight Now, 2019. https://spaceflightnow.com/2020/01/19/spacex-aces-final-major-test-before-first-crew-mission/

[2] Dodd, Tim. "*How SpaceX and Boeing will get Astronauts to the ISS*," everydayastronaut.com, 2019. https://everydayastronaut.com/crew-dragon-vs-starliner/

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[5] "*Falcon 9 Full Thrust*," wikipedia.org. https://en.wikipedia.org/wiki/Falcon9FullThrust