USE OF A SKYCRANE TO EXPLORE THE TESSERAL REGION OF VENUS

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The Tessera (mountains) of Venus have fascinated NASA scientists for decades, but no spacecraft mission has successfully landed on these peaks. Since none of these missions have yet been feasible, researchers in this study postulated a Skycrane may be more advantageous than previously suggested methods. Thus, the practicality of using a Mars Perseverance Skycrane to land in the mountains was studied for this mission, while using the same overall design as ADEPT-VITaL. In doing so, a trajectory from Earth to Venus was first modeled in MATLAB: final velocity and flight path angle values from this trajectory strongly affect dynamics after the spacecraft enters the Venusian atmosphere. Thus, using these parameters, an Entry-Descent-Landing simulation was then modeled with events, and a final Skycrane PID controller was designed. Thrust outputs from the controller were analyzed in comparison with maximum thrust needed by Perseverance; it was found that reducing mass of the ADEPT landing system by 88% is feasible if a Skycrane were employed.

Nomenclature

ConOps	=	Concept of Operations
EDL	=	Entry-Descent Landing
EI	=	Entry-Interface
eFPA	=	Entry Flight-Path Angle
FPA	=	Flight-Path Angle
NASA	=	National Aeronautics and Astronautics Administration
ODE	=	Ordinary Differential Equation
TOF	=	Time of Flight

Introduction

This mission aims to land a Venera-class spacecraft in the Tesseral region of Venus by means of a Skycrane, using the same structure as proposed in the ADEPT VITaL mission and using the same Skycrane as used in the 2020 Mars Perseverance mission. This mission includes calculating a two-body problem trajectory from Earth to Venus, then modeling an entry-descent landing simulation of the vehicle once it reaches Venus. In studying the vehicle's dynamics as it approaches the planet's surface, it can be determined if using a Skycrane is feasible by calculating total thrust and comparing that value with maximum thrust needed by the Perseverance Skycrane.

Thus, among the millions of bodies in our Solar System, Venus was chosen for this study because this planet is full of mystery: surface temperatures can reach over 900 degrees Fahrenheit, hurricane-like winds gust up to 224 miles per hour, and the planet's retrograde rotation about its axis takes 243 Earth days.[1] More mysterious, however, is the planet's mountainous region, or Tessera. As no successful mission has explored this

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region to date, it proves ever-more fascinating to scientists: many hypothesize a thorough understanding of the Tessera could unlock the secret of Venus's volatility, greenhouse effect, or even prior life on the planet.

In Latin, Tessera means "mosaic tile;" this is aptly named due to the grid-like pattern of high peaks and low valleys that are visible in this region of the planet.[2] Early in Venus's history, these tessellations were formed by tectonic activity, specifically through continuous building and breaking of felsic rock.[2] Today, they stand between 1 to 5 km tall with slopes inclined over 30 degrees and intermittently scattered boulders.[1,2] Coupled with extreme heat and winds, these uncertain rocky conditions make for a challenging and risky landing environment. Thus, since the 1960s, it has been easier to first explore the level surface of Venus, as the technology to safely land did not yet exist.[3]

Despite marked difficulty in landing in the mountains, NASA continues to express interest in understanding the Tessera. According to the Vision and Voyages Decadal Survey of 2013 to 2022, Tessera is interesting to scientists as Venus is much like Earth. Not only are the two planets of similar density, radius, and gravitational acceleration constant; Venus specifically contains "continent-like plateaus" housing rock layers that are some of the oldest on the planet.[4,5] These plateaus are, in fact, very similar to geologic structures found on Earth, as seen in Fig. 1, but are even stranger and steeper than our own mountain ranges as there is no erosion to wear them down.[7]

It has also been hypothesized that Venus once contained a significant amount of stable water: over time, however, the once-small ocean dissipated, but scientists do not understand how this happened over time.[8] Thus, as rocks hold historical data of planetary events, scientists may be able to understand past water dissipation and may even connect that to phenomena on Earth.[5] Therefore, as these Tesseral rocks may contain much evidence for the volatility and mystery of Venus, it is imperative NASA prioritizes safe Tesseral exploration.

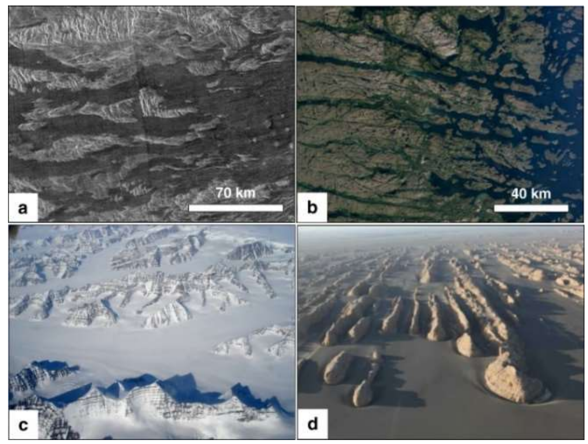

Figure 1. Images of landforms on Earth that look like Tessera on Venus. Image A is that of Venusian Tessera, image B is of Canadian fjords, image C is of Nunataks in Greenland, and image D is of the Yardang field in China.[6]

Therefore, to create a feasible path towards exploring the mountains of Venus, a Skycrane was studied due to its success in landing a Martian rover during the Perseverance mission. Additionally, ADEPT-VITaL mass estimates were re-used as ADEPT refined several previous Venusian lander designs. In the case of a Tesseral Venusian landing, a Skycrane has already proven itself to be more precise in accounting for uneven ground and steep inclines than previously postulated landing methods. Thus, in implementing a Skycrane, the risk level of a mountainous landing is reduced significantly: safer sites include those lacking large boulders or intense inclines that could lead to catastrophic mission failure.

Thus, the first step in testing feasibility of a Skycrane was to design a patched-conic approximation and coplanar rendezvous in MATLAB; doing so simulates a trajectory from Earth to Venus. Once the end conditions of the trajectory are known, critical inputs to the next phase of the problem can be implemented to model entry-descent landing (EDL). Specifically, these inputs were velocity at the entry interface (EI) and entry flight path angle (eFPA), as, in a curvilinear reference frame, they act as controls to the atmospheric dynamics of the spacecraft. Additionally, refining the trajectory reduces mission risk and may cut monetary costs, such as reducing payload mass at launch. Finally, in designing these trajectories, engineers can better understand the correct launch window, time of flight (TOF), semimajor axis of the transfer, and wait time without having to wait through several runs of tedious programs.

Between the Earth-to-Venus trajectory and the EDL phase, these different dynamical equations can be discussed in a more refined scope, as seen in Fig. 2. Figure 2 shows a flow of specific trajectory milestones from the patched-conic approximation to safe landing of the payload. These milestones have all been daisy-chained together using events in MATLAB and a PID controller in Simulink.

To test whether a Skycrane would be feasible, approximately 88% of the landing system mass from ADEPT-VITaL was removed in the trajectory and EDL phases and instead replaced with a Skycrane. Final Thrust values from Perseverance versus this Skycrane study were then compared; if the thrust value in this study was calculated to be lower than that of Perseverance, this design would be feasible.

While a successful trajectory has been planned and thrust values calculated, some future work exists to further optimize this Skycrane simulation, entailing designing the Skycrane to utilize quadcopters and batteries versus liquid fuel and thrusters.

MATLAB Work

A. Rendezvous and Patched-Conic Approximation

Throughout this research project, MATLAB was used to write programs to help researchers successfully create a scenario where a Skycrane landing is viable. This code has three important milestones: the two-body problem, interaction with the EI, and the EDL simulation. It was therefore prudent to first begin with knowing the velocity at the EI and the eFPA at the EI; these parameters are inputs to the EDL, and act as controls to optimize the entry trajectory. So, researchers had to first create a function that runs through the two-body problem from Earth to Venus to calculate the spacecraft's velocity at the EI.

Thus, to begin the patched-conic approximation, it was first assumed that, after launch, the initial parking orbit of the spacecraft around the Earth is 600 km and that the Venusian atmosphere, or the EI, is

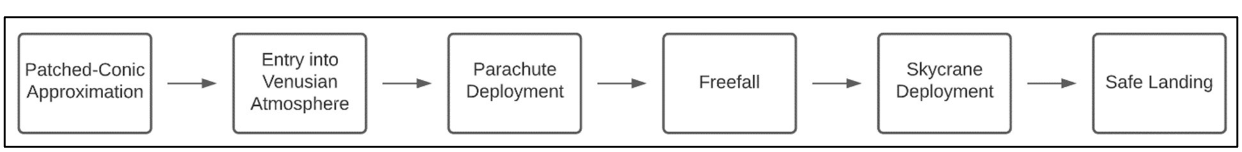

Figure 2. Flow of general concept of operations (ConOps), from the patched-conic approximation (or two-body problem) to interaction with the EI, to landing on the surface of Venus.

located at 150 km. The latter altitude value marks the beginning of the EDL simulation and is critical in calculating entry FPA and optimal g-loading on the spacecraft, which will be discussed later. Additionally, necessary constants were noted, such as the gravitational parameter of the Sun, Earth, and Venus; the semimajor axis of Earth's and Venus's orbits; the linear velocity of the Earth and Venus; and the angular velocity of the Earth and Venus.

After defining all necessary constants, a coplanar rendezvous with a Hohmann transfer was developed to plan the overall Earth to Venus trajectory. Using a Hohmann Transfer reduces overall TOF and ΔV, thus also reducing fuel and mass. Therefore, in this coplanar rendezvous, the TOF, lead angle, impulse angle, wait time, and transfer semimajor axis were calculated to calculate the spacecraft's dynamics in the Sun's frame of reference.

Next, necessary parameters in the Sun's reference frame were calculated; necessary inputs include the semimajor axis of the Earth and Venus, as well as that of the Earth-to-Venus transfer and the gravitational parameter of the Sun. Necessary outputs, on the other hand, include velocity of the transfer about Earth and Venus in the Sun's frame of reference, as well as the energy of the transfer. To calculate these outputs, the following equations were used:

$$E_T = \frac{-\mu_\odot}{2a_t} \tag{1}$$

$$V_{T1\odot} = \sqrt{2(E_T + \frac{\mu_\odot}{r_{t1}})} \tag{2}$$

$$V_{T2\odot} = \sqrt{2(E_T + \frac{\mu_\odot}{r_{t2}})} \tag{3}$$

Where $\mu_\odot$ is the Sun's gravitational parameter, a_t is the semimajor axis of the transfer, r_{t1} is a the semimajor axis of Earth's orbit, and r_{t2} is the semimajor axis of Venus's orbit.

After studying the Sun's frame of reference, it was prudent to study Earth's to calculate ΔV in the Earth's frame. Thus, important inputs to consider were gravitational parameter of the Earth ($\mu_\oplus$), transfer velocity at Earth in the Sun's frame ($V_{T1\odot}$), semimajor axis of Earth's orbit ($a_\oplus$), gravitational parameter of the Sun ($\mu_\odot$), and the parking orbit altitude around the Earth, which was defined earlier on as 600 km. Thus, in calculating ΔV, the parking orbit altitude was converted to radius from the center of the Earth by adding 6387 km (called $r_{0\oplus}$ below). Thus, the following functions were utilized for the ΔV calculation:

$$\mathrm{V_{c\oplus}} = \sqrt{\frac{\mu_\oplus}{\mathrm{r_{0\oplus}}}} \tag{4}$$

$$\mathrm{r_{SOI,\oplus}} = \mathrm{a_\oplus}(\frac{\mu_\oplus}{\mu_\odot})^{2/5} \tag{5}$$

$$\mathrm{E_{T\oplus}} = \frac{\mathrm{V_{T1,\oplus}}^2}{2} - \frac{\mu_\oplus}{\mathrm{r_{SOI,\oplus}}} \tag{6}$$

$$\mathrm{V_{0T\oplus}} = 2(\frac{\mu_\oplus}{\mathrm{r_{0\oplus}}} + \mathrm{E_{T\oplus}}) \tag{7}$$

Where $V_{c\oplus}$ is the circular velocity of the Earth about the Sun, $r_{SOI,\oplus}$ is the radius of the Earth's sphere of influence, $V_{T1,\oplus}$ is the velocity of the transfer in Earth's frame of reference, $E_{T\oplus}$ is the energy of the transfer in Earth's frame, and $V_{0T\oplus}$ is the rearranging of the energy equation to find the velocity after the transfer occurs. By then taking the absolute value of the difference between $V_{0T\oplus}$ and $V_{c\oplus}$, the first ΔV calculation was made, totaling approximately 3.38 km/s.

Next, to zoom in on Venus's frame of reference, a similar algorithm was used, but in this case to solve for the energy of the transfer in Venus's reference frame. Gravitational parameter of Venus ($\mu_♀$), transfer velocity at Venus in the Sun's frame ($V_{T2,♀}$), semimajor axis of Venus's orbit ($a_♀$), gravitational parameter of the Sun ($\mu_\odot$), the EI radius ($r_{3♀}$), and the radius of Venus in kilometers ($r_♀$) were all necessary inputs in this calculation. Thus, the following equations were used:

$$V_{c♀} = \sqrt{\frac{\mu_♀}{r_{3♀}}} \quad (8)$$

$$r_{SOI,♀} = a_♀(\frac{\mu_♀}{\mu_\odot})^{2/5} \quad (9)$$

$$E_{T♀} = \frac{{V_{T2,♀}}^2}{2} - \frac{\mu_♀}{r_{SOI,♀}} \quad (10)$$

Since $E_{T♀}$ was calculated, the velocity at the entry interface could also be calculated using conservation of energy between the end of the two-body problem and the beginning of the EI problem. Thus, both energy equations were set as equal then algebraically solved for velocity, which was calculated to be approximately 10.5 km/s. Recall this velocity is a crucial parameter for EDL design as it acts as a control for the spacecraft's descent.

<u>B. EDL Simulation and Events</u>

Once velocity at the EI was calculated, it was prudent to find eFPA of the spacecraft as this quantity has direct effect on maximum loading on the vehicle; once found, an EDL simulation could commence. In this EDL simulation, is important to note that mass values were recycled from ADEPT VITaL; mass of the landing system was not used, however, as researchers aimed to test if a Skycrane could be feasibly used in place of this system to save weight. Drag coefficient and lift coefficient were given reasonable values, and parachute area was recycled from the original VITaL mission.[9]

Therefore, next in calculating eFPA values was to study a state-time integration over four curvilinear dynamics ordinary differential equations (ODE), as seen below. Within these dynamics, the following initial conditions are initialized: time, state, drag coefficient, lift coefficient, mass, surface area, gravitational constant, mass of Venus, and radius of Venus. Once initialized, the gravity inverse square law was used to determine changing gravitational acceleration as the lander approaches the surface, a density function was created to create an atmospheric model of Venus from 0 km to 150 km, and lift and drag equations were created using gravity inverse square law, the atmospheric model, lift and drag coefficients, and state velocity of the falling spacecraft.

$$\frac{dv}{dt} = -\frac{D}{m} - gsin(\gamma) \quad (11)$$

$$\frac{d\gamma}{dt} = \frac{1}{v}(\frac{L}{m} - (g - \frac{v^2}{r}))cos(\gamma) \quad (12)$$

$$\frac{dr}{dt} = \frac{dh}{dt} = vsin(\gamma) \quad (13)$$

$$\frac{ds}{dt} = \frac{Rp}{r}vcos(\gamma) \quad (14)$$

It was then important to study the effect FPA has on g-loading, as understanding max-g helps with optimal structural design. It was found that the eFPA from ADEPT-VITaL was calculated to be neg. 8.25 degrees, but researchers wanted to know if that value was feasible.[11] Thus, in deciding an optimal FPA and checking if the eFPA from ADEPT-VITaL was best for this mission, a trade study was completed using FPAs ranging from -5 degrees -75 degrees. Each FPA—along with calculated values of radius (radius of Venus plus 150 km), velocity at the EI (10.5 km/s), and arc length (0 m)—was used as an initial condition while integrating the four above ODEs. Thus, eight altitude-versus-deceleration curves were created and plotted, as can be seen in Fig. 3. From this plot, it can be determined that entering the EI at a shallow eFPA means the body will experience far less g-loading than entering at a steep eFPA. However, entering at too small eFPA could cause the spacecraft to skip off the atmosphere. Thus, future work includes refining the trade study along with completing a ballistic coefficient parametric study and determining which FPAs cause the spacecraft to skip. Despite this, the above trade study still proved the feasibility of eFPA calculated by ADEPT VITaL; resulting g-loading from this FPA would be far less than its higher-FPA counterparts. Researchers therefore had quantities for both initial conditions needed to run the EDL simulation and began constructing events.

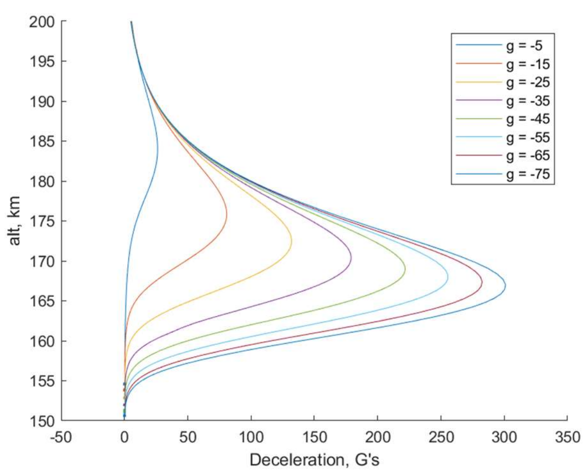

Figure 3. Plot of spacecraft altitude (km) versus deceleration; each curve represents a different eFPA as specified in the legend. “g” represents γ

The EDL simulation contains three events, including freefall with the aeroshell, parachute deployment without the aeroshell, and Skycrane deployment with touchdown. Specifically, mass of the lander and aeroshell were utilized from the ADEPT-VITaL mission, mass of the Skycrane was reused from the Perseverance Mission, and drag coefficient, lift coefficient, drogue reference area were each given reasonable values based on past missions.[9,10]

The first event, freefall, occurs directly after the spacecraft interacts with the EI. At this point, the dynamics of the two-body problem are no longer valid as aerodynamics take effect on the body. Thus, the new dynamics include the four curvilinear ODEs and the density atmospheric model. In creating the first event, researchers focused closely on this atmospheric model; values in the model originate from studies conducted by the Academy of Athens.[12] To create the model, arrays of local density and scale height were interpolated over the entirety of the Venusian atmosphere using the following equation:

$$\rho = \rho_0 e^{-\frac{\mathrm{alt} - \mathrm{h}_0}{\mathrm{H}_0}} \tag{15}$$

where, ρ is desired density, ρ_0 is the local density, alt is desired altitude, h_0 is real altitude value, and H_0 is scale height. Therefore, an approximate plot of atmospheric density over altitude is shown in Fig. 4. Once Fig. 4 was understood and interpolation complete, values for rho were used in calculating lift and drag of the body, as needed by the four dynamics functions. At this point, the dynamics could once more be integrated until the termination of the event; researchers selected this to be Mach five.

This specific Mach number was chosen by evaluating Fig. 5 below; the terminating condition was chosen well after peak Mach number so the parachutes do not burn upon deployment and lead to catastrophic mission failure. So far as future work, which will be discussed later, a study of loads on the body may be conducted based on entry g-loads; therefore, the terminating Mach number can be refined as needed. At this point, M = 5 was maintained as it was on the same order of magnitude as ADEPT VITaL.[9]

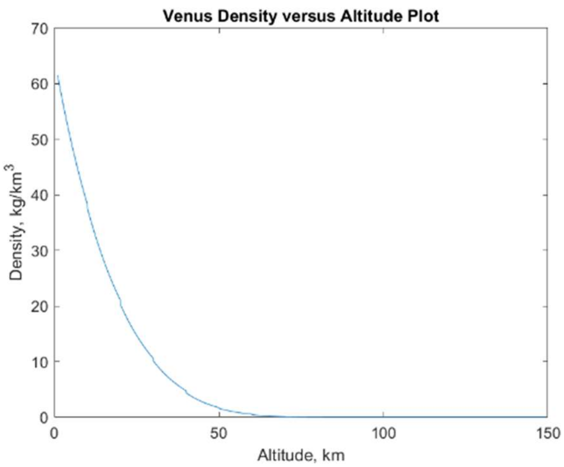

Figure 4. Plot of Density, in kg/km^3, over Altitude, in km. This is a model of atmospheric density of Venus that shows what a spacecraft experiences after EI interaction.

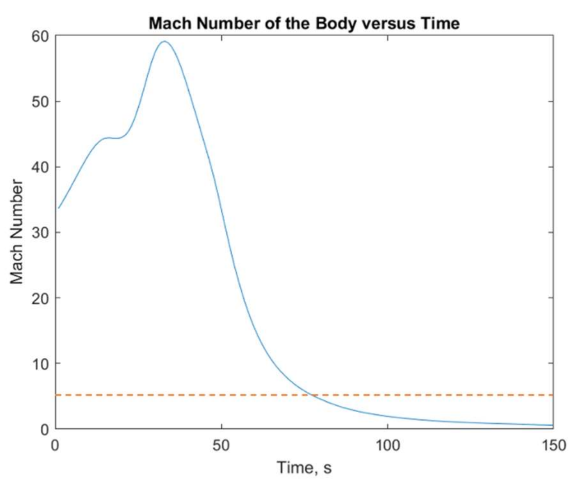

Figure 5. Plot of Mach number versus time, in seconds, represented by the blue curve. The red dashed line is M = 5, where the event terminates.

Once the terminating Mach number was chosen, it could be applied to the first event. Fig. 6, which models altitude over time, plots the solved ODE until termination. Notice that the derivative of the curve is constant until it reaches a steep change. This steep change accounts for extreme frictional effects acting on the body from high Mach number, which in turn leads to extreme heating. Once the change has been complete for approximately 25 seconds, the time window for drogue deployment has opened, thus leading to the next event. This peak heating is modeled with two vertical dashed lines in the figure.

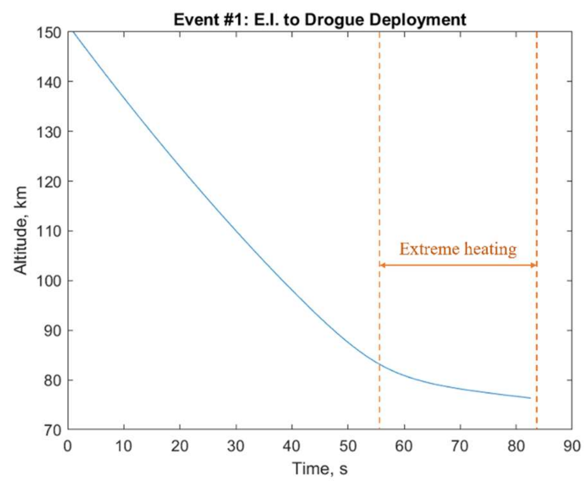

Figure 6. Plot of Altitude over time, in seconds, of the first event. The blue curve is altitude over time of the spacecraft. Red dashed lines represent extreme heating.

Once the first event terminates, the parachute is immediately deployed, signaling the start of Event 2. These parachutes remain deployed until an altitude of 5 km above Venus's "sea level," which, in reality, is approximately 2 km above Venus's Tessera; this assumes the mountains within this region are 3 km tall. Termination at 2 km was chosen because Perseverance also began Skycrane deployment at this altitude, allowing ample time for the Skycrane to deploy and thus to select an optimal landing location.[13] Within the second event, other than increasing area and drag to account for the parachutes and decreasing mass to account for the dropped aeroshell, the ODE integration remained the same, daisy-chaining final outputs of radius, velocity, FPA, and arc length from Event 1 as inputs to the dynamics. The resulting trajectory of the lander can be seen in Fig. 7.

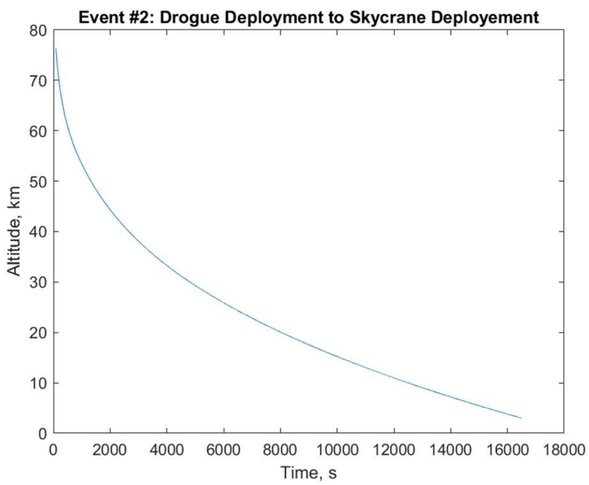

Figure 7. Plot of freefall with parachutes. The x-axis shows altitude of the spacecraft in km over time on the y-axis in seconds. This event terminates at an altitude of 5 km.

C. Controller Design

The final outputs of the second event were then used as inputs to the third and last event, which is Skycrane deployment and landing. Modelling this section of the simulation was different, as Simulink was applied to a different dynamical model: a cartesian frame of reference was used, as opposed to the previous four curvilinear ODEs. Implementing a cartesian frame, in this case, was simply easier to model. Therefore, the final outputs from Event 2 had to be modified to include initial x- and y-location, and initial velocity in the x- and y-directions. Additionally, initial specific thrust values had to be included. Therefore, the new dynamics model required six inputs. To calculate the first four inputs, initial arc length was set to zero, and initial height to the terminating condition of Event 2 was implemented. Then, sines and cosines of FPA were used to break down the velocity state from Event 2. Within the dynamics, drag in x and y on the body could be calculated in terms of ballistic coefficient, assuming high ballistic coefficient and the density atmospheric model:

$$\mathrm{D}_x = -\frac{\rho}{2\beta}\mathrm{v}_x{}^2 \tag{16}$$

$$\mathrm{D}_y = \frac{\rho}{2\beta}\mathrm{v}_y{}^2 \tag{17}$$

Where, ρ is atmospheric density, β is ballistic coefficient, v_x is velocity in the x-direction, and v_y is velocity in the y-direction. Initial acceleration values were given reasonable user-defined inputs. Then, using these drag quantities along with ballistic coefficient, acceleration in the x- and y-directions were computed by using a mass-normalized form of F = ma, as seen in equations 18 and 19:

$$a_x = \mathrm{D}_x + \mathrm{T}_x \tag{18}$$

$$a_y = \mathrm{D}_y + F_g + \mathrm{T}_y \tag{19}$$

Where, D_x specific drag in the x-direction, D_y is specific drag in the y-direction, T_x is specific thrust in the x-direction, T_y is specific thrust in the y-direction, and F_g is specific gravity.

These four quantities of accelerations and velocities were then used as inputs to a PID controller aiming to minimize Skycrane thrust while also minimizing displacement overshoot in the x- and y-directions. The controller is set to terminate at an altitude of 3000 m, which is the assumed height of the Alpha Regio mountain range, and an x-location of 50 m, which was chosen as a reasonable estimate. As seen in Figs. 8 and 9, the maximum overshoot in the x-direction is approximately 25 m and the maximum overshoot in the y-direction is approximately 6 m; this was the most optimal choice in keeping thrust values low.

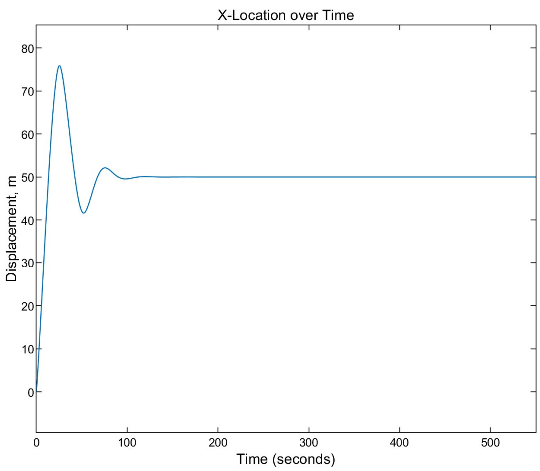

Figure 8. Plot of x-location (m) over time (seconds), tuned by PID controller.

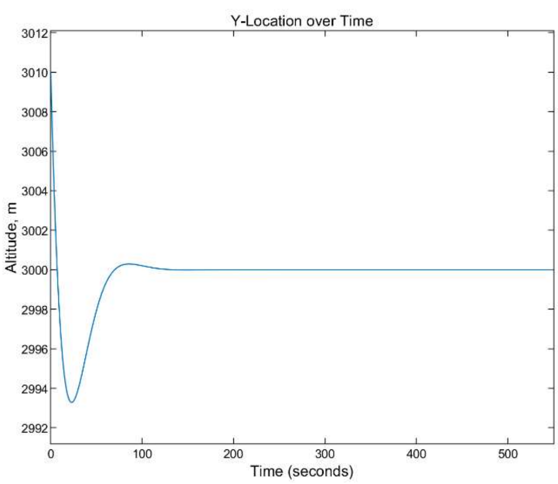

Figure 9. Plot of y-location (m) over time (seconds), tuned by PID controller.

With these values in mind, it was necessary to calculate thrust as a force, using final acceleration values from the controller. Thus, at the end of the simulation, all acceleration outputs of the controller were saved: the norm of each x and y pair was then calculated, and the maximum normalized acceleration was found. Then, the total maximum thrust required could be calculated using F = ma. The mass term in this equation is the mass of the spacecraft at the end of Event 2—or the lander, Skycrane, and landing gear—and the normalized acceleration. In this calculation, the total necessary thrust for this mission was 21,877 N.

It was then necessary to compare this thrust value with the maximum thrust needed by the Perseverance Skycrane, which had eight thrusters that could each throttle to 3,300 N.[13] Multiplying these two numbers to calculate the total necessary thrust yields 26,400 N. Thus, since the max necessary thrust of this research project was less than that of the Perseverance Skycrane, using this method in landing in a pressure vessel in the Venusian mountains is feasible.

Future Work

Some future work exists in optimizing the design of the Skycrane, as this study assumes the same design is carried over from the Perseverance mission. This optimization may include cutting weight, adding shielding to protect instruments from the harsh surrounding climate, and performing a trade study on whether thrusters with fuel or quadcopters with batteries performs best on Venus.

More future work also entails refining the altitude versus deceleration trade study. This study range from FPAs of -5 degrees to -75 degrees. However, based on the eFPA proposed by ADEPT-VITaL, it may be best to try FPAs ranging from -1 degree to -10 degrees. Additionally, including a ballistic coefficient parametric study would be reasonable, as well as conducting a study of which of the above FPAs skip off the Venusian atmosphere.

Finally, some work could be done in structurally designing the lander according to g-loads it experiences upon entry. This may help refine the terminating Mach number of Event 1.

Conclusion

Venus has fascinated scientists for decades in its atmospheric, orbital, and geologic mysteries. Embedded in its ancient rock formations, the Tesseral region may hold explanations to these mysteries; however, previous mission concepts have not yet been feasible. Thus, in creating a feasible option for landing a payload on Venus, a Skycrane was chosen for its past success on Mars. To mathematically determine feasibility, MATLAB was used to first design a two-body problem trajectory from Earth to Venus, then to use those outputs as control inputs to an EDL simulation and a PID Skycrane controller. Analyzing thrust outputs from the controller and comparing those with the thrust used by the Mars Perseverance Skycrane, it was determined that landing a vessel in the mountainous regions of Venus by means of a Skycrane would be feasible. Thus, in using a Skycrane to explore the Tessera, scientists may finally be able to provide explanations to the mysterious nature of Venus.

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