Astro 423 Final Project

Fall 2024

You are an orbital analyst supporting the current mission for the X-37C, the USSF's next-generation reusable spaceplane. As the mission unfolds, there are three phases which require your input to plan trajectories to be flown and maneuvers to be executed:

- Phase 1 – RPO: Following launch, the X-37C is placed into a Geosynchronous transfer orbit. When reaching apogee, a pre-planned delta-V is executed to place the X-37C in Geostationary orbit 50km in front of USSF's new refueling hub. The Ops team for the refueling hub notifies you that telemetry indicates the hub may have recently been hit by a micrometeoroid. Consequently, you must design an RPO trajectory to inspect the hub before ultimately ingressing to 50 m in front of the Hub at which point an automated guidance system takes over to dock and refuel.
- Phase 2 – 3-Body Problem: After refueling, the X-37C will enter a cislunar trajectory that transfers to a periodic orbit, allowing the X-37C to serve as a communications relay for a US surface drone on the far side of the Moon gathering regolith and ice samples. After the collection mission is complete, a separate sample return craft delivers the regolith to the X-37C. Before the X-37C departs back for Earth, NASA is contacted by the European Space Agency (ESA). ESA has a craft headed toward the Moon loaded with supplies to support the Artemis mission on the Moon's surface – they would like the X-37C to observe the inbound craft as it enters an L1-centered periodic orbit, pauses, then shortly after lands on the daylight side of the Moon, near the equator.
- Phase 3 – Re-entry: The X-37C will then return the Lunar regolith samples to the surface of Earth. Scientists will use the water ice to demonstrate the validly of manufacturing hydrogen and oxygen rocket fuel on the moon, and the regolith to test additive manufacturing habitats. Due to the sensitivity of the cryogenic science equipment holding the water ice the X-37C must reenter on a trajectory that limits both acceleration and vehicle heating.

Your specific tasks for each phase of the mission are detailed below.

Phase 1: RPO

Mission Brief

1. Your mission planning starts when the X-37C arrives in Geostationary orbit at 1500Z on 21 March 2025. The X-37C arrives 50 km ahead of the refueling hub, which is stationed over 75^{o} West Longitude. You may use the HCW model for your mission planning. You may assume one day and one period of a Geostationary orbit are exactly 24 hrs long for your calculations.
2. Calculate ΔVs to enter a 1km x 2km NMC (C=0.5 km) for initial inspection using visual sensors, centered at the refueling hub.
    a. The NMC should have Z_{max} = 100 m, with the position of Z_{max} in the NMC chosen to maximize the safety of the initial NMC.
    b. The maneuvers to accomplish the ingress and NMC should be designed to:
        i. Allow the X-37C to enter the NMC no later than 2.5 days after arriving in GEO
        ii. Ensure appropriate lighting for inspection with a visual sensor (CATS near 0^{o} within the X-Y plane).
        iii. Utilize less total ΔV if multiple maneuver options are feasible*
    c. The X-37C must remain outside of a spherical keep out zone centered on the refueling hub with a radius of 400 m at all times during this initial phase of the ingress and inspection.

3. The X-37C must complete two complete revolutions in the initial inspection NMC to ensure sufficient time for inspection.
4. The initial inspection reveals that the docking port on the +y face of the refueling hub may have been damaged by the micrometeoroid strike. Calculate delta-Vs needed to modify your trajectory to a 0.1x0.2km NMC (C=0.05 km) centered on the refueling hub with Z_{max}=0 km to obtain a closer look at the +y face using an on-board LIDAR system.
    a. During this phase of the mission, the X-37C must remain outside of a spherical keep out zone centered in the refueling hub with a radius of 40 m at all times.
5. After two complete revolutions in the new NMC, data from the secondary inspection reveals that all is well. Calculate ΔVs needed to ingress and park at 50m in front of the refueling hub, at which point an automated system will take over to complete the refueling and docking.
    a. During this phase of the mission, the X-37C must remain outside of a spherical keep out zone centered in the refueling hub with a radius of 40 m at all times.
6. Ensure you report the total amount of ΔV used in the ProxOps portion of the mission.

* Consider if multiple times of flight will yield the desired trajectory given the constraints and calculate a few options to try to reduce delta-V. You do not have to perform any type of optimization or in-depth analysis to minimize delta-V.

Phase 2: 3-Body Problem

Mission Brief

1. As an USSF orbitologist, you are responsible to estimate the minimum delta-V required to get from the refueling orbit to the periodic orbit for the comm relay mission:
    a. Assume that when you are to initiate the transfer, the X-37C is on the 3BP negative X-axis.
    b. Convert between frames and non-dimensionalize the initial state of the X-37C.
    c. Compute the Jacobi Constant of the X-37C initial state.
    d. From the NASA JPL 3BP website, select three periodic orbits that will possibly support your communication relay mission. (note: do not pick orbits that are nearly the same, pick a diverse set) Discuss pros/cons of each of the three orbits and select one of the three for your mission.
    e. For your selected orbit, integrate it forward in time for a full period. Then calculate the distance from the orbit to the Earth (assume a ground station on Earth's surface on the X-axis is always visible). Find the minimum and maximum range – comm engineers will use this information to determine if the link budget will close.
    f. Compare the Jacobi Constant of your initial orbit with the Jacobi constant of the L2-centered periodic orbit. Use the two Jacobi constants to estimate the minimum required delta-V.
2. Your orbitology skills are needed again and you are providing a new trajectory to get the X-37C to an L1-centered periodic orbit. You want to estimate delta-V again first to determine if your periodic orbit is feasible.
    a. From the NASA JPL 3BP website, select three periodic orbits that will possibly support your ESA Supply Ship observation mission. (note: do not pick orbits that are nearly the same, pick a diverse set) Discuss pros/cons of each of the three orbits and select one of the three for your mission.
    b. Compare the Jacobi Constants of your two periodic orbits (L1-centered and L2-centered) and estimate the minimum required delta-V.
3. Return to a 300 km altitude circular LEO, on the positive X-axis. Compute the minimum delta-V between the ESA Supply Ship observation orbit and the LEO state, using Jacobi Constant as above.

4. Compute the minimum total delta-V for the three 3BP phases outlined above.
5. Other constraints:
   a. During the comm relay mission, the Moon cannot block the X-37C's line of sight to Earth.
   b. For the ESA Supply Ship observation mission, ESA would like the X-37C to be located in the 3BP X-Y plane to minimize any minute chance of collision, as the ESA supplies will be placed near the lunar north pole for access to lunar ice fishing.
6. Ensure you report the total amount of ΔV used in the 3BP portion of the mission.

Phase 3: Re-Entry

Mission Brief

1. After returning from the Moon, the X-37C will be in a 300 km circular orbit and must land safely on Earth with all science equipment intact as quickly as possible.
   a. Vehicle Characteristics:
      i. Constant value of $C_D = 2$
      ii. Constant value of S = 100 m^2
      iii. Constant value of m = 6000 kg
      iv. $0 < \frac{C_L}{C_D} < 6.6$
   b. Assumptions
      i. β =0.14 km^{-1}
      ii. $r_0 = 6418.137\ km$
      iii. $\rho_s = 1.225\ kg/m^3$
      iv. $g_s = 9.81\ m/s^2$
   c. Constraints
      i. $\dot{\bar{q}}_s < .005$
      ii. $\left(\frac{a_{decel}}{g_0}\right) < 20$
2. Using your knowledge of astrodynamic reentry and the first order closed-form solutions, choose and defend a reentry trajectory. The two areas of deceleration and heating will be used to access the reentry.
   a. Pick values for $\frac{C_L}{C_D}$ and γ_e which meet the constraints.
   b. Deceleration
      i. What does the deceleration profile look like?
      ii. What is the maximum and where does it occur (solve for γ_*)?
   c. Heating
      i. What does the non-dimensional stagnation heat flux $\dot{\bar{q}}_s$ look like?
      ii. What is the maximum and where does it occur (solve for γ_*)?
3. Compare the first-order solution used to pick the reentry trajectory, $\frac{C_L}{C_D}$ and γ_e values to the full numerically integrated solution.
   a. Plot both the first-order solution and numerically integrated solution for $\boldsymbol{\eta}\ vs\ \left(\frac{\boldsymbol{a_{decel}}}{\boldsymbol{g_0}}\right)$ and $\boldsymbol{\eta}\ vs\ \dot{\bar{\boldsymbol{q}}}_{\boldsymbol{s}}$ clearly labeling the maximum values.

Submission Requirements

Turn-in Requirements

You are required to summarize your mission plan in a well-organized set of PowerPoint charts. Beyond the technical content, include a title slide, an overview, a conclusion and a final chart with your contact information. A PowerPoint template is provided on the Microsoft Team and must be used. You must also submit a typed (a Jupyter Notebook and/or Matlab Live Script would work well), or neatly handwritten set of calculations showing the work done to develop planned maneuvers. Finally, all code written or utilized in completing this project must be printed and turned in.

Your mission plan must address the following information:

RPO Phase: (30 pts)

- (5 pts) Maneuver plan for ingress to initial inspection NMC
- (2 pts) Calculations and/or diagrams demonstrating desired lighting conditions are obtained
- (2 pts) Considerations made to reduce total ΔV required
- (5 pts) Maneuver plan for transfer from initial NMC to secondary inspection NMC
- (4 pts) Maneuver plan for transfer from secondary inspection NMC to final parking position
- (5 pts) Appropriate, clear computer generated plots showing trajectories and other data to demonstrate that all stated mission objectives are obtained, and all constraints are satisfied (e.g., separation distances).
- (3 pts) Clear and accurate hand-written or typed calculations for this mission phase
- (2 pts) Appropriately documented code, including all functions utilized for your calculations and plots
- (2 pts) Answer the following question: Given that your mission plan was developed using the HCW model, explain any concerns you have with the validity of your solution. What steps would you recommend taking to refine your mission plan prior to implementation?

3BP Phase: (30 pts)

- (3 pts) A copy of all functions utilized for your calculations.
- (4 pts) Results for minimum required delta-Vs for all three phases and total
- (6 pts) Minimum and maximum range for communication distances from selected L2-centered periodic orbit
- (3 pts) Rationale for why you selected your chosen mission orbits
- (4 pts) Plots for comm relay mission periodic orbit options.
  - 1 3D plot with the three L2-centered periodic orbit options
  - 1 2D X-Y plot with the three L2-centered periodic orbit options
  - 1 2D X-Z plot with the three L2-centered periodic orbit options
  - 1 2D Y-Z plot with the three L2-centered periodic orbit options
- (4 pts) Plots for ESA support periodic orbit options.
  - 1 3D plot with the three L1-centered periodic orbit options
  - 1 2D X-Y plot with the three L1-centered periodic orbit options
  - 1 2D X-Z plot with the three L1-centered periodic orbit options
  - 1 2D Y-Z plot with the three L1-centered periodic orbit options
- (4 pts) Plots for selected L1-centered and L2-centered periodic orbits
  - 1 3D plot with the two periodic orbits

    - 1 2D X-Y plot with the two periodic orbits
    - 1 2D X-Z plot with the two periodic orbits
    - 1 2D Y-Z plot with the two periodic orbits
- (pts assigned in "other" below) Plot requirements:
    - All plots must have a title and axes labels
    - All plots must include a full period of each periodic orbit
    - 2D plots must have a Moon at proper scale or scaled with identified scaling
    - 2D plots must have legend identifying which trajectories are which
- (2 pts) Answer the following questions:
    - If the X-37C is trying to save fuel, should you select smaller or larger periodic orbits?
    - If you were to try to develop a trajectory connecting the two period orbits, highlight how you might go about it (hint: we did not cover this fully in class, so this is a bonus question for you to research briefly)

<u>Re-Entry Phase:</u> (30 pts)

- (3 pts) A copy of all code/functions utilized for your calculations.
- (3 pts) Explain why a space-plane is a good option for this type of reentry mission. Discuss the pros and cons of the different reentry trajectories for the mission and recommend a reentry trajectory for this mission.
- (2 pts) Calculations for γ_{*decel}.
- (2 pts) Calculations for $\left(\frac{a_{decel}}{g_0}\right)_*$ at your selected $\frac{C_L}{C_D}$ and γ_e which meet the constraints.
- (5 pts) Calculations for $\gamma_{*heating}$.
- (2 pts) Calculations for $(\dot{\bar{q}}_S)_*$ at your selected $\frac{C_L}{C_D}$ and γ_e which meet the constraints.
- (3 pts) Calculation for full $\left(\frac{\boldsymbol{a_{decel}}}{\boldsymbol{g_0}}\right)$ equation using equations 4.59 and 4.60.
- (5 pts) Appropriate, clear plot showing and discussing $\boldsymbol{\eta}\ vs\ \left(\frac{\boldsymbol{a_{decel}}}{\boldsymbol{g_0}}\right)$ profiles. Maximums clearly identified.
- (5 pts) Appropriate, clear plot showing and discussing $\boldsymbol{\eta}\ vs\ \dot{\bar{\boldsymbol{q}}}_{\boldsymbol{s}}$ profiles**.** Maximums clearly identified.

<u>Other points will be awarded as follows:</u>

- (5 pts) Consistent, clear and nice looking PowerPoint chart formatting, including use of equation editor, and computer generated graphs and plots as appropriate (**no hand-written or hand-drawn**).
    - Exception to requirement for computer generated plots: a hand-drawn mission planning sun clock is acceptable to show/verify CATS in the RPO phase
- (5 pts) List of assumptions and why assumptions are reasonable

<u>Final Notes:</u>

- Each team member must do approximately 1/3 of the total work. Additionally, each team member must contribute at least 20% of the work to at least 2 of the 3 sections of the final project. If these criteria are not met, individual points may be deducted.
- Be sure to include a complete documentation statement with your submission