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ASTROMECH: AN AUGMENTED REALITY INTERFACE FOR INTUITIVE TRAJECTORY DESIGN AND TRADESPACE ANALYSIS

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Even with the aid of state-of-the-art trajectory design tools, cislunar trajectory design tends to require expertise in the highly nonlinear dynamics of the Earth-Moon system. To make this process more intuitive for non-expert operators, this manuscript presents ASTROMECH, an interactive augmented reality trajectory design tool. In this work, we present capabilities of ASTROMECH that seek to enable fast, intuitive cislunar trajectory design and efficient exploration of the trajectory design tradespace.

INTRODUCTION

The recent resurgence in interest in cislunar space has led to a plethora of new mission concepts from a variety of government and commercial aerospace organizations, making cislunar trajectory design an increasingly popular field. However, the highly nonlinear dynamics of the Earth-Moon system cause solutions to be highly dependent on initial guesses, which can make trajectory design difficult and unintuitive for people lacking expertise in multibody dynamics.[1] Existing tools like a.i. solutions' Deep Space Trajectory Explorer (DSTE) can be useful aids for the cislunar trajectory design process, but many of these tools still require the user to possess a deep understanding of multibody dynamics.[2] Given the increasing number of organizations proposing missions in cislunar space, the aerospace industry could stand to benefit from a tool that allows non-expert operators to quickly and intuitively design cislunar trajectories.

One increasingly popular proposed method for fostering intuitive trajectory design is the use of extended reality (XR),[1–4] an umbrella term for technology that immerses its user in a computer-generated environment, including virtual reality (VR), which immerses the user in a completely virtual environment, and augmented reality (AR), which places digital elements over a view of the real world.[5] XR trajectory design tools allow users to visualize trajectories in 3D, which Guzzetti et al. estimate can lead to an order of magnitude decrease in time-to-discovery for new insights when compared with a 2D representation of the same data.[3] Additionally, a well-designed XR tool can allow a user to design trajectories more intuitively by physically interacting with the problem setup and overall design tradespace, which can help them gain an intuition for the dynamics and more easily interpret solutions.[1–3]

Some of the earliest work leveraging XR for astrodynamics involved using specially designed facilites containing 3D stereoscopic projectors to immerse users in a virtual environment; examples

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include visualizations of satellite orbits and attitude states developed for Purdue's 3D stereoscopic classroom[6] and visualizations of multibody trajectories developed for Purdue's Envision Center Cave.[7] As XR technology progressed, the majority of research into XR for astrodynamics shifted to head-mounted displays (HMD). Several XR applications have been developed to visualize trajectories designed in other tools. These applications include Greenspace, developed by Brown and Howell,[8] the Interactive VR Trajectory Walkthroughs developed by Sood,[9] an AR visualization of the Europa Clipper Trajectory developed by Stuart et al.,[10] and VR cislunar trajectory animations developed by Somavarapu et al.[11] Stuart et al. also developed a VR tool for editing an existing interplanetary patched conics trajectory by allowing a user to manipulate control points using handheld controllers.[10] Stouch et al. developed an AR tool primarily designed for space domain awareness, but it also allows a user to select a satellite and interactively edit its orbital elements.[12] Beebe developed a module for Texas A&M's simulation tool SpaceCRAFT VR to aid in interplanetary trajectory design.[13] Buchner et al. presented a VR tool to help satellite operators understand how particular actions affect satellite states and uncertainties.[14] The developers of Auburn University's Immersive Trajectory Design Facility have presented two main methods for leveraging VR for constructing initial guesses for periodic orbits in the Circular Restricted Three-Body Problem (CR3BP): correcting a user's 3D drawings[4,15] and allowing a user to construct a trajectory by manipulating the positions and velocities of control points, which is then corrected to a periodic orbit.[1,16] Anderson et al. presented an augmented reality tool that allows a user to design a Keplerian orbit by manipulating the orbital elements, a Lambert arc by moving its endpoints and changing its time of flight, and arbitrary trajectories under approximated CR3BP dynamics by directly manipulating the initial state vector.[2]

To make trajectory design more intuitive for non-expert operators, we present Astrodynamics Software for Tradespace Optimization and Manual Exploration using Computer-generated Holograms (ASTROMECH), an augmented reality interface for trajectory design (Figure 1). ASTROMECH is currently designed for the Microsoft HoloLens 2, an AR head-mounted display that uses hand tracking to allow users to directly manipulate holographic elements. Current features of ASTROMECH include an interactive Earth-Moon transfer design interface, a 3D display of the trajectory and its properties that updates in real time as the user changes the initial conditions, interactive 3D plots of the design tradespace that allow the user to select and display particular solutions, and the ability to display multiple trajectories at once. ASTROMECH is also designed to be modular, so future versions will be designed to accommodate a variety of different transfer design scenarios.

The current version of ASTROMECH runs on a laptop and is streamed to the HoloLens using Holographic Remoting. Screenshots taken on the HoloLens during Holographic Remoting often capture the holographic elements in lower quality than the user actually sees; for this reason, the ASTROMECH screenshots presented in this manuscript were taken in a HoloLens emulator with a static background image to better approximate what a user would see.

TRANSFER DESIGN ALGORITHM

Though ASTROMECH is designed to be modular, the current version of the tool is tailored to cislunar trajectory design. This section details the tool's underlying transfer design algorithm.

The Circular Restricted Three-Body Problem

In this tool, the dynamics of the Earth-Moon system are modeled using the Circular Restricted Three-Body Problem (CR3BP). The CR3BP is a simplification of the general three-body problem in

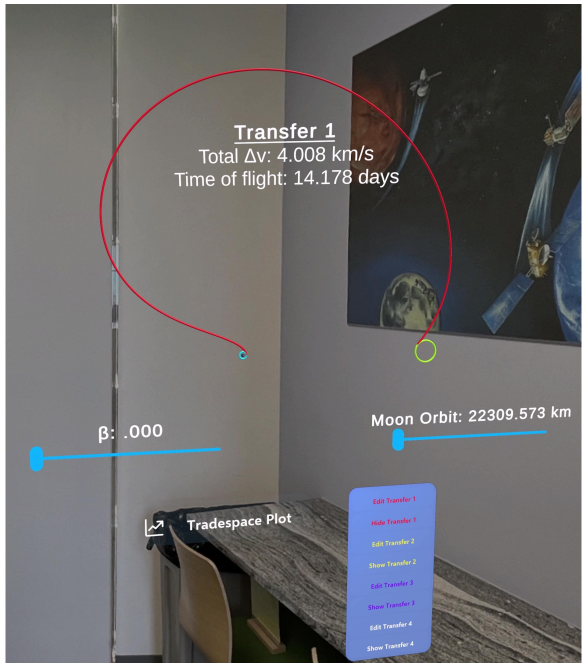


Figure 1. Earth-Moon Transfer Design in ASTROMECH

which the mass of the third body $\tilde{M}_3$ (the spacecraft, in this case) is considered negligible compared to the masses of the primary bodies $\tilde{M}_1$ and $\tilde{M}_2$ (the Earth and the Moon), and the primaries travel along circular orbits about their barycenter.[17] Though the CR3BP is only an approximation, it models cislunar dynamics with enough fidelity to be effectively used as a first pass for a variety of trajectory designs.[18,19]

The CR3BP equations of motion are defined in a frame that rotates with the primaries (Figure 2). The equations of motion are as follows:[17,20]

$$\ddot{x} = 2\dot{y} + x - \frac{(1-\mu)(x+\mu)}{r_1^3} - \frac{\mu(x-1+\mu)}{r_2^3} \tag{1}$$

$$\ddot{y} = -2\dot{x} + y - \frac{(1-\mu)y}{r_1^3} - \frac{\mu y}{r_2^3} \tag{2}$$

$$\ddot{z} = -\frac{(1-\mu)z}{r_1^3} - \frac{\mu z}{r_2^3} \tag{3}$$

where the mass ratio μ, r_1, and r_2 are defined as

$$\mu = \frac{\tilde{M}_2}{\tilde{M}_1 + \tilde{M}_2} \tag{4}$$

$$r_1 = \sqrt{(x+\mu)^2 + y^2 + z^2} \tag{5}$$

$$r_2 = \sqrt{(x-1+\mu)^2 + y^2 + z^2} \tag{6}$$

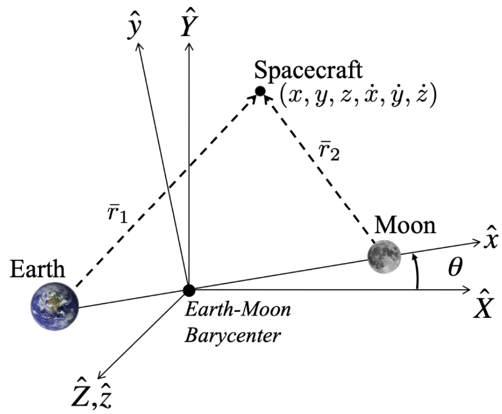


Figure 2. Conceptual diagram showing how a state vector is defined in the CR3BP Earth-Moon rotating frame (reprinted from Reference 21)

Bi-impulsive Direct Earth-Moon Transfer Design Algorithm

The bi-impulsive direct Earth-Moon transfer design algorithm by Lv et al.[22] was used for this demonstration of ASTROMECH. This algorithm designs a bi-impulsive transfer from a circular Earth orbit to a circular lunar orbit.[22] Lv et al. present algorithms for both planar and spatial transfers, though only the planar algorithm has been implemented into the current version of ASTROMECH. This algorithm was selected for its ability to capture three-body effects in Earth-Moon direct transfers (unlike Hohmann transfers or patched conics methods) as well as its relative ease of implementation. However, it is important to note that ASTROMECH is designed for modularity, and the selected algorithm is only one of many transfer design algorithms that can be implemented into the tool. Future work will explore applying ASTROMECH to other kinds of trajectory design problems as well.

In the planar algorithm, the design parameters for each transfer are the departure phase angle β, the Earth orbit radius r_0, and the desired lunar orbit radius $r_{2,des}$. For the version implemented into ASTROMECH, a fixed r_0 of 6741 km is used for all transfers to simplify the design tradespace. The maneuver to escape Earth orbit, Δv_1, is executed tangential to the velocity direction.[22] Therefore, immediately after Δv_1, the position and velocity of the spacecraft are

$$\boldsymbol{r}_0 = (-\mu + r_0 \cos\beta, r_0 \sin\beta, 0)^T \tag{7}$$

$$\boldsymbol{v}_0 = (-v_0 \sin\beta, v_0 \cos\beta, 0)^T \tag{8}$$

where v_0 is the speed of the spacecraft immediately after Δv_1.[22] A set of initial states $(\boldsymbol{r}_0, \boldsymbol{v}_0)^T$ with a range of v_0 values are then propagated until the periapsis condition is reached; that is, the position vector with respect to the Moon $\boldsymbol{r}_2$ is perpendicular to the velocity vector, or

$$\boldsymbol{r}_2 \cdot \boldsymbol{v} = (x - 1 + \mu)\dot{x} + y\dot{y} + z\dot{z} = 0 \tag{9}$$

which ensures that the spacecraft can insert into a lunar orbit of radius r_2 using a tangential maneuver Δv_2.[22]

In ASTROMECH, the circular terminal orbits of the transfer are modeled using two-body dynamics. The Earth orbit is prograde, and the lunar orbit direction is selected to match direction the spacecraft is traveling relative to the Moon immediately before insertion in order to reduce Δv_2.

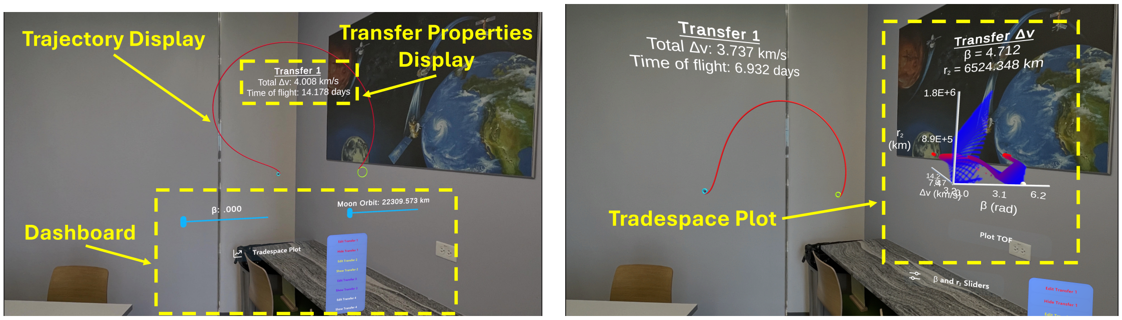
In the Lv et al. study, the values of r_2 and v_0 for all transfers are then stored in a catalog, and an interpolation scheme is used to create initial guesses for the set of $v_{0,des}$ (initial speed necessary to achieve $r_{2,des}$) values.[22] A differential correction algorithm is then used to refine these guesses.[22] In ASTROMECH, instead of using interpolation and differential correction, the catalog of solutions is used directly, and the augmented reality interface therefore allows the user to select and display pre-computed solutions by editing the design parameters (see User Interface Design). To generate this catalog, all possible combinations of 100 linearly spaced values of $\beta \in [0, 1.98\pi]$ and 250 linearly spaced values of $v_0 \in [10.4, 11.2]$ were used to generate a total of 25,000 initial states. These states were propagated until the periapsis condition was met or until the maximum integration time of 5 nondimensional units (21.712 days) was reached. Transfers with a time of flight longer than 21.712 days were not examined in this study. Of the 25,000 initial states propagated, 18,439 reached the periapsis condition within the maximum integration time, and their r_2, Δv, and time of flight values were stored in the catalog. Though a pre-computed catalog does restrict the possible transfers that can be designed in ASTROMECH, this method was selected over real-time calculation of each transfer due to its heritage in cislunar transfer design[18,19] and the computational efficiency it affords the tool. The catalog allows ASTROMECH to provide real-time updates in its augmented reality display as the user changes the design parameters of the transfer.

USER INTERFACE DESIGN

The main purpose of ASTROMECH is to provide users tools for rapid, intuitive exploration of the trajectory design tradespace. Specifically, the ASTROMECH user interface (UI) allows users to select solutions from its pre-computed transfer catalog by their β and r_2, total Δv, or total time of flight. The UI also allows users to display multiple solutions at once. The ASTROMECH UI design was driven by human factors principles, including the user experience (UX) guidelines for HMD XR applications presented in Reference 23 and the Thirteen Principles of Display Design presented in Reference 24. The three guidelines that most informed the overall UX design were "Allow Users to Feel in Control of the Experience," "Allow for Trial and Error," and "Provide Feedback and Consistency" from Reference 23.

The ASTROMECH UI consists of four main parts: the Dashboard, the Trajectory Display, the Transfer Properties Display, and the Tradespace Plot (Figure 3). The Trajectory Display is a 3D model of the two primaries, the primary-centric orbits, and the transfer orbit between them. All objects in the Trajectory Display are to scale, including the primaries. The Transfer Properties Display is a text display of the total Δv and time of flight of the selected transfer orbit. According to Wickens et al., lag in XR is more disruptive for more immersive environments;[24] because of this, both the Trajectory Display and the Transfer Properties Display in ASTROMECH update in real time as the user changes the conditions of the transfer orbit. The units of time of flight in the Transfer Properties Display automatically update to make the value easier to contextualize. If the time of flight is greater than or equal to one day, the value is expressed in days; else, if the time of flight is greater than or equal to one hour, the time of flight is expressed in hours; and so on for minutes, with seconds being the smallest unit used. This follows the Display Design Principle of discriminability;[24] shorter times of flight could be more difficult for a user to tell apart if they are expressed in very large units, and adaptively changing the unit helps ameliorate this.

The Dashboard and the Tradespace Plot comprise the two methods for selecting a transfer. Users can select solutions from the transfer catalog using sliders to select particular β and r_2 values. When active, these sliders are contained within the Dashboard (Figure 4). The sliders currently



(a)

(b)

Figure 3. Annotated views of the ASTROMECH user interface showing the Dashboard, Trajectory Display, Transfer Properties Display, and Tradespace Plot.

only allow the user to select β and r_2 values matching solutions in the transfer design catalog; as a consequence, as the user drags the β slider, the accessible values of the r_2 slider automatically update to match the r_2 values of stored solutions with the selected β. Instead of using the β and r_2 sliders to select a transfer, a user can also use the Tradespace Plot, an interactive 3D scatterplot of the design tradespace (Figure 5). Wickens et al. caution against requiring a user to judge between more than five to seven levels of one sensory variable, such as color;[24] for this reason, a 3D scatterplot was selected over a traditional 2D contour plot, as a scatterplot can use spatial distance to complement the differences in color between points to make the points more easily discriminable. The ASTROMECH Tradespace Plot builds on the VR scatterplot developed by Simpson et al.[25] with the addition of a spherical cursor for selecting points in the plot. The user grabs the cursor and drags it in 3D space to the desired point in the plot, and the cursor automatically snaps to the nearest point, thereby selecting the desired solution for display. β (rad) and r_2 (km) are plotted on the x- and y-axes of the Tradespace Plot, respectively. The z-axis can be toggled between showing total Δv or time of flight using the button directly below the Tradespace Plot. The points on the plot are also colored according to their z-values, with blue representing the lowest values and red representing the highest. A text element above the scatterplot lists the variable plotted on the z-axis along with the β and r_2 values of the selected transfer. The Dashboard contains a button to toggle between using the sliders and the Tradespace Plot. The sliders disappear when the Tradespace Plot is not in use, and vice versa; this follows the guideline "Keep Tools and Information Ready, but not Distracting" from Reference 23, which encourages giving users the option to hide UI elements. The Dashboard also contains a menu that allows the user to show up to four solutions at once, toggling their appearances on and off with show/hide buttons. The user can select any of these four transfers to edit.

For both the sliders and the Tradespace Plot, the Trajectory Display and the Transfer Properties Display update in real-time as the user changes the design parameters. Additionally, the r_2 text (either above its slider or above the Tradespace Plot, depending on which is active) turns red when r_2 is greater than the radius of the Laplace sphere of influence of the Moon (Figure 6(a)), defined as

$$r_{M,SOI} = a_M \left(\frac{m_M}{m_E} \right)^{2/5} \tag{10}$$

where a_M is the semimajor axis of the Moon's orbit, m_M is the mass of the Moon, and m_E

(a) (b)

Figure 4. Two configurations of the Dashboard. In (a), the β and r_2 sliders are active and the Tradespace Plot is inactive. In (b), the Tradespace Plot is active and the β and r_2 sliders are inactive.

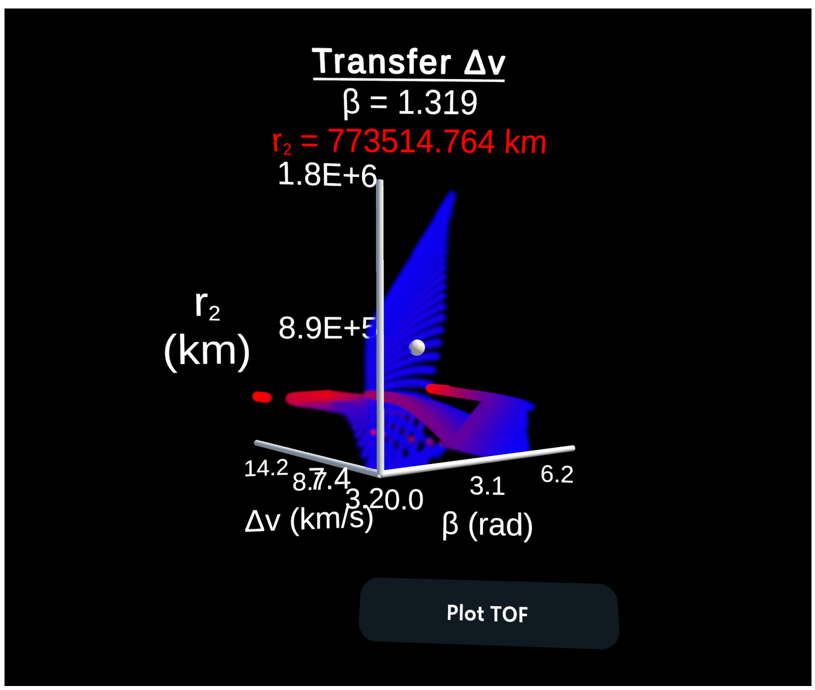
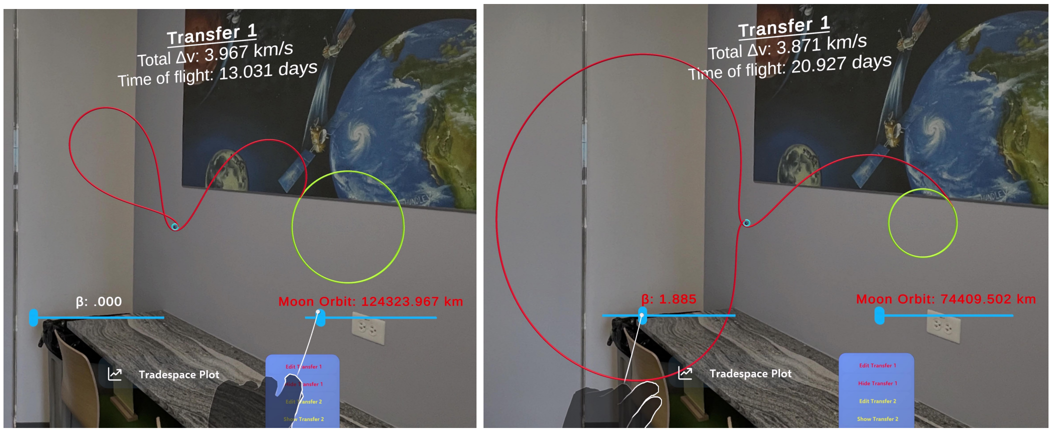


Figure 5. The Tradespace Plot, with the spherical cursor shown in front. The selected solution is outside the Moon's sphere of influence, so the r_2 display text is in red.



(a) (b)

Figure 6. (a) The r_2 text turns red when $r_2 > r_{M,SOI}$. (b) The β text turns red when the selected β value is only associated with transfers for which $r_2 > r_{M,SOI}$.

is the mass of the Earth.[26] When the selected β value is only associated with transfers for which $r_2 > r_{M,SOI}$, the β text turns red as well (Figure 6(b)). In this way, the user is still allowed to transfer to positions outside the sphere of influence of the Moon if they so desire, but the display alerts them that they have done so in case it was done in error. This follows the guideline "Use Feedback to Help Recognizes Errors and Unwanted States" from Reference 23.

Vi et al. caution against the use of persistent heads-up displays that obscure a user's vision,[23] so ASTROMECH's UI elements appear as virtual objects situated in a real-world environment rather than a persistent 2D overlay. The interactive elements can be interacted with directly like physical objects (e.g., buttons can be pressed, sliders can be dragged), which follows the guidelines "Use Real-Life Inspiration to Create Affordances in Objects" and "Pair Actions with Outcomes That Users Expect" from Reference 23. These elements can also be interacted with from afar using a ray that extends from the user's hand; the user points this ray at an interactive object then makes a pinching motion to grab the object, and they can move their hand to move or rotate objects that allow those types of interactions. For example, the user can move and rotate the Trajectory Display as they please, allowing them to view the plane of the transfer from several different angles (Figure 7); this feature could prove especially useful for spatial transfers, which can be difficult to comprehend without a 3D view. Additionally, the text elements in ASTROMECH turn to face the user to preserve legibility, as shown in Figure 7; as emphasized in the Thirteen Principles of Display Design, for a display to be usable, it must be legible.[24] The Dashboard also turns to face the user and remains within the user's reach as they move around the room.

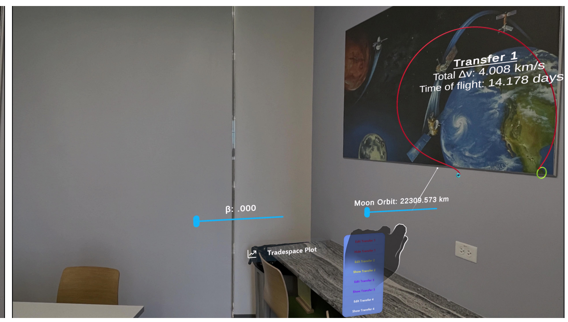
EXAMPLE USE CASES

The following section details example workflows for cislunar trajectory design in ASTROMECH.

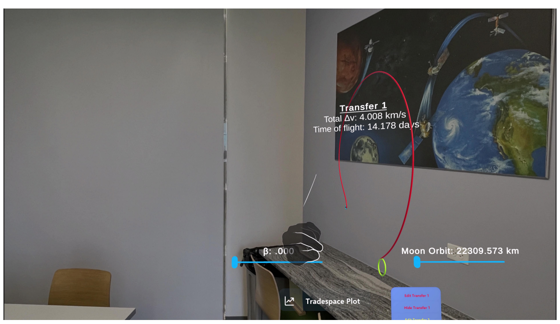
Selecting Transfer via Departure Phase Angle and Moon Orbit Radius

1. If the β and r_2 sliders are not currently active, press the Dashboard button labeled "β and r_2 Sliders."

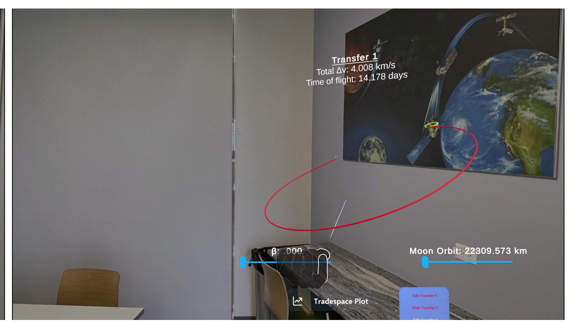
(a)



(b)



(c)



(d)

Figure 7. Demonstration of moving (a and b) and rotating (c and d) the Trajectory Display using far interaction gestures. Note that the Transfer Properties Display remains facing the user in all cases.

(a) (b)

Figure 8. Selecting a transfer via the departure phase angle and moon orbit radius. (a) The user selects a β value. (b) The user then selects an r_2 value.

2. Move the indicator (either by physically grabbing and dragging it, or using the far interaction ray to grab and drag it) on the β slider to the desired value. The values of the r_2 slider will automatically update in response. If the selected β changes the minimum value on the r_2 slider to a value beyond the sphere of influence of the Moon, the text above both sliders will turn red.

3. Once the β slider has been set, move the indicator on the r_2 slider to the desired value. If the selected r_2 value is beyond the sphere of influence of the Moon, the text above the r_2 slider will turn red.

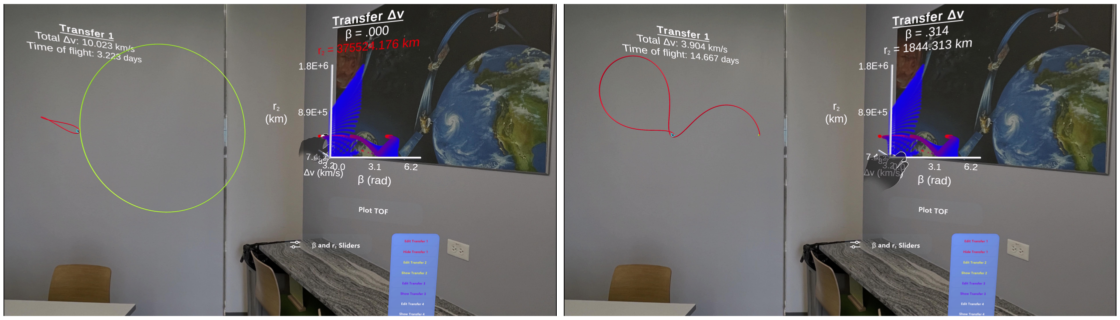
This process is shown in Figure 8.

Selecting Transfer via Delta-v

1. If the Tradespace Plot is not currently active, press the Dashboard button labeled ”Tradespace Plot.”

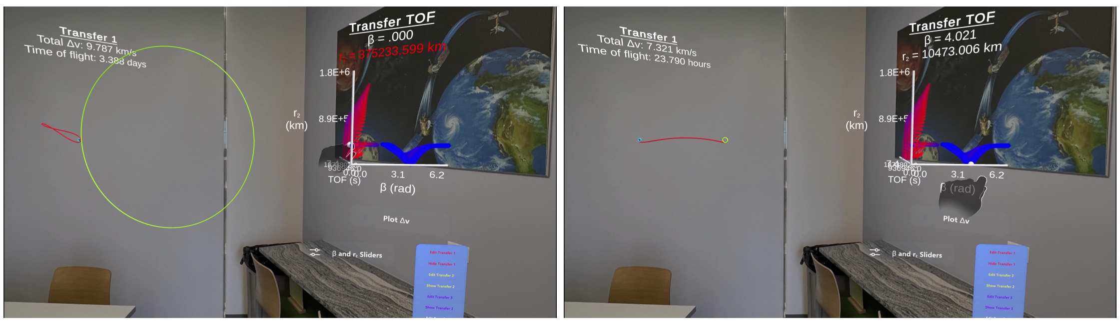
2. The Tradespace Plot will show total Δv as a function of β and r_2. Move the white spherical cursor (using near or far interactions) in space to the desired point in the scatter plot. It will automatically snap to the nearest point as it is moved. The β and r_2 text will turn red for the same conditions as in Selecting Transfer via Departure Phase Angle and Moon Orbit Radius.

This process is shown in Figure 9.



(a) (b)

Figure 9. Selecting a transfer via Delta-v. The user grabs the white spherical cursor and drags it to the desired point in the Tradespace Plot.



(a) (b)

Figure 10. Selecting a transfer via time of flight. The user grabs the white spherical cursor and drags it to the desired point in the Tradespace Plot.

Selecting Transfer via Time of Flight

1. If the Tradespace Plot is not currently active, press the Dashboard button labeled ”Tradespace Plot.”
2. The Tradespace Plot will show total Δv as a function of β and r_2. Press the button labeled ”Plot TOF” below the scatterplot to switch the z-axis variable to time of flight.
3. Move the white spherical cursor (using near or far interactions) in space to the desired point in the scatter plot. It will automatically snap to the nearest point as it is moved. The β and r_2 text will turn red for the same conditions as in Selecting Transfer via Departure Phase Angle and Moon Orbit Radius.

This process is shown in Figure 10.

Editing and Displaying Multiple Solutions

1. Use the show/hide buttons on the Dashboard menu (e.g., ”Show Transfer 3”) to show up to four transfers at a time. The transfers are numbered and color-coded; the text color on the menu matches the color of the transfer in the Trajectory Display.

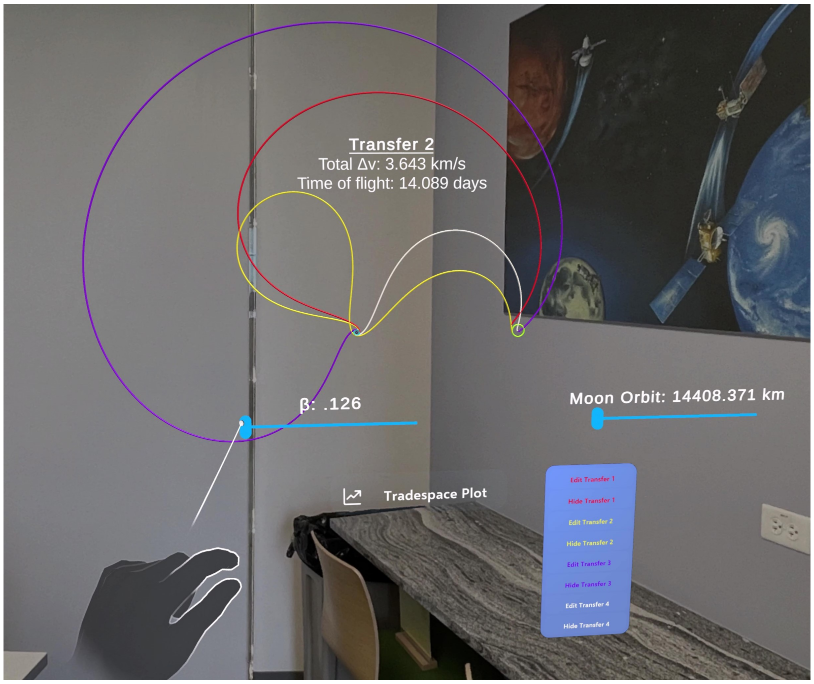


Figure 11. Four transfers are displayed. Transfer 2 (yellow) is being edited.

2. Select a transfer to edit by pushing its corresponding edit button (e.g., ”Edit Transfer 3”). When a transfer is selected for editing, its name is displayed in the Transfer Properties Display.

3. Use either the β and r_2 sliders or the Tradespace Plot to change the conditions of the selected transfer.

This process is shown in Figure 11.

DISCUSSION

Multibody trajectory design is an iterative process, and designs often require input from people who may not be experts in multibody dynamics, such as Flight Dynamics Officers.[27] Additionally, as more organizations look to cislunar space as the next frontier, it will become increasingly imperative for people to possess some level of training in multibody dynamics, whether they are undergraduate students seeking careers or Space Force Guardians beginning their training. ASTROMECH is designed to help make complex dynamics intuitive for non-expert users, which could prove useful for preliminary trajectory design, what-if analysis, aerospace education, or training.

Screen-based trajectory design tools often an additional layer of difficulty to the trajectory design process by compressing inherently spatial problems into 2D.[10] Additionally, many screen-based multibody trajectory design tools, such as DSTE, assume the user already possesses a deep understanding of cislunar dynamics.[2] Such tools can be powerful aids for experts, but they are often prohibitively difficult for non-experts. Auburn University’s Immersive Trajectory Design Facility ameliorates the 3D-to-2D issue by presenting trajectories in VR,[1] and its focus on generating initial guesses for CR3BP periodic orbits makes it a useful tool for experts. For a user to make a 3D drawing of a desired periodic orbit, they must first understand the attributes of their desired periodic orbit and whether their periodic orbit is, and to design a trajectory by directly manipulating a state vector, one requires an understanding of how those states will evolve. Similarly, the AR tool developed by Anderson et al. provides simple, intuitive interfaces for their two-body dynamics tools, but their CR3BP tool requires the user to directly manipulate the initial state vector to design a trajectory;[2] for a user to design their desired trajectory in this tool, they must already possess an intuition for how states evolve in the CR3BP.

In contrast, ASTROMECH is designed for transfer design rather than periodic orbit initial guess generation. Like the Immersive Trajectory Design Facility, ASTROMECH allows users to explore the design tradespace, but ASTROMECH allows users to select a transfer by tweaking design parameters rather instead of constructing the trajectory themselves. ASTROMECH also provides users with interactive 3D plots of the trajectory design tradespace, which can be a useful aid in optimization. A novice may benefit more from the structure and guidance provided by the ASTROMECH UI, while an expert may prefer the freedom presented by the Immersive Trajectory Design Facility. Both experts and novices would likely benefit from the 3D interactive tradespace plot feature in ASTROMECH. Future studies will focus on optimizing ASTROMECH's UI for usability, as well as applying ASTROMECH to other types of trajectory design problems.

CONCLUSION

ASTROMECH, an augmented reality interface aimed at making trajectory design more intuitive for non-expert operators, is presented, along with a demonstration of how ASTROMECH can be applied to transfer design in the Earth-Moon system. A human factors-informed UI was created to allow users to explore the trajectory design tradespace via parameters such as departure phase angle, Moon orbit radius, Δv, and time of flight. This UI also allows users to display multiple solutions at once. The UI includes a modular interactive 3D Tradespace Plot that allows users to understand the design tradespace at a glance and quickly select particular solutions based on the Δv or time of flight. Though this demonstration of ASTROMECH is tailored to cislunar transfer design, the modularity of the tool allows it to be modified for a variety of different trajectory design scenarios and algorithms.

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REFERENCES

[1] D. H. Somavarapu, *Cislunar Trajectory Design Techniques in Virtual Reality*. PhD thesis, Auburn University, 2023.

[2] J. D. Anderson, J. A. Geliga, K. Y. Tang, K. P. Kuykendall, D. Canales, and B. S. Chaparro, "Immersive Framework for Designing Trajectories Using Augmented Reality," *AIAA SCITECH 2024 Forum*, 2024, p. 1057.

[3] D. Guzzetti, D. H. Somavarapu, and G. Turner, "An Assessment of Virtual Reality Technology for Astrodynamics Applications," *AAS/AIAA Astrodynamics Specialist Conference, Tahoe, CA*, 2020.

[4] D. H. Somavarapu and D. Guzzetti, "Toward immersive spacecraft trajectory design: Mapping user drawings to natural periodic orbits," *Acta Astronautica*, Vol. 184, 2021, pp. 208–221.

[5] K. M. Stanney, H. Nye, S. Haddad, K. S. Hale, C. K. Padron, and J. V. Cohn, *Extended Reality (XR) Environments*, ch. 30, pp. 782–815. John Wiley Sons, Ltd, 2021, https://doi.org/10.1002/9781119636113.ch30.

[6] "Faculty, ITaP partnership looks at making 3-D projection a classroom staple," *Purdue Today*, 2011.

[7] K. Howell, ""Fundamentals of Libration Point Mission Design"," NESC Academy, October 2016.

[8] A. Brown and K. Howell, "Greenspace," *Envision Center Showcase*, 2016.

[9] R. Sood, "Visualization," Astrodynamics & Space Research Laboratory website.

[10] J. Stuart, B. Ramaswamy, T. Lam, N. Guy, F. Laipert, A. Menzies, N. Bradley, A. Mysore, and N. Arora, "Do You See What I See? Interactive Visualization of Mission Design and Navigation," 2018.

[11] D. Somavarapu, P. Landon, J. Busato, M. Kaiser, K. Martin, E. Miskioglu, and D. Guzzetti, "Virtual-Reality-Based Astrodynamics Applications Using A-Frame: A Tutorial," 2023.

[12] D. Stouch, U. Balasuriya, R. Hyland, M. J. Les Bird, , and C. Kingsley, "Toward Intuitive Understanding of Complex Astrodynamics Using Distributed Augmented Reality," *Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS)*, 2021.

[13] N. K. Beebe, *Advanced Onboard Spacecraft Guidance and Navigation Console*. PhD thesis, 2022.

[14] S. L. Buchner, N. Abeson, J. Wood, H. Schaub, and A. P. Anderson, "Integrated Virtual Reality Visualizations and Information Display to Understand Uncertainty in Training for Spaceflight Operations," *93rd Annual Scientific Meeting*, 2023.

[15] E. C. Mulder and D. Guzzetti, *Analyzing Data-Driven CR3BP Orbit Representations for Immersive Astrodynamics Catalogs*, 10.2514/6.2024-1670.

[16] D. Somavarapu, E. Mulder, and D. Guzzetti, "Cislunar CR3BP Periodic Orbit Identification in Virtual Reality," 08 2023.

[17] D. A. Vallado, *Fundamentals of Astrodynamics and Applications*. Springer Science & Business Media, 4th ed., 2013.

[18] D. C. Folta, N. Bosanac, D. Guzzetti, and K. C. Howell, "An Earth–Moon system trajectory design reference catalog," *Acta Astronautica*, Vol. 110, 2015, pp. 341–353.

[19] D. Guzzetti, N. Bosanac, A. Haapala, K. C. Howell, and D. C. Folta, "Rapid trajectory design in the Earth–Moon ephemeris system via an interactive catalog of periodic and quasi-periodic orbits," *Acta Astronautica*, Vol. 126, 2016, pp. 439–455.

[20] V. Szebehely, "Chapter 4 - Totality of Solutions," *Theory of Orbit* (V. Szebehely, ed.), pp. 126–230, Academic Press, 1967, https://doi.org/10.1016/B978-0-12-395732-0.50010-6.

[21] D. Folta, N. Bosanac, I. Elliott, L. Mann, R. Mesarch, and J. Rosales, "Astrodynamics convention and modeling reference for lunar, cislunar, and libration point orbits," tech. rep., 2022.

[22] M. Lv, M. Tan, and D. Zhou, "Design of two-impulse Earth–Moon transfers using differential correction approach," *Aerospace Science and Technology*, Vol. 60, 2017, pp. 183–192.

[23] S. Vi, T. S. d. Silva, and F. Maurer, "User experience guidelines for designing HMD extended reality applications," *Human-Computer Interaction–INTERACT 2019: 17th IFIP TC 13 International Conference, Paphos, Cyprus, September 2–6, 2019, Proceedings, Part IV 17*, Springer, 2019, pp. 319–341.

[24] C. D. Wickens, J. Lee, Y. D. Liu, and S. Gordon-Becker, *Introduction to Human Factors Engineering (2nd Edition)*. USA: Prentice-Hall, Inc., 2003.

[25] M. Simpson, J. Zhao, and A. Klippel, "Take a walk: Evaluating movement types for data visualization in immersive virtual reality," *Proceedings of Workshop on Immersive Analytics (IA)*, Piscataway, NJ: IEEE, 2017, pp. 1–6.

[26] R. R. Bate, D. D. Mueller, J. E. White, and W. W. Saylor, *Fundamentals of Astrodynamics*. Courier Dover Publications, 1971.

[27] A. L. Batcha, J. Williams, T. F. Dawn, J. P. Gutkowski, M. V. Widner, S. L. Smallwood, B. J. Killeen, E. C. Williams, and R. E. Harpold, "Artemis I Trajectory Design and Optimization," *2020 AAS/AIAA Astrodynamics Specialist Conference*, No. AAS 20-649, 2020.