USC University of Southern California

ΔV Optimizatized Interplanetary Trajectories to Uranus

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Project Purpose

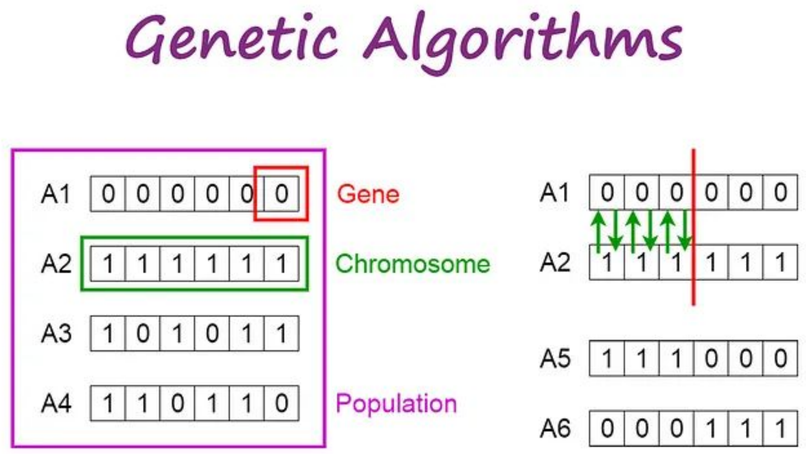
- In 2023, the National Academies of Sciences, Engineering, and Medicine identified that a mission to Uranus was their highest priority flag ship mission.
  - The last mission to Uranus was Voyager 2 in 1986
- For this mission, they suggest Uranus orbiter and probe
- Optimal launch opportunities in 2031-2032
  - Able to use Jupiter gravity assist
- Additional opportunities in 2032-2038
  - Uses inner planetary tour but will have an increased tour time

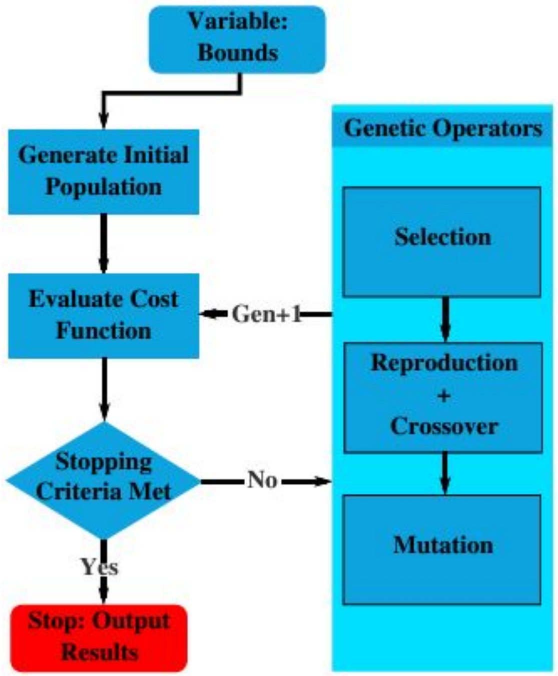
Project Methodology

- Project goal is to optimize the ΔV requirement for an Uranus orbiter to enter Uranus' orbit
    - Will assume the use of an inertial upper stage to decrease spacecraft ΔV requirement
    - Will require the use of multiple gravity assists
        - No deep space maneuvers, just velocity changes at each fly-by periapsis
    - Will use the solutions to Lambert's problem to calculate the departure and arrival velocities of each leg of the trajectory
- However, from Mercury to Jupiter there exists hundreds, if not thousands, of ways to reach Uranus
    - Will need a way to quickly search through millions of combinations of:
        - Departure and arrival dates
        - Number of gravity assists
        - Order of gravity assists
        - Length of time between gravity assists

Project Methodology

- Rather than use brute force to look at every permutation, a genetic algorithm (GA) was employed
  - Used to explore problem space
  - However, the GA often only provides optimal solution near global minimum
- After a route and timeline is identified by the GA, the route is fixed and the timeline is optimized by GA again
  - This is performed several times to improve total ΔV requirement
- After the second optimization, the route and ΔV required are saved to prevent the identification of the same flight path





Explanation: Genetic Algorithms

- Provided lower and upper bounds for each gene, generate a population of randomized chromosomes
- For each member of the population, evaluate its fitness/cost function
- Evaluate the best chromosome from the population and perform a pseudo-evolution of the population until the fitness/cost function converges on a minimum value

The Use of the GA in Interplanetary Trajectory Design

- Without considering deep space maneuvers, the total ΔV requirement is just a function of time
  - When is the departure, where are the planets going to be, and how long is the transit
  - Use solutions to Lambert's Problem to calculate the required ΔV
    - $\Delta V = | \; [(V_{Lambert, in} - V_{Planet})^2 + 2\mu_{Planet} r_P^{-1}]^{1/2} - [(V_{Lambert, out} - V_{Planet})^2 + 2\mu_{Planet} r_P^{-1}]^{1/2} \; |$

- The cost function the GA is trying to minimize:
  - $C = f(\mathbf{X}) + g(\mathbf{X})$
    - $f(\mathbf{X})$ is the ΔV requirement as a result of solving Lambert's Problem
    - $g(\mathbf{X})$ is the sum of the penalties for bad trajectories (low energy or low periapsis)
    - **X** is the chromosome assigned by the GA
      - $\mathbf{X} = [T_0, N, P_i, \ldots, P_N, T_i, \ldots, T_N, T_f, \phi_1, \phi_2]$

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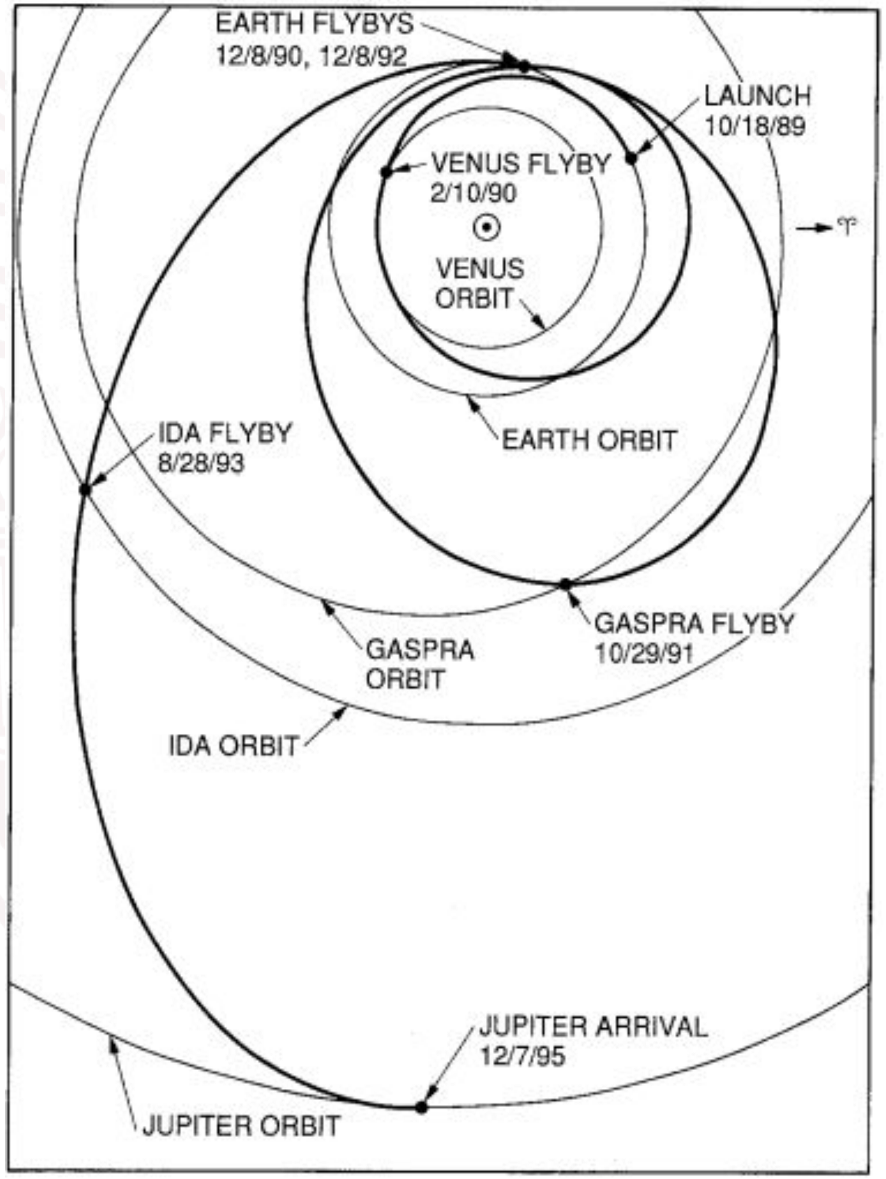
Process Validation and Verification

- To verify the work produced by the GA, it will need to replicate an existing mission:
  - NASA's mission to Jupiter with Galileo
    - Focus on recreating the gravity assists and interplanetary trajectory design
- The results of the algorithm should produce comparable results:
  - Dates of departure, close approaches, and arrival
  - Gravity assist altitudes at closest approaches
  - Total ΔV requirement by the spacecraft from deployment to Jovian capture

Overview: NASA's Galileo

- Launched in October, 1989 from the Space Shuttle Atlantis
  - Launched with inertial upper stage that had a injection energy, C_3 of 17 km^2/s^2
- Performed three gravity assists and two asteroid flybys
  - Gravity assists:
    - Venus
    - Earth
    - Earth
  - Flybys:
    - Gaspra
    - Ida
- Galileo spacecraft required 815 m/s of ΔV to reach a Jovian orbit
  - 185 m/s for trajectory corrections
  - 630 m/s for the Jovian orbit insertion



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Process Validation and Verification

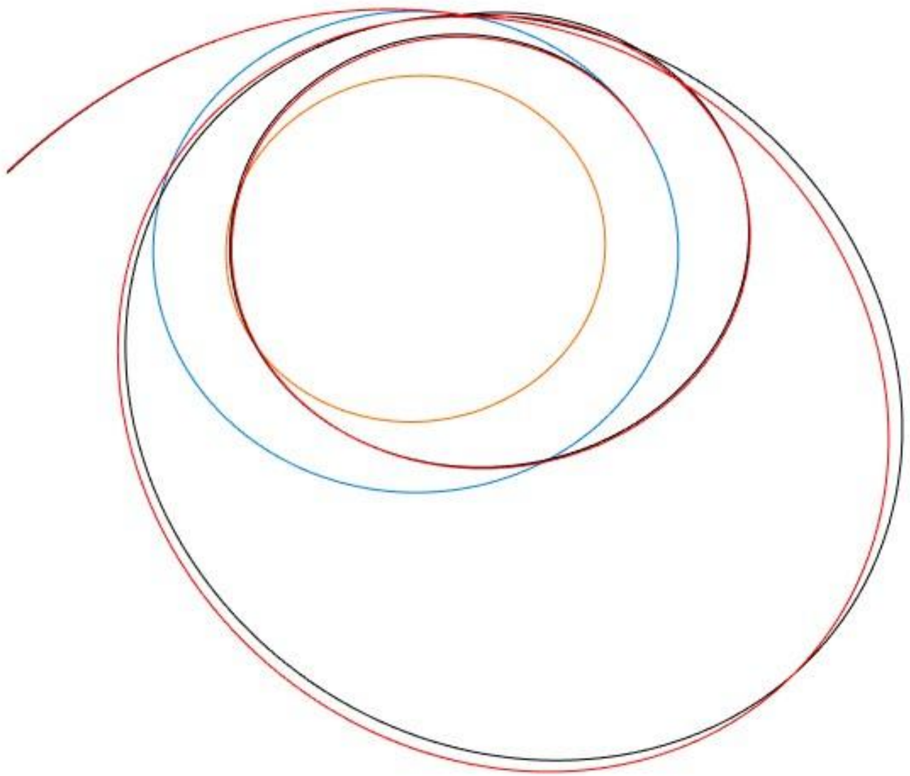
- To recreate Galileo mission, the following constraints were imposed on the GA:
  - Launch window:
    - October 1, 1989 - November 30, 1989
  - Injection Energy:
    - $C_3 = 17\ km^2/s^2$
  - Gravity assist order:
    - Venus-Earth-Earth
  - Number of gravity assists:
    - 3
  - Time between gravity assists:
    - ± 10 - 20 days compared to real flight data
      - 115 days to Venus, 301 days to Earth, 731 days to Earth, and 1094 days to Jupiter

Verification and Validation Results

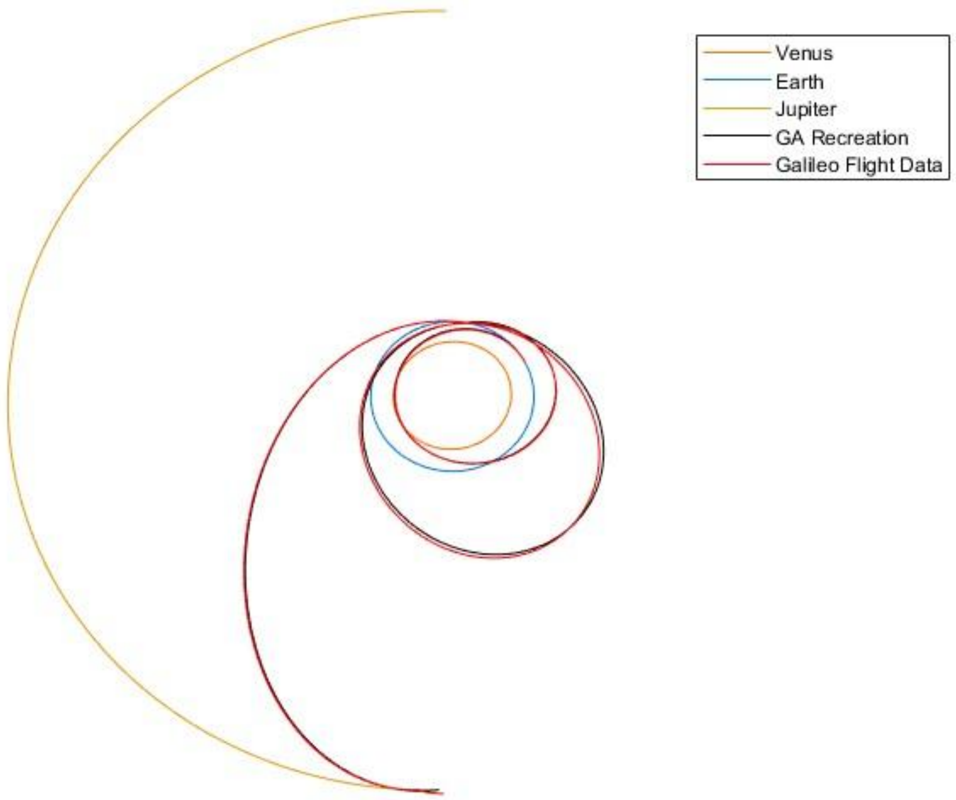
	Date (Galileo)	Date (GA)	C_3 (km^2/s^2, Galileo)	C_3 (km^2/s^2, GA)	ΔV (km/s, Galileo)	ΔV (km/s, GA)	Altitude (km, Galileo)	Altitude (km, GA)
Earth departure	October 18, 1989	October 28, 1989	13.5	14.6	-	-	296	296
Venus Close Approach	February 10, 1990	February 13, 1990	-	-	-	2.6×10^{-5}	16123	23940
Earth (1) Close Approach	December 8, 1990	December 11, 1990	-	-	-	3.6×10^{-4}	960	5671
Earth (2) Close Approach	December 8, 1992	December 11, 1992	-	-	-	0.0314	303	2819
Jupiter Arrival	December 7, 1995	January 9, 1996	-	-	0.630	0.559	286,000	286,000

Verification and Validation Results

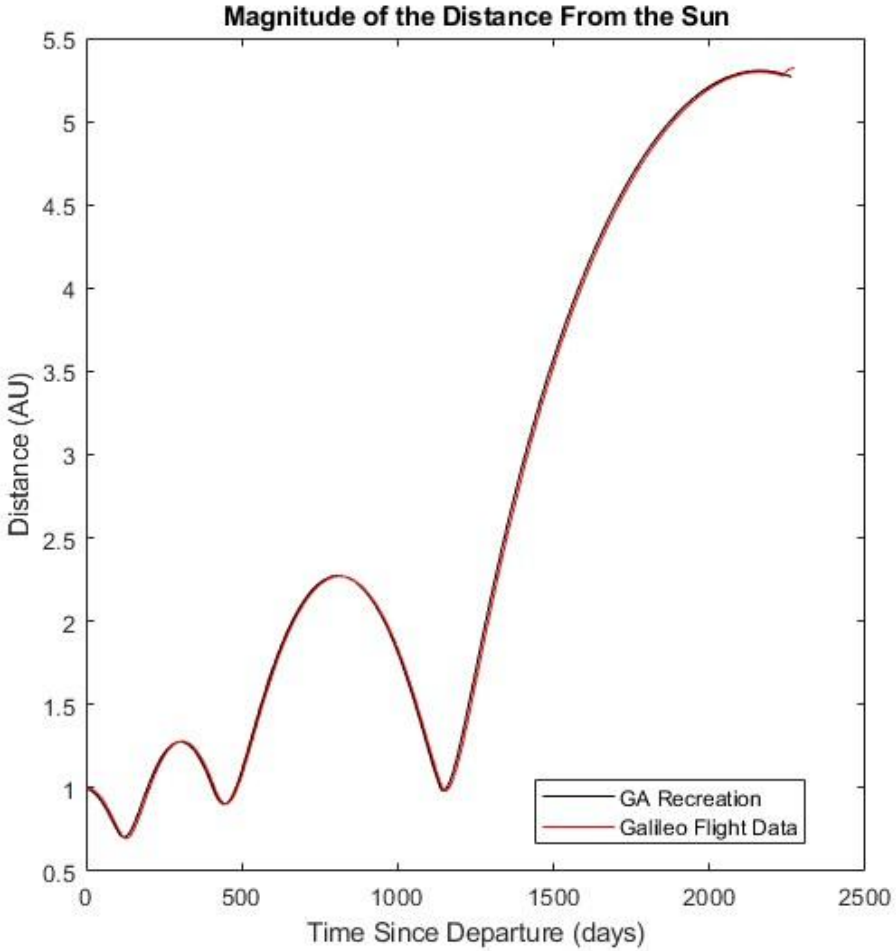
Inner Solar System Trajectory

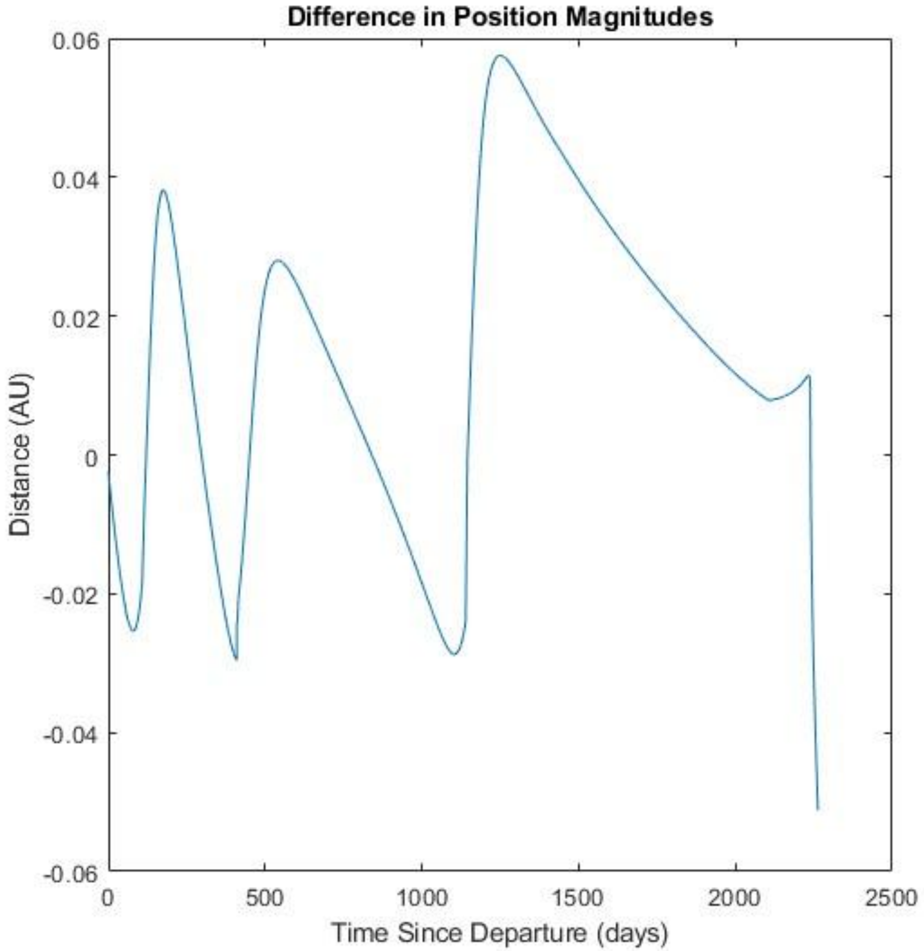


Outer Solar System Trajectory



Verification and Validation Results





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Constraints on GA for Interplanetary Trajectory to Uranus

- To create a interplanetary trajectory to Uranus, the following constraints were imposed on the GA:
    - Launch window:
        - January 1, 2030 to December 31, 2034
    - Injection Energy:
        - $C_3 = 18\ km^2/s^2$
    - Eligible gravity assist planets:
        - Mercury through Jupiter are eligible candidates for trajectory
    - Number of gravity assists
        - Anywhere from 3 to 10 gravity assists
    - Time between gravity assists:
        - 50 - 2000 days
    - Time of last leg:
        - 100-6000 days
- Ran the algorithm until 60 unique trajectories were identified

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GA Results for an Interplanetary Trajectory to Uranus

Route	Required ΔV (km/s)	Departure Date	Arrival Date	Time of Flight (years)
E-V-E-J-U	2.525	April 28, 2031	January 14, 2052	20.71
E-M-J-U	2.993	July 28, 2030	April 24, 2052	21.74
E-E-M-J-U	3.121	April 27, 2034	August 25, 2061	27.33
E-E-E-E-J-U	3.261	October 26, 2032	January 4, 2066	33.19
E-E-J-U	3.374	August 13, 2031	March 7, 2050	18.57
E-E-E-J-U	3.407	May 19, 2034	June 11, 2062	28.06
E-V-V-J-U	3.666	October 25, 2031	June 13, 2050	18.63
E-V-M-J-U	3.746	January 1, 2030	March 1, 2051	21.16
E-V-E-U	4.018	June 9, 2031	January 18, 2046	14.61
E-J-E-E-J-U	4.059	July 12, 2034	December 18, 2065	31.43

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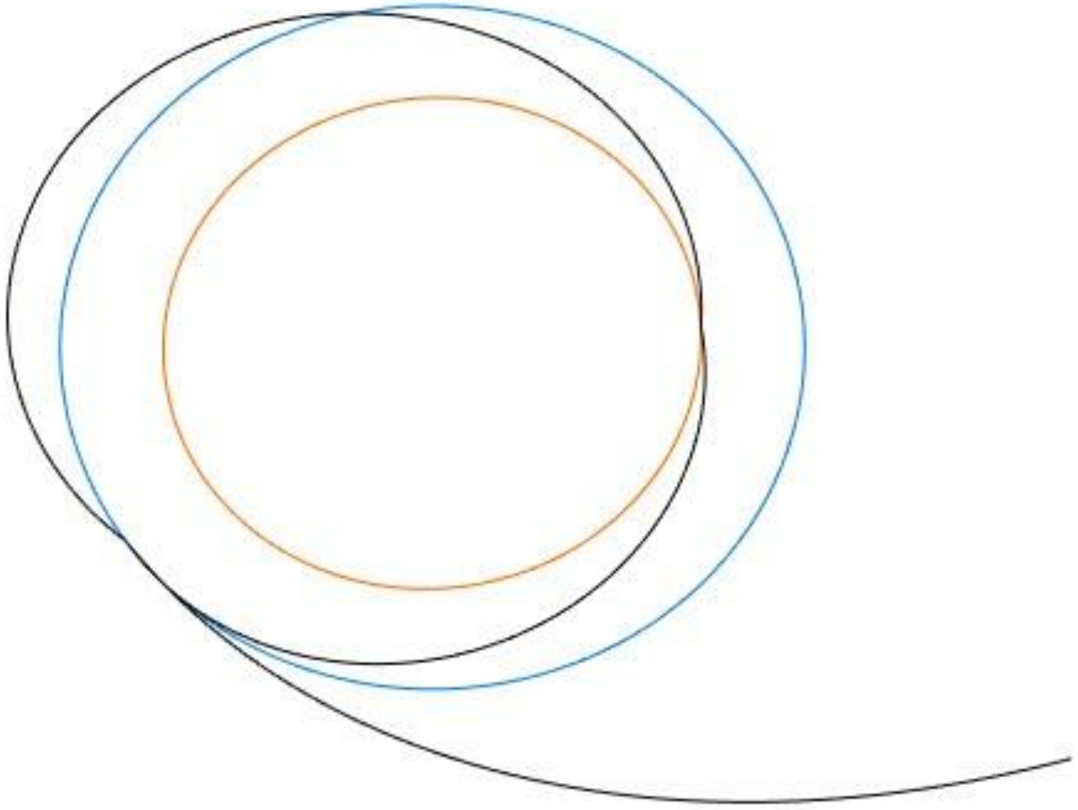
GA Results (E-V-E-J-U)

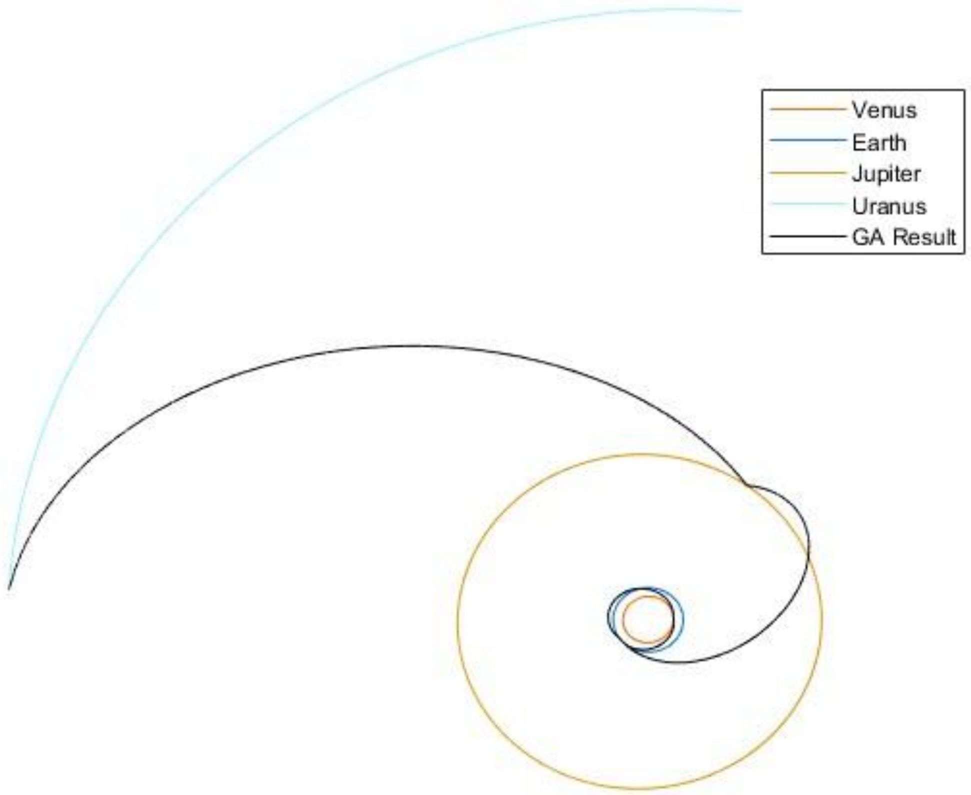
	Date (GA)	C_3 (km^2/s^2)	ΔV (km/s)	Altitude (km)
Earth departure	April 28, 2031	17.4	-	250
Venus Close Approach	September 8, 2031	-	5.40×10^{-6}	4,624
Earth Close Approach	April 25, 2032	-	0.845	318.6
Jupiter Close Approach	March 4, 2036	-	1.01	2,334,495
Uranus Arrival	January 14, 2052	-	0.668	300,000

GA Results (E-V-E-J-U)

Inner Solar System Trajectory



Outer Solar System Trajectory



Conclusions

- Although there are thousands of trajectories to get a spacecraft to Uranus, the algorithm employed for this project was able to identify 60 unique, preliminary trajectories
  - While solutions to Lambert's Problem are ideal for two-body problems, trajectories to the outer solar system can be greatly impacted by the gravitational forces of the gas giants
  - Most likely a deep space maneuver will need to be performed to counteract gravitational perturbations
  - However, this research is intended to serve as a starting point for further, high fidelity research
- Of the identified trajectories, the value of the provided injection energy greatly shaped the ΔV requirements
  - For some, the additional injection energy requirement was the greatest contributor to ΔV rather than the maneuvers during each gravity assist

Future Work

- Further development of this research should first consider deep space maneuvers as a part of GA fitness function
  - Will provide a greater baseline of possible trajectories to Uranus
- After including deep space maneuvers, the next step in this research should be to either:
  - Include a tuning algorithm to create a smooth, continuous trajectory that accounts for spheres of influence
  - Improve the process to solve Lambert's Problem so that the effects of gravitational perturbations are incorporated into the solutions
- Additionally, more work can be done in calculating other possible routes to Uranus
  - This project was limited to identifying 60 trajectories due to the computational intense nature of the GA

Lessons Learned

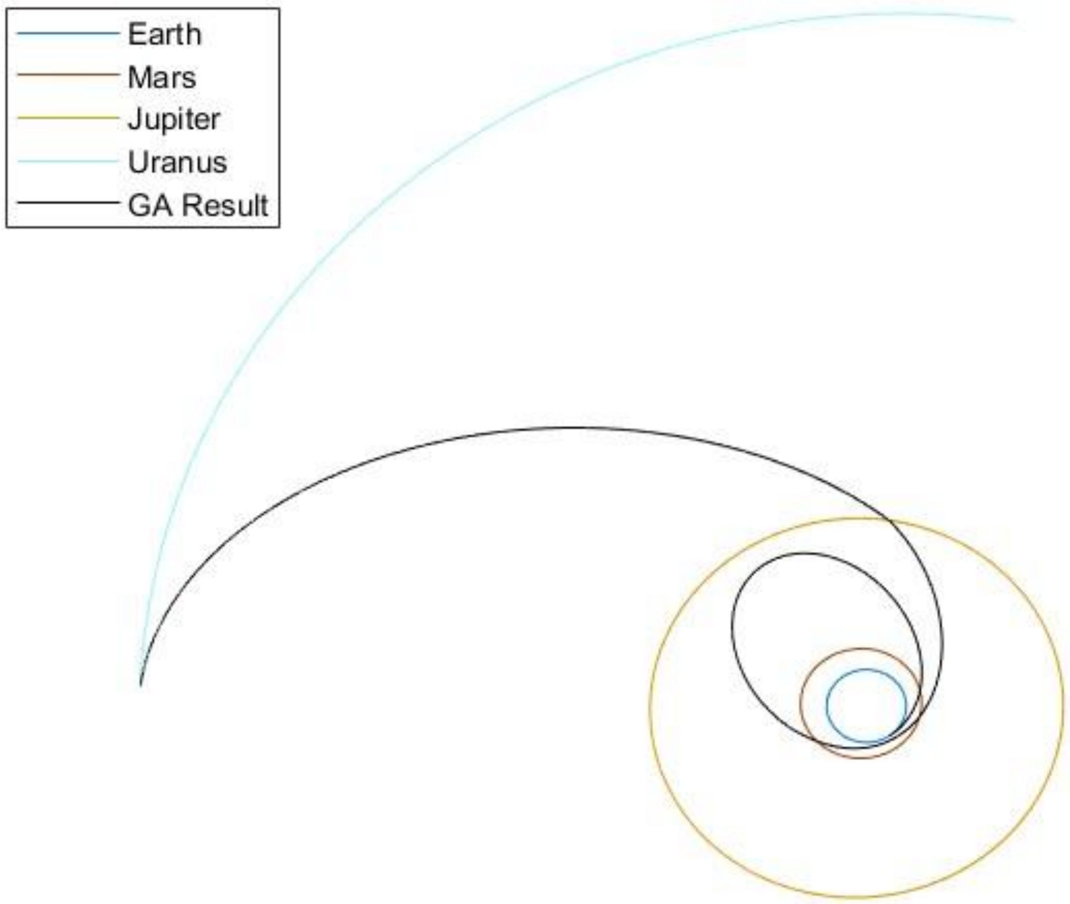
- While more interplanetary trajectory options were desired, the computer used to perform this research was pushed to its limits
  - 12+ hours and 15+ GB of RAM were required to compute all of the data for this project
- For each use of the GA, there was a different optimized solution each time
  - For V&V, the GA had to be performed 3 times before a comparable solution was identified
- Additionally, the initial solutions of the GA tended to only use the minimum number of allowed gravity assists
  - This is likely due to less opportunities for the GA to assign unrealistic trajectories that would have required hundreds of km/s in ΔV

Backup Slides

GA Results (E-M-J-U)

	Date (GA)	C_3 (km^2/s^2)	ΔV (km/s)	Altitude (km)
Earth departure	April 28, 2031	73.33	2.155	250
Mars Close Approach	September 8, 2031	-	4.869×10^{-5}	327.75
Jupiter Close Approach	March 4, 2036	-	1.077×10^{-5}	4,340,986
Uranus Arrival	January 14, 2052	-	0.8381	300,000

GA Results (E-M-J-U)



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