

PERFORMANCE ANALYSIS OF MAGNETOHYDRODYNAMIC DRAG MODULATION FOR ACTIVELY CONTROLLED AEROCAPTURE AT NEPTUNE

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Missions to the Ice Giants are a top priority for flagship missions this coming decade. However, a fully propulsive orbital insertion into these planets requires an immense amount of fuel, taking a significant portion of the spacecraft mass and restricting the scientific payload. To mitigate this, aerocapture has been heavily investigated. Although simulations have shown that aerodynamically controlled aerocapture can successfully insert into an orbit around both Ice Giants, the deep atmospheric pass required necessitates a complex, mass expensive, and sometimes prohibitive thermal protection system. Magnetohydrodynamic drag modulation serves as a potential alternative control method for aerocapture which could not only save propellant mass compared to fully propulsive orbital insertion, but also save thermal protection system mass compared to conventional aerocapture methods. Both aerodynamically controlled and magnetohydrodynamically controlled aerocapture methodologies were simulated in NASA Langley's high-fidelity six degree-of-freedom flight dynamics code, the Program to Optimize Simulated Trajectories II. Each method was simulated to identical missions to Neptune using a numerical predictor-corrector algorithm to optimize the control towards the target orbit. The results concluded that magnetohydrodynamic drag modulation can successfully capture and performs on par with aerodynamic drag modulation while significantly reducing the heat flux and aeroshell complexity.

INTRODUCTION

NASA's most recent Decadal survey has named the Ice Giants as a top priority for upcoming flagship missions. Although fully propulsive orbital insertion has been successful for planetary missions in the past, this technology is inadequate for outer planetary missions due to the inherent mass constraints of using only propulsive maneuvers. Thus, there is a strong demand for new enabling technologies. Over the past few decades, aerodynamically controlled aerocapture has been heavily researched and proposed as a potential alternative control method to reduce propellant mass concerns and enable flagship class missions to the Ice Giants.^{1,2,3,4,5,6,7,8}

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Aerodynamically controlled aerocapture uses the planet's atmosphere to decelerate the vehicle instead of using retropropulsion. Specifically, after entering hyperbolically, the spacecraft will use the atmosphere to slow down and maneuver towards the target orbit of interest, as depicted by Figure 1. Although propellant will still be needed to correct the orbit after atmospheric exit, these burns require significantly less propellant than a fully propulsive orbital insertion. The goal of the actively guided portion of aerocapture is to minimize the propellant required for these corrections. There are three main methods of aerodynamic guidance during aerocapture: bank angle modulation (BAM), direct force control (DFC), and drag modulation (DM).

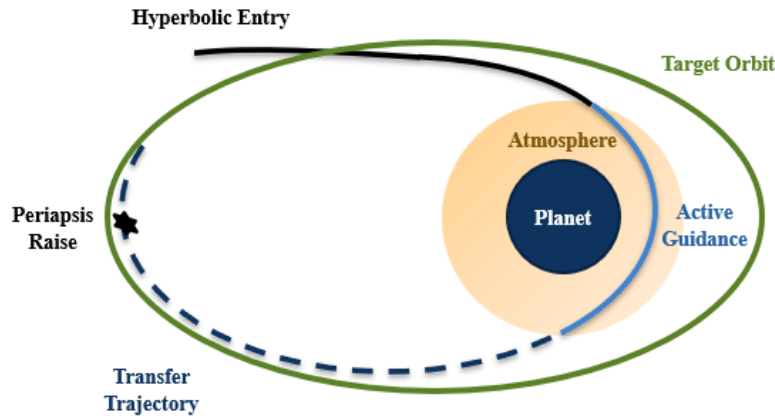


Fig 1. Aerocapture concept of operations.

Bank angle modulation controls the bank angle of the vehicle to roll the vehicle, indirectly controlling the lift and side forces towards the target orbit. On the other hand, direct force control manipulates the angle of attack and side slip angle to directly control the lift and side forces. Both of these methods control their respective aerodynamic angles through structurally complex aerodynamic flaps or through a mass expensive internal ballast which generates a moment about the spacecraft's center of gravity. Lastly, aerodynamic drag modulation manipulates the aeroshell shape or diameter to control the ballistic coefficient and subsequent drag on the vehicle. While all three of these methods have proven successful in providing propellant mass reductions for simulated aerocapture missions,^{3,4} they require either structurally complex aeroshells with moving flaps or changing diameters, or they require massive internal ballasts which negate the benefits of propellant mass savings.

Thus, to further reduce structural complexity and required mass, magnetohydrodynamic (MHD) drag augmentation is proposed as an alternative control method for aerocapture. MHD control works by utilizing the ionized plasma surrounding a vehicle during hypersonic atmospheric entry. By introducing a magnetic field through onboard electromagnets to the plasma, a Lorentz force is induced which acts equally and oppositely back on the vehicle. Then, by manipulating the magnitude of the current to each electromagnet, the magnetic field and subsequent forces on the vehicle become controllable. Specifically, if the electromagnets are equally separated about the center of gravity, assuming a uniform magnetic field, the induced Lorentz force will act equally and axially back onto the vehicle as an MHD drag, as shown by Figure 2. Thus, controlling the current to each electromagnet allows for direct control of the MHD drag on the vehicle, similarly to aerodynamic drag modulation, however, without the complex changing aeroshell.

Furthermore, previous simulations of MHD control have shown that similar magnitudes of forces can be achieved much higher in the atmosphere when compared to conventional aerocapture control methods,^{9,10} since MHD forces are more dependent on the characteristics of the plasma than

the atmospheric density. Thus, MHD control has the additional advantage of a significantly reduced heat flux, due to the shallower required atmospheric pass. The reduced heat flux can be used to either increase the entry velocity and reduce the total mission timeline, a large concern for these outer planetary missions, or it can be used to reduce the TPS complexity and mass and reallocate the savings to additional science payload mass. Therefore, MHD control has been theorized to not only provide a capable alternative control method for aerocapture, but also introduce several advantages over its aerodynamically controlled counterparts.

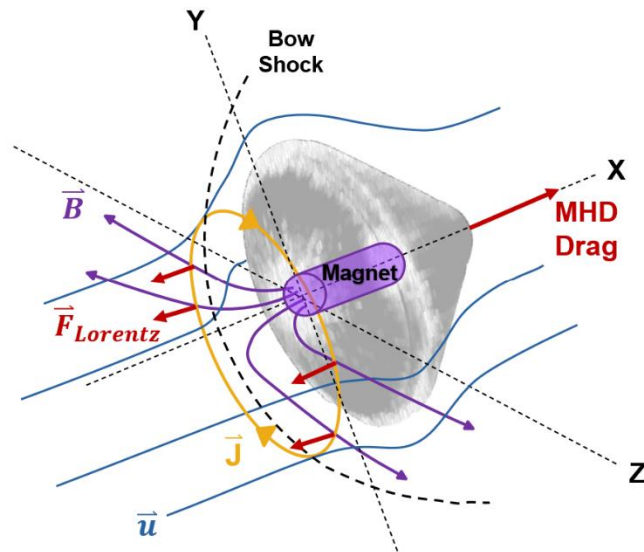


Fig 2. Electromagnet configuration for magnetohydrodynamic drag modulation.

METHODOLOGY

Physical Design of Magnetohydrodynamic Control

Most MHD control simulations to date have assumed a magnetic field strength without defining the physical system which creates the magnetic field.^{9,10} For this research, an electromagnet configuration was evenly spaced around the center of gravity in order to force a ballistic entry and isolate the effect of MHD forces. This serves to define the performance of MHD control alone; however, future work will likely place the MHD system closer to the plasma to increase the control authority or induce moments to complement MHD forces with aerodynamic forces. Additionally, this work assumes a uniform magnetic field and post-shock plasma, allowing for an upper bound performance analysis of MHD control without having to couple to Maxwell's equations in a computationally expensive and typically prohibitive computational fluid dynamics (CFD) model.

Specifically, this MHD system uses a configuration of 64 non-superconducting solenoidal electromagnets. Each electromagnet consists of a 3% iron silicon alloy core with a diameter which fits exactly within its innermost electromagnet coil. The coil was designed using two concentric copper layers with a wire gauge throughout of 6 AWG and 100 turns in each layer. The inner coil has a coil radius of 0.01 m, and the outer coil is assumed to sit directly on top of the inner coil. This point design was determined by varying the electromagnet current, coil radius, cross-sectional wire area, number of turns, and number of electromagnets until the total MHD system mass, electromagnet power consumption, MHD force, and fusing time were all in a feasible range for successful aerocapture, where the fusing time is defined as the amount of time an electromagnet can run before it is no longer functional. The magnetic field strength, mass, power, and fusing time for this

configuration are tabulated in Table 1 below. The values tabulated are calculated using a conservative assumption that a predefined maximum current of 120 Amps is run continuously; in application, the guidance algorithm will modulate the current between zero and 120 Amps to best reach the target orbit. Therefore, the power consumed and fusing time constraints are less restrictive than shown, and the tabulated values provide a worst-case example. The MHD force induced by each electromagnet will be superimposed on one another, and because the electromagnets are evenly spaced about the center of gravity and the magnetic field strength is assumed to be uniform, the total forces from the full electromagnet configuration will sum only in the drag direction.

Table 1. Wire Material Trade Study.

	Single Electromagnet	Full Electromagnet Configuration
Mass (kg)	2.15	137.48
Power Consumption (W)	211.01	13,505
Magnetic Field Strength (T)	1.0943	1.0943
Electrical Fusing Time (s)	1,010.89	1,010.89

Given NASA's current multi-mission radioisotope thermoelectric generators only produce 110 watts, new technology must be developed to meet the required power to control these electromagnets. Magnetohydrodynamic power generation has been studied for decades as potential method to produce power per unit volume up to hundreds or even thousands of megawatts.^{11,12} Following the MHD power generation equations from Reference 11, for both an ideal Faraday generator and a continuous electrode generator, given a 1 cubic meter volume, the power produced is significantly larger than the power consumed by the electromagnet array, as shown by Figure 3. These values were calculated given the nominal trajectory using MHD control, described later in this work. Given a battery capable of collecting this generated energy, MHD control should be able to be self-powering, and for this work, MHD control will not be activated until the MHD power generated is greater than the required electromagnet power consumed.

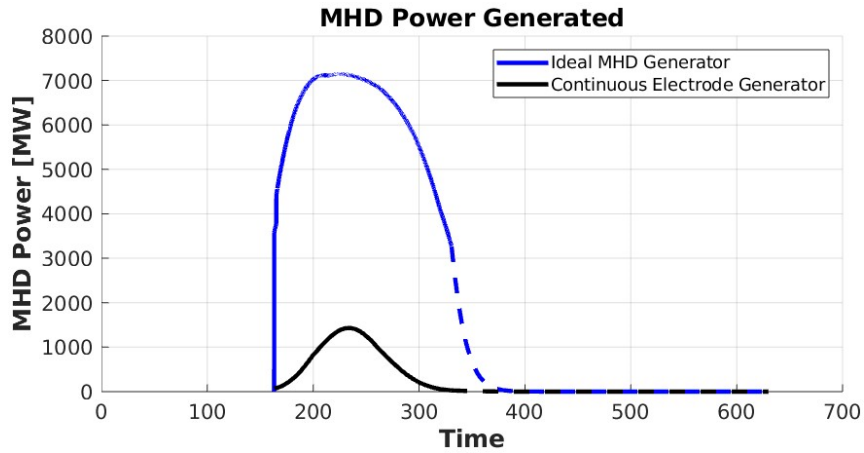


Figure 3. Magnetohydrodynamic power generated during Neptune atmospheric pass.

The Hall effect and ion slip effects are both considered in the estimation of MHD forces and MHD power generation. The Hall effect is caused by an $\vec{E} \times \vec{B}$ drift from the induced electric field, which reduces the electrical conductivity of the plasma and the available MHD force and power. On the other hand, the ion slip effect occurs when the bulk neutral gas is flowing at a speed great enough to cause the ions and electrons to slow down or “slip” against it. For these entry trajectories, the Hall effect was found non negligible for almost the entirety of the pass whereas the ion slip effect becomes strong during the pass, as denoted by the transition from a solid line to a dashed line in Figure 3.

Another unique constraint of MHD control is the fusing time of the electrical wire. While aerodynamic control methods do not have a limit on their guidance time, MHD control must capture before the electromagnet coils melt. Monte Carlo studies for BAM, DFC, and DM as control methods for aerocapture around Neptune show a guidance time of under 400 seconds for all 8000 cases, as shown in Figure 4. Thus, if MHD control can achieve control authority on par with its aerodynamically controlled counterparts, the fusing time should not be a concern.

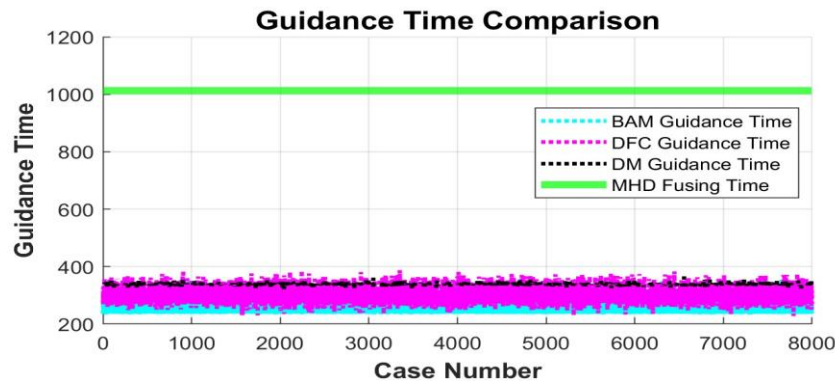


Figure 4. Monte Carlo analysis of guidance times for each aerocapture control method.

Finally, the additional mass of the electromagnet system must be considered as well. While the additional mass is not negligible, the benefits of an MHD controlled system have the potential to outweigh the added mass. First, by using MHD control, the structural complexity of aerodynamic flaps or a size-changing aeroshell is no longer necessary. Similarly, a mass expensive mass ballast, on the order of 150 kg for previous missions,¹² to maneuver the vehicle is also no longer necessary. Furthermore, MHD control is theorized to allow for control authority higher in the atmosphere, significantly reducing the thermal protection system complexity and mass. Based on previous simulations for blunt body aerocapture to the Ice Giants, the TPS mass required is roughly 20 to 40% of the vehicle mass given a Heatshield for Extreme Entry Environment Technology (HEEET) TPS system.⁴ Previous aerocapture simulations to Neptune have used heritage blunt body aeroshells with an arrival mass of roughly 2000 to 2200 kg.^{5,6} Thus, the estimated TPS mass using HEEET is between 400 to 880 kg. Because the TPS mass is proportional to the projected heat flux, MHD control has the potential advantage of significantly reducing the TPS mass, offsetting the additional mass of the electromagnet system.

Simulation Models for Aerodynamic and Magnetohydrodynamic Control

To compare the four different control methods, each trajectory was simulated in NASA Langley’s Program to Optimize Simulated Trajectories II (POST2), a six degree-of-freedom flight dynamics simulator.¹⁴ POST2 allows for precise trajectory integration while using predefined aerodynamic, aeroheating, gravitational, and atmospheric models. For this work, a 70-degree sphere-cone reentry forebody reflecting the Mars Science Laboratory (MSL) vehicle aerodynamics is

used.¹⁵ Despite not going to Mars, the aerodynamic force coefficients translate well to Neptune due to Mach independence for hyperbolic entry. Next, a Sutton-Graves model with specific inputs for Neptune is used to calculate the stagnation point heating rate. Neptune was chosen over Uranus for this work because of its history of aerocapture simulations available for direct comparison; future work aims to compare performance for Uranus as well. The gravitational model used is an unnormalized oblate planet model up to the J2 constant, and the atmospheric model is NASA's 2004 Neptune Global Reference Atmosphere Model (GRAM). Neptune GRAM provides an in-depth model of the mean and perturbed density, speed of sound, and wind profiles at different altitudes and locations across Neptune.¹⁶ These vehicle and planetary models used are predefined options built into POST2 which have years of history and extensive uses throughout several NASA missions and research efforts.^{3,4,5,6}

In order to simulate MHD control, two additional models must be added: the electrical conductivity model and the MHD force model. The electrical conductivity, σ , is defined as a piecewise function of the gas number density, n , electron number density, n_e , and electron temperature, T_e , as shown by Equation (1). These three variables can be calculated using the Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA), a NASA Langley continuum CFD software.¹⁷ Because the software is made for continuum flow, the gas number density, electron number density, and electron temperature at densities below 10^{-6} kg/m³ were logarithmically extrapolated until 10^{-10} kg/m³, after which the values were assumed to be zero. Future work may aim to improve the electrical conductivity calculation. However, results described later show that the majority of considerable MHD forces and MHD generated power occur in the continuum regime; therefore, fidelity in the rarefied regime may not be necessary to estimate the performance of MHD control.

$$\sigma = \begin{cases} 3 * 10^5 \left(\frac{n_e}{n}\right), & \frac{n_e}{n} \leq 10^{-3} \\ 2.147 * 10^{-3} (T_e)^{\frac{3}{2}}, & \frac{n_e}{n} > 10^{-3} \end{cases} \quad (1)$$

As previously mentioned, the Hall and ion slip effects are considered when calculating magnetohydrodynamic interactions. These effects are specifically detrimental to the electrical conductivity. Specifically, the ions and electrons begin to slow down against the bulk neutral gas at higher combinations of velocity and density, reducing the effectiveness of magnetohydrodynamics. The ion mobility, μ_i , and electron mobility, μ_e , are defined in Equations (2) and (3), where n_n , n_i , m_i , and T_2 are the neutral species number density, ion number density, ion particle mass, and post-shock atmospheric velocity, respectively. Because LAURA assumes a quasi-neutral plasma, the ion number density is assumed to be equal to the electron number density. The ion particle mass is defined as the mean molecular weight of the Neptunian atmosphere. Finally, the Coulomb logarithm, $\ln(\Lambda)$, is the factor of dominance between small-angle and large-angle collisions. This variable is a function of the plasma and is typically set to be a constant value between 10 and 20;¹⁸ for this work, a mean value of 15 was chosen. Given the adjusted ion and electron mobility values, the effective electrical conductivity accounting for Hall and ion slip effects can be calculated using Equation (4).

$$\mu_i = \frac{1}{2} * \frac{2}{(n_n^{-1} * 2.2 * 10^{10} * (m_i * T_2)^{-0.5})^{-1} + (14.3 * m_i^{-0.5} * T_2^{1.5} * n_i^{-1})^{-1}} \quad (2)$$

$$\mu_e = \frac{1}{2} * \frac{2}{(n_n^{-1} * 3.74 * 10^{19} * e^{33.5 * (\ln(T_e))^{-0.5}})^{-1} + (n_i^{-1} * 9.5 * 10^{16} * T_e^{1.5} * \ln(\Lambda)^{-1})^{-1}} \quad (3)$$

$$\tilde{\sigma} = \frac{\sigma}{1 + \mu_i * \mu_e * |\vec{B}_0|^2} \quad (4)$$

With the effective electrical conductivity model defined, the MHD induced Lorentz forces can be calculated and added to the vehicle's equations of motion. Given each electromagnet is equally spaced about the center of gravity, assuming each creates a uniform magnetic field, the induced Lorentz forces will sum and act equally and oppositely in the drag direction. This MHD drag can be calculated through Equations (5) through (8), where K , u_2 , B_z , A_{patch} , Δ , I_z , r_c , and D are the load factor, post-shock velocity, magnetic field strength, MHD interaction area, shock standoff distance, electromagnet control current, average coil radius, and vehicle diameter, respectively. The load factor, K , is a scale factor defined by the relationship between the load resistance and plasma resistance. This value is defined between 0 and 1,¹¹ and for this research, the mean value of 0.5 was chosen. The shock standoff distance is estimated using Equation 8 assuming the shock standoff distance is zero when the vehicle diameter is zero.¹⁰ While this approximation is sufficient for this initial performance study, future work aims to refine the calculation of the shock standoff distance using empirical data for similar aerodynamic shapes and conditions.

$$F_x = -(1 - K)\tilde{\sigma}u_2B_z^2A_{patch}\Delta \quad (5)$$

$$B_z = \frac{NI_z\mu_0}{2r_c} \quad (6)$$

$$A_{patch} = \pi r_c^2 \quad (7)$$

$$\Delta \approx \frac{\rho_\infty}{\rho_{post-shock}}D \quad (8)$$

Guidance Algorithms for Atmospheric and Magnetohydrodynamic Aerocapture

Given the electromagnet current is directly proportional to the magnetic field and subsequently the MHD drag, controlling the current to each electromagnet provides direct control of the MHD drag in a way similar to aerodynamic drag modulation without requiring a size changing aeroshell. The current to each electromagnet is optimized through a guidance algorithm aimed at capturing into a specific orbit around Neptune which allows for Triton flybys, maximizing the potential scientific benefit of the mission. This target orbit is defined by Reference 7 and characterized in Table 2 below.

Table 2. Target Orbit Characteristics.

Target Orbital Parameter	Value
Apoapsis Altitude (km)	430,000
Periapsis Altitude (km)	3,986
Longitude of the Ascending Node (°)	330.829
Inclination (°)	153.547

Each aerocapture control method uses a robust numerical predictor-corrector (NPC) algorithm to perform closed-loop guidance and optimize the control parameter as necessary. The algorithm used is the Fully Numerical Predictor-corrector Aerocapture Guidance algorithm (FNPAG), a well-established and supported algorithm which can actively optimize multiple variables at once while targeting another given variable.^{19,20} For DFC and BAM, the aerodynamic angles were actively optimized in order to minimize the propellant burns or ΔV required after atmospheric exit to reach

the target orbital parameters. Similarly, the ballistic coefficient was optimized during DM to minimize the ΔV required to reach the target orbit. Finally, MHD drag modulation optimizes the electromagnet current to minimize the required ΔV as well. More specifically, Figure 5 details how the numerical predictor-corrector algorithm optimizes the current in the inner loop and feeds that to the outer loop during each guidance call during MHD control, where the blue boxes denote the inner loop and the black boxes denote the outer loop.

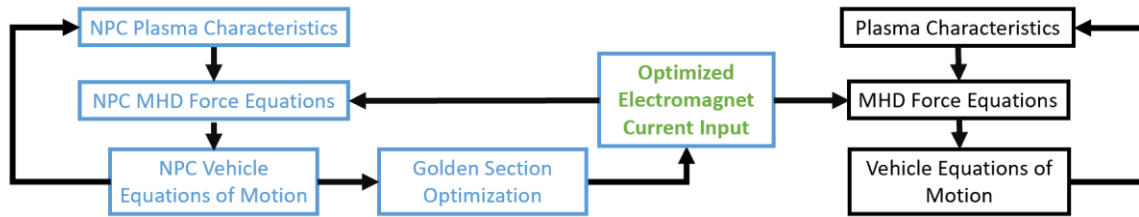


Figure 5. Closed-loop MHD guidance algorithm overview.

During each guidance call, the vehicle's current position and velocity will inform the plasma characteristics using lookup tables defined by LAURA, which will then feed into the electrical conductivity and MHD drag equations, which will finally update the equations of motion resulting in the vehicle's new position and velocity. Simultaneously during each of these guidance calls, the inner loop will also take the vehicle's current position and velocity and test multiple different control inputs chosen through the golden section optimization technique. The inner loop will take each control value and propagate each trajectory to atmospheric exit. It will then quantify the cost function, which is the final ΔV in this case, and choose the electromagnet current which generated the lowest cost. This is then fed to the outer loop and commanded in the MHD equations. The guidance ends once the outer loop is propagated to atmospheric exit.

Figure 6 shows the inner loop FNPAG commanded current matches exactly with the outer loop MHD truth current, showing that the closed-loop guidance algorithm is working correctly. MHD control is only activated once the MHD power generated exceeds the electromagnet power consumed which can be seen around roughly 170 seconds into the atmosphere. Lastly, the active MHD guidance lasts roughly 400 seconds, on par with its aerodynamically controlled counterparts. This is significantly less than the 1010 second fusing time, which was calculated using a conservative assumption that 120 Amps were run consistently. This MHD control profile successfully led to the target orbit, depicted by the agreement with the mean apoapsis altitude in Figure 7.

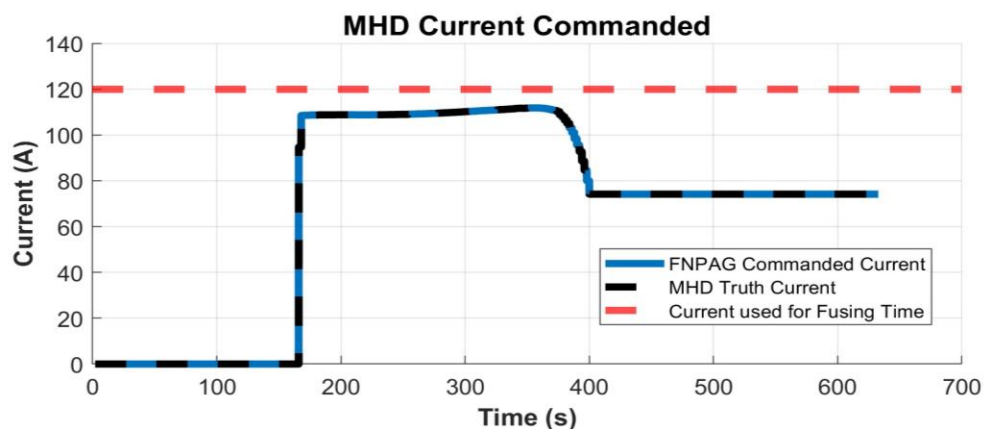


Figure 6. Magnetohydrodynamic control profile.

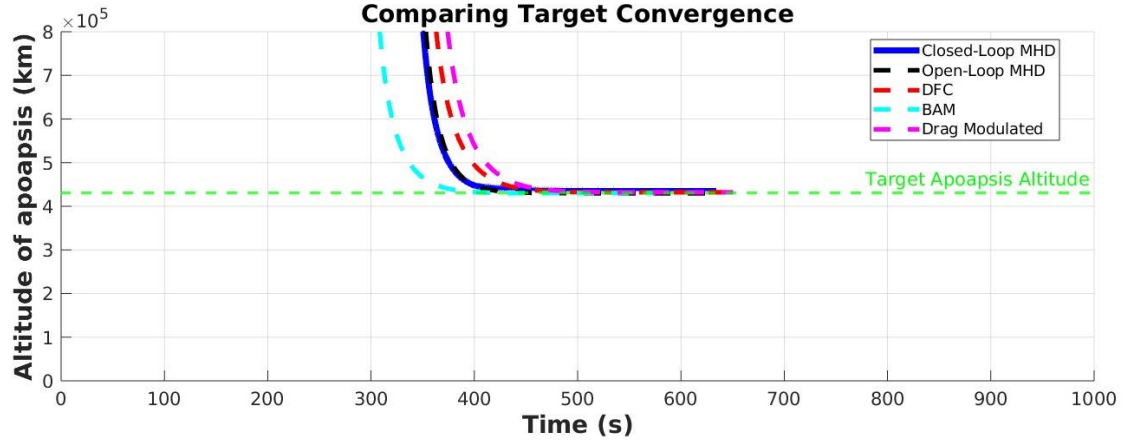


Figure 7. Aerocapture guidance method convergence with target orbit.

RESULTS

Finally, MHD drag modulation was able to capture around Neptune with a much shallower atmospheric pass. In fact, the nominal pass was roughly 50 to 100 km higher in altitude than aerodynamically controlled aerocapture methods, as shown by Figure 8. Because the pass occurred much higher in the atmosphere, the vehicle requires less force to maneuver through the less dense portion of the atmosphere, depicted by the root sum of squares of all the forces on the vehicle in Figure 9. The jump in forces in the DFC case is representative of its multiple aerodynamic angles changing simultaneously. Thus, MHD drag modulation can achieve the same control authority with significantly less total forces on the vehicle, reducing the structural load.

Furthermore, the shallower atmospheric pass leads to a smaller convective heat flux and integrated heat load. These values are quantified at the stagnation point using the vehicle's nose radius and are compared against its aerodynamically controlled counterparts in Figure 10 below. The results show a significant decrease in heat flux and heat load from DFC and BAM to MHD drag modulation. However, the heat flux results show similar performance in heat flux and heat load between aerodynamic drag modulation and MHD drag modulation.

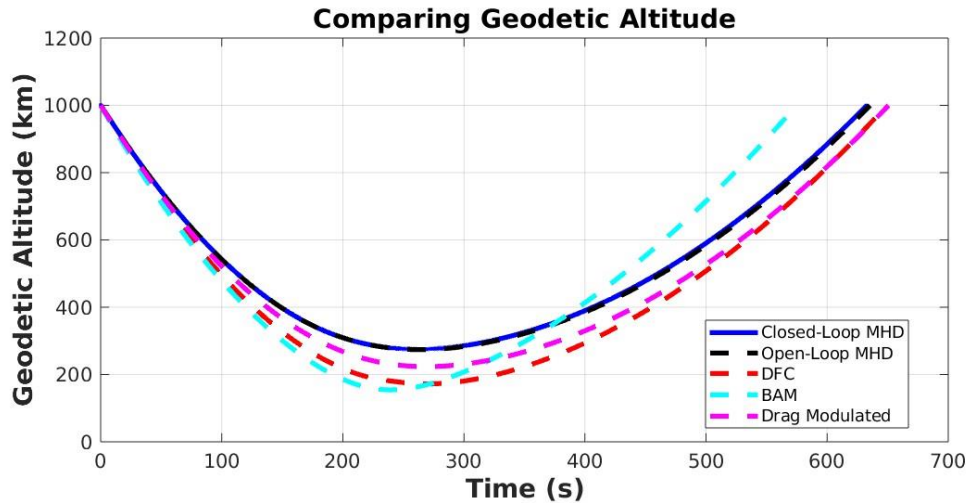


Figure 8. Geodetic altitude during each control method.

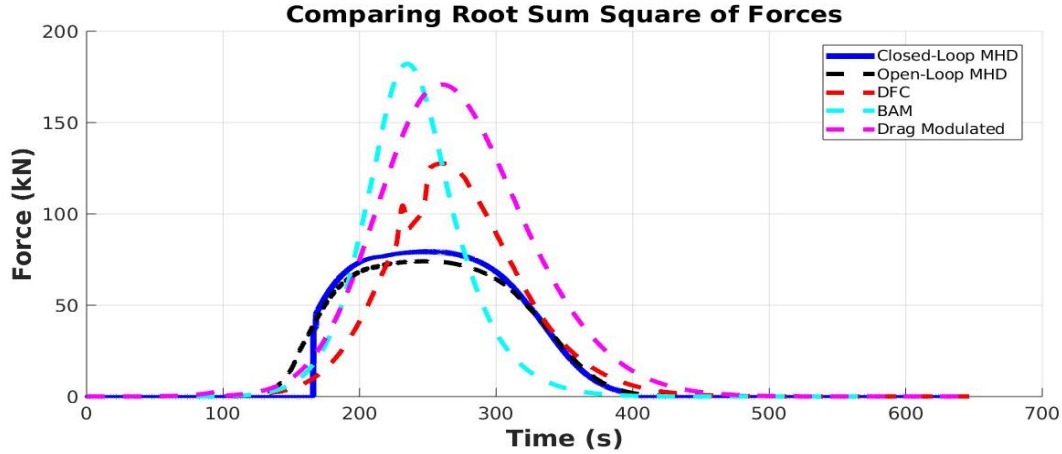


Fig. 9 Root Sum of Squares of the forces experienced in each control method.

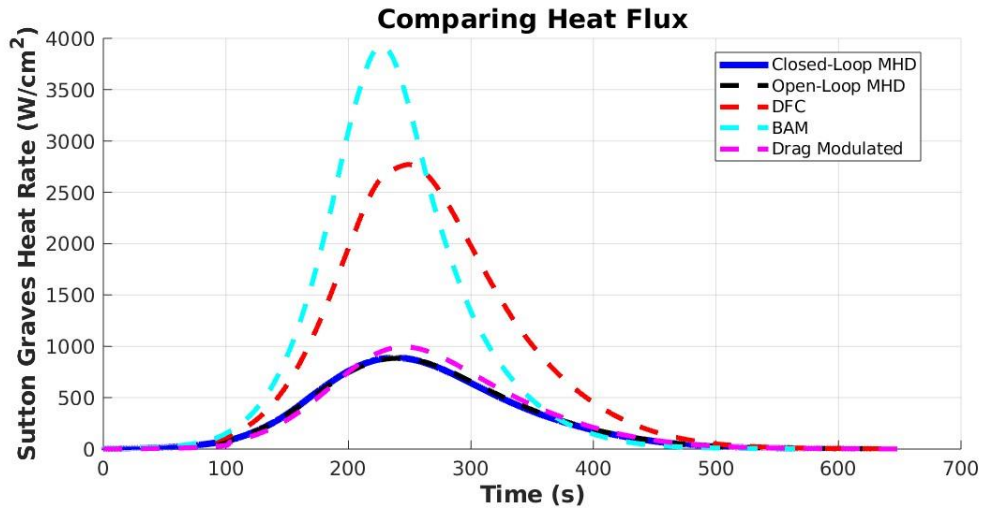


Fig. 10 Heat flux experienced by each control method.

While these results show the nominal performance of MHD drag modulation, the perturbations in the atmosphere, vehicle state, aerodynamics, and mass properties are likely and will cause off-nominal trajectories. Thus, a Monte Carlo analysis was performed to test the robustness of MHD drag modulation to off nominal situations. The Monte Carlo dispersions applied to each aerocapture control method matches those applied to previous aerocapture simulations to Neptune.⁵ The off-nominal performance of each aerocapture control method is shown in Table 3. The entry flight path angle played a significant role in the performance of each control method. Tuning the entry flight path angle sometimes led to a large tradeoff between the success rate and the ΔV required in the top percentile of cases. This is mostly evident in the two BAM cases listed. It is important to note that this entry flight path angle tuning is still ongoing for MHD drag modulation.

Table 3. Monte Carlo performance analysis for each control method.

	Top Percentile ΔV (m/s)	% Cases Successful	% Cases Landers	% Cases Hyperbolic
MHD Drag Modulation	99.87% = 654.89	79.36	7.52	13.13
Bank Angle Modulation 1	99.87% = 654.85	95.425	0	4.575
Bank Angle Modulation 2	99.87% = 2876.24	99.95	0	0.05
Direct Force Control	99.87% = 108.32	99.525	0	0.475
Aerodynamic Drag Modulation	95% = 173.75	86	8	6

Nevertheless, DFC and BAM are much more robust to off-nominal situations with a 95 to 99% success rate, where success is defined as a capture within 5% of the mean apoapsis altitude. On the other hand, both aerodynamic and MHD drag modulation perform worse with successful capture rate of 86 and 79%, respectively. This may be more indicative of the advantages of lift modulation over drag modulation than of the performance of magnetohydrodynamics. Future work could introduce MHD lift modulation instead, by using MHD to create moments on the vehicle to change the desired aerodynamic angles.

CONCLUSION

Throughout this research, MHD drag modulation has shown that it can feasibly serve as a control method for aerocapture around Neptune. Using the same closed loop guidance algorithm as DFC, BAM, and DM, MHD drag modulation can optimize the electromagnet current to generate enough control authority to successfully capture into a specific target orbit around Neptune. Furthermore, under nominal conditions, MHD DM can produce equivalent control authority with significantly less total forces, reducing the structural load on the vehicle.

MHD control also allows for a shallower atmospheric pass, which led to a significant reduction in heat load and heat flux compared to DFC and BAM. Although the heat flux and heat load are relatively the same between MHD DM and aerodynamic DM, MHD control still has the advantage of not requiring a complex continuously varying aeroshell. Finally, while MHD DM performs worse than DFC and BAM in off-nominal situations, it still performs roughly on par with aerodynamic DM. Thus, this indicates that drag modulated control methods are likely less robust to perturbations than lift modulated control methods.

In conclusion, MHD control can be used to apply drag modulation, and it performs roughly on par with aerodynamic drag modulation in terms of heat flux and Monte Carlo success rate. However, MHD control is enabling because it can do so without the prohibitive designs necessary for aerodynamic drag modulation.

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NOTATION

σ	electrical conductivity
n	gas number density
n_e	electron number density
T_e	electron temperature
μ_i	ion mobility
μ_e	electron mobility
n_n	neutral species number density
n_i	ion number density
m_i	ion particle mass
T_2	post-shock atmospheric temperature
$\ln(A)$	Coulomb's logarithm
F_x	x-component of the Lorentz force vector
K	load factor
u_2	post-shock local velocity
B_z	z-component of the magnetic field vector
A_{patch}	magnetohydrodynamic patch area
$\mathcal{A}$	shock standoff distance
N	number of turns in the electromagnet
I_z	electromagnet current

μ_0 permeability of vacuum

r_c average coil radius between inner and outer electromagnet coils

D aeroshell diameter

ΔV change in velocity

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