

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

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While the Ice Giants are a top priority for flagship missions in the NASA's near-term future, current technologies limit the scientific payload and mission timeline for future Uranian and Neptunian missions due to the need for fuel for orbit insertion maneuvers. Thus, to maximize the scientific potential of future missions, atmospheric aerocapture has been heavily researched. While atmospheric aerocapture simulations have proven enabling for capturing around Neptune, its deep atmospheric pass requires an aeroshell with robust thermal protection systems (TPS). Magnetohydrodynamically-controlled aerocapture serves as a potential solution to the limitations of both fully propulsive orbit insertion and aerodynamically controlled aerocapture. Through NASA Langley's high-fidelity flight dynamics simulation, the Program to Optimize Simulated Trajectories II, both the aerodynamic-only and magnetohydrodynamic aerocapture methods were simulated and compared for identical missions to Neptune. After applying an optimized numerical predictor-corrector guidance algorithm for both methods, the results showed that magnetohydrodynamics has not only the control authority to successfully capture around Neptune, but also the unique advantage of a shallower atmospheric pass, decreasing the maximum heat load and the required TPS mass.

INTRODUCTION

The most recent Planetary Science Decadal Survey posed a mission to one of the Ice Giants as a top priority for flagship missions for NASA. Although heritage propulsive technologies have successfully enabled planetary orbit insertion in the past, the technologies from these missions are reaching the threshold of their capabilities, specifically with higher mass and outer planetary missions due to the inherent propellant mass constraints of using primarily propulsive maneuvers. Thus, there has been an ongoing effort to introduce new methods of deceleration and flight control during planetary entry, descent, and landing to reduce the required propellant mass and enable new missions. One of the most prominently proposed solutions is aerodynamically controlled aerocapture.^{1,2} With recent technological advances in the fields of guidance, navigation, and control (GNC)

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and thermal protection systems (TPS), aerodynamically controlled aerocapture can enable a flagship class mission to the Ice Giants with current technology.^{3,4,5,6,7}

Aerocapture is the use of a planet's atmosphere to maneuver a spacecraft and capture into an orbit around that planet. As shown in Figure 1, during aerocapture, the spacecraft will enter hyperbolically into the atmosphere, begin its guidance to be put onto an elliptic trajectory towards some target parking orbit, and then finally perform a few corrective maneuvers to adjust for any uncertainties or perturbations. While these corrective maneuvers will require propulsive burns, these burns will require considerably less propellant mass than those that would have been required if aerocapture had not been performed. A common goal of the guidance algorithm during the atmospheric phase of the flight is to minimize the required propellant for these orbital correction maneuvers while attaining the desired orbit. With successful guidance and control, propellant mass for orbital insertion can be significantly reduced, and these savings can then be used to reduce the overall mission costs, increase the mission's science return, or even enable larger missions to farther targets such as Uranus and Neptune.

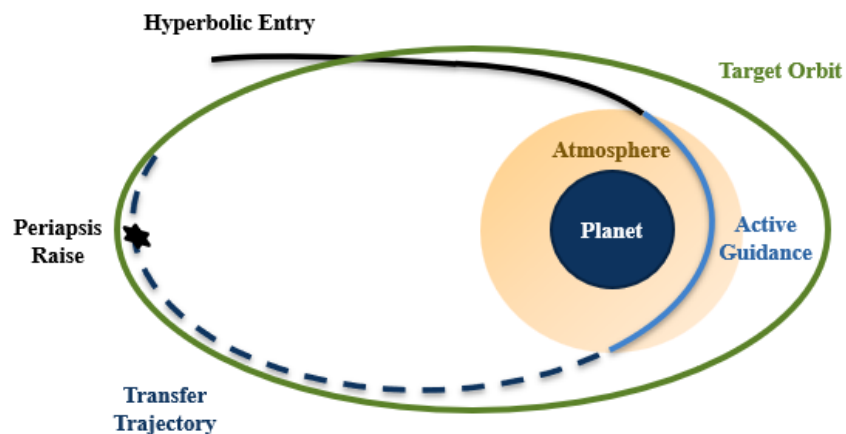


Figure 1. Aerocapture concept of operations.

State of the art research has considered three primary guidance and control architectures for aerodynamically controlled aerocapture: direct force control (DFC), bank angle modulation (BAM), or drag modulation (DM). DFC actively adjusts the angles of attack and sideslip to directly manipulate the lift and drag vectors to shape the spacecraft trajectory, while BAM actively adjusts the bank angle to rotate the spacecraft and change the direction of the vehicle lift vector. On the other hand, DM maintains a constant angular orientation and instead varies the ballistic coefficient which subsequently changes the aerodynamic drag to optimize the trajectory towards the target orbit. While research studies have shown considerable reductions in propellant mass with the use of aerodynamically controlled aerocapture over the traditional fully propulsive systems,^{1,2} relying solely on aerodynamic forces for control poses some disadvantages.

Specifically, the TPS on the spacecraft must be robust enough to survive intense atmospheric heating during the aerocapture maneuver. Although aerodynamically controlled aerocapture has overall propellant mass savings compared to fully propulsive orbit insertion, aerodynamic-only aerocapture needs to add considerable TPS mass due to its need to dip deeper into the planet's atmosphere to gain considerable control authority. Typically, these propellant savings outweigh the additional TPS mass,² but an alternative which minimizes both the propellant mass and the TPS mass would be the ideal solution to begin enabling more scientifically complex missions.

This paper proposes magnetohydrodynamic (MHD) drag modulated control as this potential solution that decreases both the propellant and TPS mass. MHD control takes advantage of the electrically conductive, ionized plasma that is created during the spacecraft's hypersonic entry into a planet's atmosphere. By introducing a magnetic field generated and modulated by an onboard electromagnet onto the ionized surrounding plasma, a Lorentz force can be induced which acts equally and oppositely on the vehicle as a controllable MHD drag, shown in Figure 2.

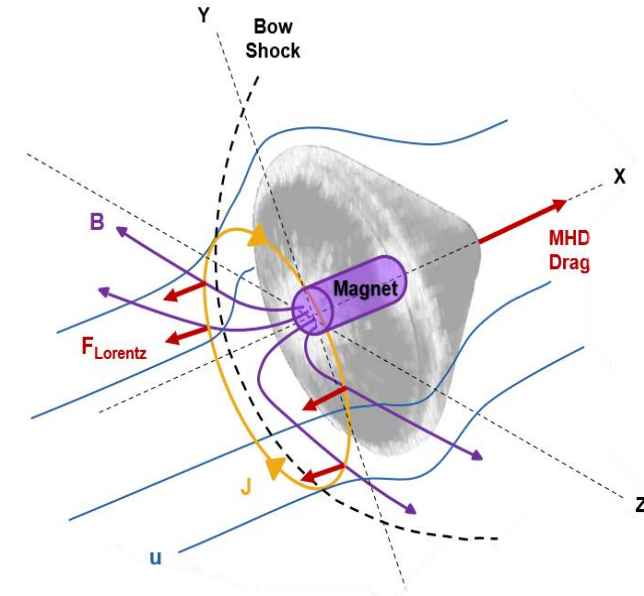


Figure 2. MHD drag augmentation force conceptual schematic.

This MHD drag can supplement aerodynamic forces as a control method in aerocapture. MHD drag controlled aerocapture can theoretically provide comparable forces at much higher altitudes compared to aerodynamic-only controlled aerocapture, which should significantly reduce the heat load and subsequently required TPS mass.^{8,9} Thus, this work aims to simulate MHD drag controlled aerocapture and compare its performance in terms of control authority and heat load to aerodynamic-only controlled aerocapture.

METHODOLOGY

Physical Design of Magnetohydrodynamic Control

This study serves to prove that MHD-controlled aerocapture can improve upon its aerodynamically controlled counterparts. The aerodynamic angle modulations required for both DFC and BAM can be controlled through either an internal ballast which applies a torque about the spacecraft's center of gravity or an external aerodynamic control surface, such as a flap, to tilt and rotate the vehicle. On the other hand, aerodynamic drag modulation is typically controlled by discretely or continuously changing the ballistic coefficient by making changes to the aeroshell diameter. Finally, magnetohydrodynamic control would be applied using a permanent magnet or an electromagnet.

In this study, an electromagnet configuration is used to induce and control the MHD drag. For the purposes of this study, the electromagnet configuration was placed at the center of gravity of the spacecraft to ensure ballistic entry. This ensures no aerodynamic moments and assures that the

control authority and subsequent aerocapture are solely due to magnetohydrodynamic control. Future applications will likely place the electromagnet configuration closer to the plasma for higher control authority.

A preliminary electromagnet mass and performance study has been conducted with non-superconducting materials to assess basic feasibility. The design for each electromagnet in this configuration focused on minimizing the electromagnet's mass and required power while still achieving a functional magnetic field strength and fusing time, where the fusing time is defined as the amount of time the maximum current could be applied before the electromagnet's wires melt. Thus, the electromagnet design becomes a multivariable optimization problem, minimizing the mass and power while maximizing the magnetic field strength and fusing time. The variables which directly affect this optimization are the electromagnetic current, coil radius, cross-sectional wire area, and the number of turns. These four variables were altered until a reasonable mass, power, magnetic field strength, and fusing time were all achieved. For the purposes of this research, the chosen design point for a single electromagnet with an iron core is defined in Table 1 below.

Table 1. Electromagnet Point Design.

Design Parameter	Value
Max Current (A)	105
Coil Radius (m)	0.05
Wire Gauge (AWG)	6
Number of Turns	80
Mass (kg)	16.66
Max Required Power (W)	552.1
Max Magnetic Field Strength (T)	0.1056
Minimum Fusing Time (s)	1010.9

There are two important notes to make on Table 1. First, the table's constraints are calculated under the conservative assumption that the maximum current will be applied continuously. Thus, the required power and magnetic field strength could vary between zero and the listed value, making the fusing time much longer in reality. Secondly, the table only refers to the design parameters for a single electromagnet and not the electromagnet configuration. Thus, for the full configuration, assuming the magnetic field vectors of each electromagnet are additive and each electromagnet is evenly placed to induce a net force on the center of gravity, a combination of ten of these electromagnets were used for a total magnetic field strength of 1.056 T, a mass of 166.58 kg, and a required power consumption 5.521 kW.

Although the power required may seem daunting, this power can be created through magnetohydrodynamic power generation. Previous research has shown MHD power generation to create usable power on the order of hundreds of kilowatts.^{10,11} Thus, the electromagnetic configuration can power itself with only a small fraction of the energy available from MHD power generation during the pass. Additionally, the fusing time, or time to melt of the electrical wire in the configuration is roughly 1,000 seconds, over 15 minutes. The results from DFC and BAM simulations

performed later in this study have found the guidance to last typically under ten minutes. Thus, if magnetohydrodynamics can perform on par with its atmospheric counterparts, this fusing time should allow the electromagnet to function without melting during the atmospheric pass.

Simulation Models for Atmospheric and Magnetohydrodynamic Aerocapture

To investigate MHD-controlled aerocapture and compare to its atmospheric counterparts, a simulation at Neptune for each method is conducted using NASA Langley’s high-fidelity Program to Optimize Simulated Trajectories II (POST2).¹² This program allowed for precise trajectory integration and optimization while using robust spacecraft aerodynamic and aeroheating models as well as planetary gravitational and atmospheric models. The models used for this research effort were predefined options built into the program which have years of history and extensive uses throughout several NASA missions and research efforts.^{7,13} The models used are listed in Table 2 below.

Table 2. Vehicular and Planetary Models.

	Model
Aerodynamic Model	MSL Aerodatabase
Aeroheating Model	Sutton-Graves
Gravitational Model	Unnormalized Oblate Planet Model up to J2
Atmospheric Model	2004 Neptune GRAM

The aerodynamic model chosen is essentially a well-defined blunt-body entry vehicle developed by the Mars Science Laboratory (MSL), and although these aerocapture simulations may not be to Mars, the vehicle shape and characteristics translate well to the similar entry and descent purposes of this research.⁶ Next, the stagnation point heating rate and the associated heating integral are calculated using the planet’s specific Sutton-Graves constant. The planet chosen for the purposes of both atmospheric and magnetohydrodynamic aerocapture was Neptune. Neptune serves as an ideal target because of its large need for mission-enabling mass savings as well as its relatively dense atmosphere when compared to not only other gas giants but also other primary scientific bodies of interest such as Mars. Lastly, the gravitational model for Neptune was defined by an oblate planetary model using Neptune’s J2 constant while the atmospheric model for Neptune was defined by a 2004 Neptune Global Reference Atmosphere Model (GRAM). In short, the 2004 Neptune GRAM allows for an in-depth model of the mean and perturbed density, speed of sound, and wind profiles at different times and locations on Neptune.

While these models are key in defining aerodynamically controlled aerocapture and supporting MHD controlled aerocapture, MHD control requires two additional models: the electrical conductivity model and the MHD induced Lorentz force model. The electrical conductivity model is critical because it determines the viability of the atmosphere to generate considerable and controllable MHD forces. The MHD force model then calculates the induced drag and adds the MHD drag to the spacecraft’s overall equations of motion.

The electrical conductivity’s accuracy is tied to the fidelity at which the electron number density, gas number density, and electron temperatures are known. Through the NASA Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA),¹⁴ a computational fluid dynamics

simulation software code, these variables were calculated with confidence for a range of atmospheric density and velocity values. These variables were then defined in a multivariable lookup table that can be imported into and used by POST2 accordingly. The main caveat with this lookup table is that it is bounded by the atmospheric density from 10^{-6} to 10^{-3} kg/m³ and by the atmospheric velocity from 16 to 32 km/s. While these bounds are appropriate for the range of velocities the spacecraft is expected to travel at, the lower bound of the density is not comprehensive of the range of densities magnetohydrodynamics can operate at. However, expanding the range of densities below 10^{-6} kg/m³ requires a more complex direct simulation Monte Carlo solver instead of the currently used Navier-Stokes solver because of the rarefied flow below that density. Future research efforts may improve upon this model; however, for the purposes of this research, these variables will be logarithmically extrapolated for the range of densities below 10^{-6} until 10^{-10} kg/m³ where any further electron number density, gas number density, and electron temperature will be considered negligible.

Next, the MHD model can calculate the induced Lorentz drag through Eqs. (1), (2), and (3) below. Assuming a uniform magnetic field from an electromagnet configuration, the produced Lorentz forces will sum and act equally and oppositely on the vehicle in only the drag direction.

$$F_{MHD,x} = -(1 - K)\sigma_e u_z B_z^2 A_{patch} \quad (1)$$

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

$$A_{patch} = \pi r_c^2 \quad (3)$$

The current to the electromagnet is proportional to the magnetic field which directly influences the induced drag. Thus, the current to the electromagnets can be optimized to control the MHD drag and maneuver the vehicle towards the target orbit. Given the optimized current, the MHD drag is calculated and combined into the POST2 trajectory integration. Thus, this MHD control methodology operates similarly to aerodynamically controlled drag modulation with a continuously changing aeroshell; however, it benefits from not requiring the complex aeroshell design.

Guidance Algorithms for Aerodynamic-Only and Magnetohydrodynamic Aerocapture

After modeling the underlying physics of the aerodynamic-only and magnetohydrodynamic control methodologies, the guidance algorithm behind each control method was developed. For this research to Neptune, the guidance was optimized to target a Triton observation orbit defined by previous aerocapture research at Neptune.⁴ For all the control methods, the Fully Numerical Predictor-corrector Aerocapture Guidance (FNPAG) algorithm, developed and historically utilized by NASA Langley,^{7,15} was used to optimize the control towards the target orbit. FNPAG is a well-established and supported algorithm which can actively optimize multiple variables at once while targeting some given variable.^{15,16} In this case, the aerodynamic angles were optimized for DFC and BAM, the ballistic coefficient was controlled for DM, and the current to each electromagnet was optimized for MHD control. All four control methods will minimize the propellant mass required for the periapsis raise and apoapsis correction to reach the target orbit after the controlled atmospheric pass.

RESULTS

Because MHD control is more dependent on the electrical conductivity than the atmospheric density, it can be activated much higher in the atmosphere compared to aerodynamic-only control methods, as seen in Figure 3. Despite being activated higher in the atmosphere, it can still produce forces within the same order of magnitude as aerodynamic control because, although the

aerodynamic forces during MHD control are smaller, the total force including MHD induced drag is quite considerable, as shown in Figure 4. Finally, the higher atmospheric control significantly reduces the heat flux the spacecraft experiences, since its trajectory is entirely within a less dense region. This is depicted in Figure 5.

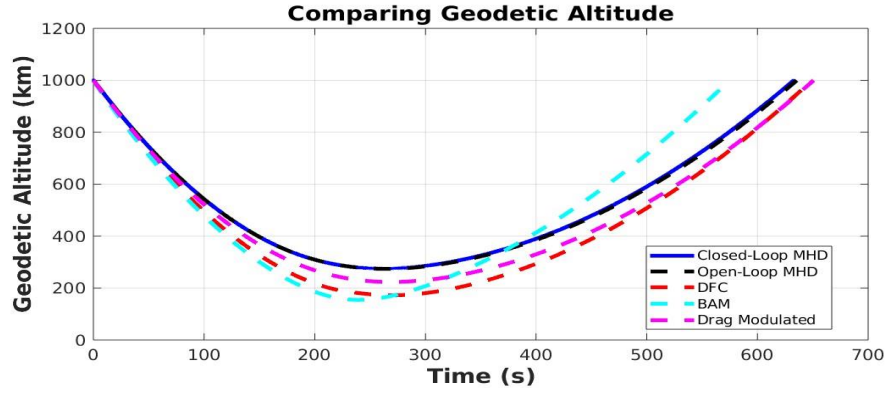


Figure 3. Geodetic altitude over the trajectory of each control method.

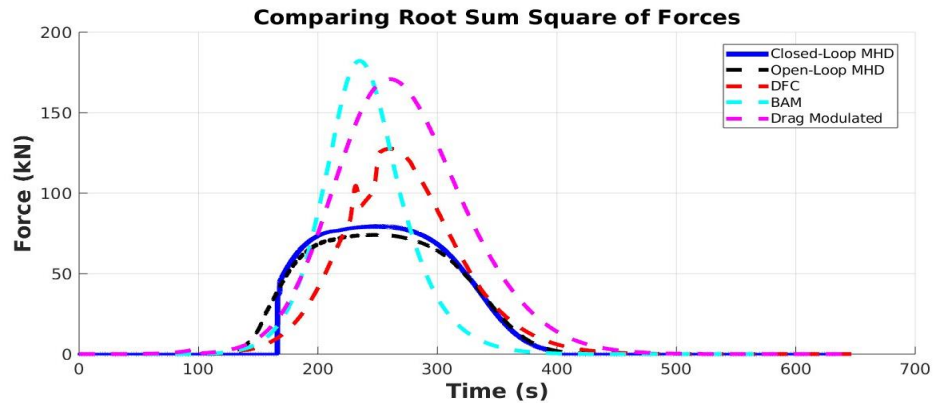


Figure 4. Total forces over the trajectory of each control method.

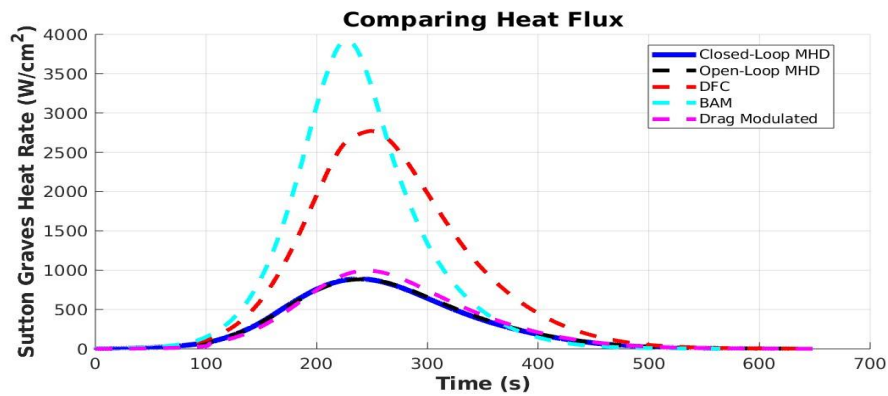


Figure 5. Heat flux over the trajectory of each control method.

CONCLUSION

Thus, MHD control has shown to not only have control authority on par with DFC, BAM, and DM, but it has also shown a unique potential advantage in its considerably lower heat load and subsequently required TPS mass. Monte Carlo analyses were performed to ensure that these results were not specific to the settings of this one simulation. Multiple perturbations were applied to the planet's atmospheric model and the vehicle's initial entry state. These Monte Carlo analyses were run for all four control methods, and the results are shown in Table 3.

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

Control Method	Top ΔV Percentile [m/s]	% Cases Successful	% Cases Landers	% Cases Hyperbolic
Closed-loop MHD Control	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
Continuously Varying Drag Modulation	95% = 173.75	86	8	6

The Monte Carlo results show that DFC and BAM perform the best with roughly a 95 to 99% success rate when these perturbations were applied over 8000 cases, where success is defined as reaching the target orbit with within a 5% error in the apoapsis altitude. On the other hand, DM and MHD control performed similarly but were both only successful for roughly 80 to 86% of the cases. However, it is important to note that the closed loop MHD Monte Carlo results were only for 1000 cases and have not been fully tuned to maximize its success rate. Despite this, these results lead to a conclusion that drag modulated control, whether aerodynamic or magnetohydrodynamic, may be less adaptive to perturbations than its angularly controlled counterparts. Thus, future work may aim to revisit MHD control as a method of changing the aerodynamic angles of the vehicle rather than only inducing drag.

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NOTATION

B magnetic field vector

J entry plasma ring current

$F_{Lorentz}$ induced Lorentz force

u	freestream velocity
u_2	post-shock local velocity
$F_{MHD,x}$	x-component of the Lorentz force vector
K	load factor
B_z	z-component of the magnetic field vector
σ_e	electrical conductivity
A_{patch}	magnetohydrodynamic patch area
r_c	electromagnet coil radius
I_z	electromagnetic current in z-direction
N	number of turns in coil
n	number of electromagnets in configuration
μ_0	permeability of free vacuum
ΔV	change in velocity

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