
2023 Richard S. Schultz ’60
Symposium Fellow Research Report

# Redesigning the Stability Control and Augmentation System of the MV-22 Osprey Tiltrotor as a Hypersonic VTVL Suborbital Aircraft

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# Redesigning the Stability Control and Augmentation System of the MV-22 Osprey Tiltrotor as a Hypersonic VTVL Suborbital Aircraft

**Richard S. Schultz '60 Military Writers' Symposium Fellow Scholarship, Norwich University Center for Peace & War, Northfield, Vermont, United States**

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## Abstract

The V-22 Osprey tiltrotor aircraft combines the vertical takeoff and landing (VTOL) capabilities of a helicopter with the range and speed of a fixed-wing aircraft. To ensure safe and efficient operations, the stability control and augmentation system (SCAS) plays a crucial role in maintaining the aircraft's stability and maneuverability. In this paper, we present a supervised Gaussian analysis of the V-22 Osprey's SCAS, utilizing a Vertical Takeoff, Vertical Landing (VTVL) model tailored to the aircraft's unique operational characteristics. By employing machine learning techniques and mathematical modeling, we aim to predict stability classes or metrics and provide valuable insights into the behavior and performance of the SCAS. With a model evaluation RMSE of 1.94e-6 and MSE of 3.76e-12, we present our own mathematical model of the MV-22 Osprey as a hypersonic, suborbital, VTVL aircraft.

**Keywords:** Marine Corps, Osprey, Tiltrotor, Hypersonic, Ballistic, Stability and Control

*No Marine left behind, Semper Fidelis!*

## Introduction

The realm of aviation has consistently pushed the boundaries of what is possible, constantly seeking to redefine the capabilities of aircraft. Among the many innovations that have emerged, tiltrotor systems stand out as a transformative concept that marries the vertical takeoff and landing (VTOL) capabilities of helicopters with the speed and efficiency of traditional fixed-wing aircraft. This ingenious fusion of technologies allows tiltrotor aircraft to seamlessly transition between vertical and horizontal flight, offering unparalleled flexibility and versatility. Whether for military operations, search and rescue missions, or civilian applications, tiltrotor systems have the potential to revolutionize how we approach aviation challenges. In this exploration, we will delve into the overarching concept of tiltrotor systems and the manifold benefits they bring to the world of aviation.

At the forefront of tiltrotor technology stands the remarkable V-22 Osprey, a true aviation marvel that has reshaped the landscape of military aviation. The V-22 Osprey is a tiltrotor aircraft that boasts the unique ability to take off and land vertically like a helicopter, yet swiftly transition into high-speed horizontal flight like a fixed-wing aircraft. This extraordinary combination of capabilities has had a profound impact on military operations. It enables rapid deployment of troops and equipment into challenging terrains, such as remote battlefields or disaster-stricken areas, providing an unparalleled advantage in critical situations. The V-22 Osprey's versatility and adaptability have not only expanded the scope of military missions but have also set a new standard for what can be achieved in the realm of vertical and horizontal flight. In this exploration, we will closely examine the operational capabilities of the V-22 Osprey and the transformative influence it has exerted within the domain of military aviation.

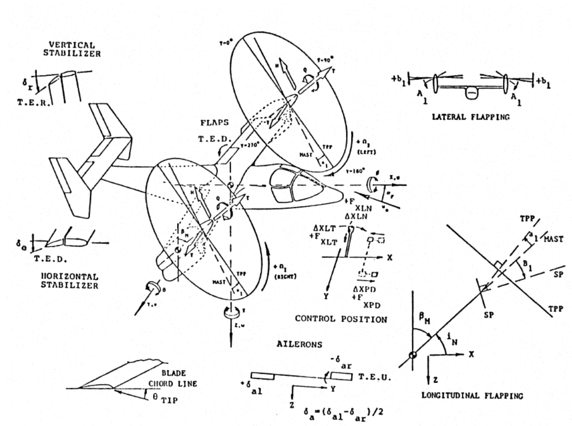



***Figure: 1 - Diagramatic Representation of the MV-22 Osprey Structure*** [1]



## Stability Control and Augmentation System (SCAS)

The significance of stability control in aviation extends to the capability to simulate and emulate the effects of the Stability and Control Augmentation System (SCAS) through advanced techniques, such as Euler Angles and the manipulation of Pitch, Yaw, Roll, and XYZ velocity components. These methods are instrumental in not only comprehending the behavior of an aircraft like the V-22 Osprey but also in developing and fine-tuning control systems to ensure safe and efficient flight operations.

In the context of the V-22 Osprey, which boasts the unique ability to transition between vertical and horizontal flight, the use of Euler Angles and these velocity components becomes particularly relevant. Euler Angles are a set of three angles that describe the orientation of an aircraft in three-dimensional space, encompassing Pitch (rotation around the lateral axis), Yaw (rotation around the vertical axis), and Roll (rotation around the longitudinal axis). These angles are fundamental in understanding and controlling the complex maneuvers of the V-22 as it transitions between its various flight modes.

In conjunction with Euler Angles, the manipulation of XYZ velocity components adds another layer of control and stability to the aircraft. These components encompass the aircraft's linear velocity in three directions: forward/backward (X-axis), lateral (Y-axis), and vertical (Z-axis). By precisely adjusting these components, the aircraft's movement can be controlled with great precision, ensuring that it remains stable and responsive throughout its flight envelope.

Using Euler Angles and XYZ velocity components, engineers and flight control system designers can simulate and emulate the effects of the SCAS, allowing for comprehensive analysis and fine-tuning of the control laws governing the V-22 Osprey's behavior. This simulation and emulation approach ensures that the aircraft's SCAS can effectively manage its unique VTVL capabilities, maintain stability, and enhance maneuverability during the crucial phases of vertical takeoff, transition, and vertical landing. Ultimately, these advanced techniques not only deepen our understanding of the V-22's flight dynamics but also contribute to the ongoing evolution of stability control systems in aviation, continually advancing the safety and efficiency of flight operations.

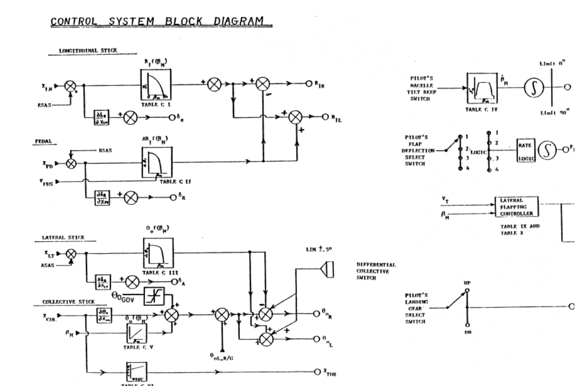



***Figure: 2 - Closed-loop Representation of the XV-15 Stability Control and Augmentation System*** [1]

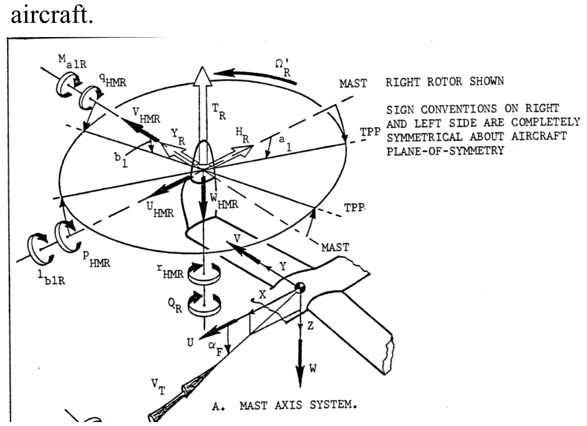
## VTVL vs VTOL

The V-22 Osprey's groundbreaking capabilities hinge on the innovative concept of Vertical Takeoff and Vertical Landing (VTVL). This concept represents a remarkable fusion of helicopter and fixed-wing aircraft technologies, enabling the Osprey to perform tasks that were once considered nearly impossible. At its core, the VTVL concept empowers the V-22 Osprey to execute a vertical takeoff, much like a traditional helicopter. However, what truly sets it apart is its ability to seamlessly transition into a fixed-wing flight mode, where it harnesses the benefits of aerodynamic lift, subsequently facilitating increased speed and extended range. This unique combination of vertical and fixed-wing flight capabilities defines the VTVL concept, making the V-22 Osprey a versatile and dynamic aircraft capable of tackling a wide range of missions with unmatched agility and efficiency.

When examining the advantages of the VTVL concept in comparison to conventional Vertical Takeoff and Landing (VTOL) systems, its superiority becomes evident. While VTOL aircraft are known for their ability to operate in confined spaces and austere environments, they often sacrifice range and speed.

In contrast, the VTVL capability of the V-22 Osprey bridges this gap, offering an extended operational range, increased cruising speed, and the adaptability to switch between vertical and horizontal flight as needed. This versatility is a game-changer, as it allows the Osprey to swiftly transport personnel and cargo across both short and long distances, while still maintaining the crucial VTOL ability. As a result, the VTVL concept provides a significant advantage over traditional VTOL systems, enabling the V-22 Osprey to excel in diverse operational scenarios and missions.

The relevance of adopting a VTVL model specific to the V-22 Osprey becomes evident when considering the complexities of the aircraft's unique flight characteristics. The Vertical Takeoff and Vertical Landing capabilities of the Osprey distinguish it from conventional fixed-wing aircraft and even other VTOL platforms. Therefore, when conducting a comprehensive analysis of the Stability and Control Augmentation System (SCAS) for the V-22 Osprey, it is imperative to account for these distinctive VTVL characteristics. By utilizing a tailored VTVL model for the Osprey, one can accurately assess the aircraft's response to various flight conditions and control inputs, ensuring the development of an effective and precise SCAS that optimizes its operational performance. In essence, the VTVL concept is not just a defining feature of the V-22 Osprey; it is a critical factor that underscores the necessity of a specialized analysis approach for this remarkable aircraft.



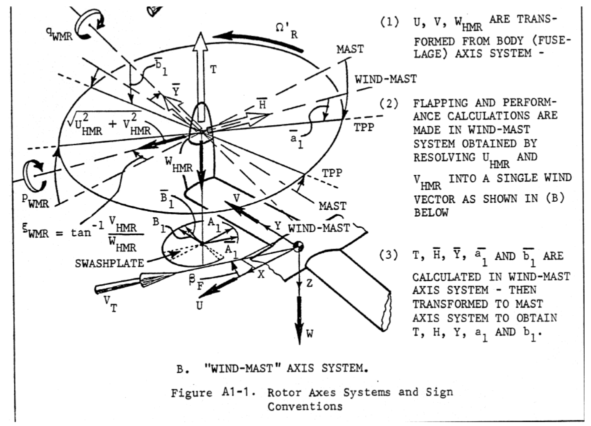




***Figure: 3 - Diagramatic Representation of the MV-22 Osprey's right and left rotors respectively*** [1]

In this study, we employ a supervised Gaussian analysis to comprehensively investigate the stability control and augmentation system of the V-22 Osprey. Leveraging machine learning techniques, we analyze a rich dataset encompassing flight conditions, control inputs, sensor readings, and relevant features specific to the V-22 Osprey's flight dynamics. By training a Gaussian model on this dataset, we aim to predict stability classes or metrics, ultimately providing valuable insights into the behavior of the stability control system and supporting the continuous improvement of this critical component of the V-22 Osprey.

## Methodology

### *Data Curation*

Recognizing the need for a unique perspective, the research diverged from conventional mathematical analysis of the MV-22 Osprey using models of the XV-15, which had limited applicability. This divergence was motivated by the distinctive characteristics of the MV-22 Osprey's VTOL capabilities, setting it apart from traditional VTOL aircraft. To address this limitation, the research explored actual models closely related to the MV-22 but with an emphasis on VTVL capabilities. The shift towards VTVL was driven by the recognition that VTOL models might not accurately represent the complexities of VTVL flight dynamics.



Realizing the importance of empirical data for a comprehensive analysis, the research collected actual flight data from Blue Origin's hypersonic VTVL suborbital aircraft. This dataset serves as a valuable resource for understanding the dynamics of VTVL flight, which is crucial for improving the Stability and Control Augmentation System (SCAS) of the MV-22 Osprey.

### *Preprocessing and Feature Selection*

The research obtained a substantial dataset comprising 40,000 flight test analysis files from Blue Origin's hypersonic test data for *Deorbit, Descent and Landing* [2]. Due to computational constraints, the data was divided into 8 files, each containing 5000 instances.

The dataset incorporated 3D spatial data (horizontal range, vertical range, z-component) and the three Euler angles (pitch, yaw, roll). The choice of pitch as the target variable was motivated by the importance of pitch control for landing gear sensitivity analysis, a critical factor in VTVL aircraft stability. Tiltrotor aircraft, such as the V-22 Osprey, have a unique flight configuration with both vertical takeoff and landing (VTOL) and horizontal flight capabilities, which introduces additional complexities in their stability analysis.

#### Vertical Stability

Tiltrotor aircraft heavily rely on their VTOL capability during takeoff and landing phases. Vertical stability is crucial to ensure smooth and controlled transitions between hover and forward flight modes. For examining crashes during these phases, the vertical stability characteristics, including pitch stability during takeoff or landing, could be the target variable of interest.

#### Transitions and Conversion

Tiltrotor aircraft undergo complex transitions when switching between vertical and horizontal flight modes. The stability during these transitions, also known as conversion phases, is essential to avoid uncontrolled motions or potential accidents.

#### Lateral and Directional Stability

During both VTOL and forward flight, lateral and directional stability are essential for maintaining the aircraft's balance and preventing uncontrollable roll or yaw motions. These stability characteristics become critical during crosswind conditions or when dealing with asymmetric thrust.

#### Dynamic Maneuvers

Crashes can occur during dynamic maneuvers or high-speed flight regimes. Stability analysis should consider the aircraft's behavior during aggressive maneuvers, including banked turns, high angles of attack, and abrupt pitch changes.

### *Mathematical Modeling*

#### Bootstrap Regression (Tree-Based Bagging)

Bootstrap regression techniques are valuable because they excel in modeling complex, non-linear relationships between variables. In our research, these models can capture the intricate interplay of factors affecting pitch control and stability. The ability to handle non-linear relationships is crucial as aircraft dynamics often involve complex, dynamic interactions between various parameters. By using tree-based bagging methods, these models can account for these complexities, providing more accurate and reliable predictions.

#### Perturbation Analysis (Linear and Nonlinear)

Perturbation analysis is vital for understanding how small changes in input variables impact the system's stability. This technique allows us to assess the sensitivity of the MV-22 Osprey to alterations in key parameters. By conducting perturbation analysis, we can pinpoint which variables have the most significant influence on pitch control. This insight is invaluable for optimizing the aircraft's performance and identifying critical factors that need attention in the Stability and Control Augmentation System (SCAS) improvement process.

#### Cross-Validation

Cross-validation ensures the robustness and reliability of the developed models. It helps in assessing how well our models generalize to unseen data. In aviation research, the ability to make accurate




predictions based on limited data is essential. Cross-validation allows us to evaluate the performance of the models under different conditions, ensuring that they maintain their predictive power and are not overfit to the training data.

**Landing Gear Sensitivity Analysis**

Conducting sensitivity analysis on landing gear configurations, with pitch as the target variable, is crucial for identifying opportunities to enhance stability during critical phases of flight. As pitch control directly impacts the angle of attack during descent and landing, understanding how landing gear adjustments affect pitch stability is essential. This analysis can guide improvements in landing gear design, contributing to safer landings and reduced crash rates for the MV-22 Osprey.

By leveraging these analytical techniques, this research combines the power of data-driven insights, non-linear modeling, sensitivity analysis, and validation to comprehensively address the challenges of improving the stability and control systems of the MV-22 Osprey. These techniques collectively enhance the accuracy, robustness, and practicality of our research findings, making them invaluable for the aviation community and the future development of VTVL aircraft.

## *Case example: Space Transportation System – NASA's Space Shuttle*

The Space Shuttle was an ingenious combination of two distinct vehicles – the orbiter and the solid rocket boosters (SRBs) – working in tandem. During liftoff, the Shuttle used three main engines and two SRBs to generate the immense thrust needed to escape Earth's gravity. This dual-mode design allowed it to harness the raw power of a rocket for ascent.

The orbiter component of the Space Shuttle was akin to a traditional aircraft with wings and tail surfaces. This design allowed for precise control during reentry and landing phases. Unlike a capsule, which relies solely on parachutes for descent, the Shuttle could glide back to Earth, offering pilots the ability to make real-time adjustments to the flight path. The Shuttle's winged design granted it cross-range capability, meaning it could change its landing site significantly during descent. This feature was crucial for emergency situations or when weather conditions at the intended landing site were unfavorable. The ability to maneuver to an alternate landing site helped reduce the risk associated with adverse conditions.

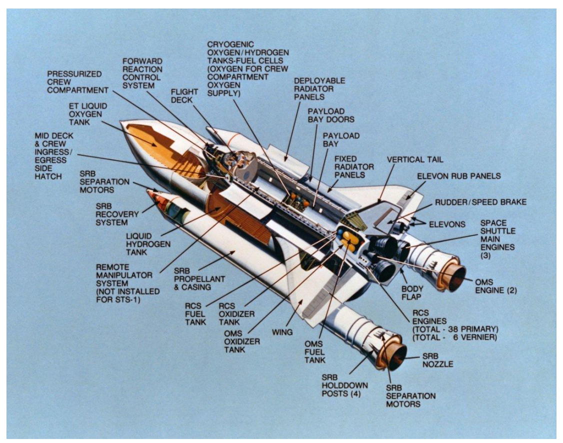
The Shuttle's thermal protection system, consisting of heat-resistant tiles, was distributed across the orbiter's surface. Unlike a capsule with a singular heat shield, this design dispersed the heat load, making it more resilient to minor damage during launch. However, it was also a contributing factor in the Columbia disaster when a damaged tile led to catastrophic failure. But given that the United States Marine Corps deals with close-air-support for amphibious operation, the shuttle VTVL this problem is highly unlikely to affect operations on the atmospheric to sub-mesospheric level.

The Shuttle was designed to be partially reusable, with the orbiter and solid rocket boosters capable of multiple flights. This approach aimed to reduce the overall cost of spaceflight and was a unique aspect of the Space Shuttle program.

While the Space Shuttle's design was groundbreaking and innovative, it also introduced some inherent risks, as demonstrated by the tragic incidents involving Challenger and Columbia. The complexity of the system, the vulnerability of the heat shield, and the challenges associated with maintenance and refurbishment were all factors that contributed to those disasters.

In contrast, the VTOL Tiltrotor concept, as exemplified by the MV-22 Osprey, primarily relies on rotating propellers to achieve vertical takeoff and landing (VTOL). While this design is suitable for some military applications, it lacks the versatility and control of the Shuttle's VTVL approach. The Osprey's Tiltrotor mechanism introduces complexity and potential failure points during the transition between hover and forward flight, making it less reliable in high-stress situations.

The Shuttle's distinct design allowed for safer maneuverability in space and a controlled, gliding descent during landing, which contributed to a lower overall risk profile despite the tragic incidents involving Columbia and Challenger. Its ability to combine rocket-like liftoff with aircraft-like maneuverability during reentry and landing remains a testament to its uniqueness and versatility in the realm of human spaceflight. This could, thus, prove useful for the high-stress tactical egress situations that the United States Marine Corps deals with.



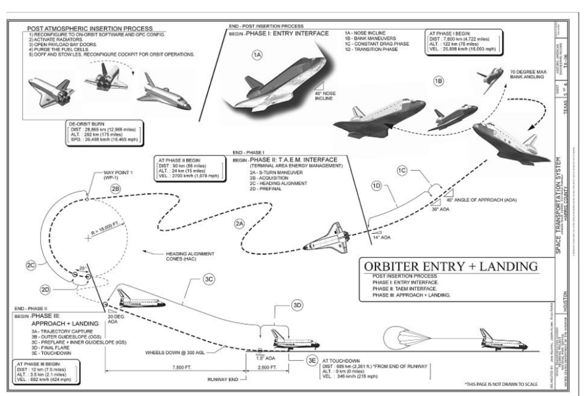
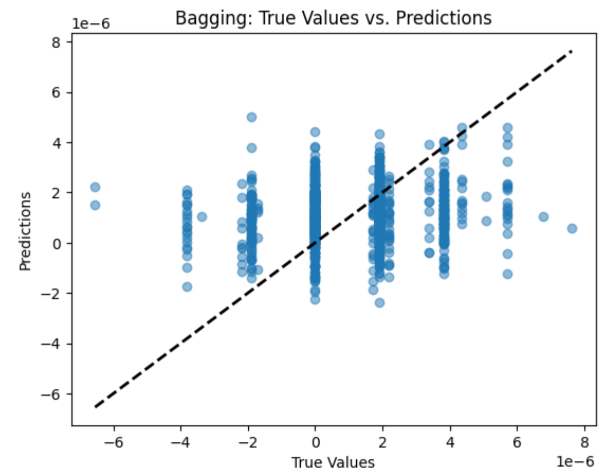



***Figure: 4 - The Space Shuttle subsystems and cross-range***

## Results

In this section we present the results obtained from our combined implementation of AI, ML, and Mathematical analysis, starting with Bootstrap Aggregating in figure 5 (dimensional reduction) with the end result of our linear equation.

***Bootstrap Aggregating (Bagging)***

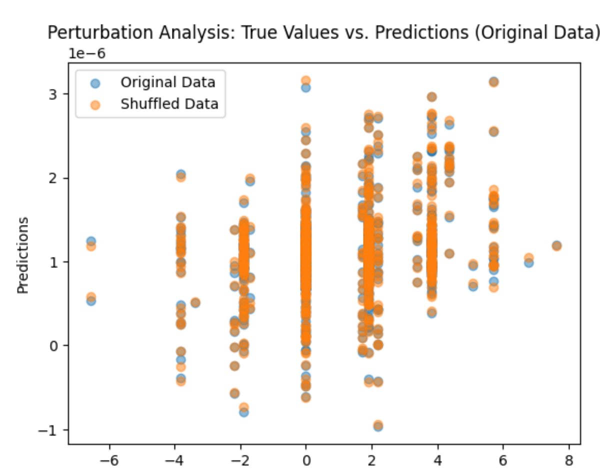



Mean Squared Error (MSE): 4.374385437561978e-12 Mean Absolute Error (MAE): 1.6563159699836112e-06 R-squared (R2): -0.1534385416443386

***Figure: 5 - Bootstrap Aggregating on the dimensionally reduced model***

***Perturbation Analysis***

Mean Squared Error (MSE) - Original Data: 3.549023558615106e-12 Mean Squared Error (MSE) - Shuffled Data: 3.5424433441524974e-12 Mean Absolute Error (MAE) - Original Data: 1.5359355862007296e-06 Mean






Absolute Error (MAE) - Shuffled Data: 1.5347959986647233e-06 R-squared (R2) - Original Data: 0.06419298981757604 R-squared (R2) - Shuffled Data: 0.06592806165378995

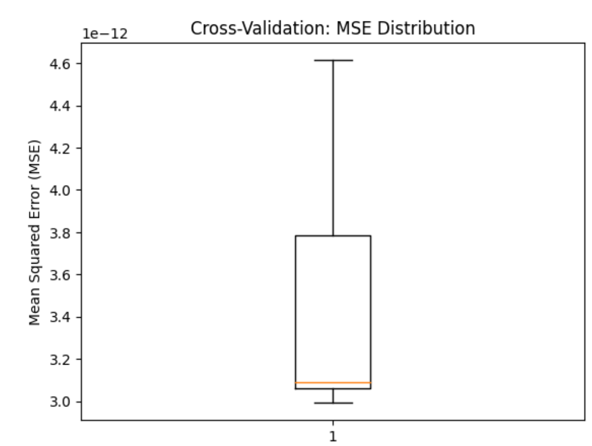
***Figure: 6 - Perturbation analysis on the dimensionally reduced model***

***Sparse Gaussian Regression***

Coefficients: [-1.11348540e-05 2.81563180e-05 3.02745299e-05] Root Mean Squared Error (RMSE) on the Test Set: 1.939738284090912e-06 Mean Squared Error (MSE) on the Test Set: 3.7625846107679554e-12

***Cross-Validation***

Mean Squared Error (MSE) using Cross-Validation: 3.5086481954417047e-12 Mean Absolute Error (MAE) using Cross-Validation: 3.5086481954417047e-12 R-squared (R2) using Cross-Validation: 0.031223120681711646



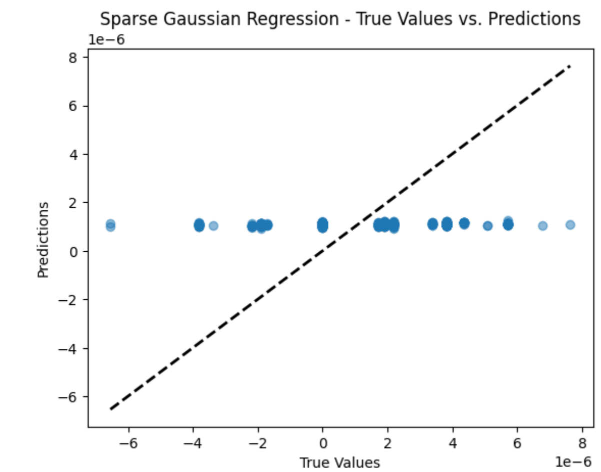




***Figure: 7 - Cross-validation and Sparse Gaussian Regression on the dimensionally reduced model***

## Discussion

Vertical Takeoff and Vertical Landing (VTVL) and Vertical Takeoff and Landing (VTOL) are two different concepts related to aircraft capabilities. Each approach has its advantages and disadvantages depending on the specific requirements and operational scenarios.

***Greater Range and Speed***

VTVL aircraft, like the V-22 Osprey, combine the benefits of both vertical and horizontal flight. Once airborne, they can transition to fixed-wing flight, which allows them to achieve higher speeds and longer ranges compared to traditional VTOL aircraft, which are generally limited to vertical flight only.

***Increased Efficiency***

VTVL aircraft leverage the lift generated by fixed-wing flight during horizontal cruise, resulting in improved fuel efficiency compared to VTOL aircraft, which typically require more power for vertical hovering.

***Versatility***

VTVL aircraft can operate in a broader range of missions and environments. They can take off and land vertically in confined spaces, making them suitable for operations in austere or challenging terrains. Additionally, the ability to transition to fixed-wing flight allows for extended range operations and adaptability to various mission profiles.

***Payload Capacity***
VTVL aircraft often have higher payload capacities than traditional VTOL aircraft due to the added lift generated during fixed-wing flight. This increased payload capacity enables them to carry more equipment, personnel, or cargo.

***Enhanced Stability***
VTVL aircraft, like tiltrotors, typically exhibit more stable flight characteristics compared to some VTOL aircraft, which may require active stabilization systems during vertical hovering.

***Reduced Footprint***
VTVL aircraft eliminate the need for traditional runways, making them suitable for operations from smaller landing zones or shipboard decks, reducing infrastructure requirements and increasing operational flexibility.

***Vertical Landing Accuracy***
VTVL aircraft can achieve precise vertical landings, which can be advantageous for certain mission scenarios, such as precise delivery of personnel or cargo to specific locations.

***Smooth Transitions***
VTVL aircraft offer smooth transitions between vertical and horizontal flight modes, reducing the complexity and pilot workload during phase transitions.

We started our mathematical analysis and modeling with the National Aeronautics and Space Administration's 1977 XV-15 Tiltrotor model, GMTRS-11 [1]. We quickly realized that the model was a giant closed-loop infrastructure with multi-input, multi-output systems and the bulk of the variables we would have had to define would be outputs from subsystems if not constants from the data tables. We, therefore, referred to the scaled-down implementation of this model [3]. Though this model helped us identify the three subsystems we needed for our primary analysis of the Stability Control and Augmentation System (SCAS) – the Center of Gravity and Inertial subsystem, the Rotor subsystem, and Landing Gear, after initial MATLAB modeling of relevant variables, we realized that the system as a whole would needed to be coded even if select subsystems were being analyzed. Regardless, the SCAS variables in GMTRS-11 are control signals and binary electronic inputs; coding them would have required an integrated simple control system implementation, not primary mathematical. Since our aim was to implement stability and sensitivity analysis, we decided to use actual flight data where Blue Origin's suborbital tests helped us.

Combined with our reasoning to use VTVL and not VTOL, and given that any tiltrotor studies been done so far have used the XV-15 for their model, we were motivated to use AI, ML, and mathematical techniques to build our own model of the MV-22 Osprey as a hypersonic VTVL suborbital launch and re-entry vehicle, granted with some modifications for atmospheric and to the most, sub-mesospheric missions for the Marine Corps.

## Acknowledgements

This project is a first step in bringing a long-held aspiration to fruition and was made possible through the Richard S. Schultz '60 Symposium Fellowship. I would like to thank Dr. Travis Morris and Ms. Megan Liptak for choosing me as the 2023 Schultz Fellow. The many complications and changes of course that I had to undertake to get to a point of implementation were possible to work through only because of the constant and relentless encouragement of my research mentor, Dr. Sean J. Kramer, who showed unwavering faith in me. Lastly, as a Norwich University cadet training and aspiring to be a United States Marine Corps Test Pilot, my journey towards commissioning as an international student at the moment is at the least an uphill battle. My Marine Corps mentor and advisor, Captain Edward J. Pingel, USMC, is my source of inspiration and strength in times of uncertainty. Alongside my Aviation Officer guide, Lt. Matt Gibson and GySgt Zachary O'Connor, he pushed me to overcome my inhibitions. They have my most sincere gratitude. I would like to acknowledge the unconditional support of my parents and twin sister for standing tough through my lofty



goals and helping me persevere through hardships. This work is a product of the sentiment, *no Marine left behind.* Therefore, I would like to acknowledge Norwich NROTC midshipmen who stood by me and inspired this project – Midshipmen Schaal, Sanchez, Kirrane, and Schmidt; thank you for not leaving me behind in a world that is alien to me. CSM Bradley Gallimore commands my respect and faith for believing in my abilities at a time I did not know if I could achieve what I envisioned. Mentor and confidante, C/1SG Shibe Couchman, you have my most sincere gratitude for helping me make this place home through my challenging commitment to serve a nation I'm fighting to be a part of. *Semper Fidelis!*

## Conclusion

This paper presents a novel and comprehensive analysis of the stability control and augmentation system of the MV-22 Osprey tiltrotor aircraft. By utilizing a VTVL model tailored to the unique operational characteristics of the Osprey, we aim to enhance the understanding and optimization of its stability control system. Through a supervised Gaussian analysis, we have attempted to provide valuable insights into the behavior and performance of the stability control and augmentation system. This work is a first step in a comprehensive and integrated model of the MV-22 with suborbital flight data meeting midway its tiltrotor capabilities. Our ultimate goal is ensuring the safe and efficient operation of the MV-22 Osprey and bringing Marines back safely.

## Future work

In the future, we will explore various avenues to address the complexities and limitations encountered during the course of this study. Originally, our intention was to construct the entire model from first principles. However, due to the constraints imposed by our reduced dataset, this approach became impractical. It has become evident that the dataset we have acquired primarily consists of instantaneous measurements (x, y, z, pitch, roll, yaw). To establish meaningful causal relationships among these variables, it will be imperative to introduce time lag considerations. For example, modeling pitch based on input from the other five components may require data from three seconds prior. Determining the appropriate time lag and justifying this choice will be a crucial aspect of our future work. An alternative approach to enhance the significance of our findings is to establish connections between the observed data and control systems. One potential avenue is to implement the Stability and Control Augmentation System (SCAS) and feed it with input from our dataset. By aligning SCAS model parameters with observed data, we can explore methods to desensitize these parameters, contributing to the reduction of pilot error.

In the short term, we will investigate the feasibility of identifying a stand-alone SCAS control model. Such a model would facilitate rapid parameter sensitivity analysis, enabling us to identify and address problematic controls efficiently. If our research objectives remain aligned with the initial goals, we will embark on the challenging task of coding the entire Osprey model mathematically and conducting a transient sensitivity analysis. This comprehensive approach would offer a deeper understanding of the system's behavior and its susceptibility to variations in parameters.

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The Richard S. Schultz ’60 Symposium Fellowship was established in 2017 as an endowed fund in honor of “Dick” by his wife of fifty years, Myrna L. Schultz, their children Marni and Alan, and his classmates and friends.

The fellowship enables Norwich undergraduates, from any academic discipline, the opportunity to pursue areas of inquiry and experiences that will promote and expand their understanding of the past and how it impacts the present and future. Through research, travel, and inquiry the Schultz Fellow and faculty advisor will offer perspectives for us to face the future with better understanding and confidence.

After a wide solicitation and competitive selection process, this annual fellowship is granted by the Norwich University Peace and War Center to an undergraduate student for a single project that may involve additional Norwich undergraduate students.

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