Novel Coaxial and Differential Thrust Vector Control Systems for Small-Scale Rockets

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Thrust vector control (TVC) systems enable directional control of thrust, which makes them crucial in the aerospace industry, particularly in propulsion systems. Typical TVC systems, which involve two linear actuators and a gimbal, provide effective thrust vectoring but pose challenges related to weight, torque, and response time. This study analyzes alternate TVC approaches that are inspired by robotic drivetrain systems: differential and coaxial swerve drive. This study compares these systems with a typical TVC to evaluate performance in the following categories: weight, cost, torque, manufacturability, response time, and control. The differential TVC has superior torque, overcoming greater moments produced by the thrust and also has a faster response time. However, it is more complex for manufacturing, when compared to that of a standard TVC. In terms of weight, the differential TVC is comparable to a standard one, although slightly lighter. As for the coaxial design, it had similar benefits to the differential, providing faster response time and more torque. The coaxial design requires high load bearings which are expensive while also being slightly heavier. In contrast, the standard system is simpler, although countered by less torque and slower response times. Altogether, the results show that while a typical TVC retains its benefits in terms of complexity, the differential TVC shows promise in small-scale rocketry and, with further optimizations, has potential in medium- and large-scale rocketry.

I. Nomenclature

CAD	=	Computer Aided Design
COTS	=	Commercial Off The Shelf
FEA	=	Finite Element Analysis
Response Time	=	Time for thrust to be vectored by 15°
RPM	=	Rotations per Minute
TVC	=	Thrust Vector Control
UAV	=	Unmanned Aerial Vehicle

II. Introduction

Thrust vector control (TVC) mechanisms allow for directional thrust adjustments in aerospace propulsion systems, offering precise control of vehicle attitude and maneuverability. Traditional TVC systems in launch vehicles and spacecrafts employ a gimbal-based mechanism actuated by two linear actuators. Although effective, this approach introduces large weight, cost, and manufacturability concerns, particularly in systems where minimizing mass and complexity is a priority. Inspired by robotics drivetrain systems, this study explores differential swerve and coaxial swerve TVC designs. Both designs offer advantages in terms of torque output, weight, cost, and control precision. These systems make use of mechanical configurations typically found in robotic drivetrain systems, which are then modified and applied to thrust vectoring in rocketry applications. The objective of this study is to evaluate and compare these designs against traditional TVC mechanisms in the following areas: weight, cost, manufacturability, response time, and control authority.

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Conventional TVC designs provide reliable vectoring but introduce several limitations: increased weight, as linear actuators must withstand significantly higher loads when compared to rotational actuators; higher cost due to the requirement of precision actuation components; and slower response times, particularly in high-thrust applications where actuation forces are substantial. Alternative TVC systems inspired by robotics drivetrain technologies include differential swerve TVC, which uses two independently actuated rotational axes to achieve thrust vectoring, enabling high torque and fast response times as both rotational actuators can be used for adjustment on each axis, and coaxial swerve TVC, which incorporates a nested rotation system to minimize backlash and enhance precision while still achieving improved response time and torque. Both designs introduce unique challenges and trade-offs, particularly concerning bearing requirements and system complexity, which will be explored in the following sections.

III. Methodology

The analysis of the TVC systems is conducted using both theoretical modeling and numerical simulations to evaluate the figures of merit of each system. For metrics which do not produce numerical values such as manufacturability, we consult experts in this field to have a deep understanding of the metric and how each of the designs compare to one another. For metrics that produce specific numerical values, such as response time and torque, a relative percent difference equation is utilized to normalize variations between different designs. This approach allows for a direct comparison of the coaxial and differential TVC systems relative to a baseline gimbal TVC. The relative percent difference formula is defined as:

$$\text{Relative Percent Difference} = \left| \frac{v_{\text{gimbal}} - v_{\text{TVC}}}{v_{\text{gimbal}}} \right| \times 100 \tag{1}$$

where v is the value of the parameter being evaluated.

A. Gimbal TVC

As mentioned, a typical gimbal TVC in rocketry applications uses two linear actuators located 90° away from each other. This system is commonly used in rocketry because of its simple mechanism and small number of components. Figure 1 shows the proposed design below.

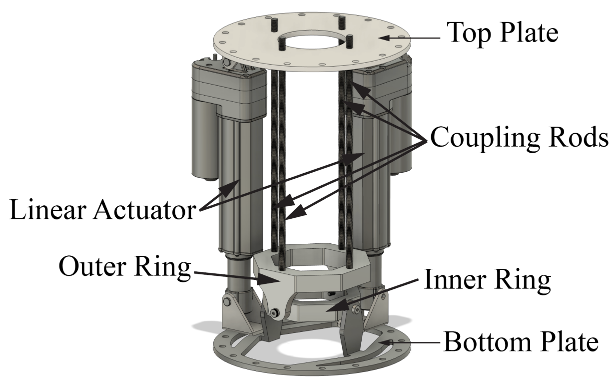
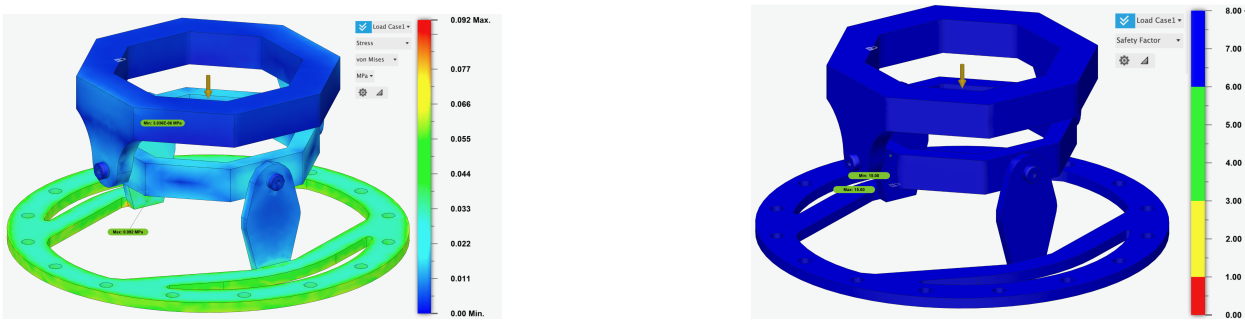


Fig. 1 Gimbal TVC CAD

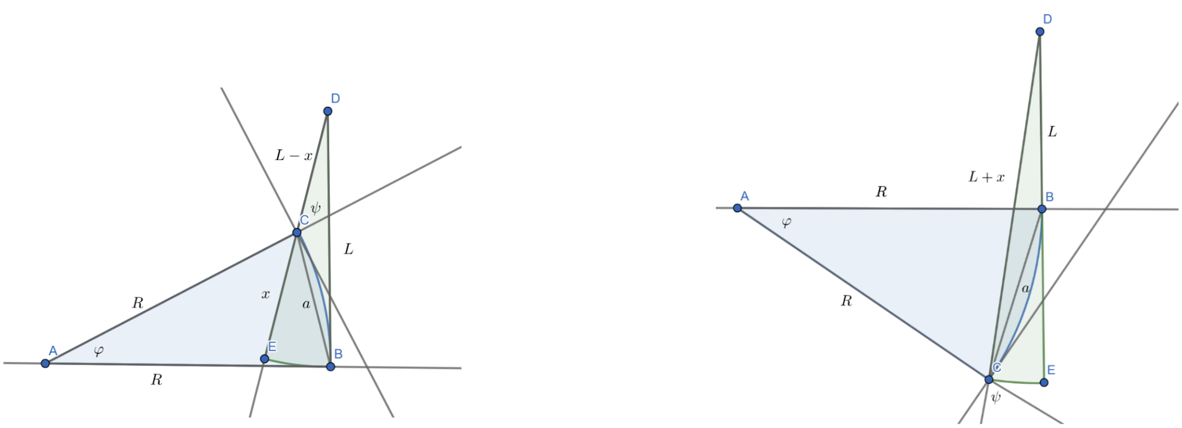
The bottom plate mounts the TVC to the engine, while the top plate secures it to the rocket body. An octagonal ring assembly is supported by four coupling rods upon which the linear actuators are mounted. The only parts requiring manufacturing are the two octagonal rings that gimbal the TVC and bottom plate. All of these parts were modeled using 304 stainless steel. Although the parts require tight tolerances, especially the mounting points, manufacturing is relatively simple using a 3-axis CNC Mill and a waterjet. A point to consider when manufacturing is that the mounting points for the inner ring are not welded. This means that during manufacturing, a significant amount of material is being removed which increases cost and manufacturing time. As part of the design process, finite element analysis (FEA) was performed to ensure the TVC Gimbal would sustain all forces acting upon it. The analysis included the bottom plate and the two rings in order to verify these parts would not experience significant deformation when being actuated. For the setup of the study, both the bottom plate and inner ring were constrained. Then, a force in the positive Y direction was placed, representing the 1000N output by the thruster. Gravity was also included in the design to point in the negative Y direction. Figure 2.a contains data pertaining to the stress applied and Figure 2.b shows the results of the analysis of the safety factor,related to the applied stress. The study shows that the minimum safety factor is 15 and the stress is 0.092 MPa which comply with the safety standards.



(a) Stress **(b) Safety Factor**

Fig. 2 FEA of Gimbal TVC

Linear actuators have a maximum dynamic force at a certain speed. Thus, the response time calculation for the 2-linear actuator gimbal setup was derived using two methods and then taking the higher number. One is by dividing the half-stroke length (x) needed to reach a gimbal angle (φ) from the neutral position with the speed of the linear actuator (v) at a force (F). A positive gimbal angle is defined as being clockwise from the neutral position and negative as counterclockwise. Although we denote counterclockwise movement as negative, φ is still taken to be positive in any counterclockwise equation. The second is numerical integration of a differential equation (defined later) derived from the same force delivered by the linear actuator. To reach a certain angle of the gimbal, the actuator needs to have a certain half-stroke length. This required half-stroke length can be calculated using trigonometry, as described below.



(a) (negative) **(b) (positive)**

Fig. 3

For Figure 3

- Point D = frame mounting point of the TVC;
- Point B and C = mounting point of the TVC onto the rocket engine;
- Point A = gimbal rotation point;
- Point E = Location of the shaft of the linear actuator when extended/retracted on the line DB.

The actuator lengths are defined as:

$$L - x = DC \quad \text{(length of the retracted linear actuator, Figure 3a)}$$

$$L + x = DC \quad \text{(length of the extended linear actuator, Figure 3b)}$$

$$L = DB \quad \text{(length of the neutral actuator for } \varphi = 0\text{)}$$

where:

- $R = AB = AC$ = length between the centerline of the rocket engine and the TVC mounting location (referred to as the moment arm);
- $a = BC = 2R\sin\left(\frac{\varphi}{2}\right)$ = intermediate variable
- ψ = angle between the force and the moment arm.

For $\varphi > 0$ and $\varphi < 0$

$$x_{\varphi+}(\varphi) = \sqrt{L^2 + 4R^2\sin^2\left(\frac{\varphi}{2}\right) - 2RL\sin(\varphi)} - L \approx x_{\varphi-}(\varphi) = L - \sqrt{L^2 + 4R^2\sin^2\left(\frac{\varphi}{2}\right) - 2RL\sin(\varphi)}$$

To calculate the response time based on the actuator speed (t_{speed}), we use the equation:

$$t_{\text{speed}} = \frac{x(\varphi_0)}{v}$$

where:

- φ_0 = desired angle of the gimbal (15°)
- v = speed of the linear actuator

The equation used to calculate the response time from the actuator force (t_{force}) is derived from the rigid body dynamics. At any instant in time t, the angular acceleration is:

$$\alpha(t) = \frac{d^2\varphi(t)}{dt^2} = \frac{FR\sin(\psi(t)) \pm mgl_z\sin(\psi(t))}{I}$$

where:

I = moment of inertia of the rocket engine about the gimbal axis, assumed to be the same in both gimbal angles;

l_z = vertical distance between the gimbal axis and the center of mass of the rocket engine;

Based on trigonometry,

$$\psi_{\varphi+}(t) = \frac{\pi}{2} - \frac{\varphi(t)}{2} - \sin^{-1}\left(\frac{l_z\sin(\varphi(t))}{2(L + x(\varphi(t)))}\right) \approx \psi_{\varphi-}(t) = \cos^{-1}\left(\frac{2Lx(\varphi(t)) - (x(\varphi(t)))^2}{4R(L - x(\varphi(t)))}\right)$$

To determine the response time from force, we numerically integrate $\alpha(t)$ using MATLAB until $\varphi(t)$ is within 1 percent of our target gimbal angle φ_0. The total angle traversed at t written as a sum is:item

$$\varphi(t) = \sum_{i=0}^{k}\left(w(it)(\Delta t) + \frac{1}{2}\alpha(it)\Delta t^2\right)$$

When item

$$\left|\frac{\varphi(t) - \varphi_0}{\varphi_0}\right| < 0.01$$

we stop the numeric solver and take the total time taken as t_{force}. Then, our actual response time t_{actual} is the bigger number between t_{force} and t_{speed}. To extract the fastest response time out of a linear actuator design, we manually adjust F,v according to the force-speed graphs provided by the actuator manufacturer until $t_{\text{speed}} \approx t_{\text{force}}$. In some cases, this was not possible because there is a minimum amount of force required to reach 15 degrees. In calculating this response time, the following assumptions were made:

- The actuator applies and stops applying the required force and speed instantaneously.
- The TVC system has negligible inertia and instantly slows down when the actuator stops pushing/pulling.
- Similarly, the actuator also has negligible inertia and stops immediately upon reaching the required angle.
- The vertical distance between the mounting point of the linear actuator shaft and the gimbal axis is negligible.

Based on the results of these calculations, we selected the TA-19 from TiMOTION [1]. This actuator yields a t_{actual} of approximately 0.439 seconds, given:

$$F = 72.5N, \quad v = 0.062m/s, \quad R = 0.105m, \quad l_z = 0.15m, \quad I = 0.244(kg)(m^2), \quad L = 0.207m$$

Although there were actuators that would have provided us with faster response times, such as the Ultramotion R/L series (t_{actual} = 0.272 sec) and the Iris Dynamics ORCA15-48V series (t_{actual}= 0.130 sec), they were either too expensive or not compact enough to fit into our design . Other COTS linear actuators considered were also either too slow in speed or had too little force.

B. Coaxial TVC

The coaxial TVC is adapted from the most common swerve drivetrain system in the FIRST Robotics Competition, used for its simple yet effective way to maneuver a robot around the large field. This involves having 1 motor powering the larger gear which provides the ability for the thruster to be rotated 180 degrees about its central axis and having another motor set to power the rotation about the thruster's center radial axes. Figure 4 shows the design of the coaxial TVC.

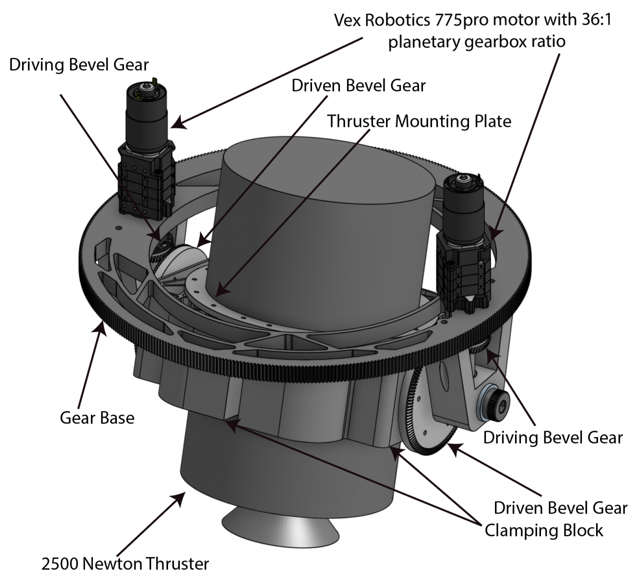


Fig. 4 Coaxial TVC CAD

The necessary torque needed to rotate the thruster starts with a calculation of the necessary angular acceleration required to achieve the goal of a 0.1 second response time. Using

$$\alpha_{\text{max}} = \frac{2\theta}{t^2} \tag{2}$$

The final angular acceleration of 52.36 radians per second per second. To convert this value to an angular acceleration, the following equation is used:

$$\omega_{\text{max}} = \alpha_{\text{max}} t \tag{3}$$

Using the previous value for angular acceleration and the time frame, we get an angular acceleration of 5.2360 radians per second. Using dimensional analysis the angular velocity value turns into:

$$\frac{5.2360\, rad}{1 second} * \frac{1 rotation}{2\pi radians} = 0.83334 \frac{rotations}{second} \tag{4}$$

Assuming that the thruster is a cylinder rotating about its center diameter axis, the moment of inertia is calculated as:

$$I = \frac{1}{4}mr^2 + \frac{1}{12}mL^2 \tag{5}$$

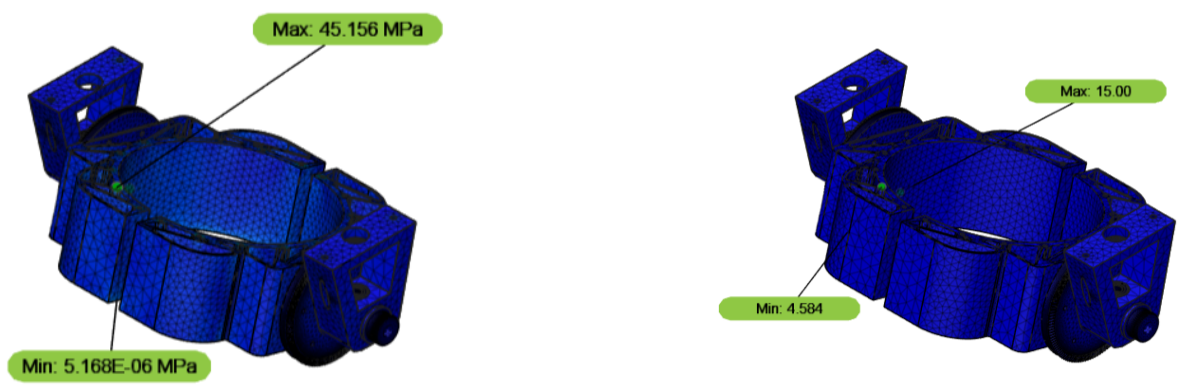
where r is the radius of the rocket thruster, 0.115 meters; L is the length of the thruster, 0.406 meters; and m is the mass of the thruster, 13.607 kilograms. This calculation results in a moment of inertia of 0.23227 $kg * m^2$ Using this moment of inertia value and α_{max} to calculate the required torque with the equation:

$$\sum \tau = I\alpha_{\max} \tag{6}$$

where I is the moment of inertia of the rocket thruster about its central diameter, calculated previously, α is the angular acceleration, whose necessary acceleration was calculated as 52.3560 radians per second per second, and is the torque. This calculation assumes that the motor immediately outputs to the maximum acceleration. Following this calculation, the necessary torque is output τ_{output} = 12.1615 Newton meters. With a safety factor of 4 this torque becomes 48.646 Newton-meters. The required output torque of the motor is calculated as follows:

$$\tau_{\text{output}} = (\text{Gearbox Efficiency}) \times (\text{Gear Ratio}) \times (\text{Torque at Desired Power Output}) \tag{7}$$

We are assuming a 94% efficiency of the planetary gearboxes [2],as we would need a two-stage planetary gearbox paired with the high-speed but low-torque motor in the 775pro from VEX robotics. The torque in the desired rotation per minute output is approximately 60% of the stall torque to preserve motor health and increase efficiency according to the 775pro motor graph [3]. Plugging in the torque calculated before as the output torque and the input torque given by the motor specification sheet at the desired output into equation 3 the resulting total ratio needed to achieve the response time goal is 123.22:1. Tracing back to the gearbox on the motor and taking into account the 2.7778:1 ratio between the driven bevel gear and the driving bevel gear, the motor ratio would be 44.358:1. Using COTS vendors for the planetary gearbox, the closest ratio would be 45:1 at REV robotics, which maintains the ratio needed for the given response time and the safety factor of 4 overall. While this value may seem low, the thrust of the 2500N engine produces no moment as it is inline with the point of rotation, and assuming that the needle bearings and the axle do not produce any friction, there are no counter forces to the system. A major design point addressed in the coaxial TVC design was the robustness of the mechanism and the safety factor. As seen in Figure 5b below, the entire part that takes most of the load of the thruster, it has almost uniformly a safety factor of 15 with the exception for a bolt hole in the top, which has a minimum safety factor of 4.584. The necessary static and pin joint constraints were applied to each bolt hole and the axle with a load force of 2500 Newtons normal to the bottom surface. Figure 5a shows the maximum and minimum stress on the system under the given load conditions, which is under the yield point stress of Aluminum, the chosen material for the coaxial TVC subsystem.



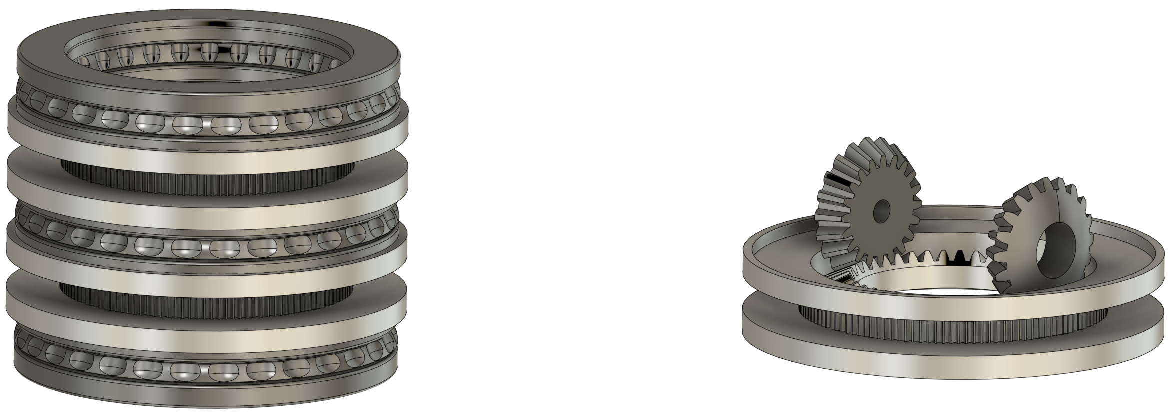
(a) Stress **(b) Safety Factor**

Fig. 5 FEA of Coaxial TVC

While parts in this model require precise manufacturing, many of the parts in the assembly can be manufactured using easily accessible manufacturing techniques such as a 3 axis CNC mill for the main upper gear and a lathe for the shoulder bolt. However, the clamping blocks do require some complex manufacturing due to the lighten pattern and the depth of each pocket. Additionally, the only material used in the design was Aluminum 6061 for its lightweight yet strong properties adequate for the coaxial TVC application.

C. Differential TVC

The Differential TVC is adapted from a swerve drivetrain system in the FIRST Tech Challenge Competition. This involves having 2 motors powering one large bevel gear each. These two large bevel gears have a drive gear in between them which is connected axially to a free spinning bevel gear 180 degrees around the large bevel gears. When the two large bevel gears are powered in the same rotational direction, the thruster rotates about the axis of the large gear, however if the two large gears rotate in opposite directions the engine rotates about the driver gear. This means that between these scenarios the engine can be rotated in both axes at the same time, or in one with the power of both actuators. Figures 6 and 7 below show the design of the Differential TVC from a few perspectives, all to help see the internal workings of this mechanism. Note that the engine mount as well as some other minor components are excluded in the visuals although used in later calculations.



(a) **(b)**

Fig. 6 Differential TVC CAD

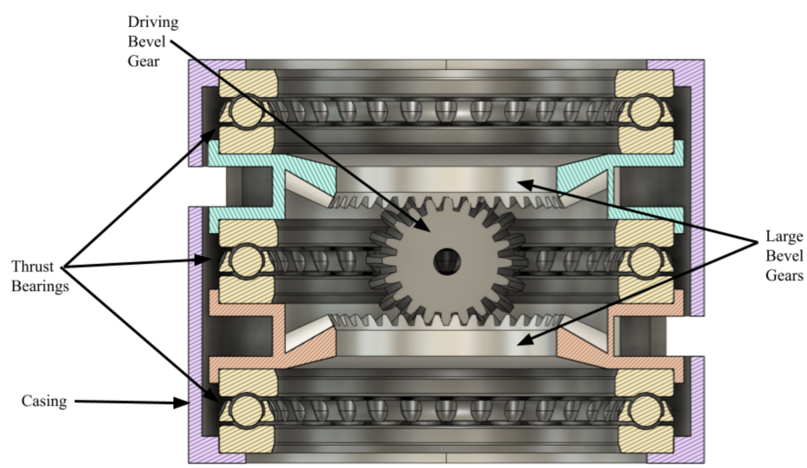


Fig. 7 Differential TVC Section View

The motors chosen for this system were Vex Robotics 775pro motors, each coupled with a high-reduction planetary gearbox, a compact, high-efficiency gear system that uses a central sun gear, multiple planet gears, and an outer ring gear to achieve high torque transmission and precise control. In order to have adequate torque, a 100:1 planetary gearbox was used, which when paired with the differential system, has a total 250:1 reduction ratio. Such a reduction ratio achieves a torque output calculated below:

$$\tau_{\text{output}} = (\text{Gearbox Efficiency}) \times (\text{Gear Ratio}) \times (\text{Torque at Desired Power Output}) \tag{8}$$

$$\tau_{\text{output}} = (0.94) \times (250) \times (0.71) = 166.85 \text{ Nm} \tag{9}$$

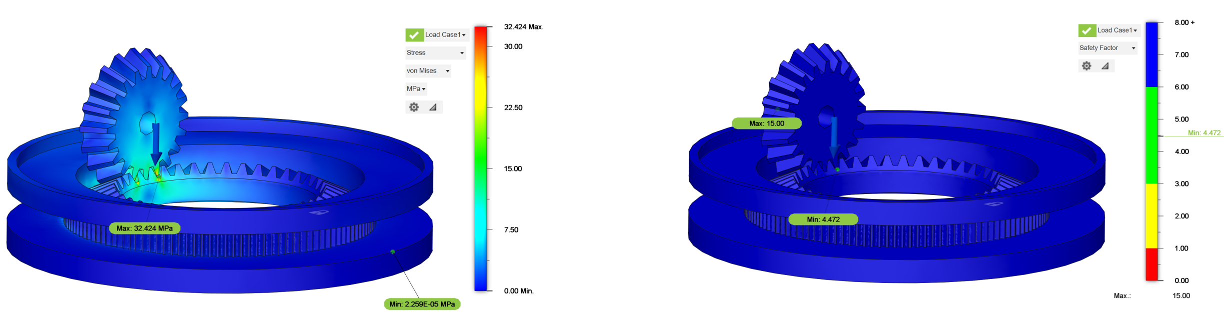
where the planetary gearbox efficiency was 94% and the motor torque was 0.71 Nm at peak efficiency. The rotational speed of the differential TVC was calculated by dividing the free-speed rotation of the 775pro motor by the gear reduction:

$$\omega = \frac{\text{rpm}_{\text{free}}}{\text{reduction}} = 0.998 \,\text{rev/sec} \tag{10}$$

To ensure proper thrust vectoring, the number of bevel gear teeth needed for smooth rotation to 15° was determined using:

$$T_{\text{required}} = \left(\frac{T_{\text{total}}}{360}\right) \times 15 \tag{11}$$

where T_{total} is the total number of gear teeth in the bevel gear system. This configuration ensured a balance between smooth rotational movement and rapid response time. The manufacturability of the differential TVC posed challenges due to the precision alignment required for the bevel gears. These gears must be machined with tight tolerances to minimize backlash and ensure smooth power transfer. Materials used included 7075 aluminum for the large bevel gears and steel for the smaller drive gears, balancing weight savings with durability. For the FEA in figure 8 the design was largely simplified to two components as they are the two which undergo the most significant point loads. A constraint was placed on the bottom of the large bevel gear as it would be attached to the frame of the rocket and therefore stationary. A vertical force was applied to the face of the small gear. The small gear was constrained to only move vertically based upon this force. This setup is designed to isolate the study to the interaction between the two gears to verify there will not be significant deformation in either component. The minimum safety factor is 4.472 and the stress applied is 32.424 MPa, which both fall well within safety standards.



(a) Stress **(b) Safety Factor**

Fig. 8 FEA of Differential TVC

Another key consideration was control precision. Unlike the standard and coaxial system, which requires independent control of each axis, the differential system requires coordinated motor inputs to achieve the desired thrust vector angle. The use of absolute encoders and PID control loops is essential to maintain accuracy, particularly under dynamic load conditions.

IV. Results and Discussion

This section presents the results of the comparative analysis between the conventional two-actuator gimbal thrust vector control (TVC) system and the novel differential and coaxial TVC designs. The performance of each system was evaluated based on weight, cost, torque, manufacturability, response time, and control precision.

A. Weight Analysis

Weight is a critical factor in rocketry applications, as additional mass directly impacts the overall efficiency and performance of the propulsion system. The conventional two-actuator, differential, and coaxial TVC systems weigh approximately 8,000, 7,000, and 11,000 grams respectively. The weight reduction observed in the differential TVC system is largely due to the elimination of linear actuators and their supporting structures, allowing for a more compact and lightweight assembly. The material optimization, by using multiple metals for various components, also provided the differential TVC with distinct advantages in weight. In contrast, the coaxial TVC system, despite using a similar actuation method, requires additional structural reinforcement and bearings to support the nested rotation mechanism, increasing its overall weight. This mechanism did exceed the structural requirements by using all Aluminum 6061 its only material and did not require material optimization. Research suggests that weight optimization in aerospace components can lead to significant improvements in thrust-to-weight ratios and fuel efficiency, making the differential TVC a promising alternative [4].

B. Cost Evaluation

Cost is a major constraint in designing and implementing TVC systems, as budget limitations often dictate the feasibility of specific designs. The conventional TVC system costs $1,600, serving as a reference point. The differential TVC system is the most cost-effective at $1,300, with an 18.75% reduction in cost, which continues to show the potential which the differential TVC has when compared to the current standard. On the other hand, the coaxial TVC system is the most expensive, at $2,500, which is 56.25% more expensive than the baseline. This is once again rather disappointing in comparison to our baseline. The lower cost of the differential TVC can be attributed to its compact size reducing the cost for metal bar stock, as well as the use of COTS bearings, and much more cost effective actuation with rotational actuators opposed to the linear actuators used in the standard TVC. Meanwhile, the coaxial TVC system incurs additional costs due to its reliance on large high-load bearings, and larger components which require larger quantities of metal, and additional control mechanisms. Cost reduction in aerospace components can be achieved through the use of modular design and material optimization. Future iterations of these TVC systems should explore cost-saving measures such as additive manufacturing and alternative material choices.

C. Response Time

Response time, defined as the duration required for the system to achieve a 15° thrust vector change, is a crucial factor in dynamic control performance. The conventional two-actuator TVC system has a relatively slow response time due to the limitations of linear actuators, measured at approximately 0.439 seconds. In contrast, both the differential and coaxial TVC designs achieve substantially faster response times of approximately 0.10 seconds each. However in both these cases, the response time can easily be adjusted to match the performance requirements defined in the mechanical subsystem profile with little cost changes. All that must be changed in order to adjust the performance of the coaxial and differential TVC is switching which gearbox is applied to each motor in the module. Such modularity is very convenient, allowing these TVC designs to be easily modifiable for various thrust requirements. This improvement in response time can be attributed to the use of rotational actuators, which offer higher speeds and greater efficiency in force transmission. Studies have demonstrated that faster actuation times in control systems significantly improve vehicle stability and maneuverability. This is especially relevant in high-speed applications, more specifically, with the rise of small scale rocketry, control has grown more important. When given significantly faster response times, it is easier to develop an accurate control system in order to maintain stable flight. Faster response times also allow quicker recoveries if unexpected external forces (e.g. turbulence) act upon the rocket [5]. The differential and coaxial systems, therefore, offer a significant advantage for applications that require rapid thrust adjustments, such as small-scale rocketry and UAV propulsion.

D. Manufacturability

Manufacturability plays a pivotal role in the practical implementation of each TVC design. The conventional TVC system benefits from its simplicity, requiring standard linear actuators and straightforward machining processes. The use of commercially available off-the-shelf (COTS) components further enhances its ease of assembly and cost-effectiveness. The standard gimbal TVC therefore, is the least complex among the three options. The differential TVC introduces more complex manufacturing challenges, particularly concerning the production of two large bevel gears that transmit power to the system. These gears must be manufactured with tight tolerances to ensure efficient torque transfer and minimal backlash. Additionally, the differential design incorporates multiple material types, including 7075 and 6061 aluminum as well as steel, to optimize strength-to-weight ratio while maintaining a safety factor of at minimum 2. The need for high-precision machining and material selection adds to the complexity and cost of production. Similarly, the coaxial TVC system requires precision manufacturing for its nested rotation system. The alignment of concentric rotational components demands high-load bearings and specialized assembly techniques. The complexity of this design increases machining and assembly challenges, particularly in ensuring consistent axial alignment and load distribution. Although, research suggests that manufacturability challenges in aerospace components can be mitigated through advancements in CNC machining and additive manufacturing techniques [6]. Such advancements increase viability for TVC alternatives such as differential and coaxial swerve.

E. Control Precision and Stability

For the conventional TVC system, control is managed by the actuators, one for each axis of gimbal movement. This approach works very well, guaranteeing movement along the entire TVC range, without having issues such as wires and tubing becoming tangled by repeated spinning motions. It is also relatively simple to program and offers great positional accuracy. However, it does contain some drawbacks. For instance, the two-actuator TVC system will move faster along the diagonals between the axes of rotation, since it takes the same time for both actuators to fully contract/extend at the same time as it does for only one. For small ranges of motion with relatively small moving moments, this will not be a problem; but, without accounting for this, moments can be created that can affect the stability of the vehicle. Additionally, without expensive actuators, response times can be slow compared to the other methods. The gears are situated such that spinning them both in the same direction will rotate the bevel gear's axle, enabling the TVC to face different directions. Rotating the gears in opposite directions will make the bevel gear spin in place, swiveling the TVC inwards or outwards. This operates similarly to how polar coordinates work. The use of rotational actuators instead of linear actuators allows for greater speed, since rotational actuators are generally faster than linear ones. However, linear actuators may have greater precision than rotational actuators. Although there is the issue of potentially having wiring and tubing problems due to this mechanism's ability to spin around indefinitely, higher response times are achievable since the full power from both motors powering the TVC can go into the movement. In essence, power from both actuators will contribute to every movement, unlike the conventional design which may or may not use power from actuators depending on the direction of travel. This higher response time allows for quicker reactions from the differential TVC, enabling it to potentially recover from more extreme situations than the conventional TVC and improving stability as long as the accuracy of the actuators allows for it. This allows for a simpler control scheme compared to the differential design, since the position of the TVC is dependent only on the position of each motor, rather than the combined history of the actions of both motors. Use of absolute position encoders, for instance, could make finding the position more reliable in this design than the differential design, which would have to rely on incremental encoder systems that are less accurate than absolute position encoders. However, this design would have a slower response time and less torque available than the differential design simply due to the fact that the differential design can use the full power of both motors at the same time, while the coaxial cannot allocate power from one motor towards the other motor's job. Compared to the conventional design, the coaxial offers much of the same benefits that the differential does. The use of rotational actuators allows for greater speed and the design ensures the movement speed of the TVC remains consistent regardless of the direction pointed.

V. Conclusion

This study explored novel thrust vector control (TVC) mechanisms inspired by robotics drivetrain systems, specifically differential and coaxial swerve TVC, and compared them against the conventional two-actuator gimbal system. The analysis considered key performance parameters, including weight, cost, torque, manufacturability, response time, and control precision. The differential TVC demonstrated superior torque and faster response times, allowing for greater control authority as well as reduced cost due to the lack of large linear actuators. These benefits came at the expense of increased system complexity, mainly an issue in terms of manufacturing. Despite these drawbacks, its weight remained similar, yet slightly lower to that of a standard TVC system. The coaxial TVC also has similar advantages, providing improved torque and response time while having disadvantages in terms of cost and complexity. Additionally, the mechanism has a larger total weight compared to the differential and standard TVC, but comes with the benefit of a higher safety factor. Furthermore, both of the novel ideas are largely feasible as manufacturing and assembly are the largest drawbacks which are clearly possible, and while they do increase complexity, the differential design makes up for it in performance. In contrast, the traditional two-actuator gimbal system retained its advantages in simplicity, making it a viable option for applications which require more simple designs relating to ease of manufacturing. However, its slower response time and reduced torque output present limitations for smaller scale rocketry, where agility and precision control are paramount. The results suggest that while conventional TVC remains a robust and practical choice, differential and coaxial TVC systems offer promising alternatives for applications that demand higher responsiveness and torque output. Differential TVC mechanisms are particularly promising having few cons when compared to the conventional TVC shown in this study. With further optimization, these novel TVC approaches could extend their applicability beyond small-scale rocketry, potentially impacting medium- and large-scale propulsion systems. Future work should focus on refining these designs to enhance manufacturability, reduce costs, and further investigate their integration with advanced control algorithms for improved flight performance.

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