An Investigation on the Relations and Effects Concerning Two Dimensional Thrust Vectoring Involving Independent Mechanical Systems and Their Corresponding Various Thruster Configurations, With Questions and a Report on the Feasibility and Practicality to Apply on Our Craft

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Part I, Introduction & Overview

This article will discuss how torque vectoring can be used for our craft to maximize thruster efficiency in different directions. For a quick comparison, the previous design applied on the Gyrodos 2024 provides around 2.83 units of thrust in any horizontal direction (take the thrust of one motor as 1 unit), and provides 4 units of upward thrust. The current layout of the Gyrodos G2.2, which is seen on the lapras, should provide 4.62 units of thrust in any of the 6 directions. Even though it is already a great leap forward compared to the 2024 design, it hasn’t applied the technology of thrust vectoring, which can divert thrust to different directions to increase the overall efficiency of the craft. This report is aiming to demonstrate and perhaps exhaust the possible layouts of the craft applying thrust vectoring.

To apply thrust vectoring on our craft, servo motors must be in place for the movement. There are already possible candidates for the servo motors, which are light and strong, and the details will be given in the corresponding chapter. This article will focus on the method of using rudder plates, fins, or flaps, to achieve two-dimensional thrust vectoring. The use of variable nozzles with mutli-axis control and other methods for three-dimensional thrust vectoring, or alternate two-dimensional thrust vectoring solutions are way too complex and bulky to apply on the 2025 craft, and will not be in the scope of the discussion of this article.

The application of thrust vectoring should significantly increase the efficiency and maneuverability of the craft, as it buffers the power in certain directions and favours the agility and precision of movement. With an enhancement in these factors, the score of our craft in the MATE ROV competition should see a huge leap, which is what we want. Therefore, we must investigate thoroughly how to apply thrust vectoring onto our craft, major technical difficulties that might occur, and possible trade-offs to apply thrust vectoring.

Part II, An Analysis of The Current and Past Designs

As briefly mentioned in Part I, the two current possible layouts for our craft offer either 2.68 units of thrust in the horizontal axis, 4 units in the vertical, or 4.68 units of thrust in every direction, given that the amount of thrusters are the same. It is, in fact, more efficient than our main competitor's current (2024) model. This seems already enough, but with the help of thrust vectoring we can make it better.

Section A, 2024 Gyrodos G2.0

Let us take a detailed look at each design. First up we have the 2024 design, which has four vertical thrusters mounted at the center of the so-called ring body, and four horizontal thrusters mounted at a 45 degrees angle at the four corners of the body. The four vertical thrusters allow movement along the vertical axis, pitch and roll. The four horizontal thrusters allow any movement on the horizontal plane, including yaw. The layout gives 70.7% efficiency when considering horizontal movement (excluding the four vertical thrusters). When it comes to roll and pitch, it should provide 4 units of thrust for such action. But the overall efficiency of this layout is not particularly high and the calculations have shown us that this layout can see more improvement.

Section B, 2024 Overdefined SPIDA

Second up, let's take a brief look at our main competitor, Fukien Secondary School's Overdefined. The layout is similar, but they mounted the thrusters at a 30 degrees angle instead of 45 degrees angle, trading a portion of the efficiency of lateral movement for more forward thrust. This allows them to achieve around 3.46 units of thrust forward.

Section C, 2025 Gyrodos G2.2

And now on our 2025 design, with 8 thrusters mounted on the angles of a cube-shaped frame, each making a 45 degree angle with each of the three axes. This allows 4.68 units of thrust in any direction, including row, pitch, yaw, if such movements are necessary, and therefore offering nearly 60% efficiency, even though statistically less, the thrust figures saw a 65% increase (From 2.82 to 4.68). Moreover, since the thrusters are mounted on the frame but not near the centre, it should provide a lot more torque while performing roll, pitch, and yaw, compared to the 2024 design. This is already a great leap forward, but we must ask the question: Can we go further?

Part III, The Theory and Application of Thrust Vectoring

Section A, Overview

Thrust vectoring is the technology that can bring us onto the Mount Everest of underwater robotics. It will increase the efficiency of our thrust management and more precise and accurate maneuvering. It should bring more benefits than trade-offs. This report will discuss the usage of independent mechanical systems, i.e. rudder, flaps, or fins, to achieve two-dimensional thrust vectoring. Note that “independent” here means it does not involve the thruster itself to achieve thrust vectoring, therefore methods involving moving the thruster directly will not be in the scope of this article.

Section B, Basic Design

For a basic view, this independent mechanical system is similar to the thrust vectoring system applied on the Lockheed-Martin F22 Raptor. To elaborate briefly on how this independent mechanical system should work, each one or two thrusters should have one such independent mechanical system, or none, judging by the need and efficiency. Each of such systems should consist of at least one servo motor, two to three movable fins or flaps, and two confining stationary plates. The movable flaps are interconnected by means of a rack or wire such that it has synchronized motion, and the rack or wire is connected to the servo via a short rod which moves the rack to control the flaps.

These independent mechanical systems offer not only thrust vectoring. It can do a lot more. For example, the two flaps can be used as mechanical braking or control surfaces to regulate drag for better control. And hypothetically, if we slightly modify the design, these flaps can also be turned slightly towards each other to act as a nozzle which pressurizes the water jet and thus increasing the thrust of the craft. The details will be discussed later in the article.

Section C, Underlying Problems and Possible Solutions

There are some possible problems that might arise as we apply thrust vectoring onto our craft. The following are some of the problems, even though it is not a full list, since the other underlying problems require actual testing for debugging and massive amounts of real data to solve.

1. On the matter of water resistance, the problem differs with different thruster layout configurations, but it should pose a threat in general, since the direction of the flaps are usually parallel to the direction of movement and thus does not increase the frontal area, i.e. does not affect drag. The servo motors will also be mounted on the frame which technically shouldn't increase the frontal areas of critical directions as long as the position of it is carefully revised. In fact, these fins should even reduce drag, as it creates an elongated tail which is better for flow attachment, reduces turbulence generation, and thus increases efficiency.

2. Regarding weight increase, its effect should be neglectable. Assume each of the eight thrusters is equipped with one of these independent mechanical systems. Each of these systems should weigh no more than 200 grams, given that the servo motor currently chosen weighs only 80 grams, and the flaps and transmissions shouldn't weigh more. Therefore, it will add at most 1.6kg to the weight of our craft, and I believe that it is not a great amount since it is merely perhaps a tenth of the weight of the whole built craft.

3. When applying thrust vectoring, it is inevitable that some thrust will be lost. According to various researches and papers, when thrust vectoring operates at a high angle, e.g. 45 degrees, the thrust lost can be up to 30%. This is where the nozzle mentioned above comes into play. Theoretically, it can provide up to 50% of thrust boost, but practically a 30% increase would be fair. It will compensate for most of the thrust lost due to thrust vectoring, and thus allow the best efficiency upon operation.

Part IV, Design For Independent Mechanical System

Section A, Basics Of Independent Mechanical Systems

The basic components of these systems are stated above. The detailed operating principles will be discussed in this section.

I. Shape of Flaps & Connection

To allow the best and most stable flow redirection, the shape of the flaps needs to be carefully designed to eliminate cavitation, vortices, and improve thrust transfer.

First, sharp edges should be avoided to minimize the effect of cavitation. It should be a flat or clipped edge. The whole flap would be curved to ensure it can duct most of the thrust of the engine. And to allow the movement of it, the side hinged and near the thruster will need to have its vertices clipped to allow the bending. The whole flap should also have a streamlined cross section which can allow better flow attachment.

Second, the flaps will be hinged to a ring roughly the same size of the diameter of the thruster, where the ring will be attached behind the thruster but directly mounted onto the frame. The ring will have the two confining fins attached, also curved and encloses the sides of the two movable flaps. This is to ensure that the water ejected does not move into the sides and cause turbulence, which is something we don’t want to see.

Third, the movable flaps should occupy 120 degrees of the circumference of the thrusters’ exit each, and the confining fins should occupy 70 degrees each, where 5 degrees of each end of the confining fin should overlap with the moving fins. This should ensure that most of the water jets are enclosed by the fins.

II. Detailed Working Principle

The two plates are connected by a rod on the side, which is connected to the servo motor. Since the plates are curved to match the thruster’s round exit, it will need to have clipped corners on the hinged end to allow it to bend and achieve thrust vectoring. But the thrust lost due to this should be minimum since we still have the stationary confining fins at the sides and the Coandă effect applies where the water flow should tend to attach to the surface of the flaps. The distance between the two flaps should be fixed, and slightly smaller than the thruster exit. The servo motor will be mounted near the flaps onto the frame. The flaps will be mounted onto a ring with slightly bigger diameter than the thruster and this ring frame will be mounted onto the ROV body and placed near to the thruster exit to enclose all of the water jet flow. To increase the stability of this ring system, another ring will be mounted on the body at the intake of the thruster and the two rings will be connected by a plate or rod. The flaps and confining fins should be made of alloyed metal for best control, since we cannot assure that the strength of composite materials can withstand the water jet and not bend and break, and withstand the rapid moving by the servo motor.

Section B, Practicality

Here are where some more calculations will be shown.

I. Mass and Volume of the Flaps

First, the cross section of the flaps not at the two lateral ends should take the shape of an airfoil, to minimize drag. To eliminate the possibility of lift and downforce generation while thrust vectoring, the flaps should take the shape of symmetric airfoils. The area of the cross section an airfoil can be obtained by the following equation,

$$A = \int_0^c 2y_t(x)dx$$

Where c is the chord length, and $2y_t(x)$ is the standard thickness distribution, i.e.

$$y_t(x) = 5t\,(0.2969\sqrt{x} - 0.1260x - 0.3516x^2 + 0.2843x^3 - 0.1015x^4)$$

Which ranges from the leading edge to the trailing of the chord, and t is the thickness-to-chord ratio.

Each flap spans 120 degrees around the thruster, and thus the volume of each flap excluding the round lateral ends can be found by the following formula,

$$V_{main} = A \times R \times 2\pi/3$$

Where A is the area found above and R is the radius of the ring body which the flaps are mounted on, and $2\pi/3$ is the angle in radians.

The two lateral ends take the shapes like half a raindrop shape, and it should have the volume from the equation below,

$$V_{ends} = A/2 \times r \times 1/2$$

Where r is half the length of the thickest part of the cross section of the airfoil. Thus multiplying this by 2 and adding it to V_{main} we get the total volume of a fin. Replace different values to find other required data. Note that the fins should be made of aluminium alloy to have good strength.

II. The Pressurizing Effect

The length and diameter of the flaps should be calculated according to various scenarios and should be engineered to apply the pressurizing effect on the water jet.

The following equation shows the relationship between thrust and nozzle area:

$$T = \dot{m} V = \rho A V^2$$

Where T is the thrust in N, $\dot{m}$ is the flow rate in kg/s, V is the exit velocity in m/s, ρ is the fluid density in kg/m^3, A is the exit nozzle area.

Now this equation explains the relationship between thrust and power:

$$P=\tfrac{1}{2}\dot{m}V^2=\tfrac{1}{2}TV$$

Where P is the power in W. To explain this, we find the following from the first equation,

$$V=T/\dot{m}$$

Thus, we can find that,

$$\dot{m}=T/V$$

Substitute this into the power equation, we have,

$$P=\tfrac{1}{2}\cdot T/V\cdot V^2=\tfrac{1}{2}TV$$

Therefore,

$$V=2P/T$$

We already know that,

$$\dot{m}=\rho AV$$

So,

$$A=\dot{m}/\rho V=T/\rho V^2$$

Then, substitute $V=2P/T$ into this equation, we have

$$A=T^3/4\rho P^2$$

Since A is the area, and $A=\pi D^2/4$, where D is the diameter not the radius. Therefore we can find the following,

$$D \propto T^{3/2}/P$$

We can then calibrate the optimum diameter for our craft's application, by substituting the T with the final thrust output we require and thus we can find the best design for our craft. Of course, fine tuning with actual data is required.

For the record, the length of the nozzle exit should be half of the diameter of the thruster.

Part V, Possible Layouts Applying Thrust Vectoring

Section A, Partial Thrust Vectoring Solutions

In this section, possible layouts involving thrust vectoring will be discussed. Note that the “partial” means only some of the thrusters are applied with thrust vectoring, while other thrusters remain to have only two operable directions.

I. Layout Involving Four Slanted Thrusters

This is perhaps the best layout I have thought of so far. It is similar to the 2024 design, with four thrusters mounted in the centre and four mounted at the corners. But in this proposed design, the four thrusters at the centre are mounted at a 45 degrees angle to the horizontal, with the centres of the thrusters lying on the same plane and the downward exit facing the back. These four thrusters are applied with the independent mechanical systems for thrust vectoring, and the slanted position of the thrusters allow these thrusters to contribute to upward motion and forward motion.

When the craft is moving forward, the four flat thrusters at the corners provide about 2.82 units of thrust. The four slanted thruster now have their thrust redirected to the back, and given that there should be around a 30% thrust lost due to thrust vectoring but a 20-30% thrust increase by the pressurizing, it should contribute,

$$4 \times 0.7 \times 1.3 = 3.64 \text{ units}$$

Of thrust to the forward motion. Thus, the craft should have a total forward thrust of 6.46 units, which is far more than the original 2024 design and the 2025 design. Even though the upward thrust will be slightly less than the 2024 design, it is still a trade-off that I consider worth it.

When it comes to downward thrust, since the thrusters are slanted and the exit on the top side is not equipped with thrust vectoring, the four corner thrusters will need to operate to cancel the backward thrust produced by the slanted thrusters. The thrust vectoring system should be pointing to the bottom, and it will create a suction effect and lower the pressure under the craft and contribute to downward motion. The final downward thrust should be around 2.82 units, maybe slightly more.

Using this layout does not add much complexity to the craft. Only four mechanical systems are applied and a minimum of only two servo motors can be used as a pair of such systems can share the same servo motor. It minimizes weight increase due to application of thrust vectoring.

II. Layout With All Eight Thrusters Placed Horizontal (I)

In this layout, all eight thrusters are mounted at the corners and make a 45 degrees angle. The thrusters are in pairs and stacks on top of each other in each pair. The top thruster is applied with thrust vectoring on both ends, with the systems operating oppositely, i.e. one goes up, one goes down. This layout allows a larger horizontal thrust at 5.64 units. When it comes to upward and downward motion, the thrust vectoring systems on the top thrusters have the flaps at the exit end pointing down, redirecting the thrust to 45 degrees beneath the horizontal, while the other end pointing up, using the suction effect to decrease the pressure above the craft. The lower thruster will also operate instead of in idle as the thrust vectoring flaps may also redirect some of their thrust downwards.

The exact numbers are very hard to estimate as it requires very detailed experiment in real conditions, but if we suppose that only half of the thrust of the lower motor is redirected, it should provide

$$4 \times 0.7 \times 1.3 \times \sin 45° + 4 \times 0.7 \times 0.5 \times \sin 45° = 3.56 \text{ units}$$

Of upward thrust, but this is only a very optimistic estimation. This design also adds complexity to the whole craft, as it requires eight of the thrust vectoring systems and at least 4 servo motors. And of course, we can apply thrust vectoring to the remaining 4 thrusters as well, but it will only add complexity to the system again.

III. Layout With All Eight Thrusters Placed Horizontal (II)

This layout is similar to the previous one, but four of the thrusters are mounted in the center of the craft facing forward, which produces an overall of 6.82 units of thrust for forward motion but only 2.57 units of thrust in vertical axes. Moreover, the sideways motion is also less. And of course you can ignore complexity and apply the thrust vectoring to the 4 motors in the center, which should buffer the vertical thrust to 5.14 units, but it really depends on real conditions. Note that if thrust vectoring is applied to the central motors, it should divert the thrust in different ends to eliminate the torque.

The numbers in this design may sound tempting but it will definitely increase the system complexity as it requires at least 16 mechanical systems and 6 servo motors.

Section B, Full Thrust Vectoring Solutions

This part is quite useless. Literally, the following are some solutions involving thrust vectoring on every thruster, except the variants from some of the solutions above. These solutions are not so recommended, since they are too unstable and only exist to demonstrate why full thrust vectoring shouldn't be used in practice(and to indulge ourselves in the beauty of optimum theoretical values).

I. Inline Eight Layout (I)

In this layout, all eight thrusters are in a straight line, all facing forward. Thus it provides maximum forward thrust, at 8 units, but restraining the craft from performing sideways motion, and only turning can be done. The upward and downward motion will be at 5.15 units. But the stability of this layout won't be good and the craft will be in weird shape.

II. Inline Eight Layout (II)

Similar to the above layout, this layout has the thrusters all facing down, maximizing vertical movement. Still, it will have bad stability, but of course it is not a must to have all eight thrusters mounted in a straight line.

III. Layout Involving Four Slanted Thrusters Stage II

As you may tell from the name, this layout includes the four slanted thrusters from the one mentioned above, but the four corner thrusters are also applied with thrust vectoring.

Part VI, Conclusion

In a nutshell, it is found that thrust vectoring can indeed improve the efficiency and thrust of our craft, and the system to achieve so is not complicated to make. It is also an innovation because there aren't any notable cases in the history of MATE ROV which are related to thrust vectoring. We could be the ones opening a new path in the MATE ROV Competition.

Even though detailed calculations with actual numbers are not included in this report since that the investigated object has been found and declared useless to us at current state. We simply cannot find a field of competition that can bring us huge benefits by using thrust vectoring. But the chances are not zero and thrust vectoring is not fully ruled out. It might come in handy some day in the distant future, who knows?

Thrust vectoring may seem to be a very good idea and indeed it is not bad at all. But we must rethink our goals. Currently the only benefits that thrust vectoring has brought us is nothing but acceleration, and there is simply no advantage of increased acceleration in a competition where the operations are mostly within a 5m radius. Thus, we must rethink our strategy on improving our design. Thrust vectoring is just not for us.

Part VII, Appendix

Section A, Citations

Not in order.

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