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Mathematics and Physics Concepts Behind Our Robot

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I am an 11th grader at Louis D. Brandeis High School in San Antonio, Texas, and a member of the TechnoWizards 16458, an FTC team that has qualified for the regional, state, and world level competitions in 2023. I serve as the electronics manager for the team, meaning I apply math and physics concepts to the robot while also manage wiring and other technical matters. I am also interested in pursuing a degree in electrical and computer engineering in the future.

Mathematics and Physics Concepts Behind Our Robot

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Abstract: In this paper, we explore the applications of mathematics and physics to design efficient and effective robots, where “efficient” means the robot is able to complete the desired tasks while consuming as little battery as possible, and “effective” means the robot is able to complete as many tasks as desired within a short amount of time. We demonstrate the usefulness of these ideas in the practice of our FTC robotics team. Specifically, we apply them to determine the exact physical properties that are needed for the robot to perform its intended tasks. This requires us to answer the following 3 research questions: What is the horizontal distance from the base of our robot’s delivery system to the tip of its (virtual) four-bar (Q1)? What is the minimum amount of torque required to extend each of its delivery and intake systems (Q2)? What is the minimum torque required to hold up its four-bar claw with a cone (Q3)? To answer Q1, we look at the robot from a horizontal viewpoint and apply advanced trigonometric functions to calculate the exact distance between the robot and the junction. To answer Q2, we use Newton’s 2nd Law of Acceleration, also known as Newton’s 2nd Law of Motion, to calculate the minimum amount of torque needed to extend each of the delivery and intake slides. To answer Q3, we also apply Newton’s 2nd Law of Acceleration to determine the minimum amount of torque required to hold the four-bar and cone in place. We then end by summarizing the lessons we have learned throughout our robotics season.

1. Introduction

FIRST [1,2], or the Foundation for Inspiration and Recognition of Science and Technology, is an international organization that includes the following categories of competitions: First Lego League (FLL), First Tech Challenge (FTC), and First Robotics Competition (FRC). Founded by Dean Kamen on March 20, 1989, in Manchester, New Hampshire, FIRST strives to expand the world of STEM to students all around the world by providing them the opportunity to participate in professional STEM activities that include organized competitive events. By striving to push STEM to places that are underrepresented and where it may be inaccessible, FIRST’s efforts create numerous windows for students to learn about STEM and robotics in a mentor-based fashion. With the program reaching more than 100 countries and consisting of over 668,000 middle and high school students enrolled, FIRST plays a crucial role in spreading STEM to younger generations all around the world.

As mentioned above, one integral part of FIRST is First Tech Challenge, or FTC. This program consists of teams designing, coding, and building robots using parts that are far more complex than Legos, which are used in First Lego League (FLL). These robots are also powered by a variety of technologies, ranging from simple servos to complex Android-enabled technologies, and are controlled by Java-based computer programs. According to the FTC website [2], FTC has proven impacts that include, but are not limited to, an 87% increase in students choosing to attend college and a 98% increase in problem-solving abilities, which can readily attest to its usefulness.

In an FTC match, there are typically two alliances competing against each other, with two teams per alliance. The match begins with a 30-second autonomous period where the robot moves solely on its own, powered by only pre-programmed code. Tele-op, the period that follows, lasts for 120 seconds, or two minutes, during which drivers are allowed to drive their robot using remote controllers. The last 30 seconds of the tele-op period is called endgame, with the only change being increased opportunities for scoring.

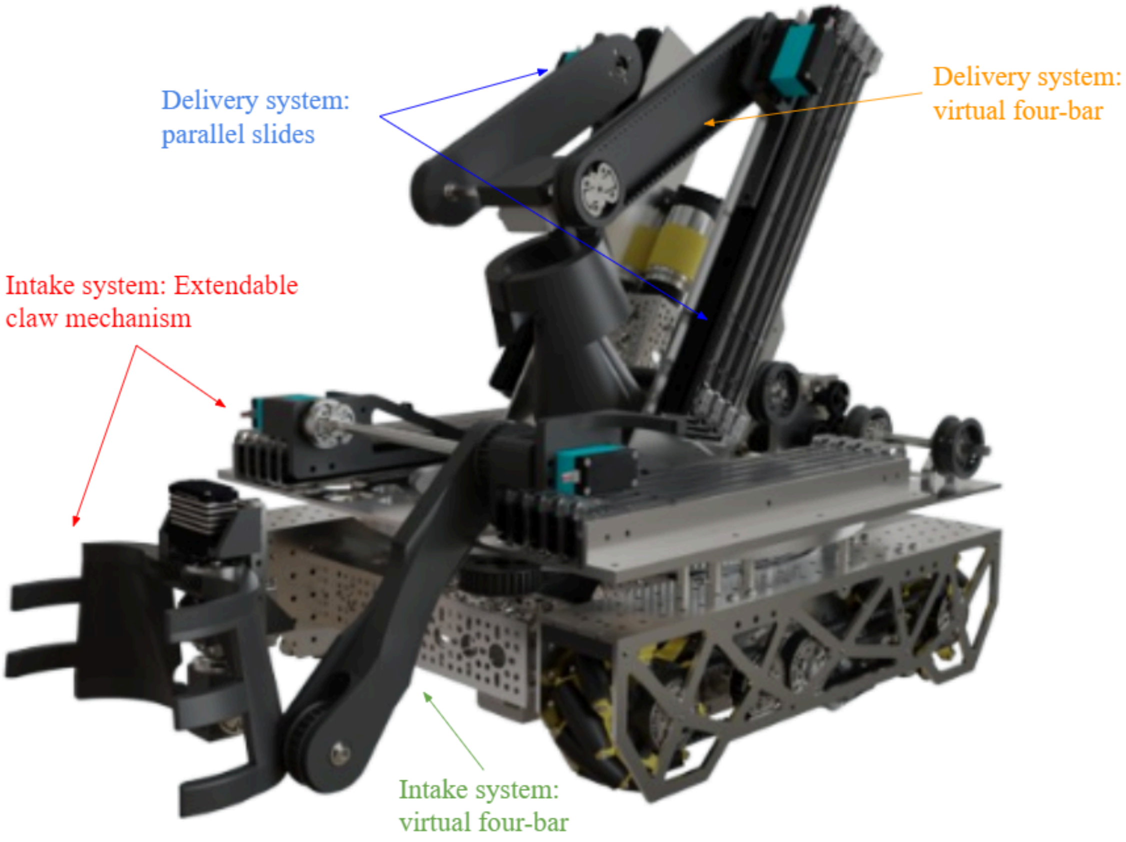

Figure 1: The robot that was conceived, designed, and built by our robotics team during the 2022-2023 season.

Figure 1 depicts our team's robot, which we competed with at the 2023 FIRST Championship in Houston, Texas. It is equipped with an extendable intake with a claw connected to a virtual four-bar at the end. The four-bar allows the claw to change heights to grab cones at various locations. Also as shown in Figure 1, there is an expandable delivery system that includes two sets of slides, which are parallel to one another and connected to the other claw that is attached to the other four-bar. The four-bar secured on the delivery system allows for the angle of the cones to remain the same throughout delivery while being transferred from the ground to the junction through the intake and delivery systems. Both the intake and delivery systems are allowed to rotate horizontally in a two-turret system, granting our team the ability to remain stationary during the delivery process. This not only greatly reduces the chances of the driver making mistakes in the process of delivering cones (i.e., reducing "driver errors"), but also lessens the robot's need to move around the field for delivery positioning (i.e., improving the effectiveness in accomplishing the task within a short given amount of time).

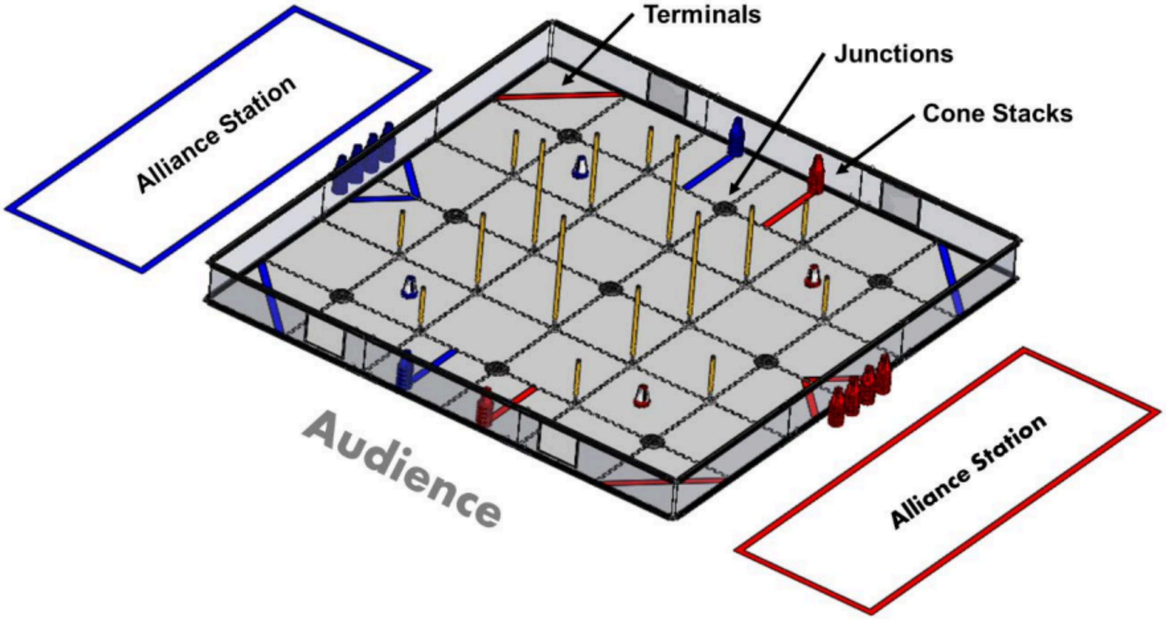

Figure 2: The field layout for the 2022-2023 FTC season *Power Play* [3], where the image is adapted from the official REV Game Breakdown [3].

In the 2022-2023 season *Power Play* [3], there are many complex rules. As shown in Figure 2, there are multiple ground, low, medium, and high junctions to which the cones that are displayed both on the side of the field and next to the alliance stations are to be delivered. The colored triangles in the center of the sides of each field mark where one member from each alliance, the human player, is allowed to place cones onto the field for the robot to pick up. The robots are encouraged to park in the terminals at the end of the match for more points. The two drivers and the driver coach from each team (while recalling two teams per alliance) stand in their respective alliance stations and control the robot from there. This description is simply a basic overview, as many more complicated rules apply as well. To summarize, there are junctions laid around the field to which cones are to be delivered. The four heights (i.e., ground, low, medium, and high) increase in both difficulty and point value, respectively. Our team mostly, if not always, delivers to high junctions, as they are worth the most points. The research described in this paper is centered around delivery to the high junctions in an efficient and effective way, where “efficient” means that the robot is able to complete tasks by consuming less battery, and “effective” means the robot is able to complete as many tasks as desired within a short period of time.

While sounding simple, there are technical issues behind the design of the robot that challenged us. Specifically, we encounter three technical challenges:

- Challenge 1: When delivering onto the junctions, the cones often miss and fall to the ground. This problem was largely caused by driver errors, as their unfortunate positioning (concerning the robot during delivery) prevented the drivers from seeing the exact location of the cones. This leads to the following research question:
    - Q1: Can we reduce driver errors during delivery by calculating the exact location and horizontal distance from the junction that the robot must be?
- Challenge 2: Since the delivery slides are extremely heavy, it was difficult to extend them as quickly as possible while conserving power. This leads to the following research question:
    - Q2: What is the minimum amount of torque required in order to extend the delivery slides as quickly as possible?
- Challenge 3: Similar to Q2, the movement of the virtual four-bar (and cone, at times) was not as efficient as it could have been. To conserve power and maximize delivery speed, we needed to execute the same process as in Q2. This leads to the following research question:
    - Q3: What is the minimum amount of torque required in order to move the delivery four-bar as quickly as possible while maintaining power efficiency?

Paper outline. The rest of the paper is organized as follows. Section 2 describes how the three research questions mentioned above (Q1-Q3) are tackled. Section 3 discusses the findings and thoughts resulting from this study. Section 4 concludes the paper.

2. Tackling the Three Research Questions

2.1 Tackling Research Question Q1

To answer Q1, we must first look at the robot from a horizontal viewpoint so we can see that the arm performing the delivery creates a right triangle shape with the ground, as shown in Figure 3. We are then able to use advanced trigonometric identities to determine the exact horizontal distance between the robot and the junction, denoted by x (the unknown). To do this, we must separately calculate the horizontal distance between the base of the delivery and the four-bar along with the horizontal distance between the four-bar and the junction, as they are tilted at different angles. After successfully calculating these values, we can add them together to find the overall distance from the base of the delivery system to the high junction.

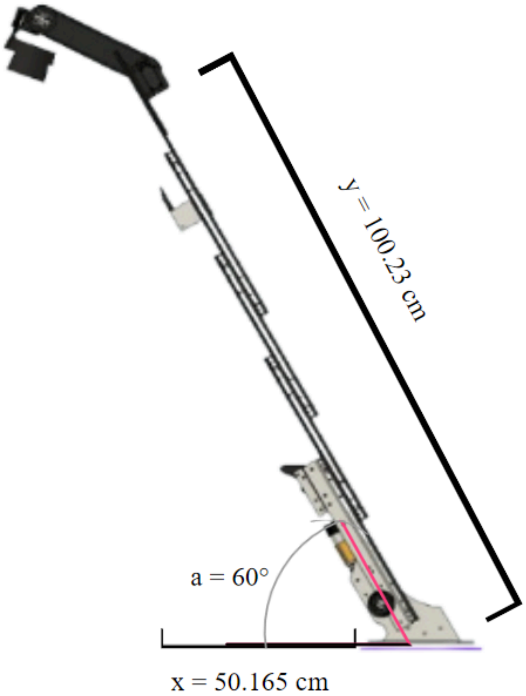

Figure 3: Illustration of the relationship between x (the unknown), y (the length of the fully extended slides, which can be measured), and a (the angle to which the delivery slides are tilted, which can also be measured).

Looking at Figure 3, we can see that the length of the slide extension, denoted by y, is tilted at an angle, denoted by a. Both of these quantities can be measured, allowing for future substitution. We can then set up a trigonometric function relating the angle of the slides' tilt to their length and substituting the measured values to calculate the true horizontal distance spanning from the base to the end (where the four-bar is attached) of the delivery slides. Note that we have cos(a) = x/y, or x = cos(a) * y.

We can then plug in the measured values of the angle of the slides' tilt (a = 60°) and their length (y = 100.33 cm, or about 1 meter) and solve for x, the horizontal distance that the slides alone cover. That is, we have

x = cos(60°) * 100.33 cm, leading to **x ≈ 50.15 centimeters** or **0.5 meters**.

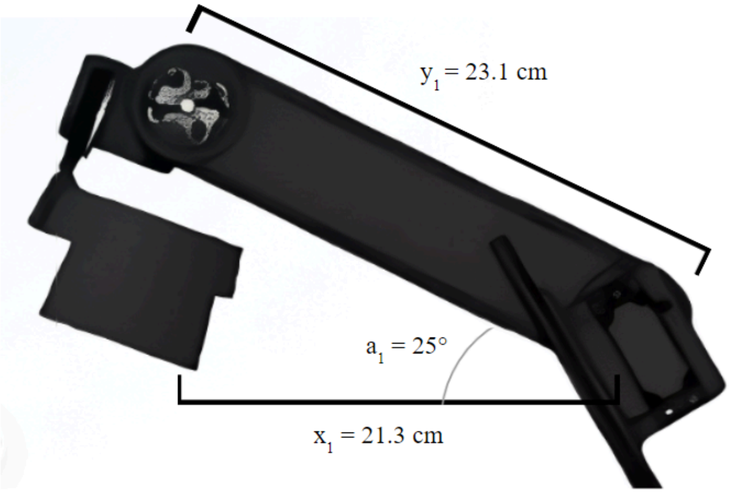

Figure 4: Illustration of the relationship between x_1 (the unknown horizontal distance), y_1 (the length of the virtual four-bar, which can be measured), and a_1 (the angle the four-bar is tilted at, which can be measured).

We must also apply this calculation to the four-bar at the top of the delivery system as it is tilted at its own unique angle, as shown in Figure 4. To do so, we can once again plug in the measurements of both the tilt and length of the virtual four-bar to the same formula and substitute the measured values to calculate the true horizontal distance the four-bar covers. To differentiate between the calculations made with respect to the slides and the four-bar, we denote the represented variables in the four-bar calculations with a subscript of 1. We now have

$\cos(a_1) = x_1/y_1$, leading to $x_1 = \cos(a_1) * y_1$.

We can then plug in the measured values of the angle of the four bar's tilt (a_1 = 25°) and its length (y_1 = 23.1 cm, or about 0.02 meters) and solve for x_1, the horizontal distance that the slides alone cover. That is, we have

x_1 = cos(25°) * 23.1 cm, or **x_1 ≈ 21.3 centimeters** OR **0.231 meters**.

2.2 Tackling Research Question Q2

To answer Q2, namely calculating the minimum amount of torque needed to extend each of the delivery and intake slides, we must take a different approach using physics. Starting with the delivery slide, we can create a free body diagram (FBD), as shown in Figure 5, which helps us visualize the different torques acting on the pulley that affect the extension of the delivery slides.

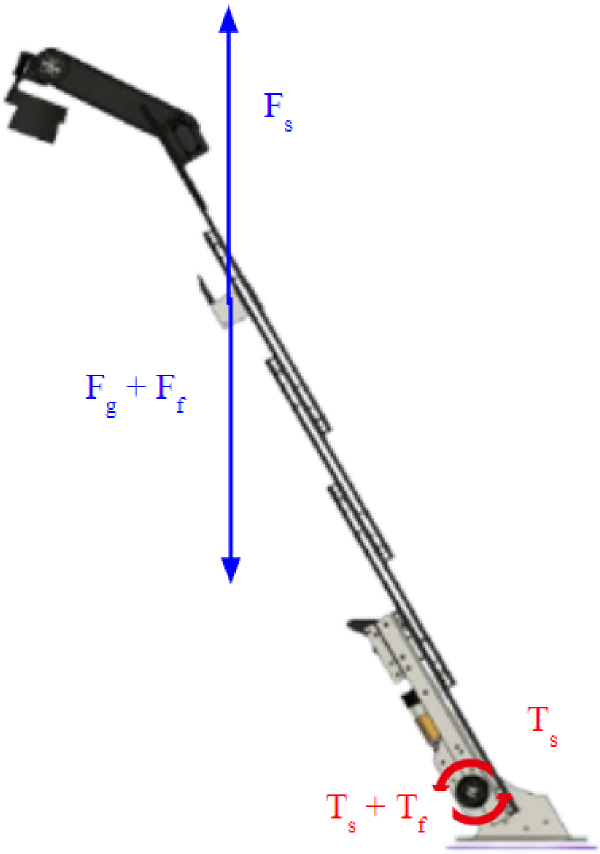

Figure 5: A free-body diagram (FBD) of the delivery system used to illustrate the different forces and torques acting on it.

We can then combine these torques to determine the amount of torque necessary to cancel out the net torque that is already acting on the pulley from the weight of the delivery system. This is somewhat complicated, so we proceed in the following three steps:

1. Calculate the vector component of gravity pulling down on the slides from their weight by using the formula M * g * sin(a), where M is the mass of the slides, g is the acceleration due to gravity (which is a constant), and a is the angle of the tilt of the

slides (the same as used in answering the first part of Q1). Corresponding to the parameter values shown, we have 2.15 kg * 9.81 * sin(60°) = **10.55 N** of force.

2. Convert this force into a torque, which we can do by multiplying the weight (which we have just solved for) and the radius of the pulley (in meters) together to get 10.55 N * 0.02 m = **0.211 N** x **m** of torque.

3. Finally, we can plug in this value, along with the amount of torque created by friction (measured to be about **0.1588 N** x **m**), into Newton's Second Law equation to calculate the minimum torque required from the motor to extend the delivery slides. Since Newton’s Second Law equation is $\Sigma\tau = I\alpha$, we can expand it to include all the torques previously calculated to get the equation $T_{min} = T_f + T_g$. After plugging in the values for the torques, such as the torque created by friction for T_f and the torque created by gravity for T_g, we get T_{min} = 0.1588 N x m + 0.211 N x m = **0.3698 N** x **m** of torque.

Since these torques are in the opposite direction in which we want the slides to extend, the torque from the motors needed to extend the delivery slides must cancel them out at the least, meaning that **0.3698 N** x **m** is the minimum amount of torque needed to extend the delivery slides.

To find the minimum amount of torque needed to extend the intake slides, we must go through a similar process to the delivery slides. One notable difference between these two calculations is that we no longer need to factor in the weight of the slides, as the intake slides are horizontal, meaning their weight does not contribute any torque to the pulley system. We can then proceed in the following four steps:

1. Construct another free-body diagram, as shown in Figure 6, that represents all the torques that act on the pulley system attached to the intake

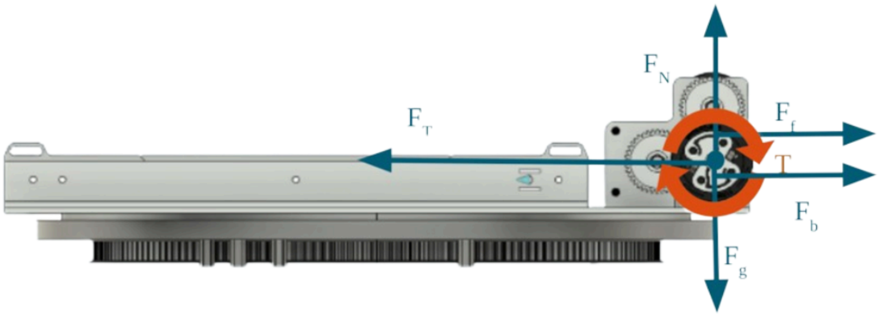

Figure 6: Another free-body diagram (FBD, used for tackling Q2). The forces of friction and the pull of the badge holder are the causes of the torques resisting against the rotation of the motor. The force of gravity and the normal force of the pulley are also acting on the pulley, but they do not produce any torques.

2. Derive an equation from Newton's Second Law to determine the torque required to extend the intake: $F_{min} = F_f + F_b$, where F_{min} represents the minimum amount of torque required, F_f represents the amount of torque caused by friction from the motor, and F_b represents the amount of resisting torque created by the badge holder After that, substitute the physical values for the variables to get F_{min} = 0.8415 N + 2.4525 N = **3.294 N** of resistance.

3. To find the amount of torque that these resisting forces create, we must multiply them by the radius of the pulley to get 3.294 N * 0.02 m = **0.07848 N** x **m** of torque.

4. Divide this value by the gear ratio from the gearbox to determine the amount of torque needed from the motor itself: **0.07848 N** x **m** / 4:3 Gear Ratio = **0.05886 N** x **m** of torque.

This value, namely **0.05886 N** x **m**, is the minimum amount of torque that is needed to extend the intake slides as the torques due to friction from the motor and the resistance of the badge holder only need to be canceled out at the minimum. Along with this, we can note that this value is far less than the torque required to extend the delivery slides, as the intake slides not only have a gear ratio that increases the power output, but also their own weight is not creating a negative torque acting against the motor.

2.3 Tackling Research Question Q3

To answer Q3, we can use the same concepts as in Q2 to determine the minimum amount of torque required to hold the virtual four-bar in place. To do so, we can proceed in the following 3 steps:

1. Construct a free-body diagram to visualize the different torques acting upon it, as shown in Figure 7.

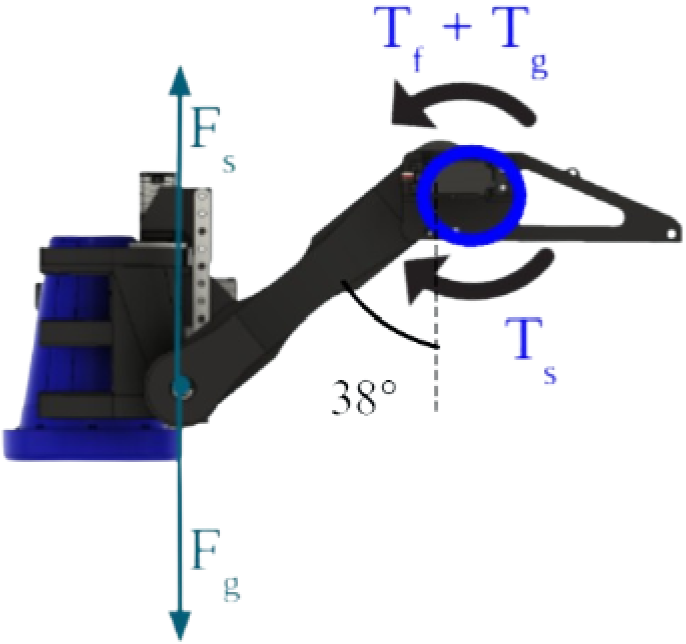

Figure 7: Yet another free-body diagram (FBD) to visualize the different torques acting upon it (used for tackling Q3). The force caused by gravity pulling down the claw and cone results in a torque resisting the turn of the servo to raise the claw. When grabbing a cone, the four-bar is typically held at a 38° angle

2. To calculate the amount of torque the weight of the four-bar, claw, and cone create, we write out an equation that multiplies the length of the four-bar by its weight:

   Torque = Force * Radius * cos(a)

   We can then substitute the physical values for each of the variables and solve for the exact value of torque:

   8.0677 N * 0.231 m * cos(38°) = **1.469 N** x **m** of torque

3. To find the total amount of resisting torque, we need to add all the torques that oppose the motion of the motor during extension. This includes the torque caused by friction and the torque caused by the weight of the four-bar, claw, and cone:

   $T_{min} = T_g + T_f$

   Combine this value with the torque caused by friction from the servo to determine the minimum torque needed, and we have:

T_{min} = 0.117 N x m + 1.469 N x m = **1.586 N** x **m** of torque**.**

2.4. Further Justification on the Importance of Tackling Q1, Q2, and Q3

We did this to ensure that our robot could accomplish the required tasks while running at its maximum efficiency. For instance, we needed to find the horizontal distance from the robot to the junction in Q1 because it allows us to determine the exact positioning required of the robot to be able to deliver cones to the junction reliably. Determining this exact distance from the base of the delivery system to the junction allows us to pinpoint the exact positioning the robot must be at to deliver. Along with this, it also reduces human error when positioning for delivery, and with enough practice, can result in extremely high rates of success. In Q2, we needed to find the minimum torque required to extend both the intake and delivery slides because it allows us to optimize gear ratios. In Q3, we needed to find the minimum amount of torque that is necessary to hold the four-bar in place while holding a cone, as its weight along with the cone could cause it to collapse if there is not enough torque being put out. Stall torque is the amount of torque required for a motor to maintain an output rotational speed of zero [4]. As shown in Figure 8, the amount of power output produced by the motor peaks at exactly half of the stall torque, meaning the torque being put out by the motor should be around that amount. By calculating the exact amount of torque required for each component in the intake and delivery systems (in Q2 and Q3), we are then able to half this amount to find the amount of torque that results in maximum power and efficiency,

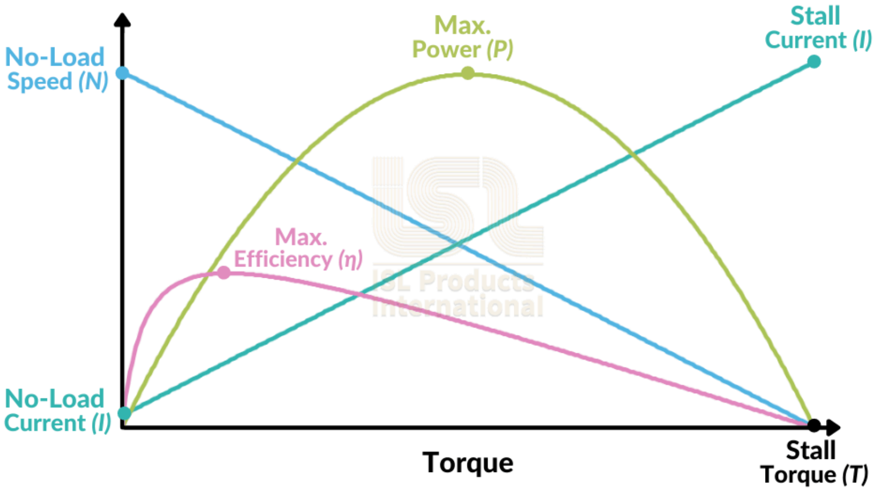

Figure 8: The idea that is leveraged to tackle Q2. The green line on the graph shows that the maximum amount of power output occurs when the amount of torque being produced by the motor is exactly half of the amount of stall torque. Image source: ISL Products International [5].

2.5 Efficiency and Effectiveness of Our Robot

Figure 9 plots the scores of our robot in the 7 meets of the 2023 season. For each meet, we plot the average score during the autonomous period (65.4 being the highest), the average score during the tele-op period (103.8 being the highest), and the average score during the endgame period (46 being the highest), where "average" is the total number of points scored divided by the number of qualification matches our team played during that meet. We observe that there is a vertical line separating meets 1 and 2 from meets 3, 4, 5, 6, and 7 which represents when the calculations described above and their corresponding modifications to our robot took place. From both the autonomous and tele-op perspectives, we observe there has been a fairly steady increase, and from the endgame perspective, we observe it has been fluctuating. By summarizing the findings, we observe that the incorporation of calculations and the modifications that follow, which are also further explained later in the paper, are extremely useful in increasing the number of points scored. These findings collectively indicate that answering the three research questions (Q1-Q3) helped us improve our robot.

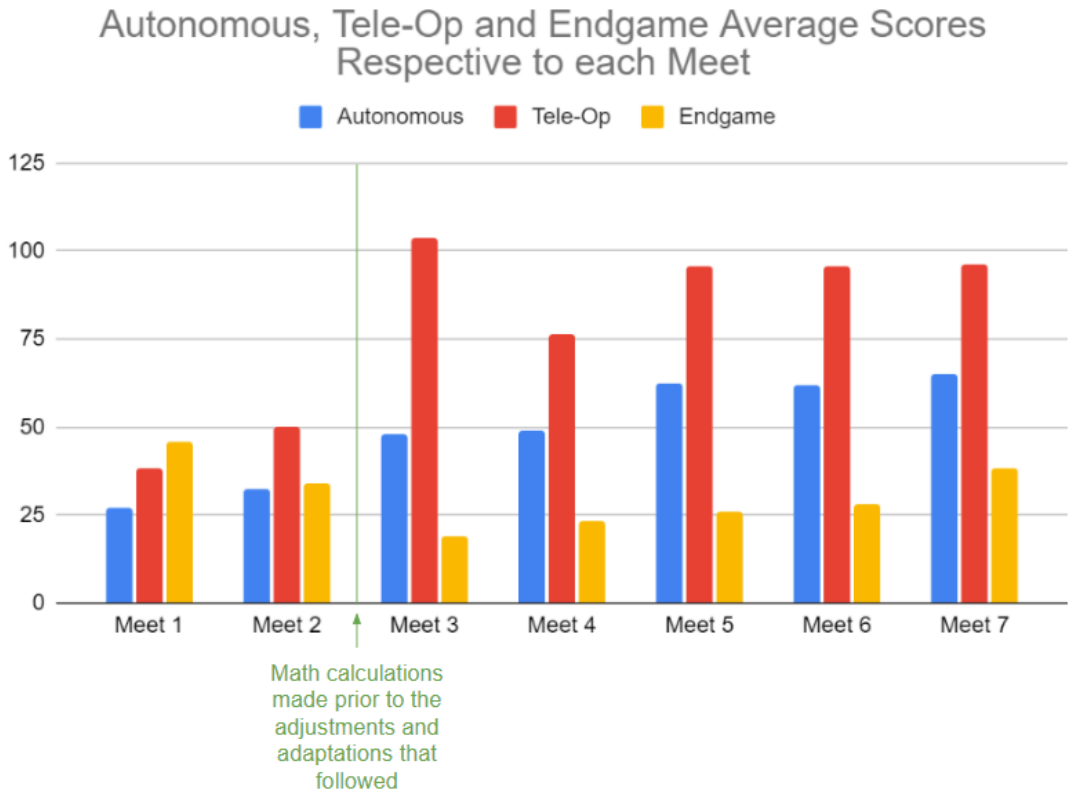

Figure 9: A comparison between the performances of our robot throughout the 7 meets our team attended during the 2022-2023 *Power Play* season. The bar graph shows the average scores of the autonomous, tele-op, and endgame scores respective to each meet.

3 Discussion

3.1 Summary of Mathematics and Physics Concepts Used in Our Robots

In summary, the mathematics and physics concepts used in our robots are as follows. Firstly, we used advanced trigonometric functions to calculate the exact horizontal distance that was required for delivery between the base of the delivery system and the four-bar holding the cone. Secondly, we applied physics concepts surrounding Newton's Laws to find the minimum amount of torque that is required to extend each of the delivery and intake slides, which was important for maximizing extension speed and minimizing battery usage. The third concept I used was similar to the second, namely calculating the minimum amount of torque required to move something. However, this process slightly differed from the previous one, as rather than moving up and down, the four-bar was made to rotate around an axis. What this means is that now, only a vector component of the claw, four-bar, and cone's weight would be creating an opposing torque on the motor, rather than the weight of the slides pushing against the pulley as it did in the delivery system.

3.2 Lessons Learned

By applying the aforementioned mathematics and physics concepts to the practice of designing and building robots, I, personally, have learned many valuable lessons that could potentially influence my future.

Firstly, I now realize that these concepts and methods that are taught in the classroom have many applications that other students may not even know or recognize. For instance, the formulas and calculations employed above may appear to be mundane and strictly classroom-based, but they are, in reality, extremely useful for real-world applications such as designing and building robots. Since my STEM career has simply only begun, I expect that future training will provide me with more advanced technical skill sets that can be used in my future endeavors. Even though my career in FIRST, or more specifically, FTC, will eventually come to an end in my first technical chapter, I can continue to build on more advanced technical skills and utilize them when tackling more challenging tasks in the near future. For instance, when I attend college, I intend to study engineering so that I am able to learn even more about physics and mathematics concepts that I can either connect with or extend from what I already know. By building on these skills either through mentorships, internships, in the classroom, or any other methods available to me in the future, I will be able to transform these classroom-learned concepts into real-world skills. For instance, if I am to help design or work on robots in the future, I will already have a certain skill set that may provide me with competent preparation or readiness. Not only will this prove more efficient, as I already have a grasp on either the basics or the majority of the process of completing the project, but this may also allow me to choose between different technical approaches to completing challenging tasks. With the knowledge I already have along with the knowledge I intend to build upon, I will be able to either lead others or assist in the development of new technological innovations in the future, as I will be able to contribute to the flow of diverse methodological ideas.

Secondly, I have gained much insight and experience from having to both work in a team and with other teams. Although seemingly trivial, teamwork plays a vital role in the development of not only FTC teams, but also engineers themselves. Teamwork was constantly required to both compete in alliances and coordinate during outreach. Since teams often work together to spread the word about STEM throughout the world, it is important to coordinate events such as podcasts and conferences so that they can make an even larger impact. Although these teamwork skills prove extremely effective in the present with FIRST and robotics, they can also become useful in my future career paths. For instance, in college, students will most likely be expected to work together in group projects, providing an opportunity for them to exercise their communication skills. Even outside of school, employees may be expected to work in teams to complete projects. Teamwork is an extremely important quality that is often made commonplace in many, if not all, collaborative environments as it can result in effective collaboration between subordinates due to the presence and flow of diverse ideas and perspectives. Since I, similar to many others, was able to develop these skills through the FIRST program(s), I am now able to exercise these skills in practically anything I do, especially my future career path in engineering,

3.3 Recommendations for Our Education System

As mentioned above, although the knowledge that students gain from middle and high school classrooms is undoubtedly useful, there are still no real-world applications that come with it. Before I joined FTC in 2019, I believed there was no practical use of these topics and that we were simply required to memorize information for tests. However, after I joined, I found that there were actually several real-world applications I could apply this knowledge to. Since many students lack opportunities to apply their textbook knowledge to real-world scenarios, they are often discouraged from pursuing projects outside of school. To reduce the prominence of this issue, schools can create more hands-on opportunities for students to apply their knowledge, so that they do not simply memorize it for a short period. Not only will this allow students to find meaning in the material they learn in school, but it can also engage them and prepare them for their respective future career paths. For instance, when I was younger, I was unsure of what career path I wanted to take when I grew up. Although this may seem like a common dilemma for young children, this problem often remains for a long time, sometimes even throughout college. If students are provided with more chances to explore the different career fields to which they can apply their knowledge, they will become more passionate about the topics they learn about in school, similar to how I became more eager to learn about STEM topics after being introduced to FTC. Along with this, if students are allowed more of these opportunities, they will become even more prepared for their futures. This is because they will be able to gain experience, similar to how I now have experience in the engineering and robotics fields due to FTC, rather than just textbook knowledge. This factor is crucial in the transition from school to real careers, as not only will students be more prepared, but also they will already have several skills they can readily apply.

I recommend that both schools and teachers attempt to employ more hands-on learning methods, rather than merely lectures. My own high school physics teacher provided me with a launching pad from the classroom into the real world of engineering. By demonstrating real-world applications of the topics that he teaches, he engages his students and encourages them to ask questions about his lessons while also effectively educating them about the necessary topics. Personally, his style of instruction was one of the most vital factors that prompted me to pursue the field of engineering, as it allowed me to realize that these calculations and concepts are something that I enjoy learning about. Not only did he contribute most of the knowledge that I was able to write into this paper, but he also assisted me with several calculations along the way. I urge teachers all around the world to implement these sorts of real-world teaching styles, as it can also encourage students to pursue their passions related to their careers.

Finally, I also recommend that schools and teachers educate students more about real-world applications. Although I was able to learn most of this material from my classes, there was still much knowledge that I had to do self-research for. Joining FTC has expanded my knowledge in robotics and engineering by great amounts, as I was able to learn about topics that I previously did not even know existed, and I believe that allowing students to explore these fields can allow them to learn more about certain career paths that they may even end up enjoying

3.4 Recommendations for Future Roboticists

My advice for FTC teams is to follow the process (i.e., the research questions) described above when designing a robot in the future. As shown in Figure 9, after implementing the modifications that were deemed necessary following the calculations described in this paper, the number of points we scored per meet continuously increased. By doing so, not only can teams maximize their speed and efficiency as previously described, but it also reduces the amount of trial and error required throughout the season. Prior to making these calculations, our team experienced several issues related to driver error and power distribution. However, after calculating these values, we were able to modify our robot to allow it to perform at its maximum potential. Although these issues could also be solved using a trial-and-error approach, it proves to be far more efficient to use simple calculations.

Not only will this boost the performance of other teams’ robots, but it will also provide them with the skill set that they may be able to utilize in the future. Since I can readily attest that these skills are useful in FTC now and will most likely be useful again in my future career, I wholeheartedly believe that this will affect others in the same way. This allows the textbook knowledge that most students (not only those involved in FTC) learn to be applied to real-world scenarios and can spark interest in the STEM field while also serving as a more effective form of instruction.

3.5 The Value of FIRST in Educating Future Generations in STEM

In the future, those who pursue STEM careers can apply this knowledge to help solve real-world problems. While FTC may simply appear as a program for high schoolers who are interested in robotics, it can also mark the beginning of a new generation of engineers. The students who are currently involved in FIRST, not just FTC, serve as generations of engineers who are capable of creating technological innovations in the future. For instance, if students can develop their problem-solving and robotics skills now, they may be able to apply them to far more complex tasks in the future, such as space or deep sea exploration using robots.

Although still young, those who are enrolled in youth STEM programs, such as FIRST, are guaranteed to be the future of STEM and engineering, meaning it is crucial to educate them about these topics as early as possible. These people, who are currently students, have the potential to solve problems on a local, national, and even global scale in the future. Allowing them to develop and sharpen their skill set now by providing them with the opportunities to do so is the most effective way to set them up for success, as it provides them with the necessary experience required for the field.

4. Conclusion

This paper presents how our FTC team leveraged several mathematics and physics concepts to allow our robot to operate as efficiently and effectively as possible, where efficiency concerns the distribution of power around the robot, and effectiveness concerns whether or not the robot is able to complete its designated tasks within a short given time frame. More specifically, this paper tackles three questions: What is the total horizontal distance from the base of the delivery system to the tip of the virtual four-bar (Q1)? What is the minimum amount of torque required to extend each of the delivery and intake systems (Q2)? What is the minimum amount of torque required to hold the four-bar and cone in place (Q3)? Empirical results show how tackling these problems improved our robotics team's performance, which was proven in our increase in average scoring. Along with answering these questions, this paper also discusses my thoughts on how it is crucial to bring STEM and its real-world applications into the classroom.

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