POLITECNICO DI TORINO

Department of Electronics and Telecommunications

Master of Science degree in Mechatronic Engineering

MASTER'S THESIS

Design and fabrication of a high performance human powered hydraulic hybrid vehicle

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Declaration of Authorship

I, Tommaso GRECO, declare that this thesis titled, "Design and fabrication of a high performance human powered hydraulic hybrid vehicle" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
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"It is good to have an end to journey toward, but it is the journey that matters in the end."

Ursula Le Guin

POLITECNICO DI TORINO

Abstract

Department of Electronics and Telecommunications

Mechatronic Engineering

Design and fabrication of a high performance human powered hydraulic hybrid vehicle

by Tommaso GRECO

Efficiency and simplicity are the key aspects that make cycling the most widely used methods of human powered transportation. On the contrary fluid power is a world in which great loads and forces are the masters. The leading question and challenge of this master's thesis is whether it is possible to combine these two very different worlds in an effective way.
Starting from this question the National Fluid Power Association (NFPA), in order to engage as many people as possible into this problem, challenges every year college students in the Fluid Power Vehicle Challenge (FPVC) asking them to design a human powered vehicle that uses hydraulics as the only way of performing the power transmission.
Based on this premise, a long and complex work including designing, simulating, building and testing has been carried out during the whole academic year and the purpose of this thesis is to describe the whole process of production of the vehicle, from the definition of the problem to the final competition in mid-April 2019.
The dissertation will be divided in several chapters and will define the context of the project in details, then carry on with the design of the three main systems: the hydraulic system has been used to transfer the power from the rider to the vehicle implementing an innovative hybrid secondary control achieved through the switching of a shut-off valve; all the components have been sized using the combination of two optimization routines embedded in the software Simcenter Amesim. The frame and steering assembly has been designed in order to place all the components and simulated trough FEA analysis to evaluate its expected mechanical behavior during standard conditions and eventually a digital electronic system has been designed and implemented on the vehicle in order to read data from the main vehicle's systems and provide useful information for the rider. The main core of the electronics was a Raspberry Pi and all the software has been written from scratch using the Python language.
After that there will be a short illustration of the building phase, carried out autonomously in the Maha lab premises and the description of the final competition where the team scored high marks across the board, prior a structural failure that meant the end of the competition. In the very end, all the expected performances compared to the actual results will be summarized, followed by the description of some future developments that might result interesting.

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List of Abbreviations

NFPA	**N**ational **F**luid **P**ower **A**ssociation
FPVC	**F**luid **P**ower **V**ehicle **C**challenge
STEM	**S**ational **T**luid **E**ower **M**ssociation
CCR	**C**ubic **C**entimeter (per) **R**evolution
NLPQL	**N**on **L**inear **P**rogramming (by)**Q**uadratic **L**agrangian
SQP	**S**equential **Q**uadratic **P**rogramming
GA	**G**enetic **A**lgorithm
DC	**D**uty **C**ycle
CAD	**C**omputer **A**ided **D**esign
FEA	**F**inite **E**lement **A**nalysis
GPS	**G**lobal **P**ositioning **S**ystem
HDMI	**H**igh **D**efinition **M**ultimedia **I**nterface
GUI	**G**raphic **U**ser **I**nterface
ME	**M**echanical **E**ngineer
ABE	**A**grigultural (&) **B**iological **E**ngineering
com	**c**enter **o**f **m**ass
loc	**l**ine(s) **o**f **c**ode
OS	**O**perative **S**ystem
PC	**P**ersonal **C**omputer
ADC	**A**nalog (to) **D**igital **C**onverter
PWM	**P**ulse **W**idth **M**odulation
QML	**Q**t **M**odelling **L**anguage

List of Symbols

Hydraulics Chapter	M_1	Pump Torque	N m
	M_2	Motor Torque	N m
	V_1	Pump Displacement	cm^3
	V_2	Motor Displacement	cm^3
	Q_1	Pump Flow	m^3/s
	Q_2	Motor Flow	m^3/s
	p_1	Pump Pressure	N/m^2
	p_2	Motor Pressure	N/m^2
	δp	Main Line Pressure Drop	N/m^2
	n_1	Pump Rotary Speed	s^{-1}
	n_2	Motor Rotary Speed	s^{-1}
	α	Regulation Grade	
	α_1	Pump Displacement Grade	
	α_2	Motor Displacement Grade	
	ν	Gear Speed Ratio	
	τ	Gear Torque Ratio	
Mechanics Chapter	ν	Gear Speed Ratio	
	ν_1	First Stage Speed Ratio	
	ν_2	Second Stage Speed Ratio	
	r_A	Input Gear Radius	m
	r_B	Output Gear Radius	m
	N_A	Input Gear Teeth Number	
	N_B	Output Gear Teeth Number	

Chapter 1

Problem Statement

Efficiency and simplicity are two of the main reasons as to why cycling is among the most widely used methods of human transportation. Fluid power instead is mankind's way of manipulating forces to move great loads. The marriage of these two different worlds presents a unique engineering challenge.

Starting from this consideration, the **N**ational **F**luid **P**ower **A**ssociation (NFPA) asks the question: how does one combine these two platforms to rethink and redesign a traditional bicycle to create a vehicle that uses hydraulics as the mode of power transmission. In order to engage others on the topic, NFPA involves college engineering students in the Fluid Power Vehicle Challenge, to stimulate the involvement in practical hydraulics, pneumatics and sustainable energy devices for motion control and also provide students with experience in real-world engineering under a strict timeline of designing, simulating, material sourcing, building, testing and demonstrating their designs.

In this context I was kindly given the opportunity to coordinate a team of engineering students from Purdue University (Lafayette, IN, United States) taking their capstone design course during their senior year with the common aim of designing and building a human powered vehicle using only hydraulics to perform the power transmission and compete at the national competition sponsored by IMI Engineering in early April 2019. During this stay in the United States I've been hosted at the Maha Fluid Power Research Center which is the largest academic hydraulics lab in the USA, sponsored by Purdue University [1]. In the premises of the lab the whole process of production of the vehicle, from the design to the testing, passing from the building, has been carried out.

[1]https://engineering.purdue.edu/Maha/

The problem definition of this year's competition is the following:

There is a need to design and build a human-powered vehicle that uses fluid power to transfer and store energy using novel approaches and innovative technology.

Furthermore, for additional points, the vehicle should include an energy recovery system. The bike must be able to race in three different races within the same competition event: a sprint race, an efficiency challenge and an endurance trial.

In order to ensure that every team follows the same rules and undergo the same safety requirements, a list of guidelines has been released by NFPA [7] prior to the start of the academic year. These can be divided in technical requirements, safety requirements and final competition rules and will be depicted in the following sections.

1.1 Technical Requirements

In order to be allowed at the final competition all vehicle must abide the following vehicle requirements:

- Vehicle propulsion must be accomplished through fluid power (hydraulics or pneumatics) with human power serving as the prime mover in the system. No internal combustion, electric drive motor, chains, belts, or other modes of propulsion are permitted. Gears, chains or belts are allowed in order to transfer power to the fluid power pump/compressor, but a fluid link (oil or air) is required between the pump/compressor and the motor
- Vehicle designs must include an energy storage device.
- Gas pre-charging systems will be available at Final Event location. The total accumulator pressure including the fluid and/or nitrogen gas charge cannot exceed the safe working limits of the storage device and system components. A safe limit rating must be maintained on the fluid power components (manufacturers rating). After pre-race pressurization, additional pressurization can only be supplied as a result of the design, i.e., supplied by the rider and/or the course (braking or gravity).
- There is no requirement for the method of switching between the circuits, i.e., electronic or manual but the circuitry must be designed to include direct propulsion and regenerative breaking.
- Vehicles must use environmentally-friendly fluids furnished by the Fluids Supplier.
- Vehicle design must be for a single rider. The rider must be able to enter, exit, start and stop the vehicle unassisted.
- Style of vehicle design is open. There are no requirements for the number of wheels or for either a standard, recumbent, or multi-wheel drive.
- Maximum weight of the vehicle is 210 pounds (95.25 kg) without rider.

1.2 Safety Requirements

At the competition, every vehicle must undergo a vehicle inspection in order to evaluate if the following safety rules have been respected.

- All designs must comply with safety policies.
- Active Leak: An active leak is when a droplet forms and drips off a surface.
- Residual oil left on components in hard to clean areas is acceptable, but an active leak, such as when a droplet forms and drips off the surface, is not.
- There is a zero-tolerance for active leaks in the system. If there is an active leak, teams will have the option repair it, but must be able to completely stop the active leak before their time to compete.
- All vehicles must be reviewed by the judges and the Technical Liaison prior to operation.
- If vehicles have an unfixable design flaw related to safety the result is elimination from event race(s) where that design element(s) is required.
- If vehicles have a design flaw, teams will have the option to repair it to be readmitted to the event races, pending review by judges and the Technical Liaison.
- All vehicles must have multiple, fully active, independent brakes that provide a failsafe braking condition. Brakes should be able to hold the vehicle at a stop under the full charge of the accumulator.
- If shipping to the final event, vehicles are to be void of hydraulic fluid pressure and no more than 50 PSI (3.45 bar) of gas charge. Vehicles are to be shipped at least 10 days before the Event. Vehicles can weigh no more than 210 pounds (*95.25 kg*). Instructions will be provided.
- Each rider must wear a helmet. The helmet must comply with a nationally recognized standards organization. All bicycle helmets must carry a CPSC sticker. The burden of proof of meeting this guideline will rest with the participant.
- Guards are required to protect the rider from moving components, where deemed necessary for safety reasons.
- Vehicles will be eliminated from the event races for any of the following reasons:
  - Insufficient braking capability
  - Lack of stability
  - Poor visibility
  - Dangerous protrusions
  - Unsafe design features
- During the competition, any participant demonstrating unsportsmanlike conduct will be disqualified from the Challenge and forfeit any and all awards. Driving under the influence is automatic elimination. Same rules apply as driving a motor vehicle on the highway.

- Any safety concerns not covered in this document will be evaluated and addressed at the discretion of judges and Technical Liaison.

1.3 Final Competition Rules

In the end all the rules strictly related to the final competition. Below are illustrated some general guidelines first and then all those related to a specific race, one for each subsection.

1.3.1 General rules

- Each team starts with storage device void of hydraulic fluid. Maximum 10 minutes allowed to manually pressurize the storage device.
- The pre-charge of the accumulator may not exceed 50 PSI (3.45 bar) if the vehicle is being shipped. The Technical Liaison and Judges will gas charge the accumulator to the safe, desired pre-charge pressure.
- No mechanical, hydraulic, or pneumatic failures are allowed due to poor design or application of components. Vehicle failures during the Sprint Race and Efficiency Challenge will result in elimination.
- Reservoirs, components, and plumbing must meet reasonable industry standards. No duct tape or other examples of insufficient workmanship. There is zero tolerance for active leaks in the system.
- Be sure to include instrumentation (pressure gauge).
- The manufacturer's size and rating of the accumulator must be easy to read. If air is used, the size of the receiver and pressure must be known.
- All course competitions will begin with a standing start.
- The vehicle system configuration does not need to remain the same for all races. Teams may modify the configuration as long as there is no loss of oil during the change-over, other than a few drops.
- Teams that need to make repairs will have that option only until their specified race start time. No additional grace period will be provided.
- All repairs need to be done in the designated "shop area," not in the field or on the race track.
- The event race schedule is final unless teams agree to swap start times on their own. Judges and program staff will not make accommodations.
- Drivers must maintain a safe speed and adhere to all instructions from the course marshals. Failure to comply will result in penalties, disqualification of event races or elimination.
- The decisions of the judging panel are final. This includes tie breaking decisions. All ties will be broken based on adherence to the design criteria and performance.

1.3.2 Sprint Race

A classic speed race where whoever runs faster wins. The ability of the vehicle to transfer power from the user to itself is tested and evaluated.

- Heats of multiple bikes at a time on a 600 ft (183 m) course.
- Standing start, one rider on vehicle, no pushing.
- Each team is allowed up to two attempts, and must use the same rider in both attempts.
- Best time for places 1st, 2nd, and 3rd.
- Timing in Minutes: seconds: tenths of seconds: hundredths of seconds.

1.3.3 Efficiency Challenge

In this race the ability of the vehicle to effectively store and most efficiently use the smallest amount of energy that has been stored to travel the greatest distance without active participation of the user in the propulsion is tested and evaluated.

- The vehicle that goes the farthest is NOT necessarily the most efficient. Similarly, the most stored energy does not automatically indicate the winner either.
- The vehicle must travel a minimum distance of 100 ft (30 m) Braking is not required. Vehicle will go as far as it can before coming to a complete stop.
- The vehicle, rider, and safety gear will be weighed at the track, immediately before starting the event.
- Each team is allowed up to two attempts and must use the same rider in both attempts.
- Standing start, one rider on vehicle. There can be no assistance in making the machine move on its own. No windshields or wiggling of handlebars is allowed. Rider must remain on the vehicle for the entire event. If a foot touches the ground, this distance will be measured from the starting point.
- Rider will not be allowed to operate the pedals or any other mechanical input device from the start of the event until the vehicle comes to rest. Braking is allowed for energy recovery, but not required.
- The vehicle's pre-charge pressure used in the calculation below will be the pre-charge that is requested by the team and deployed by approved Technical Liaison only.
- The volume of the storage device used in the calculation will be as stated on the vessel by the manufacturer (Pressure storage devices manufactured other than by Parts Supplier must be approved by the Technical Liaison).
- The winner will be the determined by the following parameters and equation:

  L = total distance traveled from starting point (in inches).

W = weight of the vehicle and rider (in pounds).

P = gas pre-charge pressure (in pounds per square inch (PSI)) (Note: The minimum accumulator gas pre-charge pressure during filling will be 100 PSI (7 bar))

V = gas volume of storage device (in cubic inches).

$$Scoring\ ratio = \frac{W \cdot L}{P \cdot V} \tag{1.1}$$

- This calculation is a dimensionless ratio and will provide an objective measurement to judge vehicle/system efficiency. It quantifies the winning vehicle as providing the most work with the smallest amount of stored energy.
- In the simplest terms, the vehicle that completes the challenge with the least amount of energy per pound of weight, wins.

1.3.4 Endurance Trial

In this event the reliability, safety and durability of the whole vehicle assembly will be tested and evaluated.

- Two bikes leave every two minutes.
- The course may consist of laps in a slalom fashion and will total no more than 1 mile. Maximum time to complete will be 30 minutes. Specific course will be determined and communicated prior to the Competition Event.
- To test the regenerative braking circuits of the vehicles, the course will require at least one stop and restart of the vehicle.
- Standing start, one rider on vehicle, no pushing.
- Teams are allowed up to two drivers, as an option, although not a requirement to complete the course.
- Driver changes will only be allowed in a designated area. For safety sake, vehicle will come to a complete stop to change drivers, no pushing.
- If vehicle breaks down during the Endurance Challenge, it must be moved to a safe distance from the track. The team will have 15 minutes to repair. The clock is not stopped for repairs.
- Best time for places 1st, 2nd, and 3rd. Timing in minutes: seconds: tenths of seconds.

1.4 Program Cadence

Since the FPVC easily embedded into the capstone design course that most STEM students take in their senior year, NFPA helps them keeping track of the work during the whole academic year by dividing the Vehicle challenge in 5 phases:

Phase 1 - Kickoff - *September to October*

Students confirm the participation to the competition and, after taking contact with their supervisors and industry mentors start studying the documentation and set a plan defining objectives and the main deadlines.

Phase 2 - Design Phase - *October to December*

After having gained knowledge in fluid power components, circuits and systems, students start brainstorming in order to decide what kind of design use for the vehicle. They create an initial hydraulic design and mechanical drawings and they simulate it to analyze the behavior of the system and expected performances. When the design is completed and satisfactory the students choose and order all the components.

Phase 3 - Build and Test - *December to March*

The team receives the components from the suppliers and begins to construct the vehicle prototype. After testing the vehicle students can make adjustments and give the final touch to the vehicle

Phase 4 - Verification Review - *March*

Students have to send all the final design drawings and information together with a video of the vehicle in operation to the Program Manager, which confirms the entry into the final competition event if the vehicle respects all the design and safety requirements. If this is the case, the team prepares a final presentation of the design project and vehicle operation and sends it to Program Manager.

Phase 5 - Final Competition Event - *April*

Students travel to the designated location and then participate to the final competition event which will take place during 2 days.

Here a Gantt chart that summarizes all the phases with relative deadlines:

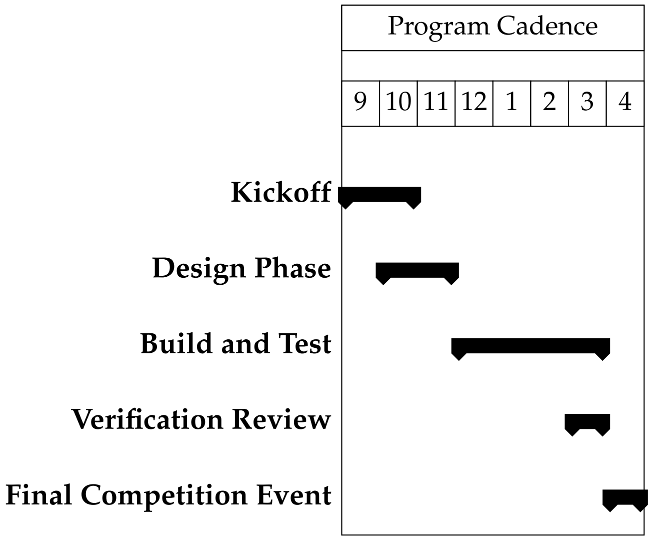


FIGURE 1.1: *Program Cadence Gantt chart*

1.5 Design Objectives

The first phase of the project, described above, has been crucial for the preparation of the whole process. The team has met very often during the month of September in order to brainstorm and define all those objectives and guidelines to be followed during the whole year in order to accomplish the best results and avoid unfortunate complications and incidents where possible. The objectives are many and various and they fall under different areas of interest.

1.5.1 Technical Objectives

In the very first moment every member of the team was of course letting his imagination run wild about the vehicle layout and appearance together with its practical building, so some goals and guidelines were defined in order to set a common base for everyone to follow during for what concerns the technical aspects of the vehicle design.

There was no much choice whether to use hydraulics or pneumatics; in fact, even if the latter are easier to be designed and controlled, way safer and more reliable, hydraulics can supply way more power, are highly responsive, can move much higher loads due to the incompressibility of the fluid and are more efficient in transmitting power.

Since the vehicle is to be completely human powered, all the sources of resistance need to be minimized.
This means designing all the systems trying to achieve maximum efficiency possible. This translate into designing the mechanical moving parts so that friction is as low as possible and decreasing pressure losses and maximizing fluid flow since it is directly related to the increased efficiency of the hydraulic components. Leakages have also to be avoided for this reason together to a safety matter and even if can seem quite

banal or insignificant, this played an important role when was necessary to decide whether to use pipes or hoses for the hydraulic connections.

A lot of time has been spent considering if it was useful using chains to transmit mechanical power but eventually the need of a tight packaging and the point penalty provided a considerable incentive not to use them.

Last thing, even if the regeneration is necessary for competing since in the endurance trial one start and stop using only regenerative braking is imposed, it has been decided to push the design of the regenerative system into the back burner. That is because based on some literature we found and previous knowledge and experience we imagined we would have used that particular system only when dictated by the competition, due to its lack of effective benefit.

1.5.2 User Friendliness

Riding a bike is second nature for most people and is second only to walking as far as human-powered is concerned. For this reason the riding experience has been a priority in our design and the rider's needs have strongly influenced many design choices.

Hence, the bike needed to be durable, comfortable, stable, easy to use by everyone and not too far from a normal bike in terms of design and mode of use. We also wanted to keep it as lightweight and easy to be transported as possible. In this phase also we first thought about putting a touchscreen monitor on the bike for the user to have all the information about the bike or the race at one's fingertips and enhance the rider's experience.

1.5.3 Personal Growth

Last but not least any of us wanted to make the most out of this experience in terms of personal growth as well. Therefore we set some personal goals, useful also for carrying out the project, such as being always on time, communicating with the others, being organized and forward-looking and trying to learn as much as possible from the other students, the professors, the industry mentors and of course from our errors. Moreover, even if we were lucky enough to have available the actual bikes and the all the documentation related to the previous editions of the competition at which Purdue participated, we made the resolution of designing from scratch as many things as possible without compromising the participation to the competition and under no circumstances taking components or items from any of the previous bikes.

1.6 Background Research

The NFPA Fluid Power Vehicle Challenge has been in existence for the last eleven years with some minor changes to some of the rules. Upon the project's inception, the team met with their technical advisors, Andrea Vacca and José Garcia-Bravo to discuss about their experience(s) with the project. In this way they were able to give a lot of advices and some inputs about where to start with the design along with a lot of material that resulted being very useful for the definition of the problem and the way of proceeding with the project.

Together with these, our last preliminary work was the research related to prior year's designs with Purdue being the last in order to avoid unintentional bias and dampening creative thoughts. During this research phase, the team spent lot of time focusing on what worked well for other teams and what did not. Eventually our focus ended up on two designs that were very different but somehow winning.

In this context two expected Gantt charts have been created, one for the Fall semester (the 17 weeks going from the 27^{th} of August to the 21^{st} of December) and the other for the Spring one (the 14 weeks going from the 7^{th} of January to the 12^{th} of April):

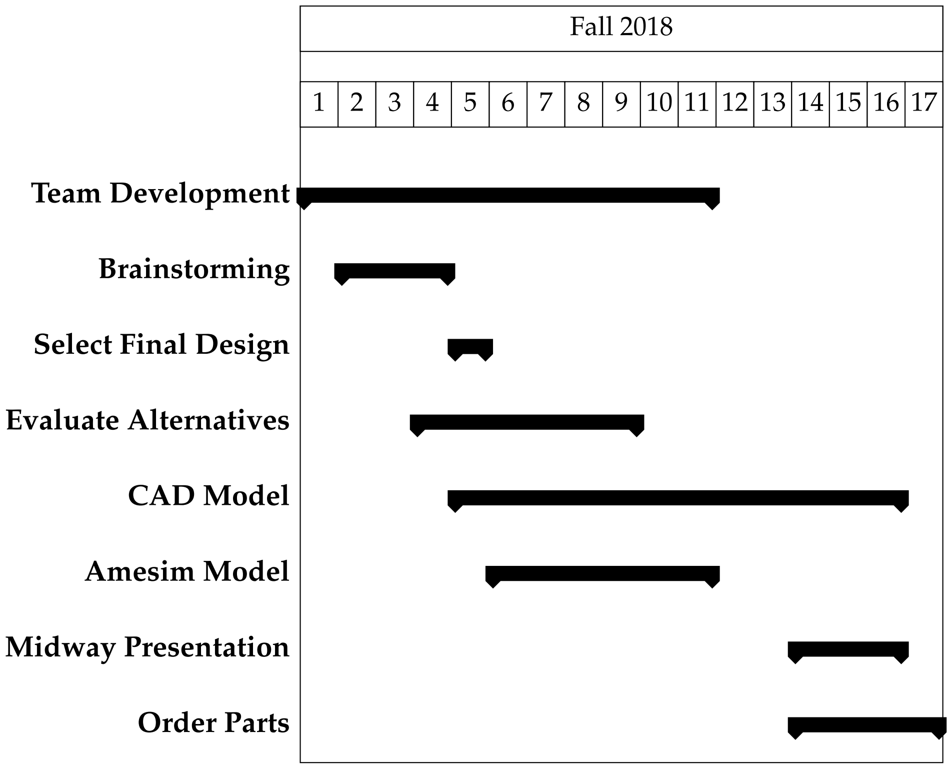


FIGURE 1.2: *Fall semester Gantt chart*

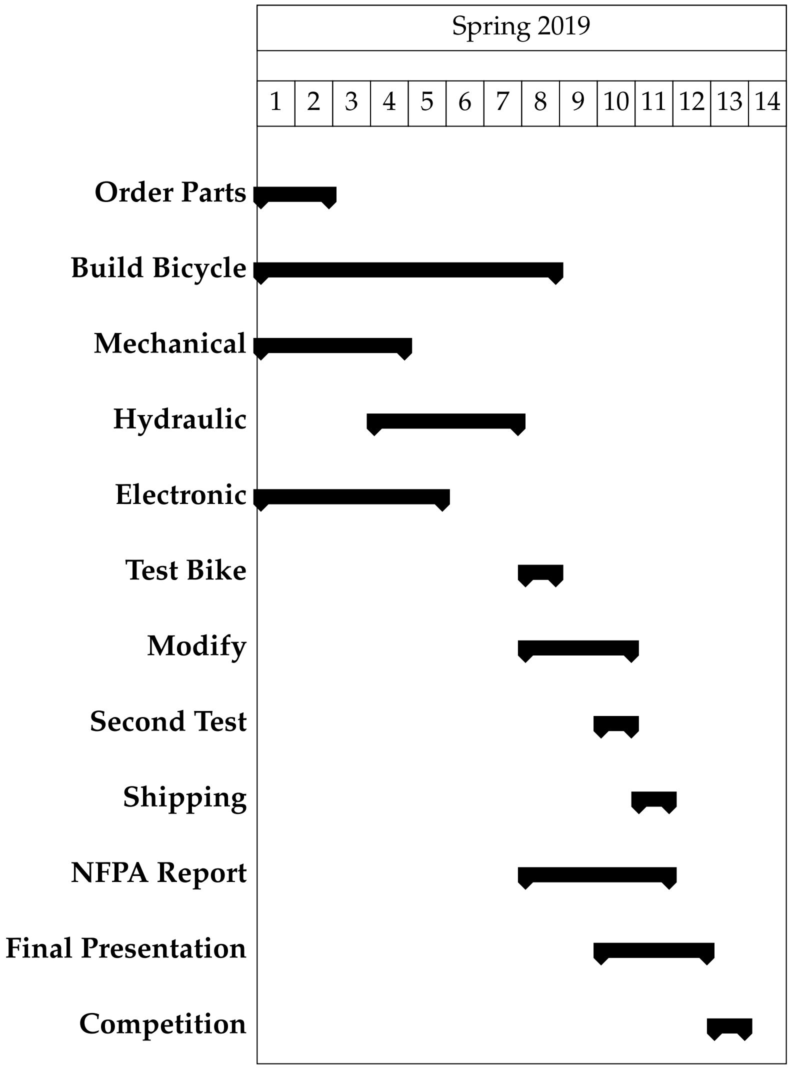


FIGURE 1.3: *Spring semester Gantt chart*

1.6.1 Purdue University 2017 Design

During the 2017 edition Purdue university built the *Purdue Tracer* (shown in figure 1.4 on the following page), the two-wheeled bike which won the event that year and was the starting point for this year's design.
This design was very different than most bicycles competing because it featured a tank integrated into the aluminum frame, showing how a very simple idea may lead to a huge advantage at the competition. Another strength of that bike was the smartphone with integrated application attached to the vehicle's handlebars. This was a huge innovation at the time, allowing the user to read the pressure that existed in the hydraulic lines, the speed and distance of the bike, the heartbeat of the rider along with information about the geolocation and the weather.
The main flaw of this bike is represented by the increasing resistance that the hydraulic system imposes to the pedal during the normal use, resulting in a jerkily movement of the feet, advancing by 180°at the time.

FIGURE 1.4: *2017 Purdue Tracer*

1.6.2 Murray State University 2018 Design

Unlike other teams which relied heavily on efficient mechanical gearbox designs, Murray focused on efficient hydraulic usage with a massive amount of fluid storage. Their interpretation of the rules (that don't forbid the usage of the accumulators during the sprint and endurance races as well) allowed them to redefine the concept of human-powered vehicle, creating something that was more similar to a rocket (their accumulator was able to store almost 10 liters of hydraulic fluid at 210 bar) than an actual bike (in figure 1.5). Eventually their design had an unprecedented impact on the challenge, even if they were disqualified due to technical problems; the main defect of the design was in fact the heaviness of the vehicle that ended up not being reliable at all.

FIGURE 1.5: *2018 Murray State bike*

Chapter 2

Hydraulics

From a chronological point of view the starting point of the design phase has been the one related to the hydraulic system.
The main reason is that talking with our supervisors has emerged that hydraulic components are those most difficult to source and presenting the highest lead time, so this system resulted being the most troublesome during the past years.

2.1 First Design

The very first idea has been the one of reproducing the approach used by Murray State last year, storing as much energy as possible before each race and relying completely on that.
Since in the Maha lab some huge accumulators were present, with some of them being more than 1.5 meters long, at first it has been considered the idea of creating the whole bike around the accumulator, using it as frame of the vehicle.
In order to evaluate the feasibility of this layout, some simulations were carried out using the software Simcenter Amesim (see figure 2.1).

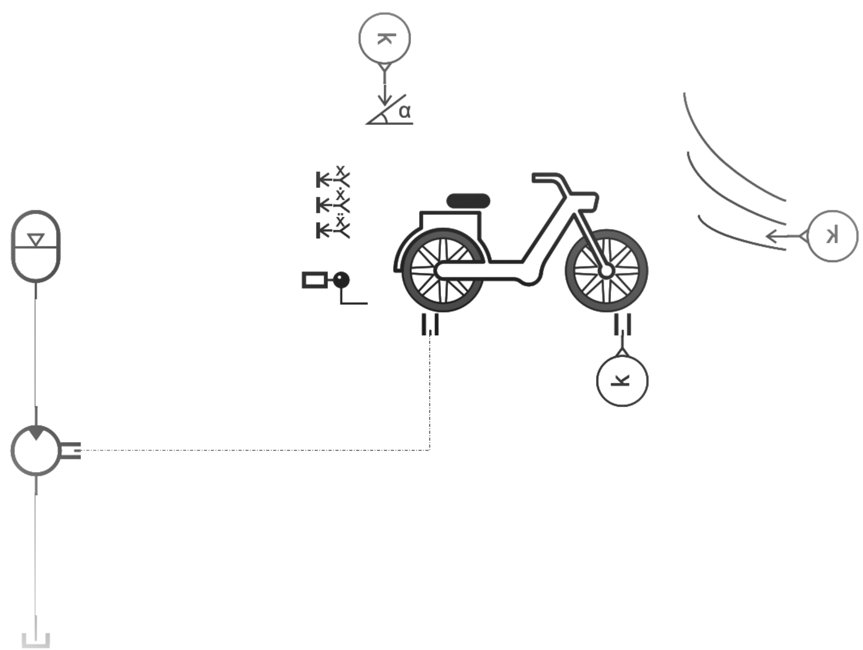


FIGURE 2.1: *First Design Idea*

The two accumulators in the lab were:

Accumulator 1 22 USG (83 liters) - 500 PSI (34 bar)

Accumulator 2 22 USG (83 liters) - 7000 PSI (482 bar)

Two problems were encountered during the simulations, one for each accumulator. The first accumulator's rated pressure in fact was not high enough to provide an appropriate torque on the driving wheel, resulting in a poor acceleration (see figure 2.2).

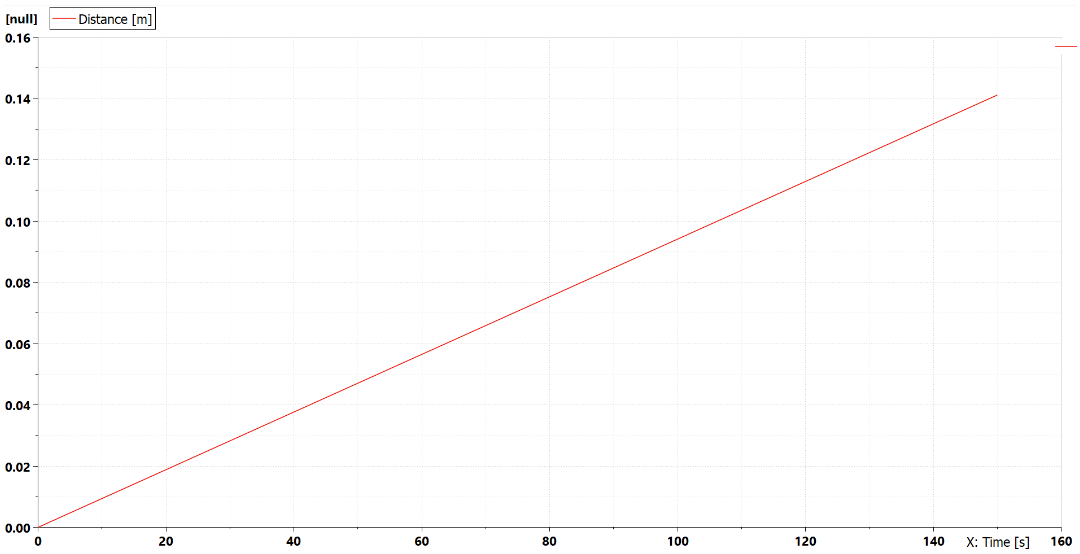


FIGURE 2.2: *Displacement over time using Accumulator 1*

For what concerns the second accumulator, considering its pressure and the amount of fluid allowed seemed a very encouraging solution and the first simulations confirmed this, showing in particular the possibility of completing all the three events with the accumulator solely (see figure **??** on page ??).

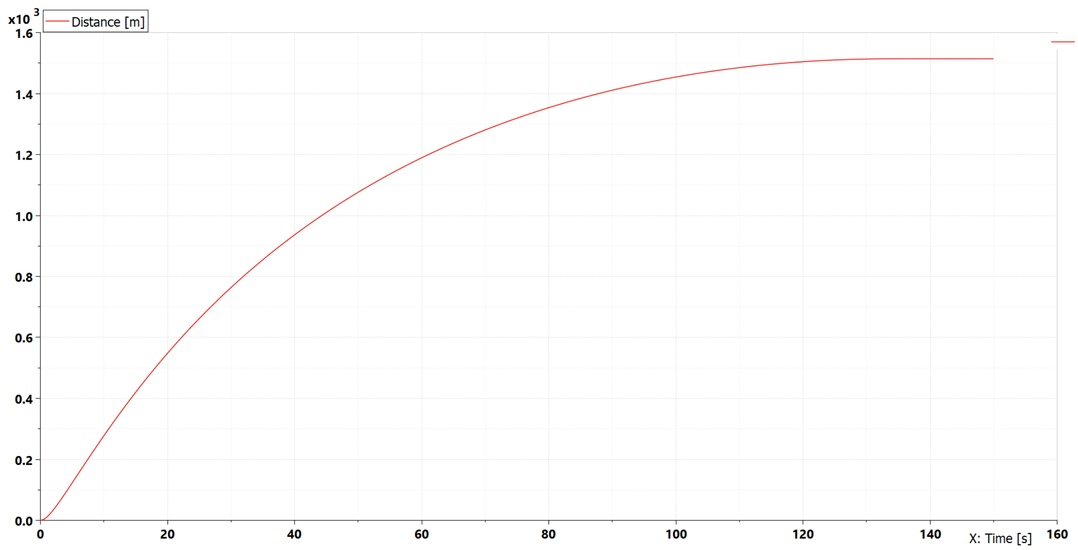


FIGURE 2.3: *Displacement over time using Accumulator 2*

However, having the NFPA introduced this year the rule imposing 10 minutes for charging up the accumulator(s), it was needed to evaluate whether this amount of time was reasonable for charging the accumulator, even if not completely. This has been accomplished using another circuit on Amesim to simulate the charging action of the accumulator using a generic pump (see the figure 2.4) with displacement set up in such way that is possible for a human pedaling with a frequency of 2 Hz (120 rotations per minute) without exceeding the 300 W of power generated [8, p. 867] (figure 2.5); in fact, from some researches about physiology this resulted being the maximum power output for a human being on a bicycle over 10 minutes. Such pump displacement resulted being $\approx 62.5 \frac{cc}{rev}$.

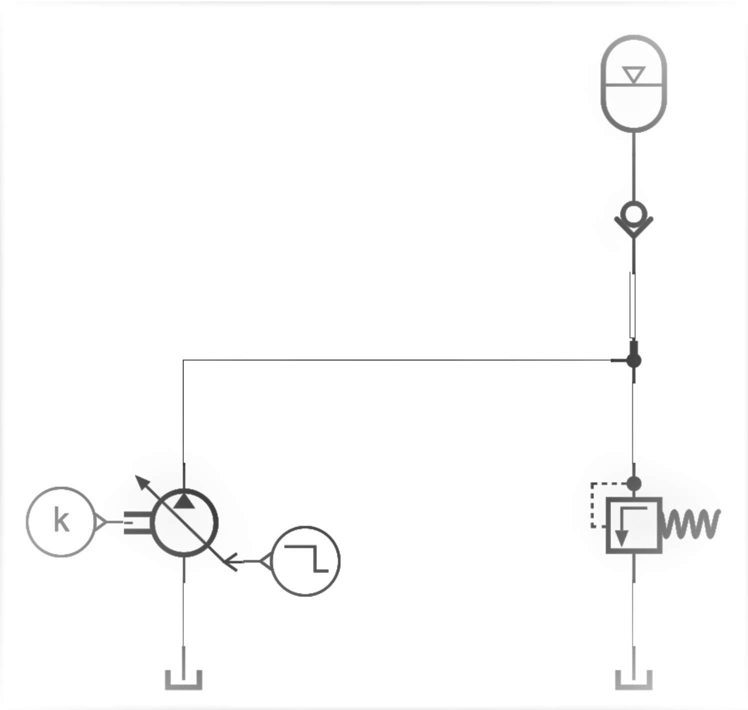


FIGURE 2.4: *Schematic of the charging simulation system*

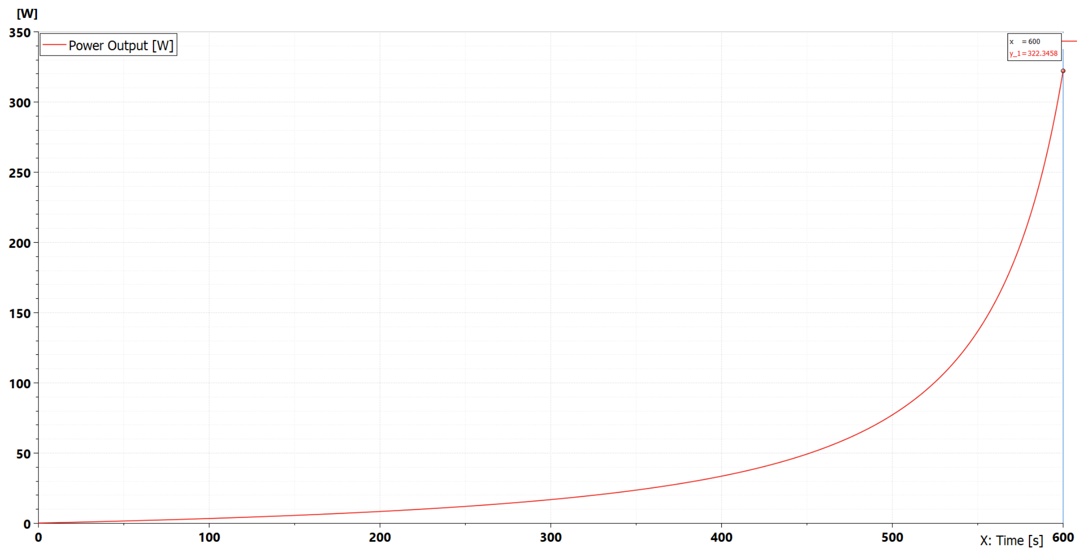


FIGURE 2.5: *Power over time needed from the user*

Running the simulation for 10 minutes (600 s) the software showed a pressure of $\approx$ 25 *bar* inside the accumulator (see figure 2.6). In this way can be shown that it would be useless using such a big (and heavy) accumulator without taking advantage of it. It can be noticed that in this way the component would be in the same starting condition of the first accumulator, making it useless to carry on with the simulations.

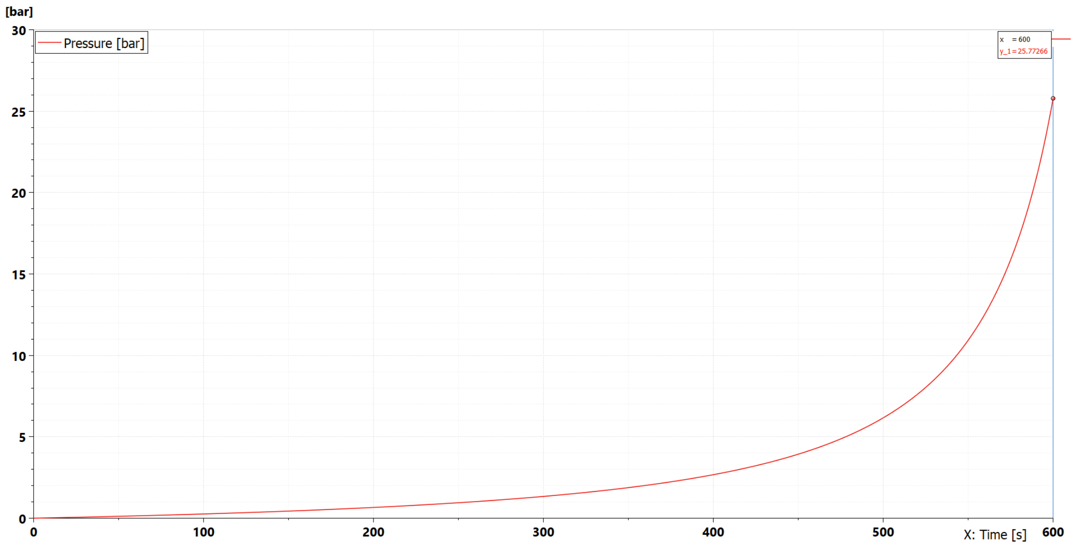


FIGURE 2.6: *Pressure over time building up in the accumulator*

2.2 Two accumulators design

After finding that the first idea was impractical, another idea has been examined (figure 2.7 on the following page). Since in the three races we want very different behaviors of the bike, why not inserting two accumulators and using them simultaneously or alternately depending on the race?
In this way we can describe 3 different scenarios:

Sprint Race In this race the accumulators would be operated simultaneously, in order to have the maximum quantity of fluid flowing to the motor during a short period of time to provide a high starting acceleration and reach a high speed as fast as possible.

Efficiency Challenge In this challenge the aim is to achieve the highest distance possible, no matter how much time it is needed to do it. This means that all the possible causes of losses must be avoided, including those derived by the friction between the wind and the vehicle (proportional to v^2); so, in this case the idea is to discharge the first accumulator on the motor and, when this is done, the second accumulator can release its fluid on the motor.
In this way it should be possible to maintain a lower average speed for longer.

Endurance Trial Now, since in this race it is needed to maintain a good speed over a long time, the main idea is to alternately discharge one accumulator while the user can use the pump to send fluid in the one that has already been emptied in order to charge it again.

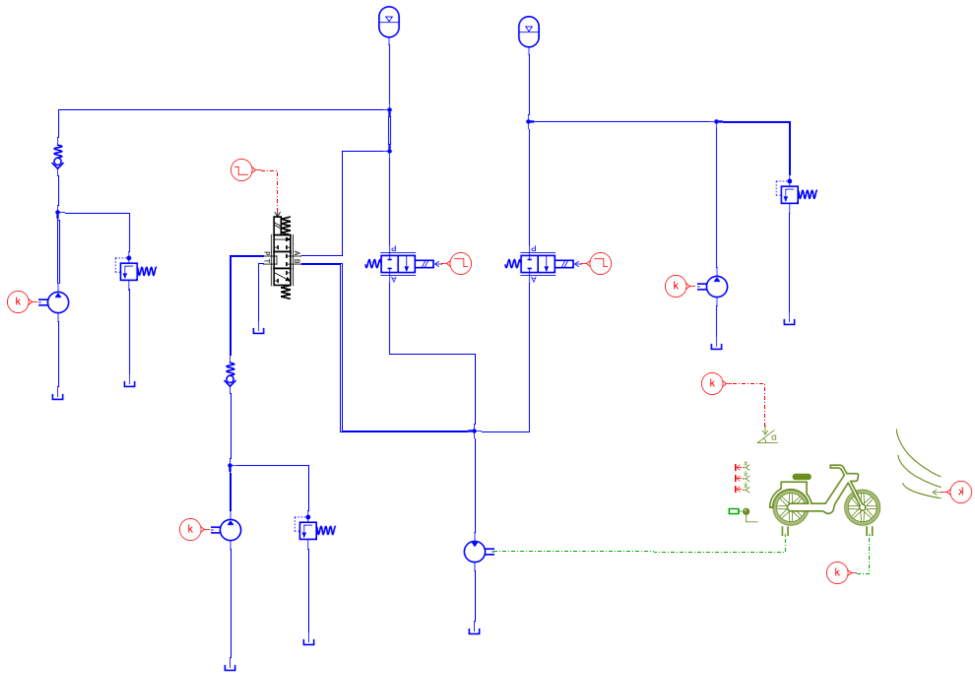


FIGURE 2.7: *Two Accumulators Design schematic*

2.3 Final Design

Eventually, after having attended Prof. Vacca's lessons about hydrostatic transmission another idea popped up, not based on repeatedly evaluating one idea after the other but based on a well consolidated solution.
A hydrostatic transmission is a system constituted by rotary units that allow the conversion of mechanical power, coming from a prime mover, into hydraulic energy and then mechanical again [6, p. 244].
The motivations and necessities to use this transmission are:

- Varying with continuity the power, torque and angular speed components, depending on the load. In this way the desired mechanical characteristic can be obtained being freed from the operating conditions of the prime mover.

- Transmitting power between two shafts at high distance.

In this study case the usage of a hydraulic transmission is imposed but it can be seen how it is possible to take advantage from this system.

The easiest implementation of hydrostatic transmission is the open circuit configuration:

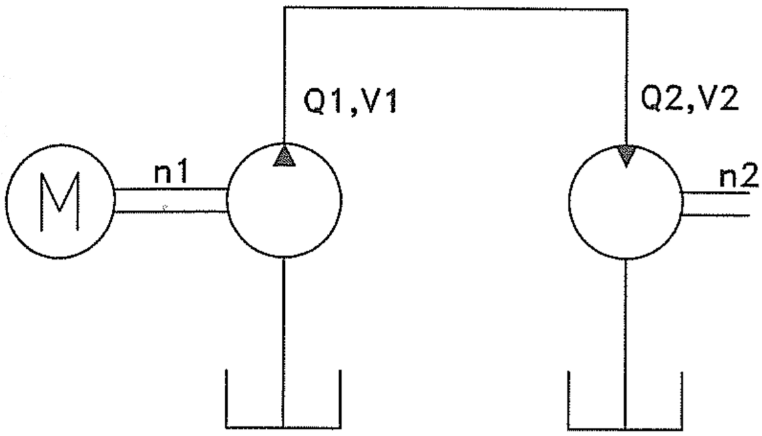


FIGURE 2.8: *Open circuit configuration*

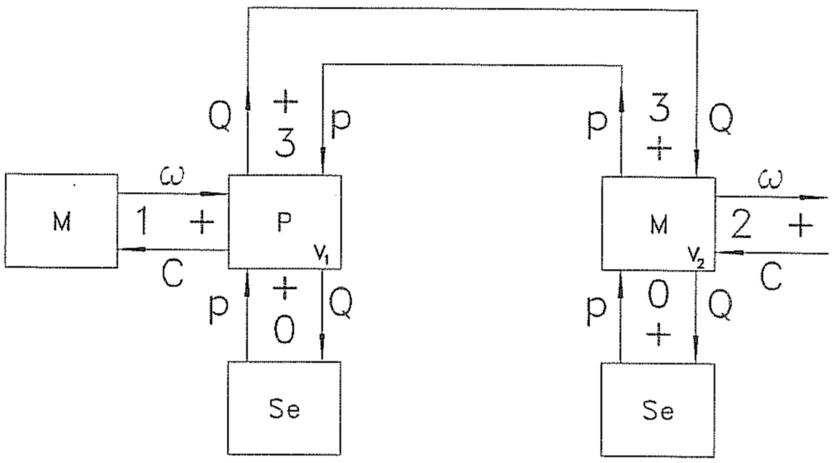


FIGURE 2.9: *Open circuit schematic blocks*

where:

Pump	Motor
$Q_3 = \omega_1 V_1$	$\omega_2 = \frac{Q_3}{V_2}$
$Q_3 - Q_0 = 0$	$Q_0 = Q_3$
$-C_1 = (-p_3 + p_0)V1$	$-p_3 = -\frac{C_2}{V_2} - p_0$

TABLE 2.1: *Schematic blocks equations*

And with:

- V_1 = Pump displacement
- V_2 = Motor displacement

Since $p_0 = 0$ we obtain:

$$C_1 = V_1\ p_3 \tag{2.1}$$

$$C_2 = V_2\ p_3 \tag{2.2}$$

$$C_2 = \frac{V_2}{V_1}\ C_1 \tag{2.3}$$

$$\omega_2 = \frac{V_1}{V_2}\ \omega_1 \tag{2.4}$$

It is possible to notice that in this way it is not possible to vary the speed or the torque. Also (considering all the components ideal) all the flow (constant) from the pump goes to the motor (**flow coupling**) and the δp at the ports of pump and motor are the same (**pressure coupling**) and determined by the load.

If it is needed to have a speed regulation the system can be slightly modified introducing a motor with variable displacement and the transmission becomes the following:

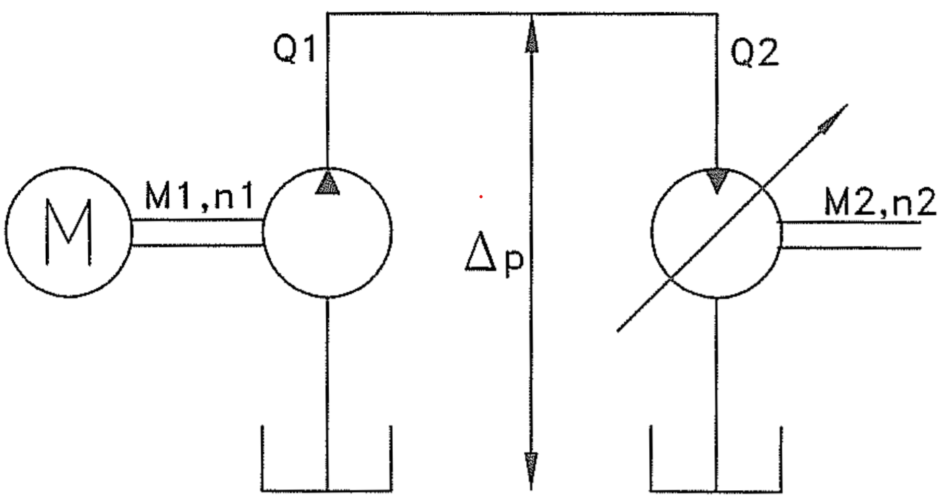


FIGURE 2.10: *Fixed pump Variable Motor*

Imposing:

$$n_1 = const; \qquad V_1 = V_2; \qquad \Delta p = \Delta p_1 = \Delta p_2 = const \tag{2.5}$$

And noticing that there is pressure coupling it can be written:

$$Q_1 = Q_2 = V_1\ n_1 = \alpha_2\ V_2\ n_2 \tag{2.6}$$

$$\nu = \frac{n_2}{n_1} = \frac{V_1}{\alpha_1\ V_2} = \frac{1}{\alpha_2} \tag{2.7}$$

$$\tau = \frac{M_2}{M_1} = \frac{\alpha_2\ V_2\ \delta p}{V_1\ \Delta p} = \alpha_2 \tag{2.8}$$

Obtaining:

$$\tau = \alpha_2 = \frac{1}{\nu} \tag{2.9}$$

In the year 1977 H. Nikolaus had already patented a hydraulic transmission concept with pressure imposed and secondary regulation using hydraulics only (even if only starting from 1985 began marketable). [6, p. 252] This represents an alternative to the traditional hydrostatic transmission and takes the name of hybrid secondary control.

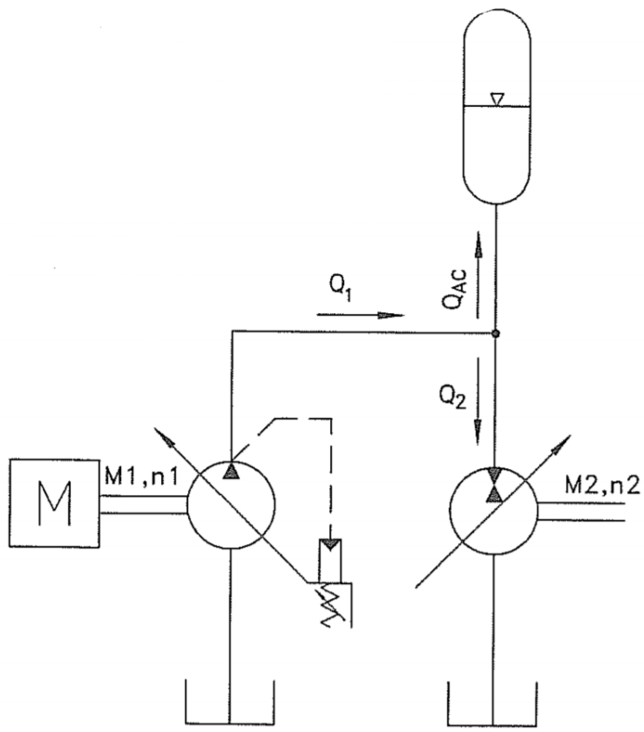


FIGURE 2.11: *Hybrid Secondary Control*

In order to get the characteristic of the system it can be quite useful to suppose the pressure in the system constant. In this way, the characteristic of the transmission corresponds to that of the motor itself, constituted by the following (considering an ideal case) [9, p. 129]:

$$M_2 = \delta p\ \alpha\ V_2 \tag{2.10}$$

$$Q_2 = \omega_2\ \alpha\ V_2 \tag{2.11}$$

Thus, for a certain regulation grade (α) it is directly set the torque while the speed, and hence the flow, comes from the equilibrium with the external load.
This *spontaneous* propriety of the transmission is difficult to be used directly in many applications and so particular subsystems with automatic displacement control methods need to be implemented in order to create the desired characteristic. These methods are many and different; remarkable the work of the late professor Monika Ivantysynova, who studied deeply this problem, with a case study on a power split transmission [3] [4] [2], on a Toyota Prius modified in order to implement a continuous hydraulic transmission [5] and on a hybrid secondary system regulated through a multi-input multi-output H_{inf} controller [1].

The solution proposed in this report is based on the configuration described above but represents a complete innovation. The regulation system here is not represented by a fancy controller in order to control the displacement of the motor but a shut-off valve is interposed between the accumulator and the motor; since the races are not supposed to last very long an high acceleration (high torque) is preferred over the need of maintaining an high speed with less torque and the purpose of the valve is to be closed periodically so that the pump can send fluid to the accumulator and continue keeping the pressure as high as possible (it is important to remember that in a secondary control the pressure is directly proportional to the torque on the motor shaft).
Thus, two working conditions can be defined:

Charge phase The shut-off valve is closed and the fluid coming from the pump is stored in the accumulator.

Discharge phase The shut-off valve is now opened and the fluid from the pump and the accumulator can go to the motor. In this way the accumulator sets the working pressure of the motor and supplies fluid in case the flow coming from the pump solely is not enough.

Moreover, the accumulator acts as a dampening item for the pressure spikes coming from the pump that, as said in the previous chapter at the paragraph1.6.1, represented the main comfort matter for the Purdue Tracer.

Based on this premises the final design has been drawn (see figure below: 2.12 on the next page)

All the components used will be described:

Main Pump This is the main pump activated by the user through the pedals. It pumps oil from the tank to the system, in our case the accumulator.

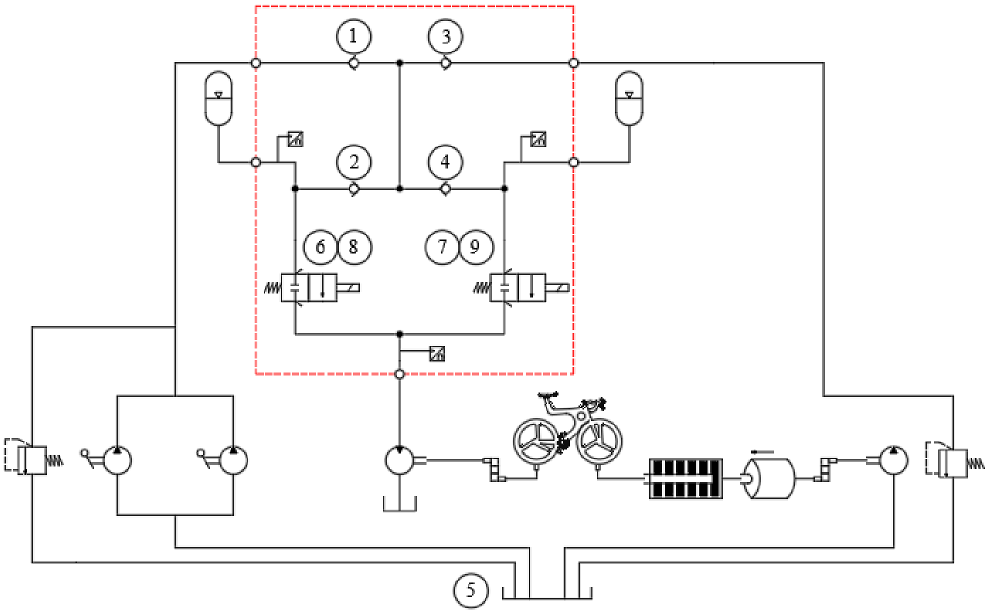


FIGURE 2.12: *The Final Model*

Accumulator The accumulator is our way of storing energy inside the system. It acts as a pressure dampener and allows us to store energy as fluid under pressure.

Shut-off valve This particular kind of valve can commute from a completely open to a completely close position depending on an external signal, acting de facto as a hydraulic switch. In this particular case the control signal is electronic and the valve is normally close for safety reasons.

Motor The motor is the second main component for the hydraulic transmission. It transforms the hydraulic power carried by the fluid into rotational mechanical power acting on the shaft of the motor itself.

Regeneration Pump This second pump in the system is connected to the wheel and, when the latter spins, pushes fluid inside the accumulators allowing the regeneration of a part of the energy.

Clutch When the regeneration is acting, the pressure inside the accumulators acts on the pump creating a resistive torque, making the wheel brake. For this reason, we don't want the bike to always be in regenerative mode and a clutch is used to engage and disengage the pump from the wheel.

Gears In order to transmit mechanical power and modify the ratio between torque and speed of rotation, two gearboxes have been introduced in the system. One connecting the motor and the wheel and the second one between the wheel and the regeneration pump.

Check Valve Several check valves have been introduced in the system in order to avoid back flows in the connections.

2.3.1 Operating Modes

Now that the system layout has been shown, it is easy to notice that not all the components will be used at the same time in every situation of the competition. In particular, four principal modes can be defined and described.

Charging Mode (*figure 2.13 on the following page*)

This mode is used whenever it is needed to charge the accumulators before a race. The shut-off valve is closed and the regeneration pump is not engaged, so pedaling (and activating the pump) the fluid is moved from the tank to the accumulator. Of course, while filling up the accumulator with oil, the pressure of the latter will increase, making it gradually more difficult to pump fluid inside the component; in this way the user will have to apply more torque on the pedals.

Boost Mode (*figure 2.14 on the next page*)

During the second race (Efficiency challenge) the user is not allowed to pedal, so all the propulsion has to come from the energy stored inside the accumulators. In this mode the main pump is connected to the system but not operated, so the only energy flow is the one going from the accumulator to the motor. The valves need to be switched on to let the fluid flow to the motor and a duty cycle (DC_{ef}) can be used to limit the fluid passage.

Pump Mode (*figure 2.15 on page 25)*

This mode of operation is the default one when operating the vehicle and can be seen as a hybrid between the previous ones. In fact here the pump is operated by the user in order to send fluid to the accumulators where it is stored and in the meanwhile the valves are opened to let the fluid flow to the motor.
In the competition context, this mode is used both in the sprint race and in the endurance trial but we want to obtain different behaviors in each one, so two duty-cycles have been defined for the two events: DC_{sp} for the sprint race and DC_{en} for the endurance trial.

Regeneration Mode (*figure 2.16 on page 25*)

Last but not least, since it is essential for the completion of the last trial, the regeneration mode. Here the vehicle needs to be stopped and a hydraulic brake can be used to recover some energy using our accumulator.
Hence, operating the clutch, the regeneration pump can be rigidly connected to the wheel and use its motion to pump fluid inside the accumulator.

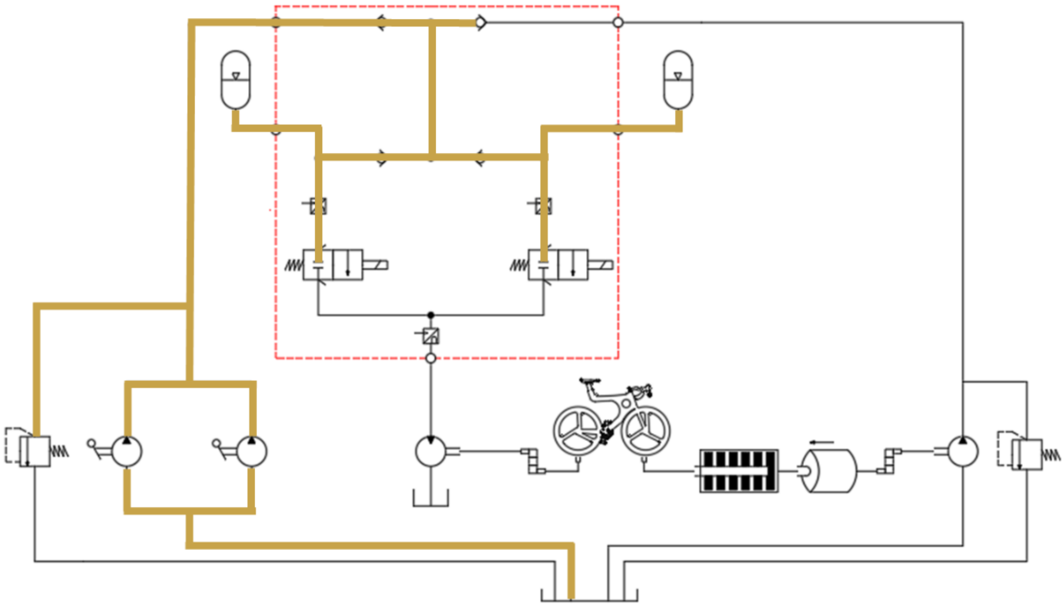


FIGURE 2.13: *Charging Mode Schematic*

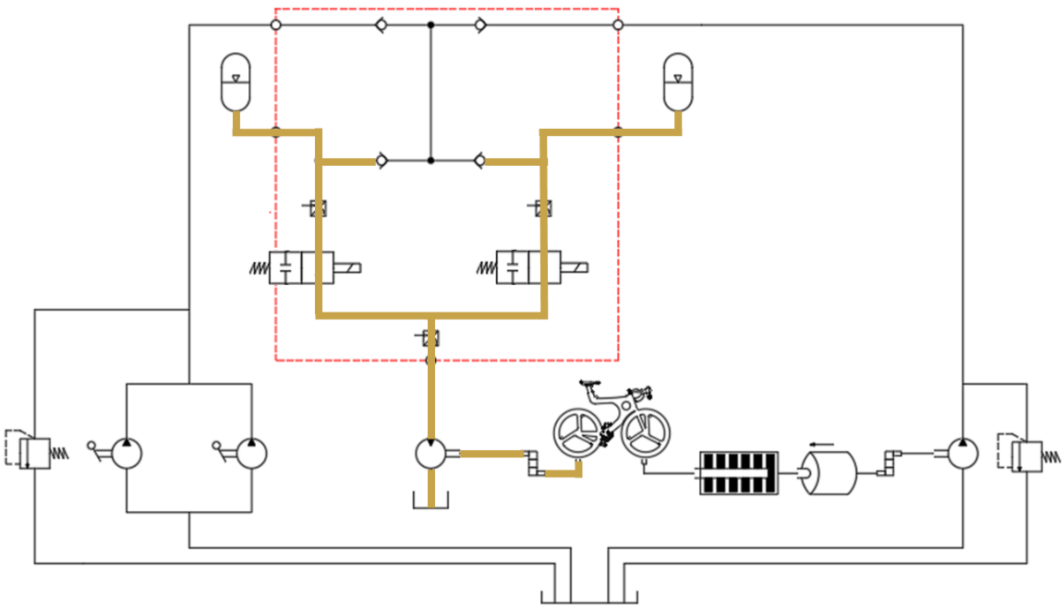


FIGURE 2.14: *Boost Mode Schematic*

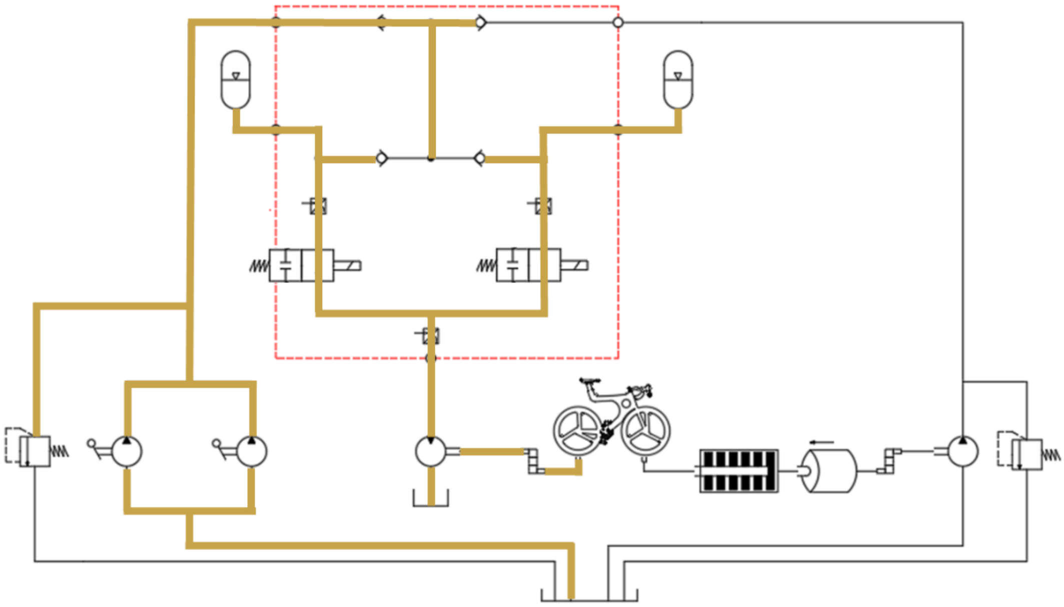


FIGURE 2.15: *Pump Mode Schematic*

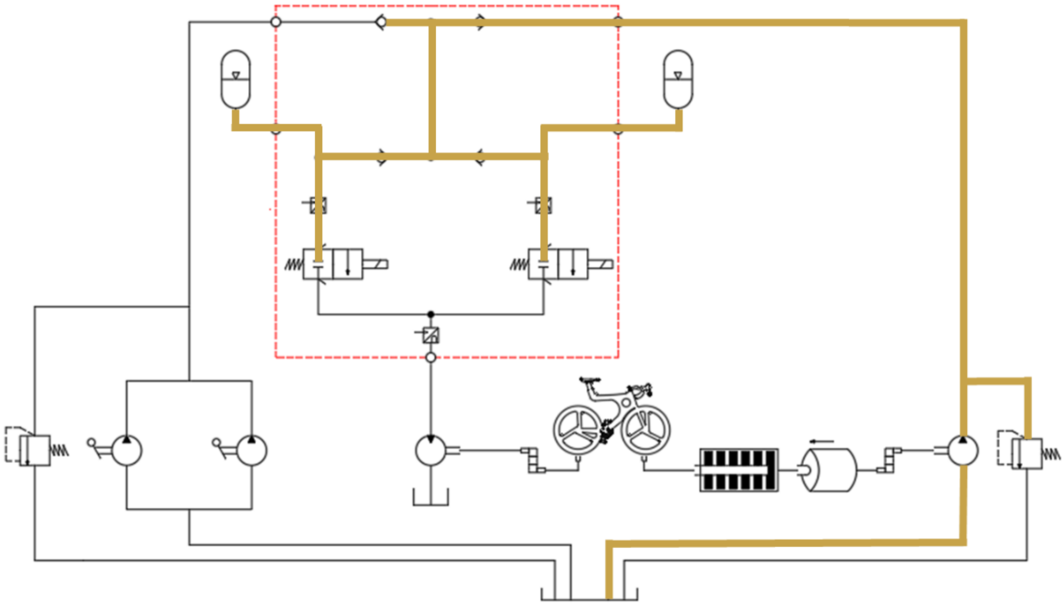


FIGURE 2.16: *Regeneration Mode Schematic*

2.3.2 Preliminary Sizing

After the system had been defined, the successive hurdle has been sizing properly all the components in order to obtain the desired performances. At first a preliminary ballpark estimation has been done using the free body diagram (figure 2.17), starting from some basic assumptions and considering a simple hydraulic transmission (accumulator's contribution is here neglected).
Assumptions:

- Slope: a = 1.14°
- Rolling coefficient: f = 0.002
- Mass: M = 225 kg
- Wheel radius: r = 0.66 m
- Working pressure: P = 207 bar
- Gear ratio: n = 3
- Motor efficiency: $\mu = 0.95$

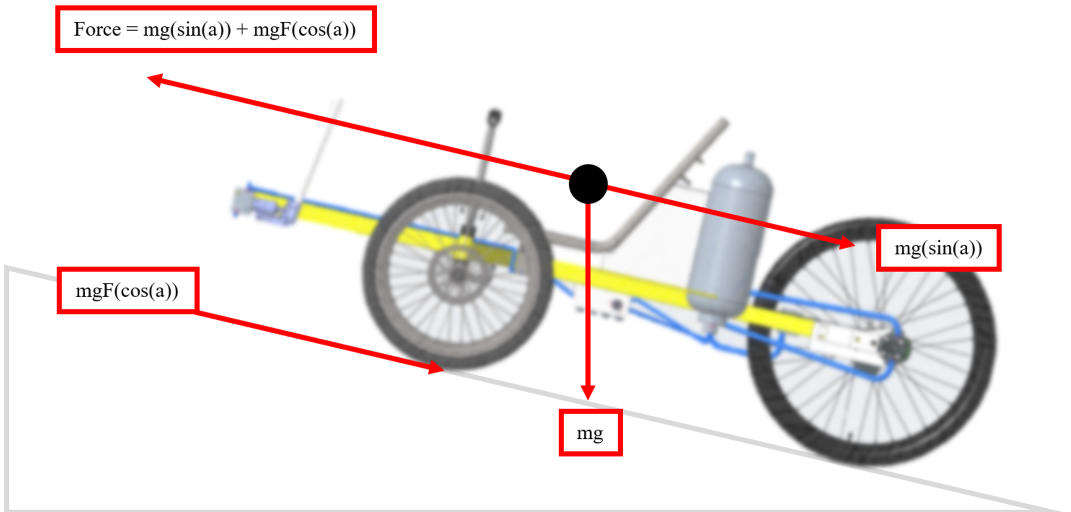


FIGURE 2.17: Free Body Diagram

It is possible then to find the total pull of the vehicle:

$$F = g \cdot (M \cdot sin(a) + M \cdot f \cdot cos(a)) = 48.31\ N \tag{2.12}$$

From this the torque needed to push the vehicle forward can be derived:

$$T = r \cdot F = 31.89\ Nm \tag{2.13}$$

Considering the gear ratio, the torque to be exerted by the motor will only be:

$$t = \frac{T}{n} = 10.63\ Nm \tag{2.14}$$

Finally from this it is possible to calculate the motor displacement wanted:

$$displacement = \frac{t \cdot 2\pi}{P \cdot \mu} = 3.40\ \frac{cc}{rev} \tag{2.15}$$

2.3.3 Software aided sizing

It is quite easy to figure out that a system with this many components, each of one described by one or more parameters, is very difficult to be sized through hand calculations using all the analytical formulas and probably wouldn't bring to the best solution possible.
This is why the already mentioned Simcenter Amesim has been used to find the best size for each component. The software in fact comes with an integrated tool used for optimization purposes, with the possibility to use two different optimization algorithms:

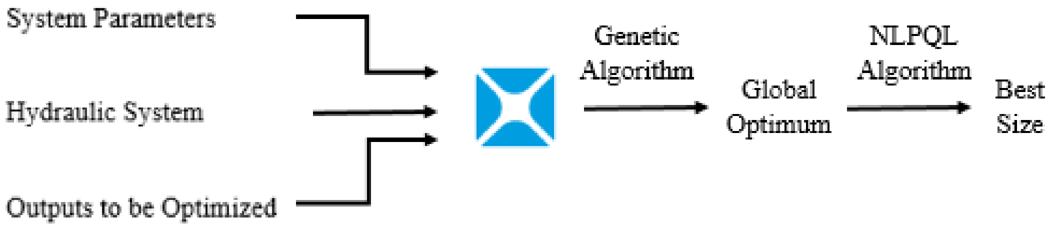


FIGURE 2.18: Optimization Process

Genetic algorithm A genetic algorithm is a metaheuristic algorithm based on Darwin's natural selection theory. The algorithm starts creating a population of solutions is created semirandomly and then mutated randomly to evaluate the fitness of every individual. This process is iterated for a certain number of times and at each step (usually called generation) the more fit individuals are stochastically selected to replace the old generation.
The genetic algorithm is recommended when many parameters are present in order to find the global optimum.
When setting a genetic algorithm there are several parameters that need to be set:

- **Population size** number or starting population. It is recommended to impose $population\ size \geq 4.5 \cdot number\ of\ parameters$ to obtain good results.

- **Reproduction ratio** the percentage of individuals that will be replaced after each generation. With and high reproduction ratio the algorithm is more likely to fast converge, but it can lead to a local convergence. As rule of thumb a ratio between 50% and 85% works quite well.
- **Mutation probability** this sets the probability of each individual of having its parameter mutated.
- **Mutation amplitude** it is a value between 0 and 1 that describes the quantity of noise that is added to the parameters for each individual. Setting a value close to 0 will lead to a faster convergence, while setting it close to 1 will increase the "exploration" of the solutions and decrease the chance to converge to a local optimum.
- **Number of generation** is obviously the number of iterations that the algorithm will perform. The bigger it is and the more accurate will be the final result, but the algorithm will take more time to complete; in any case it has to be ≥ 10 to get relevant results.

NLPQL algorithm This particular kind of algorithm that stands for **N**on **L**inear **P**rogramming (by) **Q**uadratic **L**agrangian is used to find an optimum when the system is not very complicated (low number of parameters) or when the neighborhood where to find the solution is already known.
It is a particular implementation of an SQP (**S**equential **Q**uadratic **P**rogramming) in which the gradients of the objective functions are computed in every direction of the design space (every input is a direction) with the method of the finite difference and stops whenever a local minimum is found. This is the reason why if the problem is large it is suggested to perform this kind of algorithm only after a GA run.

Hence, in order to find the optimum for the system, the two algorithms have been used sequentially; at first the genetic algorithm has been run in order to find a global optimization then an NLPQL routine has been launched to obtain a local optimum in case the previous algorithm had been inaccurate. Of course, the algorithms need more than some settings to work; in fact Amesim is taking as input other sources to be processed and return the optimum sizing as output.

Schematic Of course the schema of the model is needed because the algorithm has to evaluate the behavior of the system during each iteration. Since, as stated before, the hydraulic and mechanical design have been developed during the same time span, when the optimization tool was ready some mechanical advancement had been achieved, resulting in a slight change of the main schematic (see figure of updated schema).
In particular it has been decided, in order to have more balance and stability, to use two accumulators of the same size to be placed symmetrically on the vehicle instead of a single one. Moreover, after a biomechanics of human body study, it has been decided to use two linear single piston pumps instead of a rotary one (please refer to the Mechanics chapter for more details).
Since the goal of the optimization was to find the best values for all the parameters in the system in order to have the best overall performances in all the 3 events of the competition, three versions of the original Amesim model have been put together in the same sketch, each one representing one event.

Parameters Amesim needs all the parameters (i.e. the system unknowns that need to be sized) so that he knows what to aim for.

In our system these parameters, grouped component by component, are:

Shut-off valve

- Duty cycle for sprint mode - DC_{sp}
- Duty cycle for efficiency challenge - DC_{ef}
- Duty cycle for endurance trial - DC_{en}

Accumulators

- Maximum pressure [bar]
- Gas pre-charge pressure [bar]
- Total volume [L]

Main Pump

- Displacement $[\frac{cc}{rev}]$

Motor

- Displacement $[\frac{cc}{rev}]$

Motor-wheel gear

- Gear ratio

Looking at these parameters one might ask himself why those related to the regeneration system are not listed. The reason is that, as stated before, the regeneration system is of less importance and it had been decided to use the same ratio of the gearbox implemented the previous year and a pump from the same manufacturer of the motor (that later ended up being Vivolo) with the displacement as close as possible as the prior year's one (8.2 $\frac{cc}{rev}$).

System objectives Of course Amesim needs to know which is the goal (or goals) of the optimization. Thus, the sizing objectives (called outputs in the optimization environment embedded in Amesim) are defined.

During the brainstorming sessions, a plan of action had been defined: instead of focusing only on one of the races to aim for the first place, the strategy was to try to aim for the podium in all the three events. Starting from this assumption, the objectives for each race had been determined:

Sprint race

- Maximize acceleration
- Maximize maximum speed
- Minimize time to reach 180 m

Endurance challenge

- Maximize scoring ratio $\frac{W \cdot L}{P \cdot V}$

Efficiency Trial

- Maximize steady state speed

All these objectives have to be "translated" in mathematical terms in order to be processed by the software; moreover the algorithms designate for the optimization work in a peculiar way: they are only able in fact of minimizing a parameter in the system.
For this purpose the so called "composite outputs" come in handy because allow to define new output performing mathematical operations on the "simple outputs". In this way for example the multiplicative inverse operation transforms a maximization problem into a minimization one.

Constraints Last but not least, it is necessary to define some constraints for the optimization. First of all, for each component's parameter a range has been defined in order to tell the algorithm in which boundary look for the solution. Other than that, it has been imposed a power input in the main pump of 300 W maximum (also coming from the biomechanics study) and the fact that the accumulators need to be fully charged in 10 minutes.

After everything was set, the genetic algorithm has been set up and launched and, after more or less 5 days of continuous calculations, the results of the first optimization were available:

- Sprint Duty-cycle: 99.23%
- Efficiency Duty-cycle: 35.64%
- Endurance Duty-cycle: 33.42%
- Accumulators' Pressures: 227.45 bar
- Accumulators' Pre-charge: 22.73 bar
- Accumulators' Volumes: 5.83 L
- Main Pump Displacement: 7.35 $[\frac{cc}{rev}]$
- Motor Displacement: 3.39 $[\frac{cc}{rev}]$
- Gear ratio: 3.45

These values were not the final one, but have been used as starting point for the NLPQL algorithm to be performed. This routine (that took way less time with respect to the other one) returned the following results:

- Sprint Duty-cycle: 99.87%
- Efficiency Duty-cycle: 35.92%
- Endurance Duty-cycle: 34.80%
- Accumulators' Pressures: 213.71 bar
- Accumulators' Pre-charge: 22.91 bar
- Accumulators' Volumes: 5.33 L
- Main Pump Displacement: 6.89 $[\frac{cc}{rev}]$
- Motor Displacement: 3.24 $[\frac{cc}{rev}]$
- Gear ratio: 3.45

2.3.4 Component Sourcing

At this point we had all the parameters for our system and it was necessary only to find the right component for our system. Easier said than done! In fact, sourcing all the components has been everything but easy, because it has been necessary to find the right compromise between aiming for the best component, in line with the results coming from the optimization and trying to keep the project under budget.
Eventually, thanks to various donations and the generosity of Purdue University the desired components have been ordered, determining the definitive version of the hydraulic system. The complete list of components belonging to the hydraulics can be found below:

Accumulator

- 2x Steelhead composite bladder type accumulators
- Maximum pressure: 3000 PSI ($\approx$ 207 bar)
- Total volume: 1.3 USG ($\approx$ 4.92 L)

Main Pump
- 2x Hydac hand pumps - Model MP10
- Displacement: 7.5 PSI ($\approx$ 207 bar)

Motor

- 1x Vivolo gear motor - Model X1U2362BGFA
- Displacement: 3.12 $\frac{cc}{rev}$
- Right rotation

Regeneration Pump

- 1x Vivolo gear pump - Model X1P3462BBBA
- Displacement: 7.54 $\frac{cc}{rev}$
- Right rotation

In the list are not appearing all the components that have been sized with the optimization routines; for the gear trains' design please look into the mechanics chapter.

2.3.5 Custom Manifold

Together with some basic components like fittings and valves, Sunsource and Eaton, two of the main US hydraulics manufacturers gave each team the opportunity to ask for a custom manifold to be inserted in the system. A manifold is a component from which various connections in a hydraulic circuit can be connected; thus, primary fluids can be split in more secondary directions or exhausts can be converged in the same line.
In this way a complicated and bulky system of hydraulic components and their links can be compacted in a space-saving steel block. Since the manifold can integrate directly some standard components such as check valves and offer a housing for hydraulic sensors and shut-off valves, the manifold has been designed to incorporate the part of circuit that is inscribed in the red box of the figure 2.12 on page 22. In figure 2.19 on the following page the CAD schematic of the complete manifold circuit that has then been used by the SunSource guys for creating the actual component.

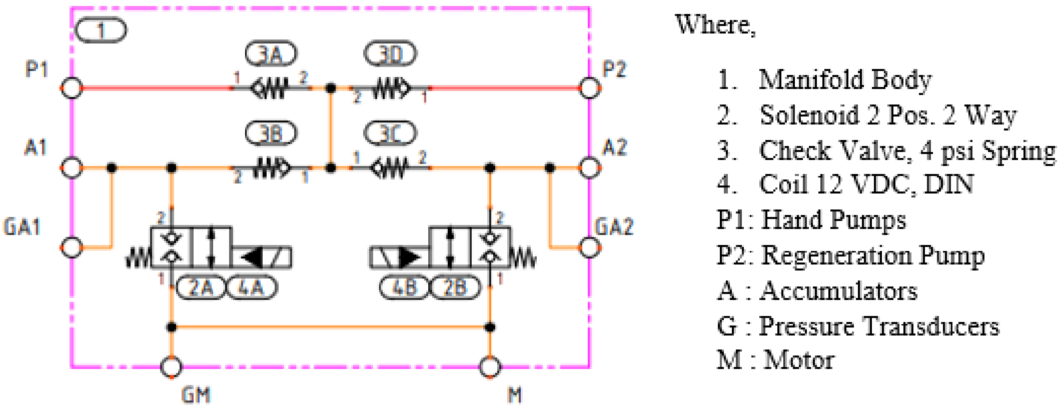


FIGURE 2.19: *Manifold Schematic*

2.3.6 Simulations

The last act of the design phase regarding the hydraulic system has been the performing of some simulations in order to evaluate the expected performances of the vehicle using the parameters of the actual components that had just been ordered. Again Simcenter Amesim has been used for simulating the system. The results of the first two events have been simulated, obtaining the following results:

Sprint Race
- Time to run 600 ft (180 m): 33.26 s

Efficiency Challenge
- Scoring ratio: 50.81

Chapter 3

Mechanics

Together with the design of the hydraulic design, the team has worked intensely at the mechanical problem, defining the frame, how to place all the components on the bike while leaving enough room for the user and the sizing of the gear trains and other moving parts.
It is mandatory to mention that the contribution to this part of the design from my side has been marginal, but still it is important in order to have an overall view of the vehicle design and the progresses made through the development of the project. In any case will be specified when the whole team (me included) or the Mechanical Engineering (ME) students completed the work described. In this chapter will be described the mechanical design with an approach top bottom, starting from the decision about what kind of frame to use to the problem of placing all the components on the vehicle to the design of all the single components or systems of components, arriving to the final CAD model and FEM analysis.

3.1 Frame choice

One of the first dilemma that has been encountered while discussing at the very beginning of the project was:

what kind of bike were we going to design?

Looking back at the Purdue experience within the FPVC it had been possible to notice a prevalence of two-wheelers. This is probably due to the presence of undeniable advantages coming with this layout that determined its spreading in everyday life as well, such as the maneuverability and the user-friendliness, being very compact and having the layout everyone is used to.
Moreover, in this particular context, it makes it really easy to include a tank hidden in the frame, taking as example the 2017 Purdue Tracer. However, this design comes with some annoying disadvantages:

- Difficult to place components
- Need to keep balance all the time
- The force that can be applied one the pedals is limited by the weight of the rider
- It is difficult to start from a standstill

The second layout that has been deeply analyzed is the recumbent bike, in particular the one with three wheels (from now on referred to as trike). In this particular kind of bike, the rider is not standing upright but leaning on the seat and can take advantage of this, because pushing with the back on the seat it is possible for him to apply more force on the pedals. This is not the only advantage of the recumbent trike, because it is more stable and, with the same power coming from the user, it can reach higher speeds. It allows also to have more space for the components, which comes in handy for our purposes.
Of course, there are some downsizes like the fact that it is harder to steer and in general the rider has to get into an uncomfortable position.

It has been at this point that for the first time the Pugh matrix for making design decisions has been used. A set of criteria is established and for each design option these criteria are assigned a score with respect to a *datum* and summed to obtain a mark that can be ranked. In this case four different designs "competed" to find the most appropriate: the recumbent trike design, two two-wheeled layouts (mountain bike and road bike) with a townie representing the datum.

Criteria \ Option	Datum	Trike	Mountain Bike	Road Bike
Stability	S	+	S	S
Versatility	S	S	+	+
Weight	S	-	+	+
Ridability	S	+	S	+
Rolling Resistance	S	S	+	+
Component Routing	S	+	+	+
Aerodynamics	S	+	S	+
Component Space	S	+	+	+
Cost of Modifications	S	-	S	S
Modification Time	S	S	S	S
Weldability	S	+	S	+
Aesthetics	S	S	+	+
Ergonomics	S	+	+	+
SUM:		7	7	10

TABLE 3.1: *Frame Pugh matrix*

As it can be seen in the Pugh matrix right above, the road bike seems to represent the most advisable layout, but the rules of the competition require to change the kind of vehicle from one year to another, on pain of the loss of points (thing that had already happened to the Purdue team during the 2018 FPVC), thus the second best design had been chosen. Now, two different kind of recumbent trikes are known:

Delta configuration This configuration presents one wheel on the front and two on the rear. It is usually more comfortable to get into and to ride, because with a very tight turning radius it is easy to maneuver even in tighter place.

Tadpole configuration In contraposition to the previous trike, this comes with two wheels in the front and only one at the back. It is faster and more responsive when cornering and presents more overall stability.

Since the trike was mainly supposed to compete and not be ridden in everyday life, the ridability and speed have been preferred over the comfort of the user, making the tadpole trike the definitive layout.

3.2 Main Pump choice

The second decision that had to be taken was related to the kind of main pump to be used. In fact there are several types of hydraulic pumps that have been taken in consideration to take as input the mechanical power from the user and transfer it to the fluid under form of hydraulic power. The different pumps taken in consideration are:

Dual hand pump Since the pump has to be activated by the two feet (or hands) of the user, a system consisting of two single acting piston pumps (also known as linear pumps) to be used simultaneously or in a reciprocating manner.

Rotary gear pump This is the same kind of pump that has been used for the regeneration system. They are in general compact, pretty cheap but also fixed displacement.

Rotary piston pump In contrast to the previous pump, the piston pumps are heavy, bulky and very expensive but this allow to have a pump that can reach very high pressures and manage multiple displacements.

Option / Criteria	Datum	Dual Hand Pump	Rotary Gear Pump	Rotary Piston Pump
Stability	S	+	S	S
Weight	S	+	+	+
Ridability	S	+	+	+
Component Routing	S	S	S	S
Component Space	S	S	S	+
Cost of Modification	S	+	+	+
Modification Time	S	+	+	S
Aesthetics	S	+	+	+
Innovation	S	+	-	+
SUM:		7	5	6

TABLE 3.2: *Pump Pugh matrix*

Taking a single linear pump as datum, above is shown the Pugh matrix that the team has generated to have some aid for the choice. A superiority of the system consisting of two linear piston pumps is highlighted by the concept matrix, so this method has been chosen.

3.3 Riding configuration choice

After the question about what to use as pumping item had been answered, the one related to how to activate the pump popped up. In fact, from the preliminary research carried out in the very first weeks of the project it came out that many and different ways of driving a trike have been used in the years, mainly either pedaling with the legs and maneuvering and steering with the hands (by far the most common) or vice versa. In this vehicle project, having already decided the kind of pump to use, the choice has been between three different concepts:

Leg press-like concept This layout seems to be the most intuitive, with the feet of the user pushing the lever of the piston pumps while the hands are kept free for the handlebars in order to steer and maneuver the bike. Using the reaction force of the seat when pushing with the feet (in a movement similar to the one when using the leg press machine at the gym) is possible to output a relatively high amount of power.

Hand pumping concept This concept is exactly the opposite of the previous one. Here the pumps are installed close to the user's upper body and activated by the hands of the user, while with the feet is possible to rotate a bar that allows the steering of the two front wheels. The drawback of this solution is that obviously the hands are weaker than the legs, so less force can be applied on the linear pumps; moreover, the legs are less indicated than the arms for precise movements and control.

Rowing-like concept The last solution (as suggested by the name) wants to reproduce the movement used when rowing on a boat or an ergometer at the gym. Here the feet are used both to push in the first part of the movement and steer the bike, while the arms pull a cable attached to the pumps' levers. By far this is the system that allows the highest power output by a human being, but has a couple of weak points. First, in order to have the maximum power output a sliding seat is needed, increasing the complexity of the design and imposing a longer vehicle (more weight, more difficult to maneuver, longer hydraulic lines) and second, if the legs need to be used to push and create the most of the power along the whole stroke, when there are curves a good propulsion can't be guaranteed.

Probably from the description of the three possible solutions the decision already seemed obvious, but the Pugh matrix removed all doubts. The leg press solution is the more balanced and carries the best compromise between power and maneuverability.

Criteria \ Option	Datum	Leg-Press	Hand Pumping	Rowing
Stability	S	S	-	-
Versatility	S	S	-	-
Weight	S	+	+	+
Power	S	+	-	+
Aerodynamics	S	S	S	S
Smoothness	S	-	-	-
Component Routing	S	+	+	-
Component Space	S	+	+	-
Complexity	S	+	-	-
Aesthetics	S	-	S	+
Ergonomics	S	-	S	S
SUM:		5	3	3

TABLE 3.3: *Riding Pugh matrix*

3.4 Gear design

Before proceeding with the drawing of the CAD model it has been necessary to design the only missing system: the gearbox between motor and the rear wheel, because for the gear system on the regenerative side the 2017 design has been reused, as it has been pointed out before. As described in the hydraulic chapter, the optimization routine suggested a gear ratio to connect the hydraulic gear motor and the wheel of 3.45. Someone might think that having a particular ratio there are infinite combinations of gears that can be used, and from a strictly theoretical point of view that is true. However, the gears are standardized and one must comply with the available components. In this case the ME students who were responsible for the gear sizing used the same company that sourced the gears during all the past years in which Purdue was involved in the competition: Misumi. As introduction it has to be said that the gear ratio in a gear train is determined by the ratio between the two radius or by the ratio between the teeth of the two items:

$$\nu = \frac{r_B}{r_A} = \frac{N_B}{N_A} \tag{3.1}$$

Consulting the catalog of the vendor numerous gears with different number of teeth (from 12 to 110) are available. After some boring but straightforward tries, the couple of gears with respectively 55 and 16 teeth has been found, returning a ratio of $\nu = \frac{55}{16} = 3.4375$, the closest to the desired on obtainable with the gears available. Obviously also the assembly with gears teeth of 110 and 32 presents the same ratio, so which one to choose? Again, from the theory it is known that a higher number of teeth results in a smoother transmission and the possibility of delivering a higher power, while smaller on the other hand have lower mass and inertia and are less likely to have an unwanted lateral displacements and cause misalignments. Thus, the 55 and 16 teeth spur gears (2.0 module) have been the final choice for the gear train.

The gear on the regeneration side has been copied from the previous year's design. The gear train is composed of two single transmission in series, system usually called "double reduction gear", in which the total gear ratio can be calculated as the gear ratio of the first stage times the ratio of the second. In the case of the system that has been adopted, there is one gear train presenting ratio of $\nu_1 = \frac{50}{16} = 3.125$ while the other one determines a gear ratio of $\nu_2 = \frac{56}{20} = 2.8$, resulting in an overall stage ratio of:

$$\nu_{tot} = \nu_1 \cdot \nu_2 = 3.125 \cdot 2.8 = 8.75 \tag{3.2}$$

3.5 CAD Model

Now that everything has been set and designed it is only matter of drawing a CAD model of the frame and then placing all the components on top of that, in order to evaluate the space capacity and the positioning of all the components. The reference for the base frame has been the previous 3-wheeled bikes that were stored at the Maha lab, even if this year's one ended up being slightly bigger in order to accommodate all the components and modified specifically to place the two pumps at the very front of the vehicle.

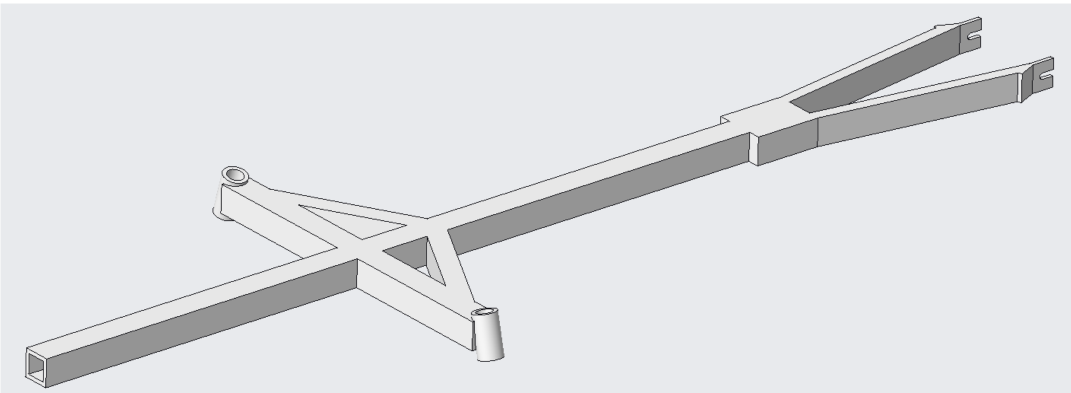


FIGURE 3.1: *Base Frame*

As can be seen in the figure 3.1 the frame is a very simple skeleton based on a cross design. On the short arm's extremities are present two journal bearings apt at supporting the steering handles and the wheel assembly. By looking at the main arm instead, on the front can be found a protrusion for the placement of the two main pumps while in the back it is possible to see the two flanges that form the fork holding the rear wheel in place. The length has been optimized to place all the components with ease while leaving enough room for the user to ride it comfortably.
All the assembly has been built with 6061-T6 aluminum coming in different shapes and dimensions:

- Square tube 1.75" x 1.75", 0.125" thickness (4.5 cm x 4.5 cm, 3 mm thickness)

- Rectangular tube 1.75" x 1.5", 0.125" thickness (4.5 cm x 3.8 cm, 3 mm thickness)
- Plate 0.19" thickness (5 mm thickness)

On this basic frame a **F**inite **E**lement **A**nalysis has been run in order to evaluate the mechanical behavior under certain static loads. This was important to have an estimation of how the vehicle was going to perform in the competition. Both the drawing and the FEA analysis were completed using Creo Simulate. The vehicle was constrained at the two journal bearings and at the rear fork; a total load of 350 lbs (159kg) has been distributed on the frame: 275lbs (125 kg) in the middle of the frame where the rider was supposed to weigh on (the weight might seem high but the team has always been thinking about designing a vehicle ridable by anyone) and a force of 75 lbs (34 kg) placed on the connection between the main bar and the fork, to simulate the weight of the tank and accumulators full of oil, plus the motor, pump and gearboxes.

The FEA showed very good results, with very low stresses on the majority of the frame (in blue in the picture) and some high stresses (in orange/red) located at the constraints. The highest stress of the frame was located on the housing of the rear wheel, exactly where it was expected to be, since that point has the smallest cross-section in the whole assembly. In any case the maximum stress in that point was 8700 PSI (59 MPa) while the yield stress of the aluminum we were going to use is of 45000 PSI (310 MPa), resulting in a safety factor of more than 5. A successive deflection analysis has been carried out, returning a maximum value of deflection of 0.021" ($5 \times 10^{-4} m$) on the tip, absolutely negligible.

After making sure that the frame was safe and strong, all the other components have been placed on the frame, giving the first visual idea of the vehicle that was in the process of coming to life (in figure 3.2).

FIGURE 3.2: *The first version of CAD model with all the hydraulic and bike components on*

As said, the two piston pumps have been laid out on the very tip of the vehicle and motor and regeneration pump have been connected to the rear wheel, the driving one. Pretty much everything else has been placed close to the center of the vehicle, in order to avoid high weight far from the center of mass creating moments; in particular right behind the seat, has been placed the tank with the two holders for the accumulators.

The final result, presented with proud to the NFPA technical liaison, is shown in the two pictures below (3.3 and 3.4):

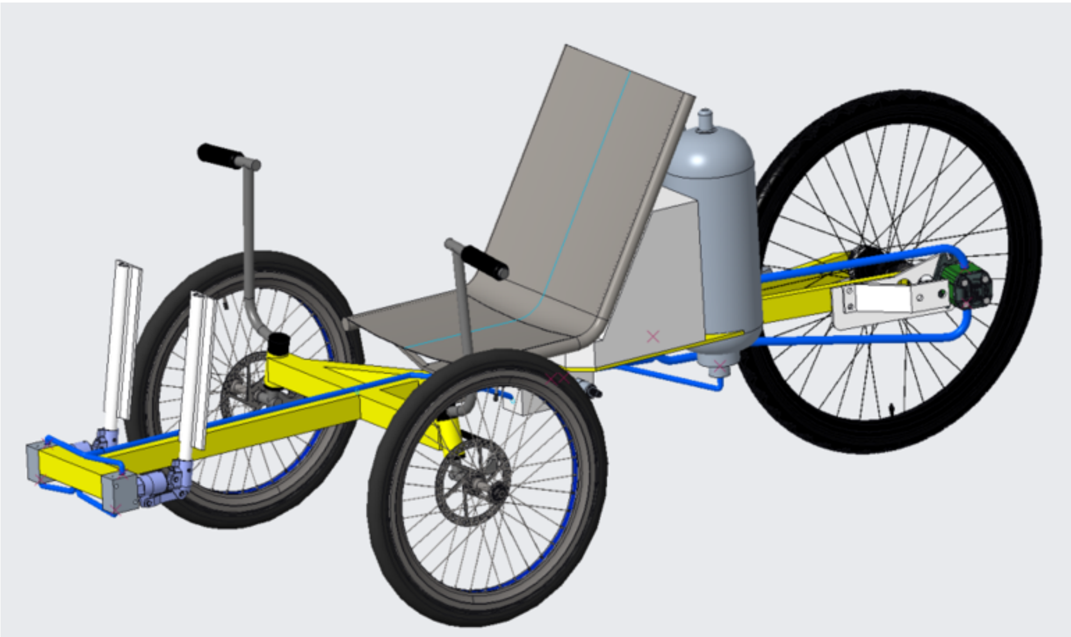


FIGURE 3.3: *Finished CAD model*

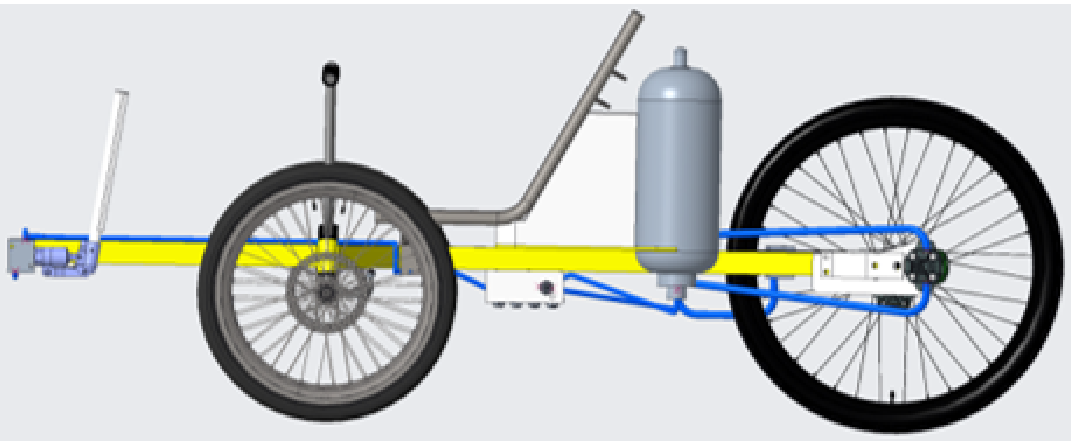


FIGURE 3.4: *Lateral view of the final CAD model*

Chapter 4

Electronics

By thinking about the vehicle design one might think that it is composed of a metal frame with some bike parts mounted on it and holding all the hydraulic components necessary to the propulsion. On the contrary, even if secondary, a major electronic design has been developed both to implement the control of the hydraulic system, both to help the user in keeping track of the state of the system and gather data that can be useful for analyzing the performances of the bike.

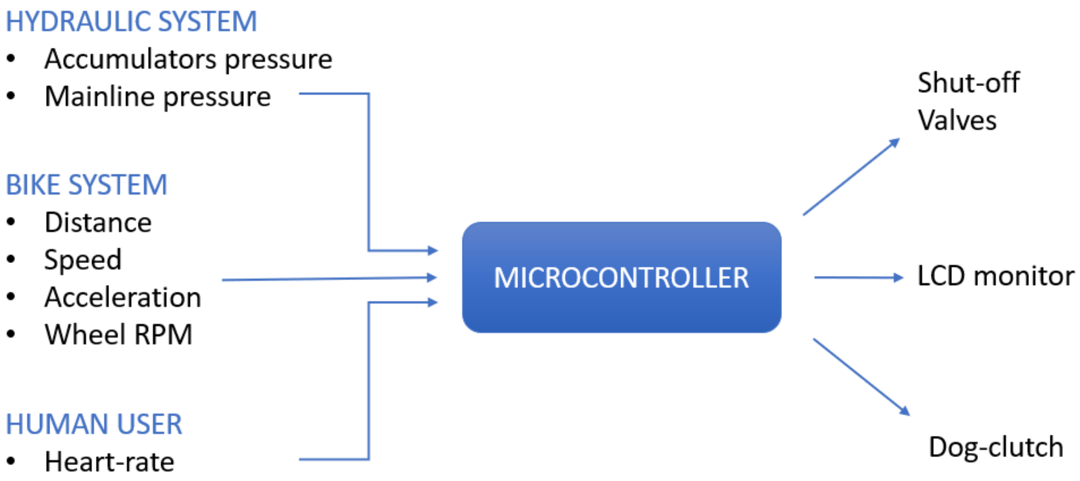


FIGURE 4.1: *Electronic Layout*

4.1 Microcontroller choice

In an electronic system the central component, the one with the purpose of managing all the data exchange and processing is the microcontroller (μC). Thus, the first choice regarding the electronics has been the one related to what type of μC to use; in this design it has to be fast, to allow an easy connection to several sensors located throughout the vehicle and powerful enough to manage all the data flow necessary for a good operation of the system. Previous years' team members opted for two different approaches: the easy-to-use and fragile Arduino or the powerful but complex IQAN system by Parker. These two have been taken in consideration with the addition of another "competitor", the Raspberry Pi that is becoming more and more popular. Let's introduce these μCs:

Arduino With the word Arduino one usually refers to a set of several models produced by the Italian company Arduino. The common characteristic of all these models is the one of being light, very flexible and in particular easy to program. However, it is not very powerful and it has to be programmed through a PC and then inserted in the system and launched, making the debug and troubleshooting quite difficult. Moreover it is not very reliable as it is easy to burn and undergoes frequent data losses.

IQAN Parker's line of IQAN product is designed with the only purpose of controlling and managing hydraulic systems through a complete line of products going from microcontrollers to displays to specific sensors and, of course, a dedicated software. This solution is obviously very powerful and completely developed for this purpose but on the other hand is expensive and the software is helpful only after some very specific training.

Raspberry Pi The last solution is the well-known Raspberry Pi. This name as well defines a line of different microcontroller that are always updated and improved. The latest model, the Raspberry Pi 3B+ represents the state of the art of this set of platforms. The strength of this μC is its power and reliability, allowing the management of numerous complex tasks at once. Moreover it allows the installation of an OS on it, making it in effect closer to a small computer than a microcontroller and it is just slightly more expensive than an average Arduino board. The drawbacks that come with the Pi are that, contrary to the previous two solutions, it doesn't come with an integrated ADC (Analog Digital Converter) so the management of external sensors is not that easy and it has to be programmed using the Python language that can be quite complex for one that is not very familiar with it.

Eventually the Raspberry Pi has been chosen, for its flexibility (an operative system means the possibility of running potentially any software), the reasonable price and the fact that my Python knowledge was already at a quite good level.

4.2 Hardware Design

The next step has been the preliminary design of the electronic system in order to define the hardware needed.

4.2.1 Input devices

In order to monitor the hydraulic state of the system, it has been necessary to read the values of pressures at the inlets of the two accumulators and the inlet of the motor (so called main line pressure), so three hydraulic pressure sensors have been used. In order to have information about the distance, speed and acceleration of the bike, different methods could have been implemented. The most accurate and reliable would be inserting a GPS module on the bike but they are very sensitive and overly precise for the purpose of this project. Eventually it has been opted for a hall effect sensor: inside the component there is a tiny metal strip, when a magnetic field passes through this, the electrical charges are deflected towards the two opposite sides of the strip, resulting in a voltage spike. The last input for the electronic system is coming from a heartbeat sensor, capable of reading and continuously updating the heart rate coming from the user.

After consulting with the supervisor and known companies the following items have been source:

- 3x Pressure Sensors by Bosch-Rexroth, model PR4600MB05/10
- 1x Hall effect sensor by Allegro, model A1120EUA-T
- 1x Heart rate sensor by PulseSensor, model PulseSensor_864620000204

As previously said the Raspberry Pi doesn't come with an integrated ADC support and the pressure sensors and the heart rate sensor have an analogical output, making it necessary to buy an external ADC. In the documentation of the heartbeat sensor the ADC module MCP3008 (8 channels, 10 bit resolution) by Microchip was suggested and, being it compatible also with the pressure sensors, it resulted being the most convenient choice.

4.2.2 Output Devices

All the data gathered are then processed by the μC and signals and further data are generated. In particular it is quite useful to visualize the speed, acceleration and pressure values in real time, so it has been decided to mount a small screen on the vehicle in order to show the user all the useful data. Furthermore, the microcontroller is responsible of the generation of the square waves used to command the two solenoid valves of the hydraulic system and, since the ones used need a signal of 12V while the Raspberry GPIO can output at maximum 3.3V, a relay module has been used. Thus, in summary, these components have been used:

- 1x LCD 3.5" touch screen by UcTronics
- 1x 2-relay module by SunFounder

4.2.3 Actual Implementation

After all the components had been chosen and sourced the final schematic has been drawn with the help of the free software Fritzing:

This system has been then built with the actual components using a breadboard and the actual components (see figure 4.3 on the next page)

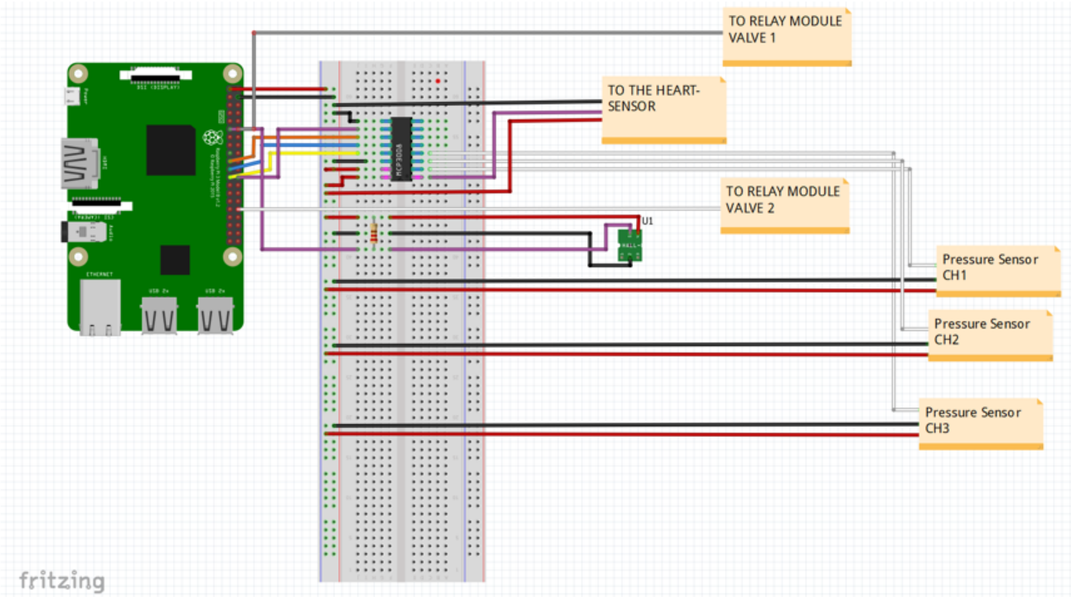


FIGURE 4.2: *Fritzing Schematic*

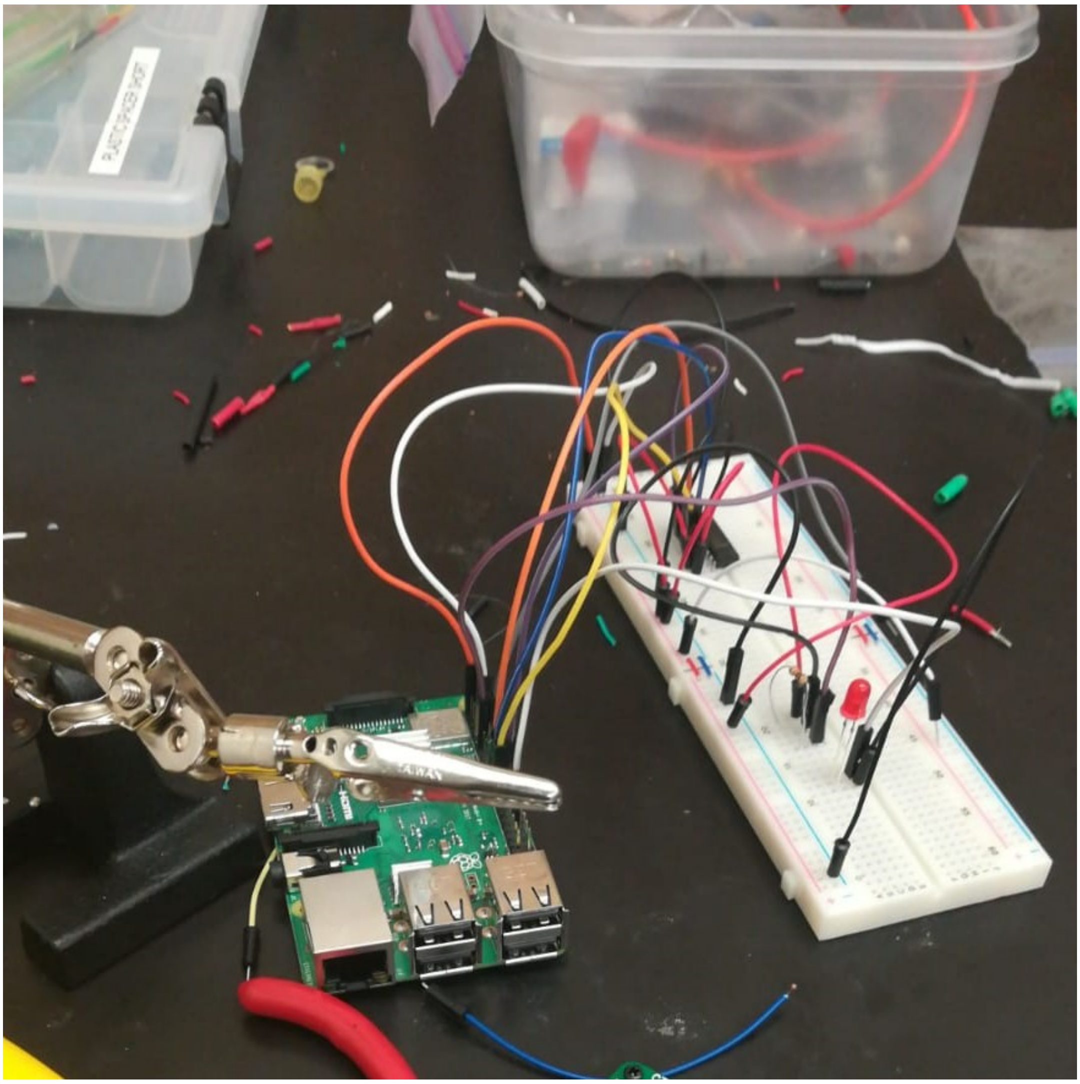


FIGURE 4.3: *The electronic system during the prototyping phase*

4.3 Software Design

As previously said, the Raspberry Pi, working as a miniature computer, allows the installation of some custom OS distribution. On the prototype the latest Raspbian [1] distribution has been installed; this already included all sort of software that can be found on a basic OS plus some programming tools that allow anyone to create its own programs.
All the programs have been written in python language and run from terminal using the python command.

4.3.1 Heart Rate Sensor

The first program implemented is the one used to read the heartbeat values. In this case there has not been necessity of writing the program and interfacing it with the ADC because the sensor already came with the ADC drivers and the code to implement a simple program that allows the user to read a heart rate value every second on the terminal [2].

4.3.2 Pressure Sensors

Having already interfaced the ADC with the Raspberry Pi, it has been really simple to write a program in order to read the pressure values in the system. The sensor's data sheet indicated a ratiometric output signal going from 0.5V (at 0 bar) to 4.5V (at 600 bar), that can be translated into a characteristic with equation:

$$Voltage = \frac{4\ V}{600\ bar}\ Pressure + 0.5\ V \tag{4.1}$$

as shown in the graphic below:

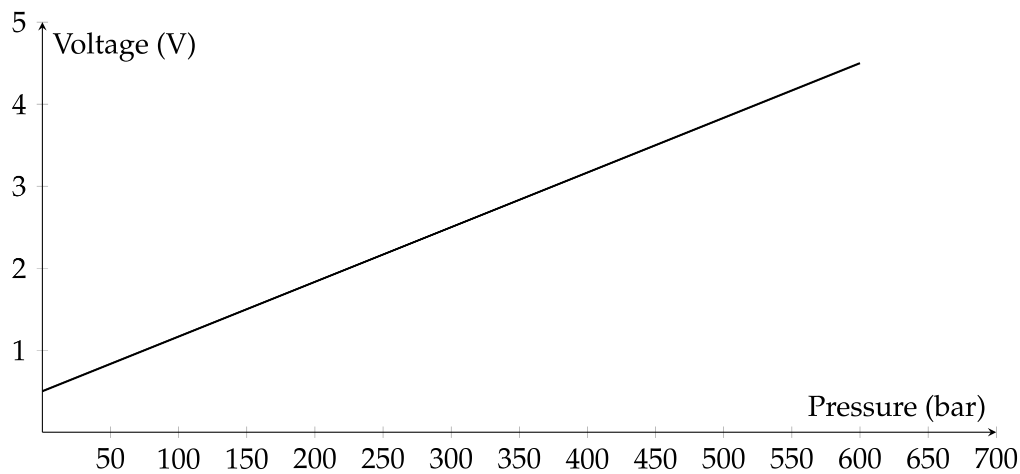


FIGURE 4.4: *PR4 Sensor Characteristic*

[1] https://www.raspberrypi.org/downloads/raspbian/
[2] https://github.com/WorldFamousElectronics/Raspberry_Pi/blob/master/PulseSensor_C_Pi/PulseSensor_C_Pi.md

The ADC module takes as input an analog value, and returns a digital value; the voltage is in a range between 0V and 3.3V while the maximum digital value that can be read is: $D = 2^{10bit} - 1 = 1023$.
Neglecting the quantization performed during the actual conversion, the following characteristic is obtained:

$$DigitalOutput = \frac{1023}{3.3\ V}\ Analog\ Input \tag{4.2}$$

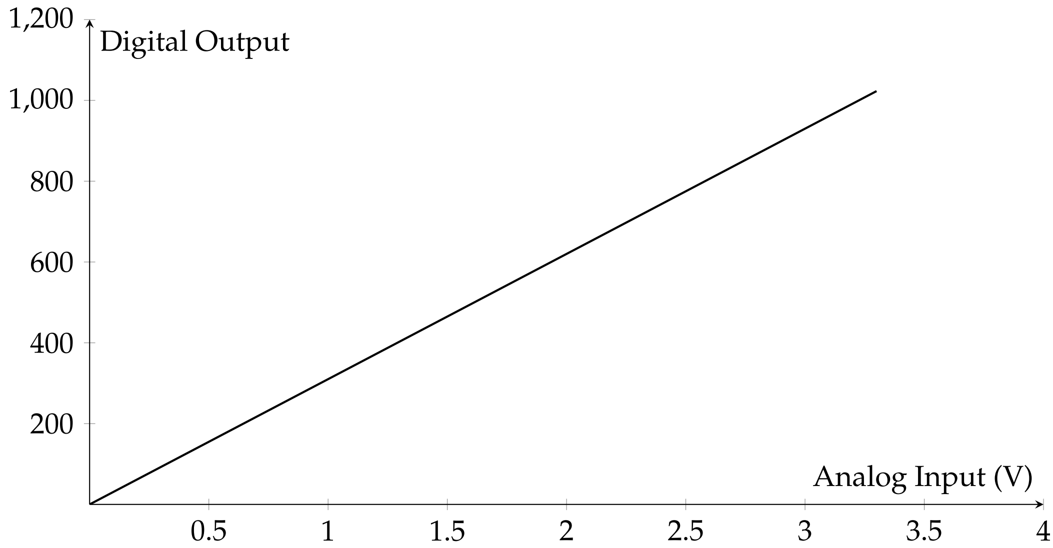


FIGURE 4.5: *ADC Characteristic*

In the electronic system the pressure coming from the hydraulic system is "translated" into a voltage that is then converted in digital form through the ADC. So, substituting the formula 4.2 into 4.1 it can be found the total characteristic of the sensor + ADC system:

$$Digital\ Output = (Pressure\ \frac{4\ V}{600\ bar} + 0.5\ V)\ \frac{1023}{3.3\ V} \tag{4.3}$$

The python program written to read the pressure value simply performs a read operation on the corresponding channel of the MCP3008 and stores it as digital value. To print it on the terminal as a pressure value the program needs to transform the analog data to pressure back again. This can be done inverting the equation 4.3 obtaining:

$$Pressure = (Digital\ Output\ \frac{3.3\ V}{1023} - 0.5\ V)\ \frac{600\ bar}{4\ V} \tag{4.4}$$

In the code there are also some lines of code dedicated to writing the measurements on a file (along with information on the time in which the readings have been taken) and the complete script can be seen here:

```
# Simple example of reading the pressure sensor value
#through Channel 1 of MCP3008

# Author: Tommaso Greco
# License: Public Domain
import time
import datetime

# Import SPI library (for hardware SPI) and MCP3008 library.
import Adafruit_GPIO.SPI as SPI
import Adafruit_MCP3008

# Hardware SPI configuration: !!VALID FOR HW SPI ONLY
SPI_PORT   = 0
SPI_DEVICE = 0
mcp = Adafruit_MCP3008.MCP3008(spi=SPI.SpiDev(SPI_PORT, SPI_DEVICE))

#Time import
date = datetime.date.today()

#Open file to log data
f1 = open("ch1.txt","a+")

print ’Date:’ ,date

f1.write(’\n\n\n’)
f1.write("Date: %s %s %s" %(date.day,date.month,date.year))
f1.write(’\n\n’)


print(’Pressure sensor CH1 value:’)
# Main program loop.
while True:
value = 0
value = mcp.read_adc(1)
pressure_1 = ((value - (1023 / (3.3 * 2))) * 3.3 * 600)/(1023 * 4)
hour = datetime.datetime.now()
# Print the ADC values.
print("Pressure CH1: %f" %(pressure_1))
f1.write("Pressure CH1: %f, Ora:%s %s %s %s" %(pressure_1,hour.hour,hour.minute,hou
f1.write(’\n’)
f1.flush()
# Pause for one second.
time.sleep(1)


#f1.close()

```

Three scripts of this kind have been created, one for each channel and pressure sensor.

4.3.3 Speed Sensor

Unlike the previous sensors, the speed sensor already presents a digital output and doesn't need an ADC to be interfaced with the Raspberry. By gluing a magnet on the rim of the rear wheel it is possible to detect the exact moment when the magnet is passing next to the sensor (as in figure 4.6). Knowing the radius of the wheel (0.33 m) it is possible to know its circumference using the formula:

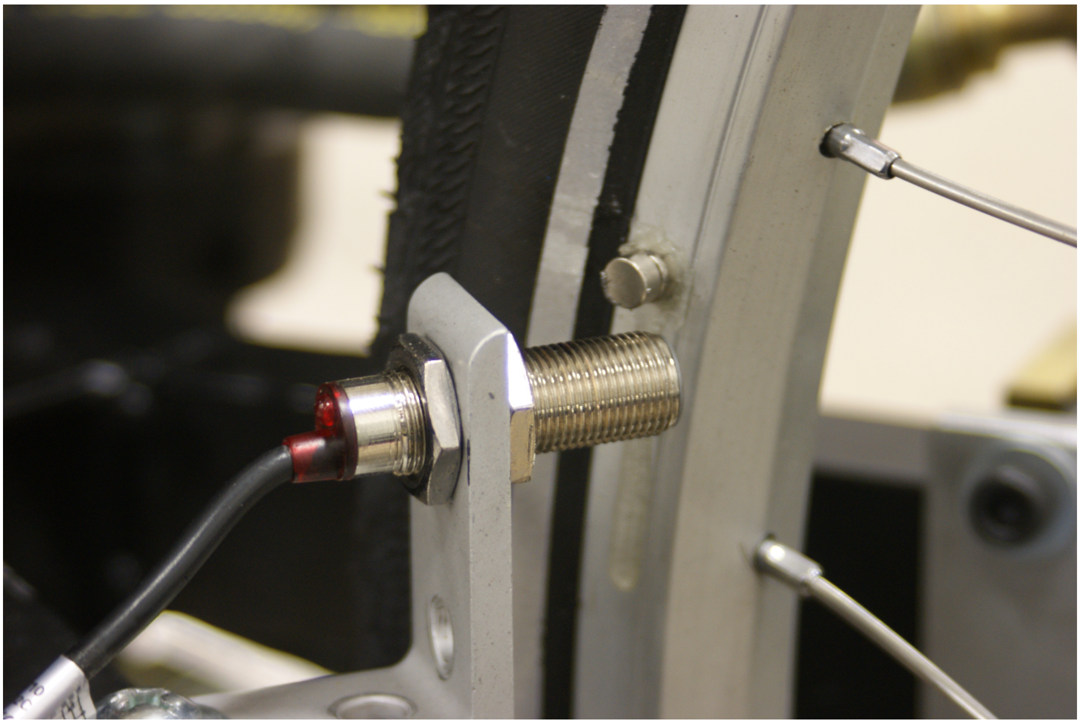


FIGURE 4.6: *The magnet attached to the rim of the wheel passes by the Hall effect sensor*

$$C = 2 \cdot \pi \cdot r = 2 \cdot \pi \cdot r = 2.07\ m \tag{4.5}$$

Every time the wheel completes a turn, it means that the bike has advanced of slightly more than 2 meters. It suffices measuring the time that passes between two detections of the magnet and it will be possible to calculate the speed of the vehicle. The python script loops continuously until an edge on the GPIO pin dedicated to the hall sensor is detected and, using the interrupt manager of the Raspberry, calls a routine that updates the distance and the speed in both $\frac{m}{s}$ and $\frac{km}{h}$. Again the time at which each measurement takes place and its output are logged on a .txt file.
Here is the code:

```
# Simple example of reading the total distance plus the speed using
# a hall effect sensor or similar

# Author: Tommaso Greco
# License: Public Domain

import time
import math
import datetime
```

```
import RPi.GPIO as GPIO

starttime = time.time()
endtime = 0
elapsed = 0
total_distance = 0
speed = 0
#parameter = 0
diameter = 0.65

date = datetime.date.today()

fhall = open("hall.txt", "a+")

fhall.write('\n\n\n')
fhall.write("Date: %s %s %s" %(date.day,date.month,date.year))
fhall.write('\n\n')

def sensorCallback(channel):

global total_distance, endtime, starttime, elapsed, speed, parameter

hour = datetime.datetime.now()

#parameter += 1

endtime = time.time()

total_distance += diameter * math.pi
#total_distance = round(total_distance,3)
elapsed = endtime - starttime

speed = diameter / elapsed
kph = speed * 3.6

print ("Speed [m/s]: %f, speed [km/h]: %f , distance [m]: %f Ora:%s %s %s %s" %(spe

fhall.write("Speed [m/s]: %f, speed [km/s]: %f , distance [m]: %f Ora:%s %s %s %s"
fhall.write('\n')
fhall.flush()

starttime = endtime
#  # Called if sensor output changes
#  timestamp = time.time()
#  stamp = datetime.datetime.fromtimestamp(timestamp).strftime('%H:%M:%S')
#  if GPIO.input(channel):
#    # No magnet
#    print("Sensor HIGH " + stamp)
#  else:
#    # Magnet
#    print("Sensor LOW " + stamp)
```

```
def main():
# Wrap main content in a try block so we can
# catch the user pressing CTRL-C and run the
# GPIO cleanup function. This will also prevent
# the user seeing lots of unnecessary error
# messages.

# Get initial reading
sensorCallback(20)

try:
# Loop until users quits with CTRL-C
while True :
time.sleep(0.1)

except KeyboardInterrupt:
# Reset GPIO settings
GPIO.cleanup()

# Tell GPIO library to use GPIO references
GPIO.setmode(GPIO.BCM)

print("Setup GPIO pin as input on GPIO20")

# Set Switch GPIO as input
# Pull high by default
GPIO.setup(20 , GPIO.IN, pull_up_down=GPIO.PUD_UP)
GPIO.add_event_detect(20, GPIO.BOTH, callback=sensorCallback, bouncetime=200)

if __name__=="__main__":
main()
```

4.3.4 Relay Command

The last script(s) created for the project has been the one to create the square wave taken as input by the relay module in order to control the hydraulic shut-off valves. In order to do this it has been used the PWM module integrated on the Raspberry Pi. It suffices to set the GPIO channel where the wave has to be generated along with the frequency and the duty-cycle and the controller does the rest. Here the code used for the endurance challenge (frequency: 1 Hz, DC: 35.9):

```
# Simple example for the wave generation using the PWM module of
# the Raspberry Pi

# Author: Tommaso Greco
# License: Public Domain
```

```
#This program will generate PWM on GPIO 18 (Pin 12)
# Frequency = 1Hz, Duty-Cycle = 50%

import RPi.GPIO as GPIO
from time import sleep
import time


GPIO.setmode(GPIO.BCM)
GPIO.setup(12,GPIO.OUT)
p = GPIO.PWM(12,1)
p.start(35.9)
GPIO.cleanup()
```

For this project three different scripts of this kind have been prepared, one for each duty-cycle but all presenting the same frequency.

4.4 Graphic User Interface

When the electronic system has been first put on the vehicle and tested the first thing that has been noticed was the discomfort in operating the electronic system; the terminals used for the data monitoring were prepared before operating the vehicle using an external keyboard, but then the user had to use the touch pen and the on screen keyboard of the Raspberry to launch the desired wave generation python script in order to control the valves and let the vehicle operate.
To overcome this problem and offer the user a more friendly experience a **G**raphical **U**ser **I**nterface has been prepared. The concept idea for the GUI was to give an additional tool for the user to always have an eye on what is happening inside the system and to navigate through the various modes allowed for the riding mode of the vehicle.
The GUI has been programmed using the software Qt Creator [3], available for both Windows and Raspbian; in this case the interface has been written and tested on Windows first and then migrated on raspbian using the cross-compiling tool of Qt Creator that allows to define a target device where to load the program. As for the programming language it has been used QML (**Q**t **M**odeling **L**anguage), a declarative language for designing user interface applications. When launching the application by default the Dashboard page popped up, five elements can be seen:

Sensors Start On the top left of the dashboard is present a button that starts the reading of all the sensors. When pressed all the python scripts are called and the values are returned to the GUI.

Main View At the center of the screen are visible all the indicators where are visualized the values coming from the sensors:

[3] https://www.qt.io/

- In the middle a double dial showing the speed of the vehicle in both $\frac{m}{s}$ (inner dial) and mph (outer dial)
- On top of the previous one a meter showing the motor inlet pressure (in bar)
- on the left and right are shown the pressures of the two accumulators, on the corresponding sides (in bar)
- On the bottom two indicators, the one on the left showing the distance traveled (in m) while the one on the right dedicated to the Heart Rate (bpm)

Energy Flow On the bottom left there is a section that allows to see a schematic showing how the energy flows in the hydraulic system for each mode. The views of the four modes can be seen in the pictures from 4.8 on the next page to 4.11 on page 54.

Race Selection On the bottom right there are 4 buttons that allow the user to enter in race mode. When pressing on one of them the page updates and the dials at the center are still visible along with a start button that recalls the python scripts for wave generation. When exiting each race mode, the wave generation is interrupted and the user gets redirected back to the dashboard.
It can be noticed that the charging mode selection doesn't actually change affect the system but can be used as backup reset of the system.

Exit At the end an exit button is present to close the application. Before closing all the processes, the sensors are deactivated and the corresponding log files closed.

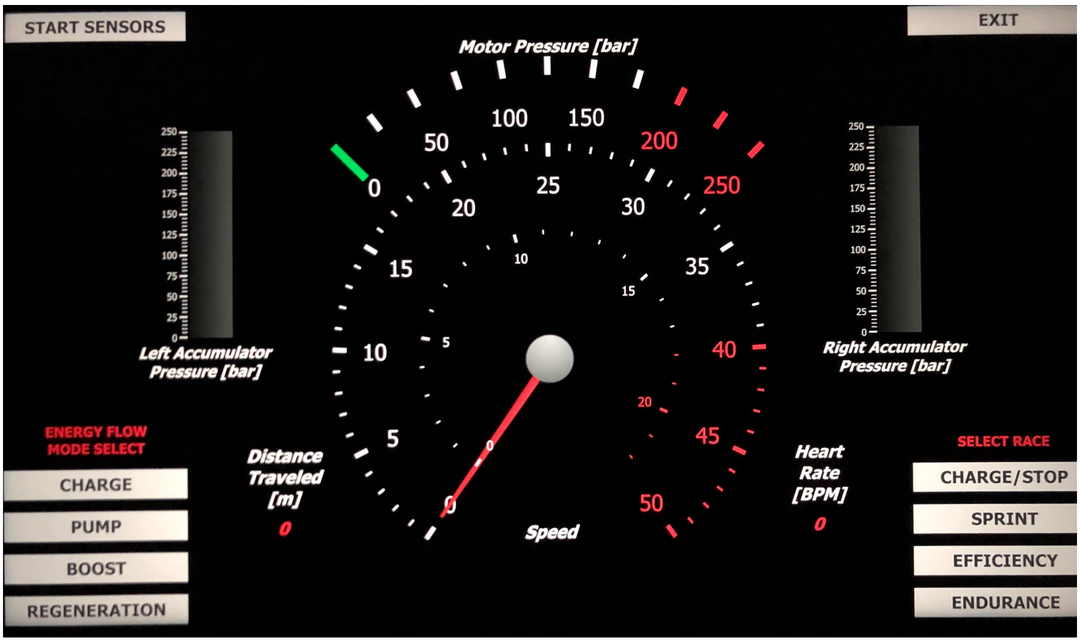


FIGURE 4.7: *The main page of the GUI*

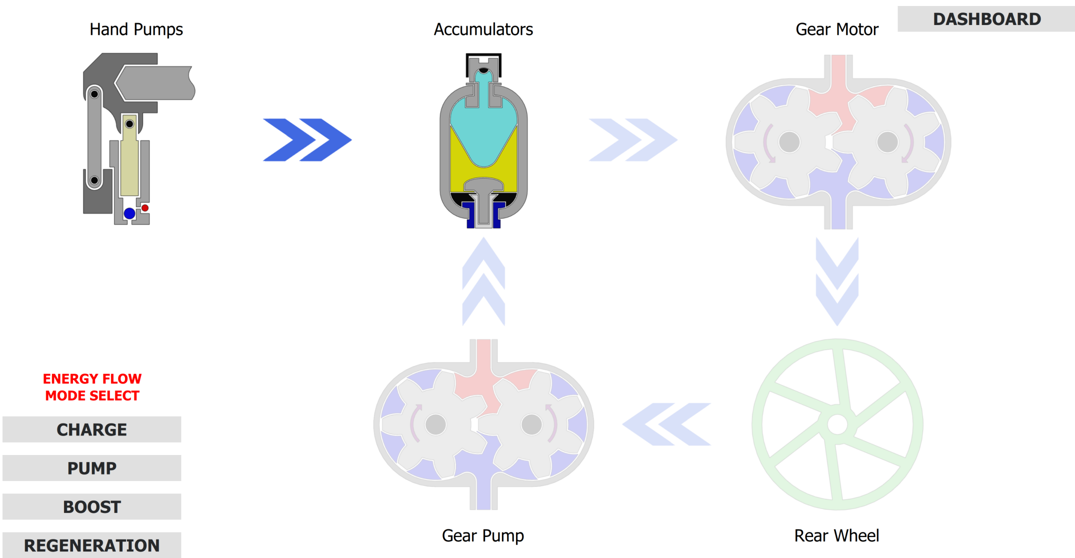


FIGURE 4.8: *Screenshot of the charging mode energy flow*

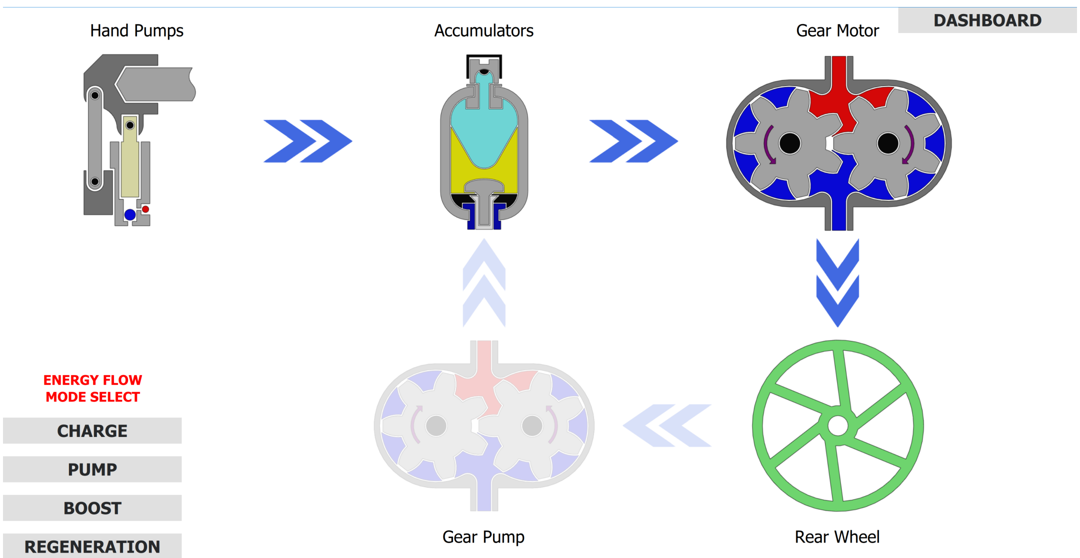


FIGURE 4.9: *Screenshot of the pumping mode energy flow*

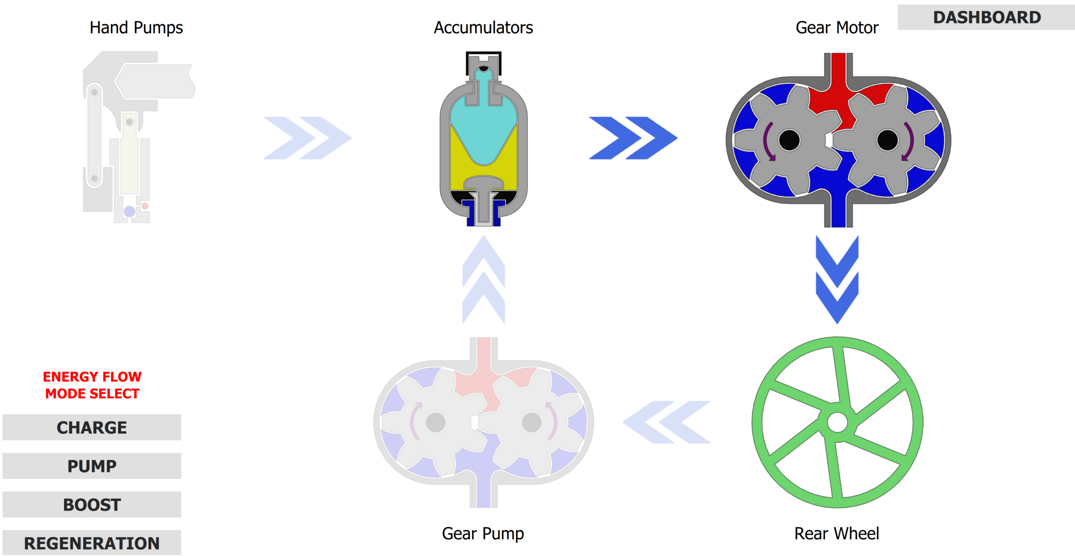


FIGURE 4.10: *Screenshot of the boost mode energy flow*

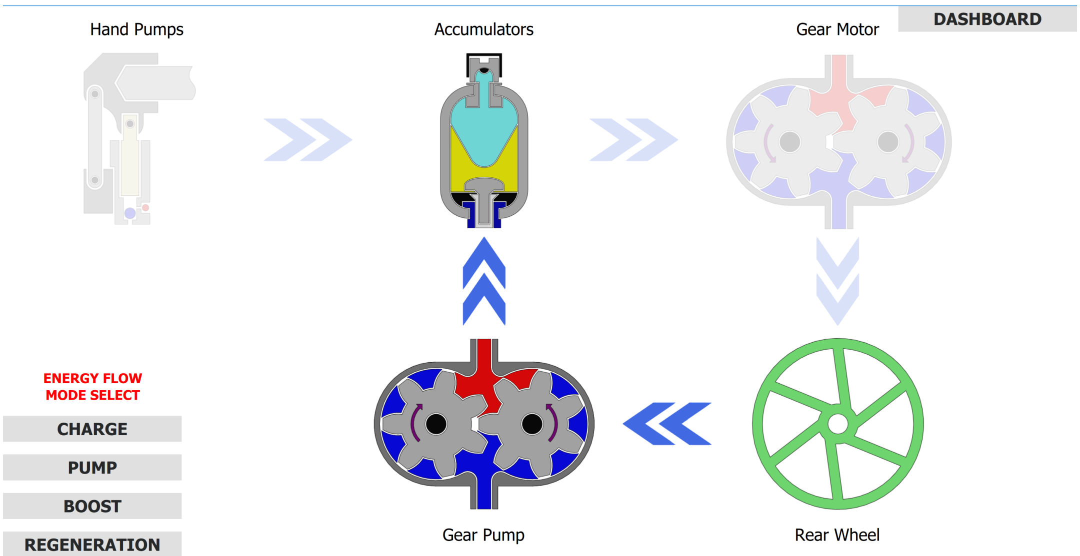


FIGURE 4.11: *Screenshot of the regeneration mode energy flow*

4.5 Final Implementation

Since the bike was meant to be ridden outside it was not possible to have the electronics just fixed on the bike with all the cable exposed and just plugged inside the breadboard; this was unacceptable both for safety and reliability reasons. Thus, the system has been moved from the breadboard to a way more compact prototyping board; this can be plugged on the Raspberry Pi using the GPIO pins and be used as a sort of breadboard but with the possibility of soldering the cables on top of that. In figure 4.12 can be seen the board with the ADC soldered on it and in 4.13 on the following page the finished compact system. This has then been closed in a sealed case and placed in the space behind the seat of the trike.

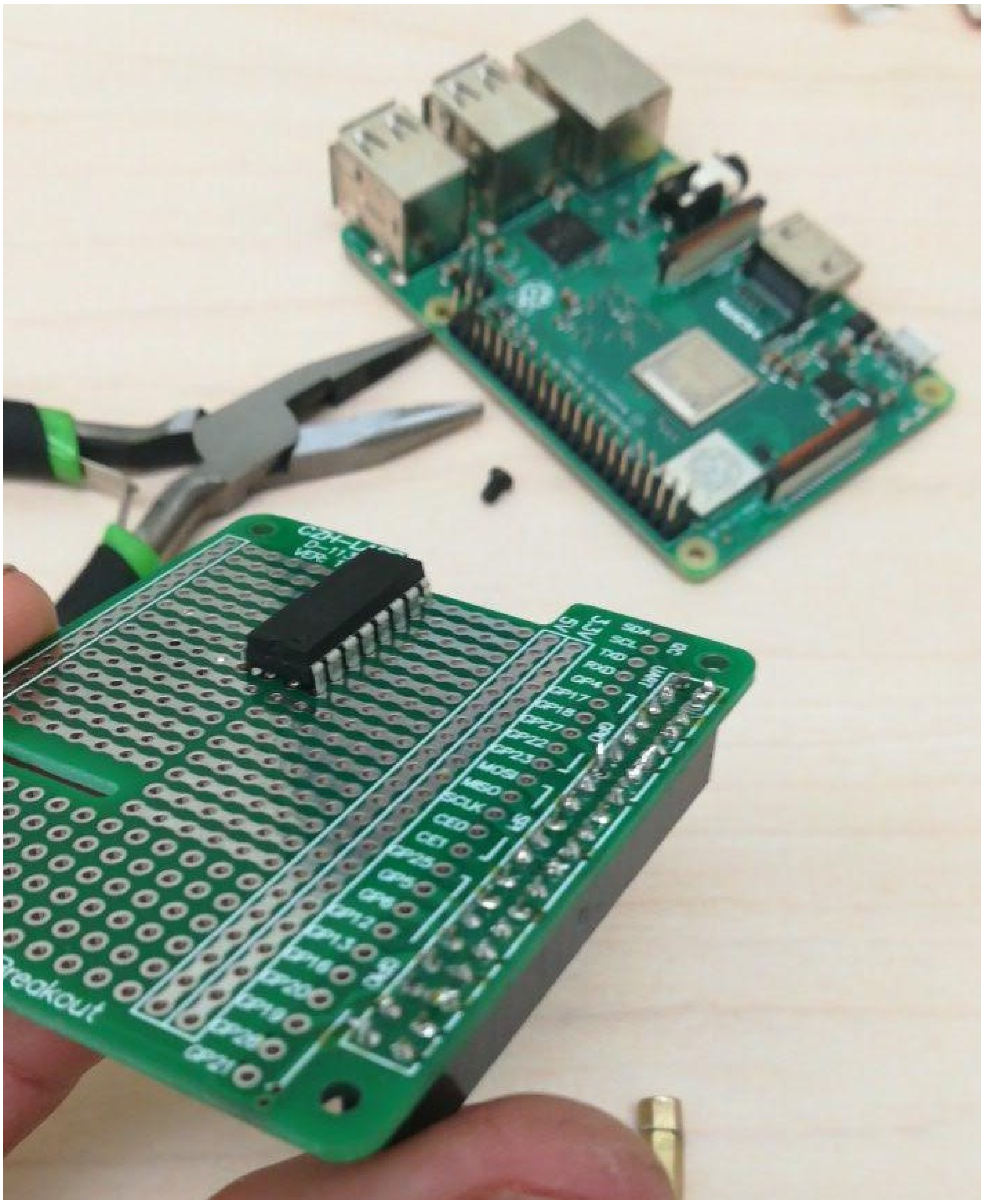


FIGURE 4.12: *The prototyping board during the migration of the components from the breadboard*

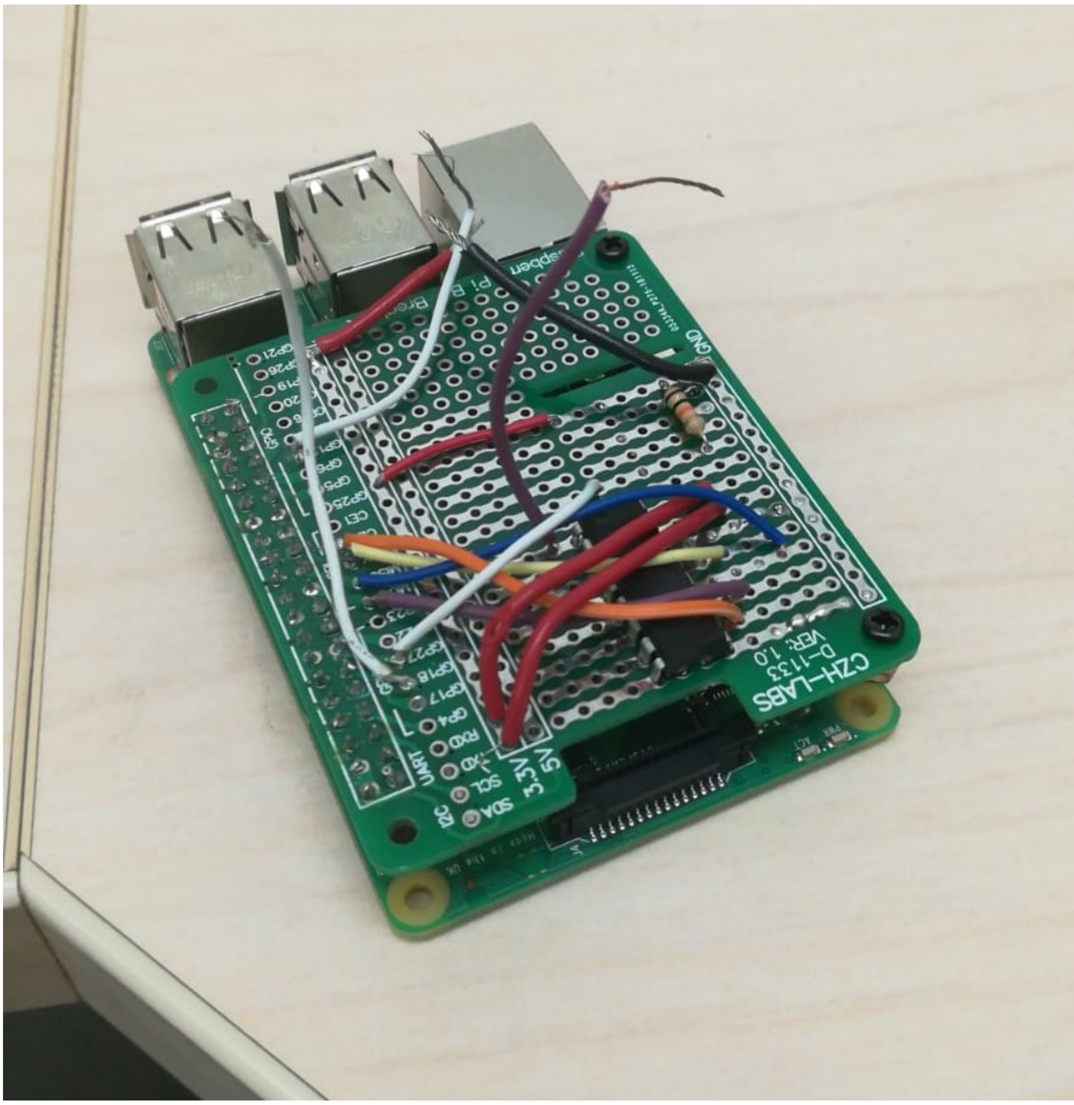


FIGURE 4.13: *The finished electronic system with the board on top of the Raspberry Pi board*

Chapter 5

Manufacturing and FPVC

5.1 Building and Testing

The design phase discussed in the previous chapters took place chronologically during the period from October until December, with all the materials sourced and ordered before the Christmas Holidays (21^{st} of December), with exception of the electronic system which has been designed and built in the numerous idle times when the team was waiting for components to arrive or for the technician to complete all the jobs that needed an expert hand.

From mid-January onwards the components started arriving and everything has been stocked and catalogued until the aluminum for the frame was delivered. Hence, the team started cutting and shaping the aluminum tubes and plates so that the lab technician could weld the frame together, included the hydraulic tank (see Appendix A).
The whole frame has been then primed and painted in black (figure 5.1).

FIGURE 5.1: *The completed frame drying out after being painted*

For what concerns all the bike parts that weren't subject matter in the design process, all the components had been found, but eventually it came out that buying all the spare components was more expensive than buying a classic trike and taking only the components needed. Thus a 3-wheeled bike (TerraTrike Sportster x16 [1]) has been

[1] https://www.terratrike.com/product-category/trikes/sportster/

FIGURE 5.2: *For the first time all the steering system has been tried on the frame*

ordered and dismantled in order to take out the wheels, the seat and the steering system (brakes included) and put them on the newly built frame (some of them visible in the picture 5.2).

At this point all the hydraulic components have been installed on the bike:

- The motor has been connected to the wheel on the right-hand side of the bike (see figure 5.3 on the next page) through the gear train designed (visible in figure 5.4 on page 60). Both the motor and the gear were sustained by a flange wedged inside the rear fork of the frame (see Appendix A) .
- The regeneration pump has been mounted on the bike using a flange (Appendix A) similar to the one bearing the motor (in figure 5.6 on page 61). In addition a dog clutch system (shown in the figure 5.7 on page 61) has been inserted in order to avoid having the regeneration always working (this would cause a resistive torque on the wheel); a cable activated by the brake lever on the left handle engages the wheel with the gear system (figure 5.5 on page 60) and thus the regeneration pump.
- The two linear piston pumps have been fixed on the T shape tip of the frame using two brackets. The two pedals have been created welding two round aluminum bars with a certain angle and then screwing inside them the original trike pedals; more than one has been created to make the pedaling comfortable for riders with different heights. At the end a return system aided by two springs has been inserted to help the rider pull back the pedals to start again the active movement. The whole system can be seen in figure 5.8 on page 62
- The custom manifold donated by SunSource has been placed and fixed screwing it on a plate that had previously been welded under the frame, in correspondence with the tank (visible in figure 5.9 on page 62).
- The two accumulators have been placed right behind the tank supported by the two plates shaped specifically for that purpose.

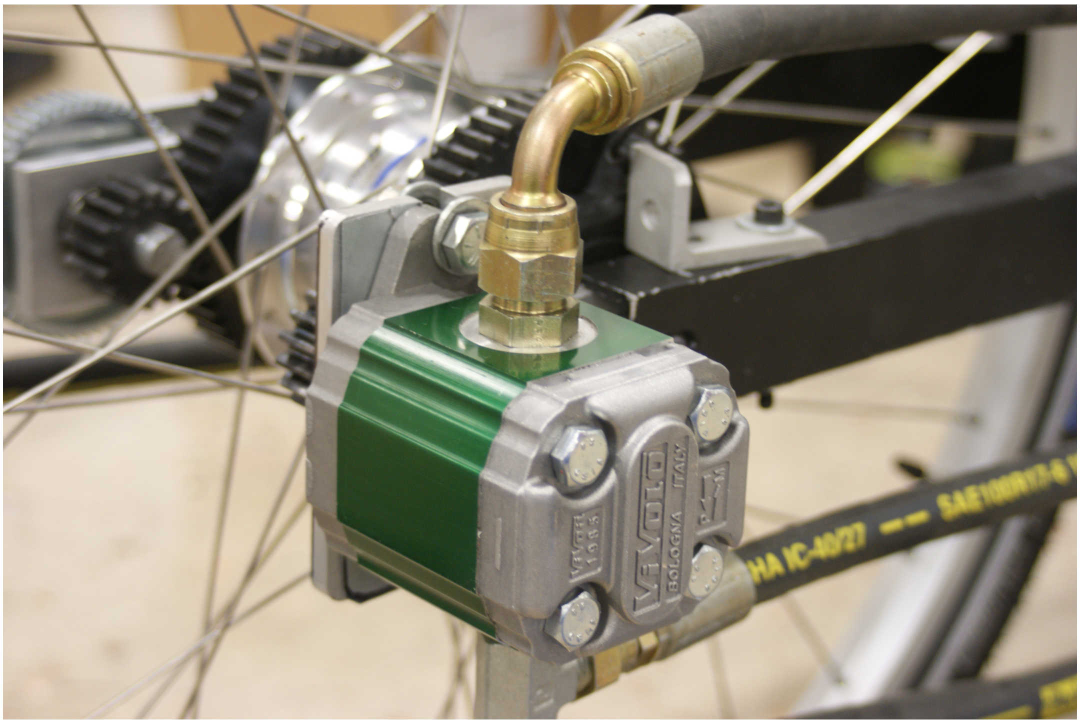


FIGURE 5.3: *The hydraulic motor placed on the flange in correspondence of the rear wheel*

- All the other hydraulic components (i.e. check valves and pressure relief valves) have been placed on the frame using small manifolds (figure 5.10 on page 63).

At this point only the hydraulic connections were missing and the choice between pipes and hoses has been harsh. On one hand the pipes introduce more pressure losses and are more expensive, but the pipes lengths need to be determined with high precision to avoid dangerous leakages. Moreover, pipes too long are subject to deformations that can lead to stress on the fittings.
Thus, it has been decided to use hoses for the main connections, especially those going from the manifold (at the center of the bike) to the pumps and motor (at the extremities) and pipes or fittings for very short connections with no relative motion, for example in the connection between the two linear piston pumps (as shown in figure 5.11 on page 63)

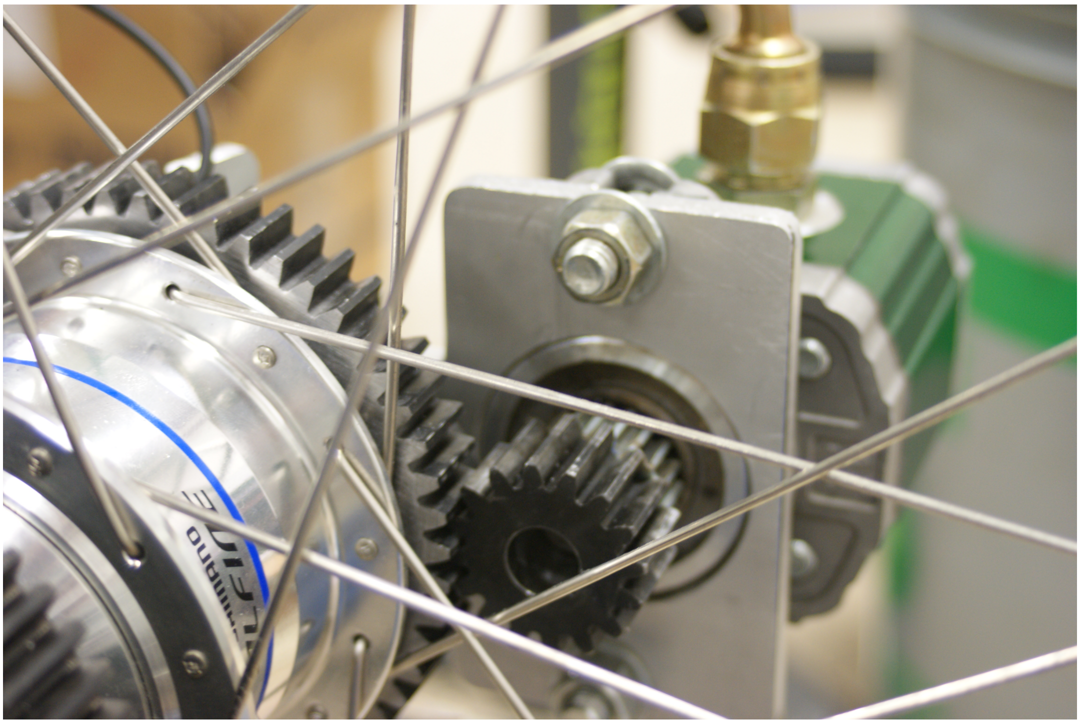


FIGURE 5.4: *The gear system that connects rigidly the motor shaft and the wheel*

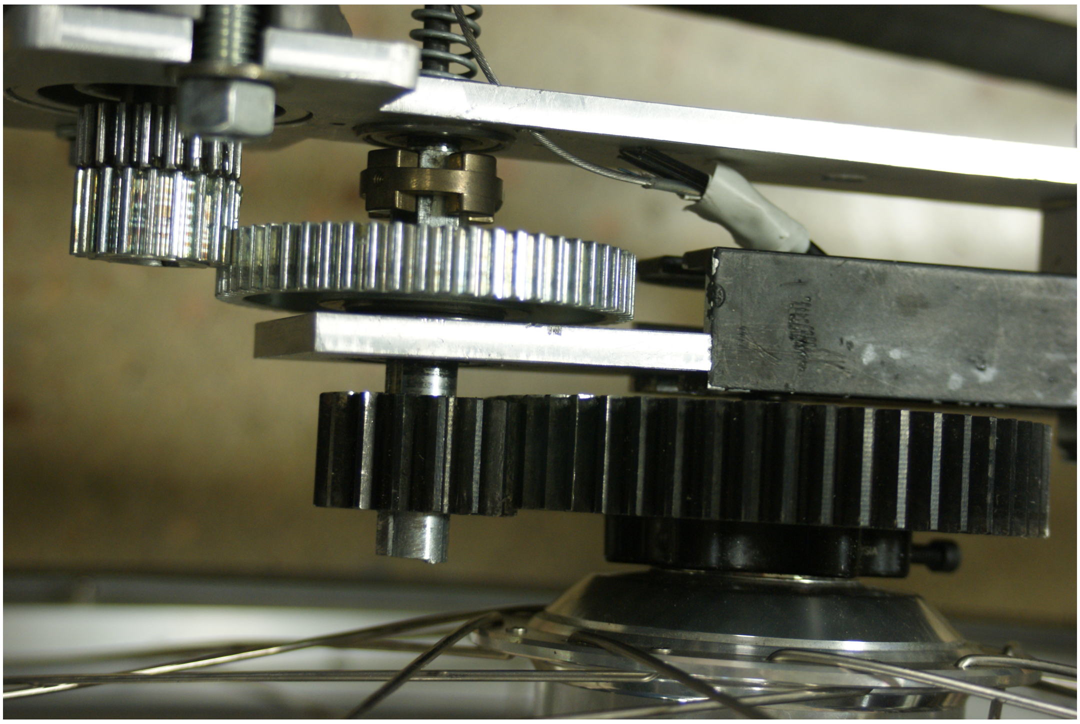


FIGURE 5.5: *The two stage gear system between the regeneration pump and the wheel*

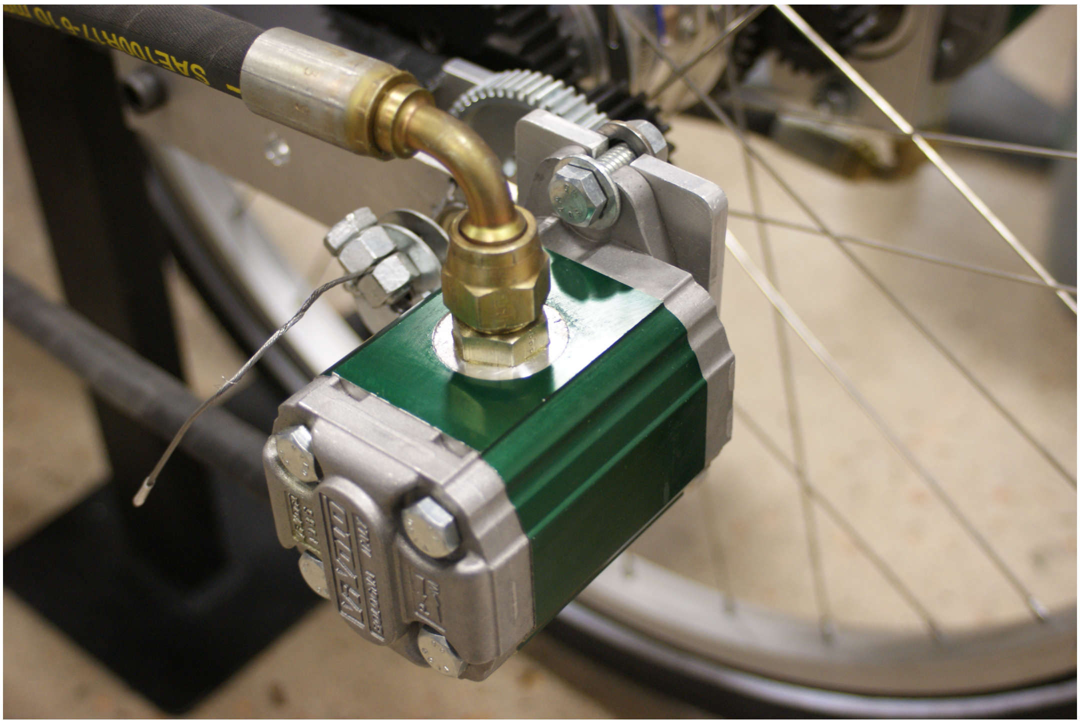


FIGURE 5.6: *The regeneration pump mounted on the dedicated flange*

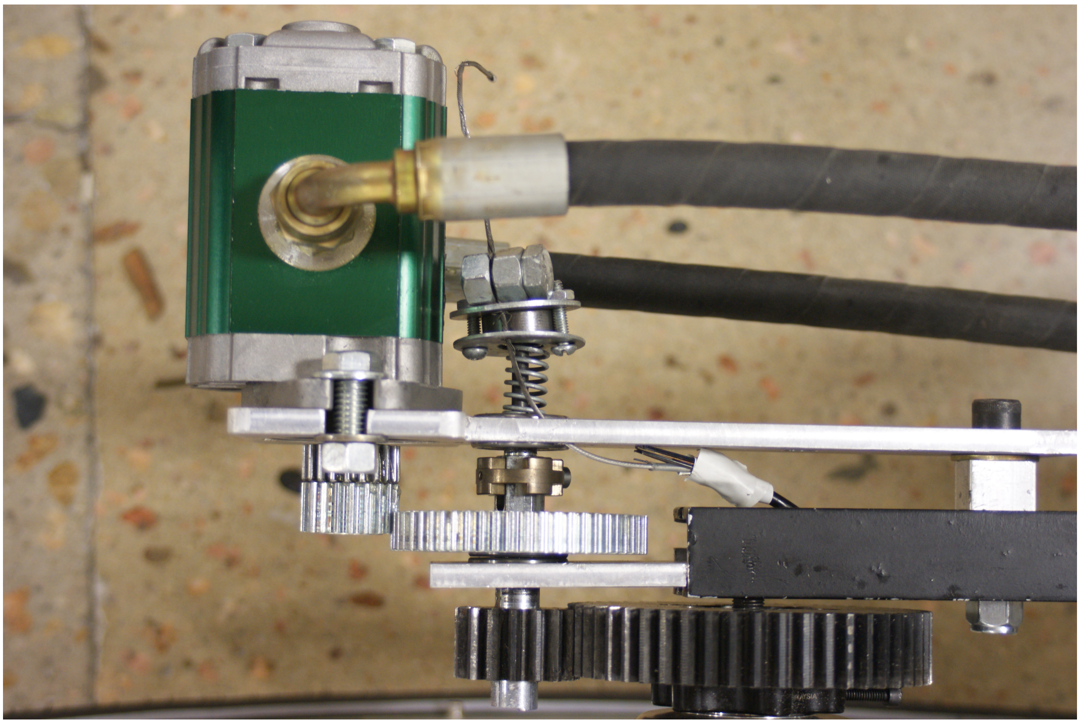


FIGURE 5.7: *The regeneration pump mounted on the dedicated flange*

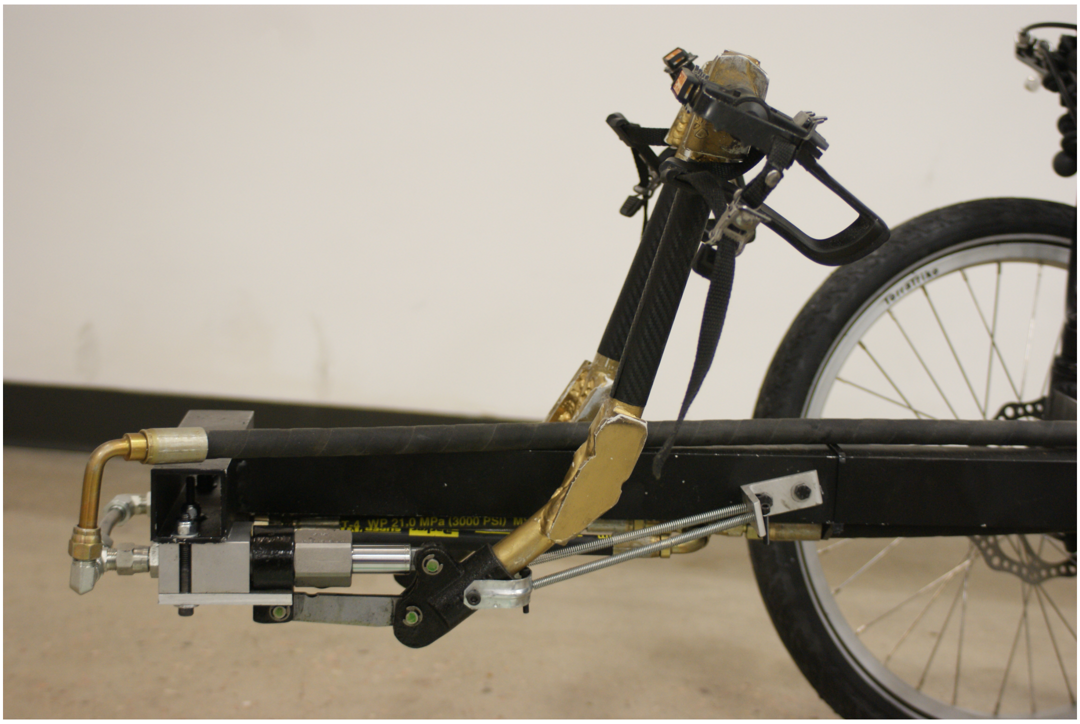


FIGURE 5.8: *The linear piston pumps attached below the frame and complete with pedals*

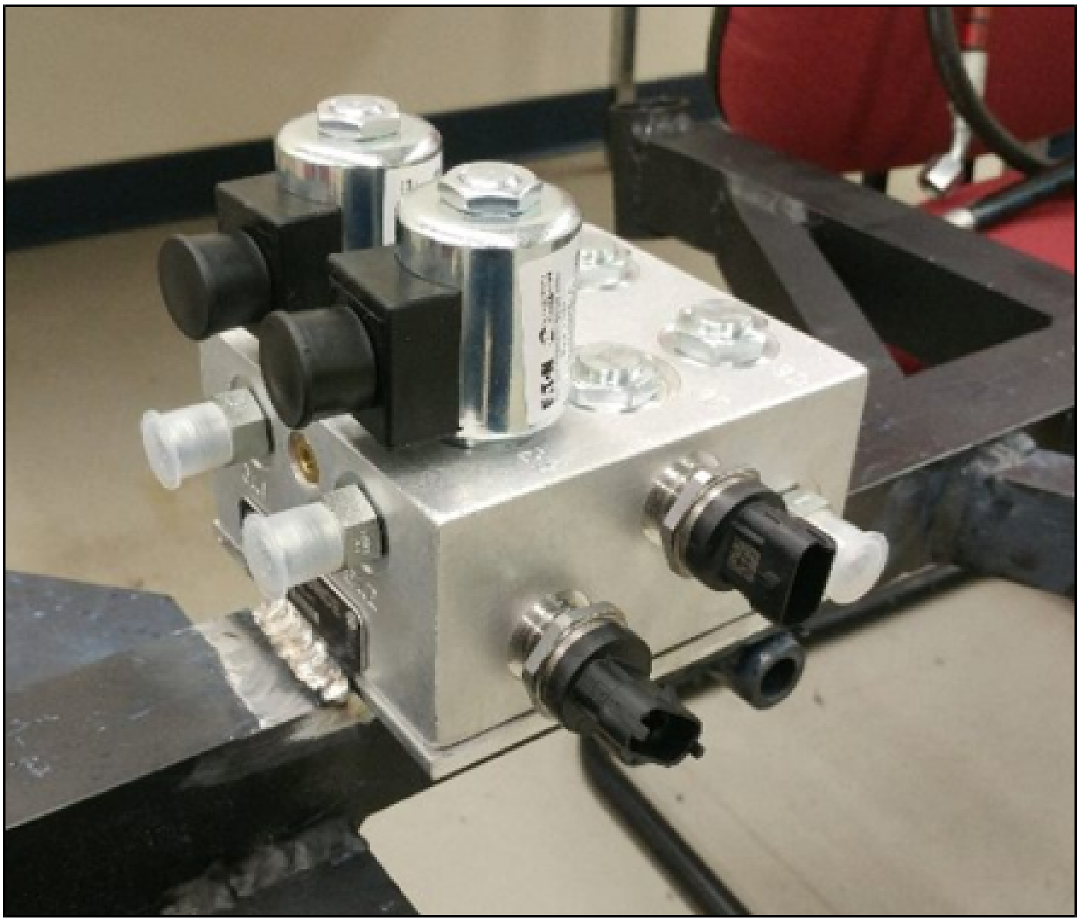


FIGURE 5.9: *The custom manifold with the connected hoses, shut-off valves and pressure sensors*

FIGURE 5.10: *Two pressure relief valves inserted in their manifolds and attached to the rear fork*

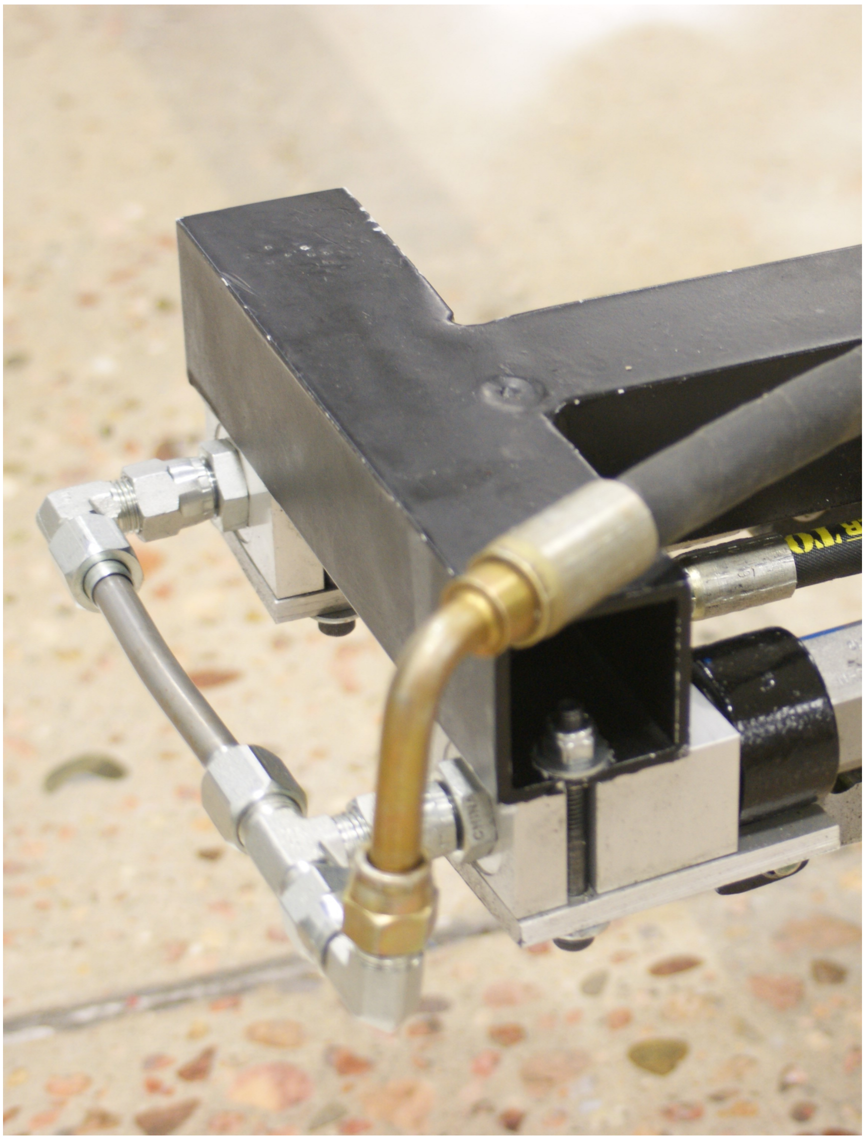


FIGURE 5.11: *A solid pipe has been used to connect the two main pumps*

Having a trike and needing the left brake lever for the regeneration system, the lever on the right handle has been tweaked to control the brake calipers of both the front wheels in order to perform a symmetrical braking action.

At this point the bike was ready from a mechanical and hydraulic point of view but, since the electronic system was still not operative a main adjustment has been made on the hydraulic system. In fact another branch has been introduced in order to connect one accumulator to the motor, with a ball valve in the middle; in this way it became possible to operate the vehicle (without secondary control) even in case of failure of the electronic system. After two months of hard work, the trike for finally ready for the first tests. The tank has been filled with hydraulic oil Mobil EAL 224H [2] and all the components and lines have been filtered and flushed using an external pump to remove all the residual material and debris caused by the welding and cutting of the aluminum (figure 5.12 on the following page).

It was time for the first tests and actually the bike wasn't performing very well. For what concern the "speed" test, the accumulators released all the fluid very fast on the motor, discharging completely in few seconds. Also the motor shaft resulted being too short and the 16 and 55 teeth gears weren't fully meshing, causing a non-homogeneous and poor power transmission. More than 50 seconds were needed to reach the 180 meters of the sprint race. The second test has been performed in order to simulate the efficiency challenge. Without pedaling and opening and close the valve by hand trying to keep the ratio between open and close at approximately $\frac{1}{3}$ it was possible to complete a lap of the Maha facility (more or less 400 m).
However, the biggest problem has been encountered with the test related to the endurance rally: steering and activating the ball valve while pedaling was very complicated and without the electronic control after the first transient due to the accumulators it was very difficult to bring again up the pressure before the bike arrived to a complete stop. So it eventually ended up being a frustrating succession of starts and stops.

Starting from these tests some improvements have been made on the bike.

- A new 16 teeth gear, similar to the prior one but presenting a longer body has been ordered, making the meshing between gears way better.
- The electronic system has been completed and implemented on the bike (as shown in figure 5.13 on page 66).
- An additional smart gear system has been implemented on the vehicle. Shimano offers a solution for high performances bikes called Shimano Alfine [3] offering a wheel hub with internal gearing and a module that allows to shift gears electronically.
- The accumulators have been finally pre-charged at the desired pressure (22.9 bar)
- A bracket has been created and attached to the top side of the tank in order to keep the accumulators in place (figure 5.14 on page 66).

[2]https://www.mobil.com/italian-it/industrial/pds/glxxmobil-eal-224h
[3]https://bike.shimano.com/it-IT/product/component/alfine-s7050s705-di2.html

FIGURE 5.12: *The tank is filled and emptied numerous times to remove all the welding debris*

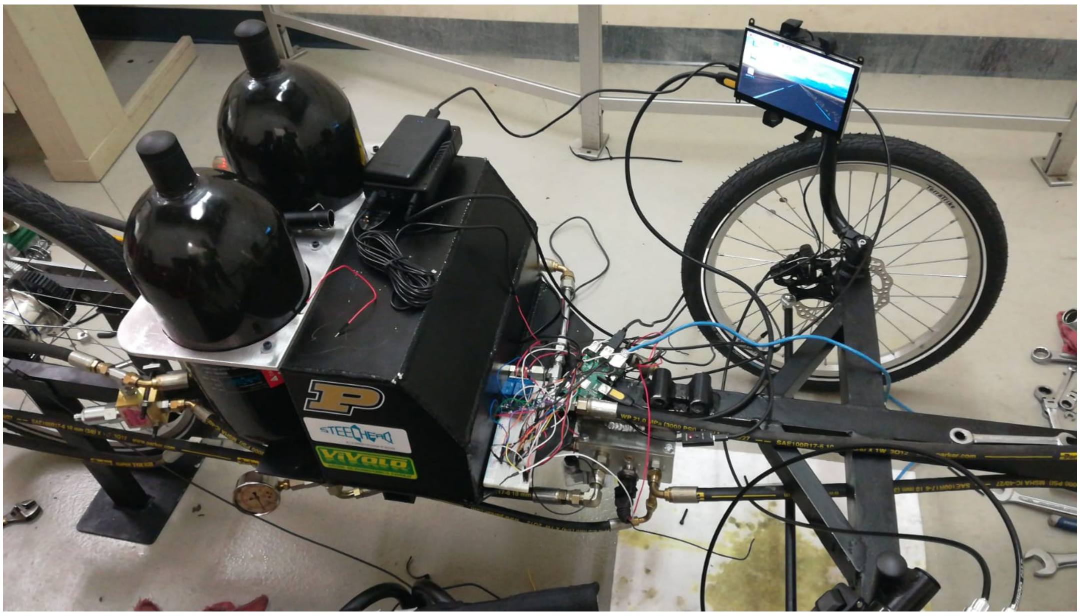


FIGURE 5.13: *The prototype of electronic system is mounted on the bike*

FIGURE 5.14: *The bracket used to keep the accumulators in place*

After some preliminary tests to validate the functioning of the electronics system, the compact version of it has been put finally on the bike and, uploaded the GUI as well, the final version of the vehicle was ready.

Unfortunately, due mainly to organization and logistic problems and inclement weather, only one afternoon has been available for the conclusive tests. In order to test in conditions as close as possible to those of the final competition, these tests have been carried out in the close Renault facility with a large loading area completely available. Even without measurements the difference with the unfinished version of the bike was clear as day. Many trials have been carried out and eventually the results have been:

Sprint race Average time to reach 180 meters: 23.37s

Efficiency challenge Average scoring ratio: 46.91 (corresponding to an average distance of: ≈ 950 m)

These results are quite different from the preliminary simulation made with Amesim on the hydraulic chapter (in subsection 2.3.6); in particular there is a deviation of almost ten seconds for the sprint race while in the efficiency more or less 5 points have been lost from the simulations. This is probably due to the rough values inserted in the model of the 2 axles vehicle on Amesim (the weight or other parameters depending on the geometry of the bike were not known at the moment of the simulations) and the fact of having placed the Shimano gear system on the bike that had not been modeled via software.

5.2 Final Competition

As soon as the bike has finally been ready, the travel and accommodation for the final competition have been arranged. To avoid sending the vehicle in a crate to destination, the team preferred driving all the way to Denver, Colorado in a one-day trip 1800 km long. One van and a pick-up truck have been rented to bring the bike and the whole team to destination (in figure you can see the trike fastened on the bed of the truck)

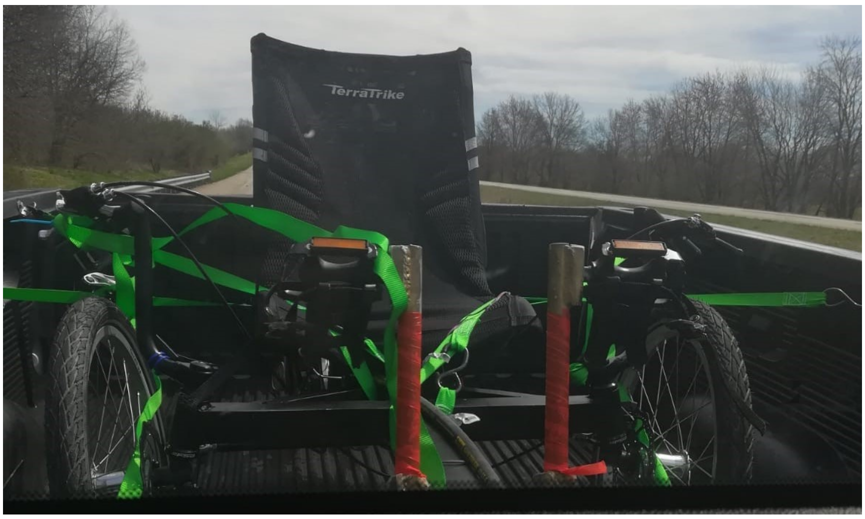


FIGURE 5.15: *The trike is being taken to the competition event*

In Denver, after the first day dedicated to presentations (figures 5.16 and 5.17), a safety training and a tour of the IMI Precision Engineering facility, finally on the 12^{th} of April the competition took place. All the bikes have been measured, weighted (rider included) and underwent a safety assessment (figure 5.18 on the next page).

FIGURE 5.16: *The trike is being presented to all the participants and judges*

FIGURE 5.17: *The team presenting the project to the jury*

FIGURE 5.18: *The trike is being inspected by the technical liaison*

The first race has been the sprint one: multiple heats of two bikes started together and every bike had two attempts.

FIGURE 5.19: *The trike and Murray State's one are taking place on the starting line for the sprint race*

The results of this race have been:

First attempt Final time: 24.78 s

Second attempt Final time: 22.24 s

Only the second time has been considered for the ranking and the vehicle placed 4^{th} out of 15 in this first race.

Moving to the endurance challenge track the team was quite surprised by its conformation; the track, that the team was expecting to be a straight line or a lap on a flat surface was actually an elliptical lap with on a test area having a slope of at least 10°. The race conditions changed a lot from the ones in the simulation but the bike has been capable of running several laps before stopping completely, amazing all the participants.
Eventually the final distance has been communicated by the judges: 4809 ft (1466 m or 57708 in) thus resulting in a score of:

$$scoring\ ratio = \frac{W \cdot L}{P \cdot V} = \frac{290lbs \cdot 57708in}{600cin \cdot 700PSI} = 39.846 \tag{5.1}$$

It can be worthy of mention the fact that the second longest run has been the University of Cincinnati with 1044 ft (318 m). As soon as all the bikes completed the efficiency challenge, the endurance test started.

The team's rider was doing great, keeping a great rhythm and speed. However, at the 4^{th} lap (the second to last) the disaster. In a sharp turn the arm of the frame that was supporting the right handlebar and wheel detached completely from the frame because of a welding failure. It might have been a lack of penetration in the welding or an improper FEA analysis (only static conditions have been taken into account) but in any case this meant the end of the competition for the team: there was none to weld the frame back and the tie rod for the steering was permanently bent and unusable.

FIGURE 5.20: *The trike laying on the race track after the failure*

Definitely out of the competition, all that remained was to go back home with the wreckage of the trike. This has then been rewelded and is now functioning and shown in the Maha lab.

Chapter 6

Conclusion

In this final chapter the final competition experience will be described, together with a sum up of the whole project and some possible future improvements.

6.1 Conclusion

This thesis project started within a competition context, a competition in which students are challenged to explore not only a complex field, the one related to hydraulics, but its implementation in a human powered vehicle where the loads are never excessive and all the components operate very far from their high performance area.
At the end of the whole path that lasted seven months, an innovative and working prototype has been designed and built from scratch and has been a strong contender during the 2019 edition of the Fluid Power Vehicle Challenge.

The thesis has gone through all the process of design and manufacturing of the bike and the main aspects have been described and highlighted. In the first place the design of the hydraulic transmission, the keystone from which NFPA starts in the pointing out of the problem; an innovative approach has been chosen, even if based on previous solutions used in the competition or not: the hybrid secondary control on the motor performed using a DC based command and a shut-off valve can't be found in literature and ended up performing very well against other teams' bicycles. The second noteworthy contribution has been the electronic with its custom GUI that impressing and intriguing all the participants and judges at the competition, ended up being the true discussion topic around our bike.

Nevertheless, not everything turned out working as expected and the failure during the competition is proof of this. During all the phases there have been some organization problems that lead to delays or little care to the details of some subsystems. Among all an aerodynamic analysis and a more complete FEA analysis (with dynamic loads and the effect of the user pushing on the pumps) was planned but other tasks ended up having a highest priority. Also, leaving some more time for the testing wouldn't have harmed in order to evaluate better the performances of the bike, its weak points and operate accordingly.

Lastly, a such vast problem leads to a broad variety of solutions and there is plenty of room for future improvements.

Reversible Hydraulic Motor The type of transmission used in this project can be modified using a reversible (bidirectional) motor. Its normal functioning is the one as motor, but reversing the direction of rotation of the shaft while keeping the same pressures at the inlet and outlet, it can behave as a pump, sending fluid to the accumulator.

FEA Analysis A more complete FEA analysis can be carried out in order to evaluate properly the behavior of the frame under stress. In this year's case the highest stress contribute after the weight of the components and the user was the action of the latter during the pedaling motion, pushing on the seat and the pedals; a dynamic FEA analysis could have studied the effects of this cyclic load, plus those of potential bumps on the terrain.

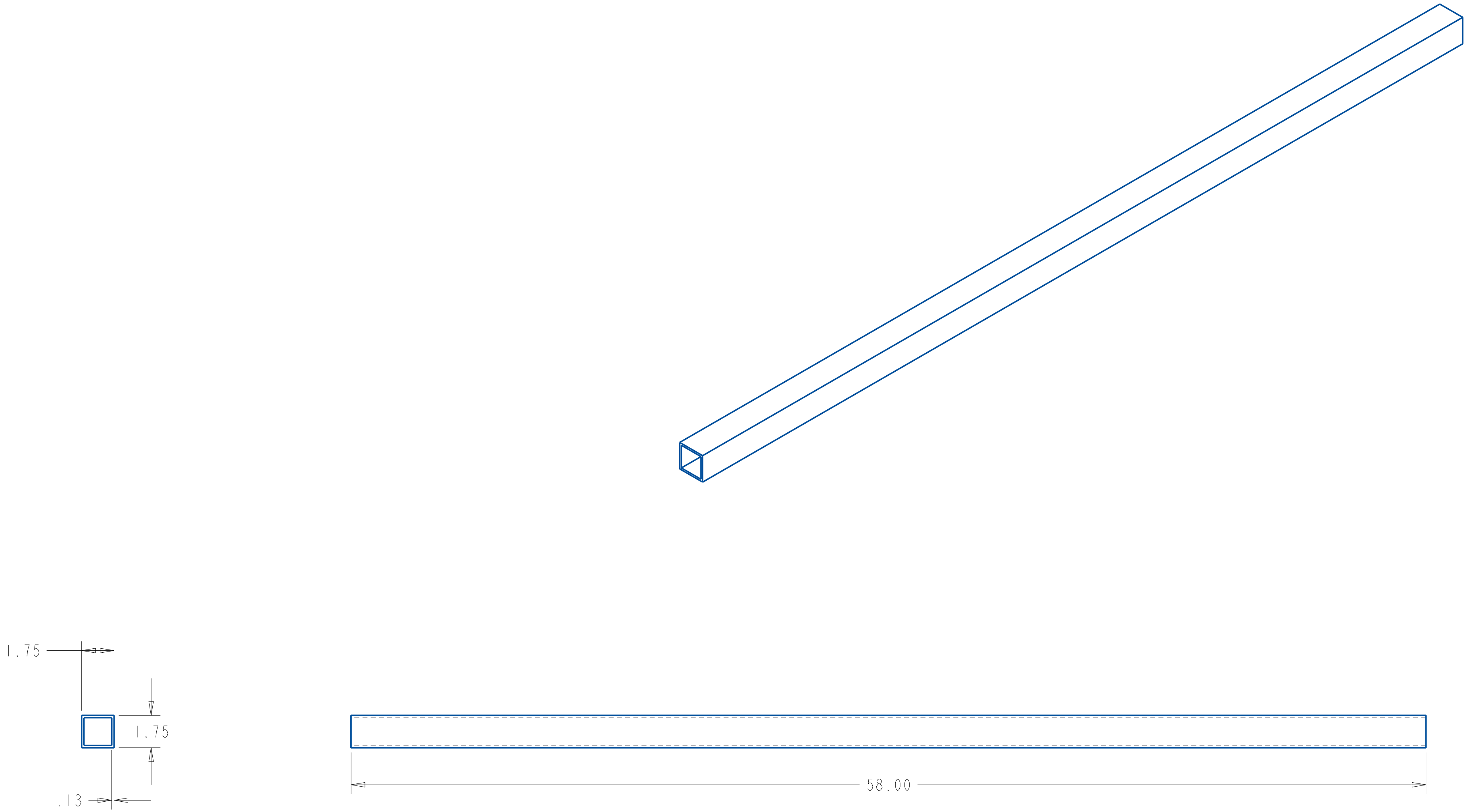
Camber Angle The camber angle is the angle between the vertical axis of the wheels used for steering and the vertical axis of the vehicle when viewed from the front or rear. When properly designed can enhance the handling performances of a particular suspension design. In this year's bike the same angle of the TerraTrike Sportster has been used, but design the camber geometry based on the performances needed in the competition might improve the comfort and performance of the steering.

Rowing Motion The rowing solution described in the pedaling choice section can, if implemented, provide the highest power output from the user. As in an ergometer, a flywheel can be introduced in order to store the kinetic energy and increase the efficiency of the system.

Aerodynamic Shell One of the drawbacks of the trike configuration is its poor aerodynamic behavior, for the shape and dimension of the frontal surface that creates drag. An aerodynamic shell that covers the front of the vehicle might be useful to eliminate a high component of resistance and losses.

Appendix A

Frame CAD Drawings



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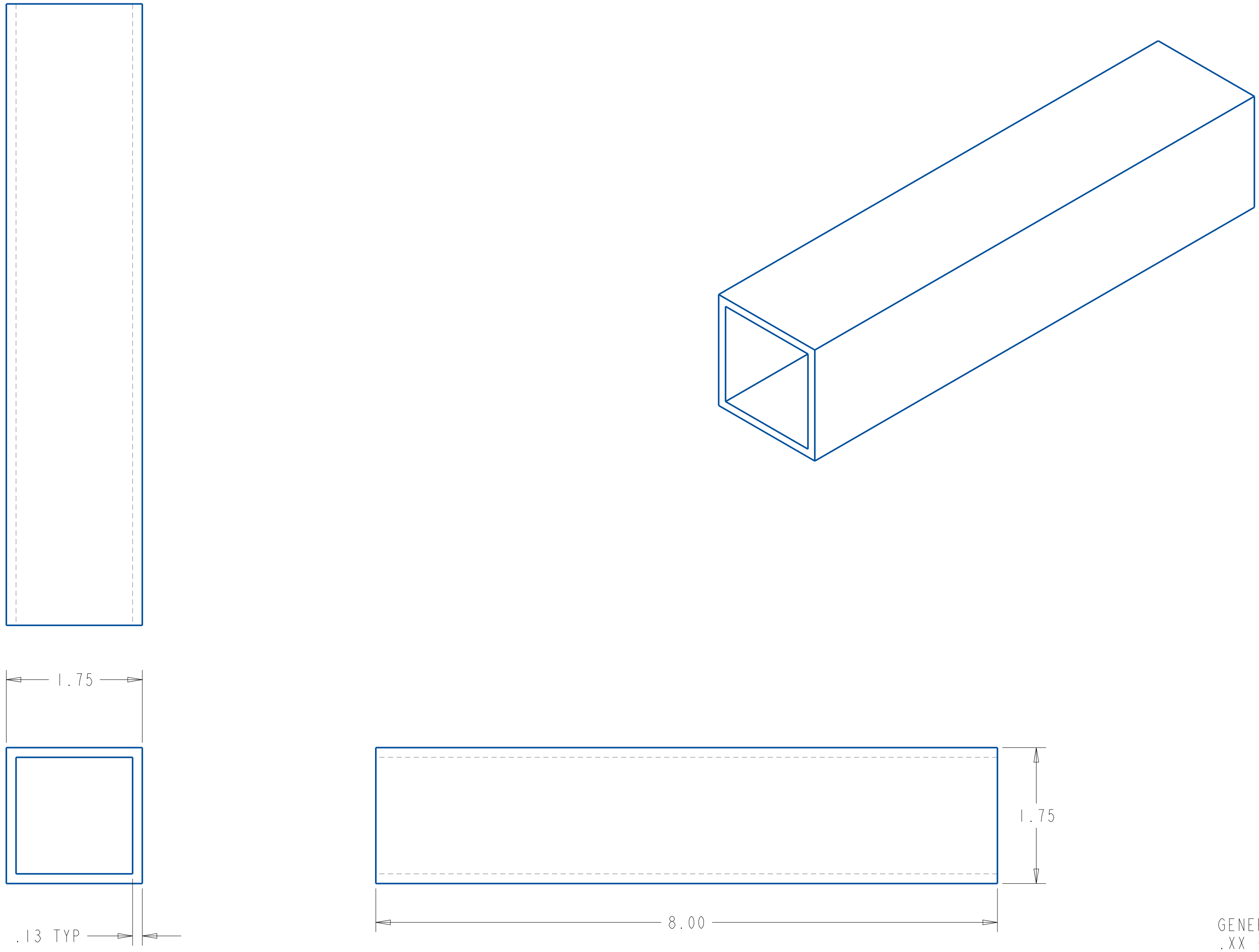
UNITS
INCHES



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.XXX +/-.005

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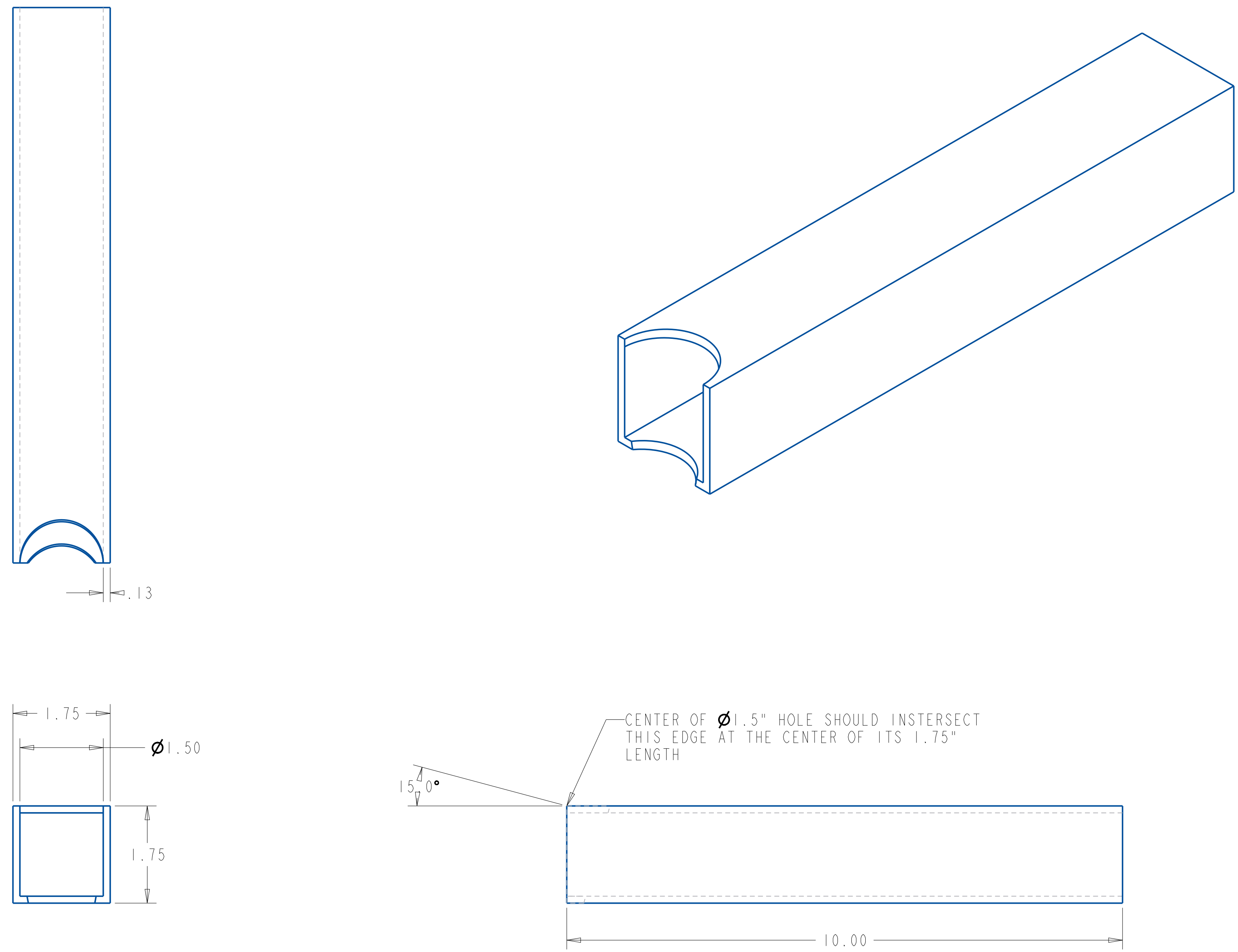

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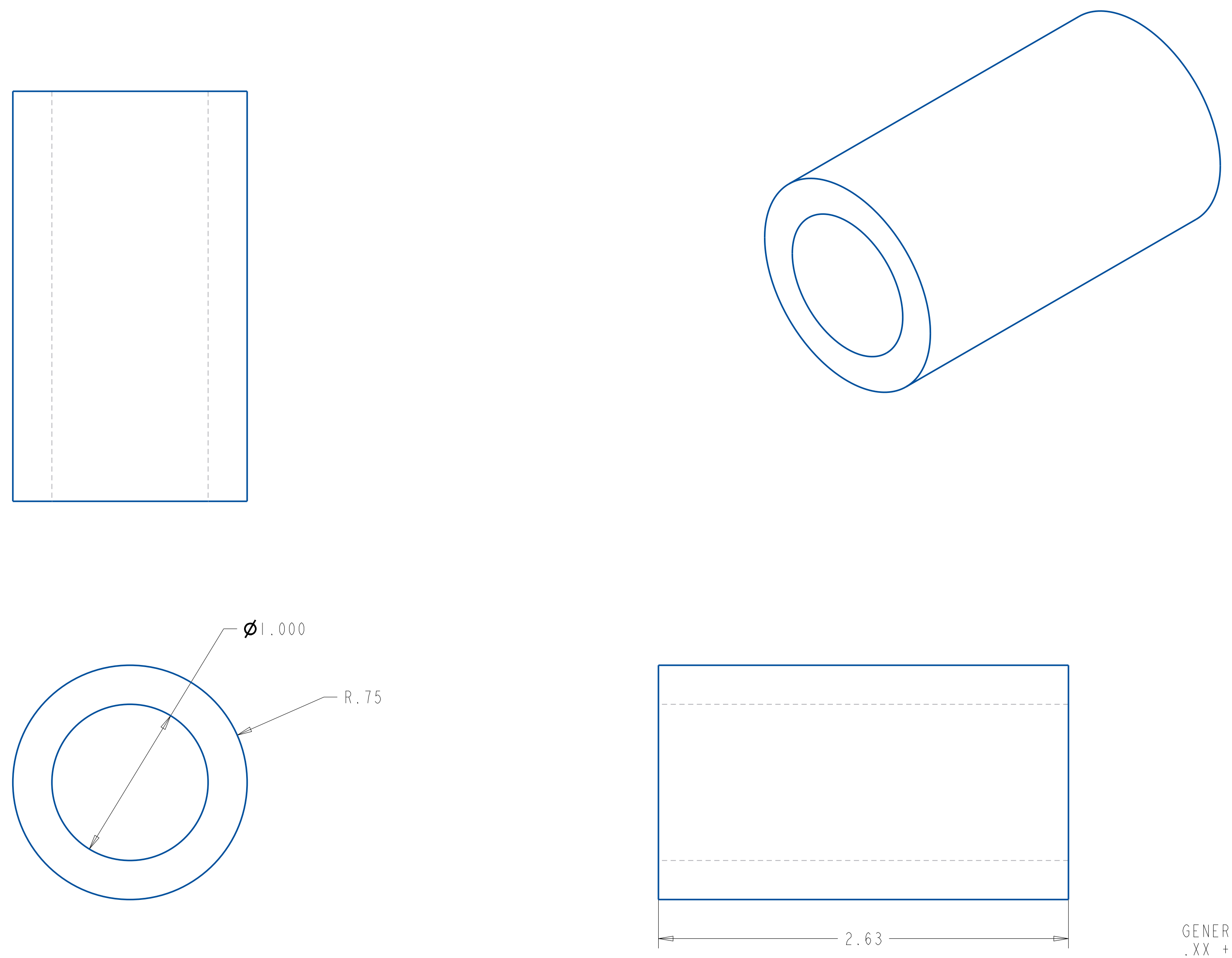

GENERAL TOLERANCES
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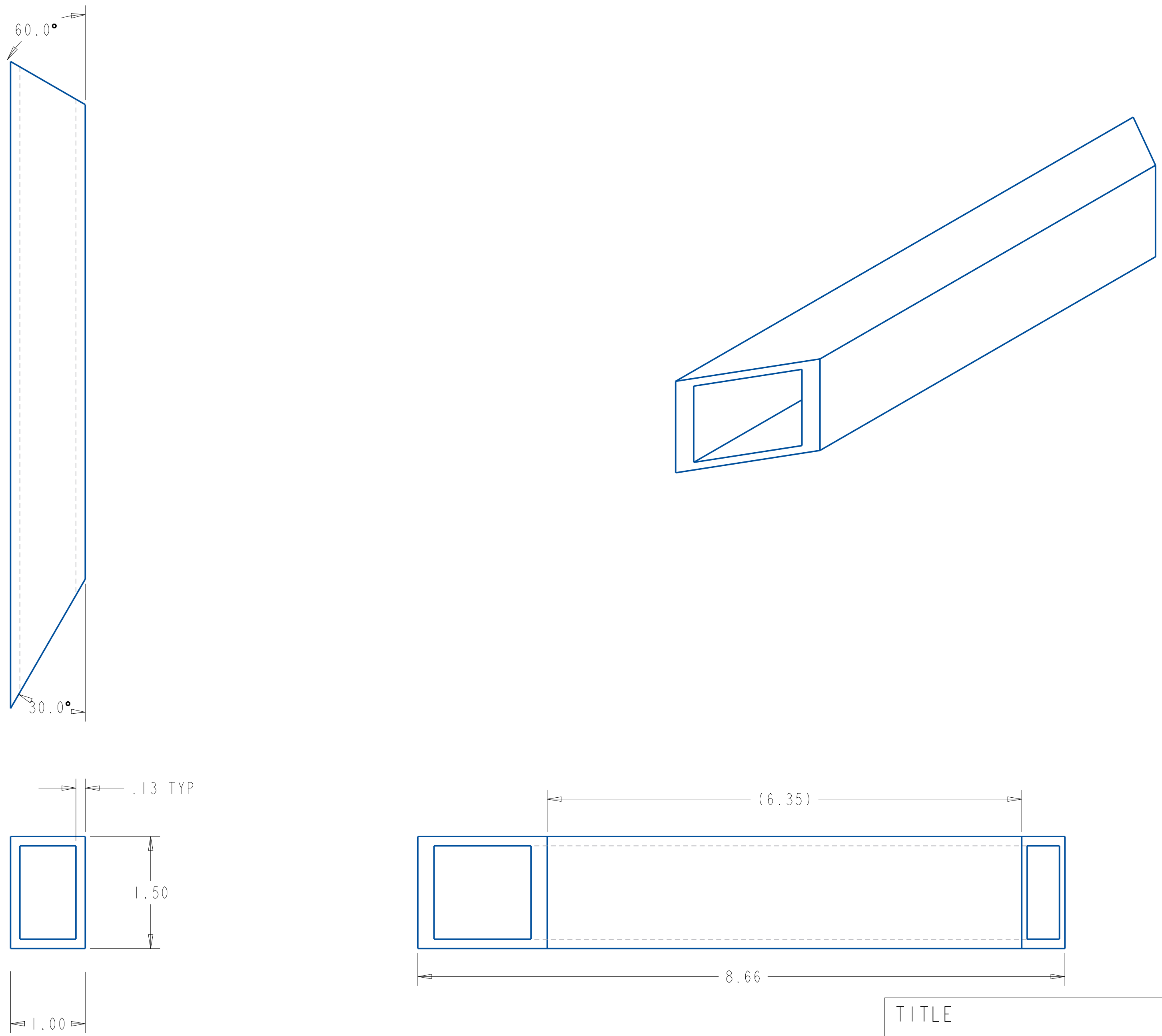

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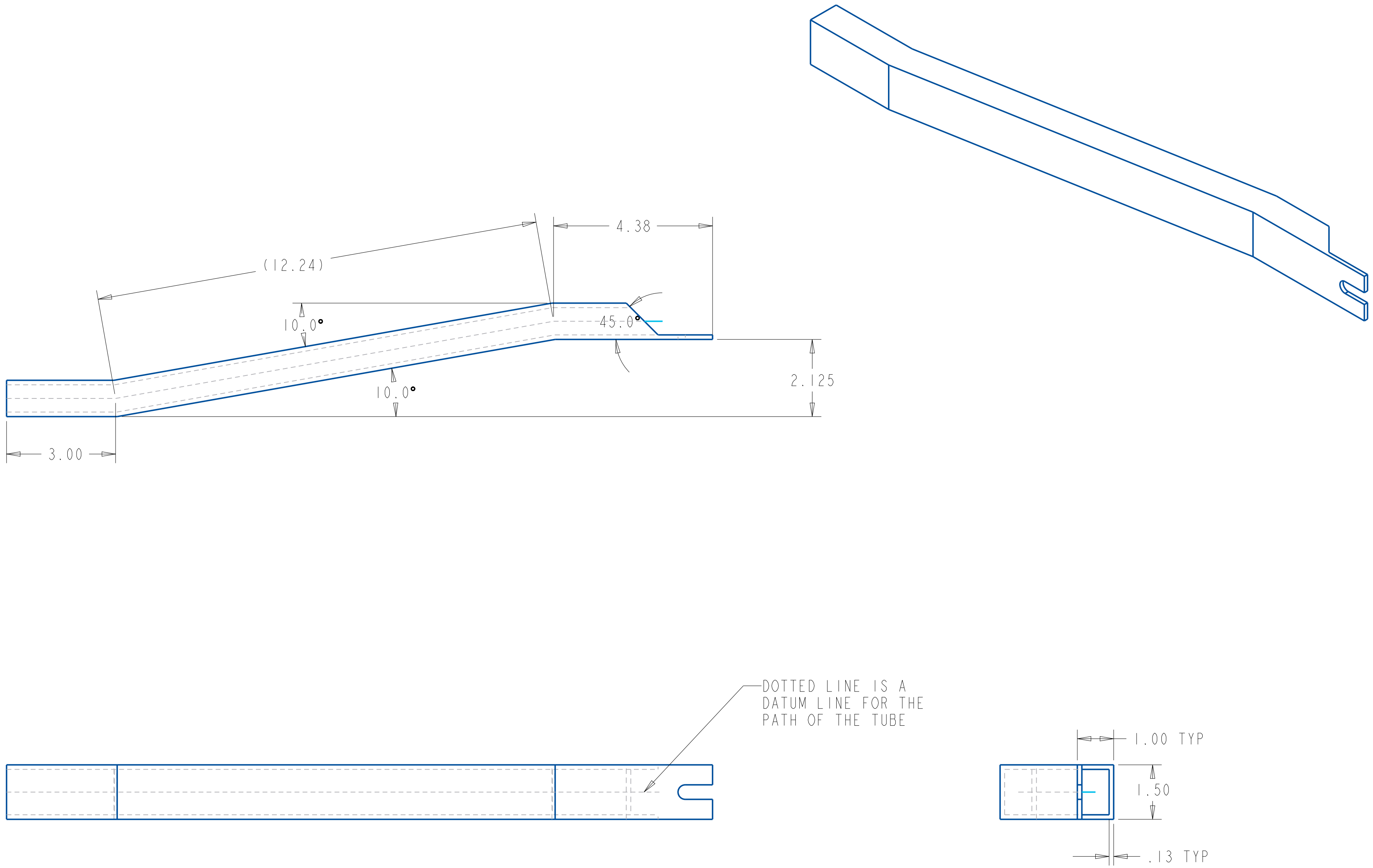

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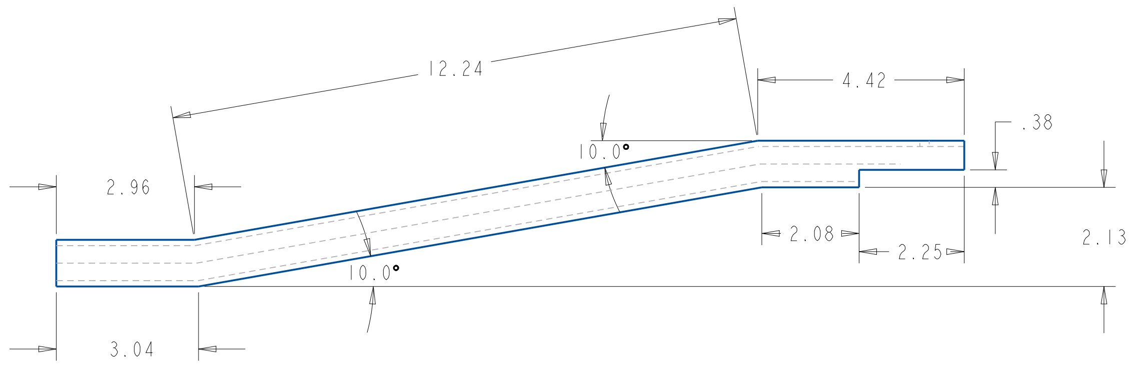

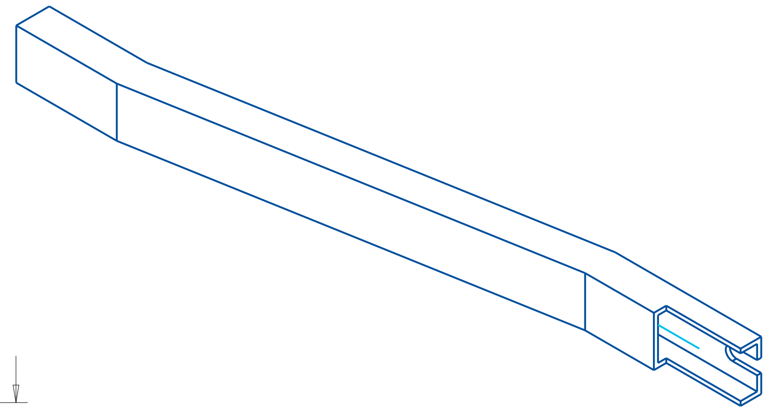

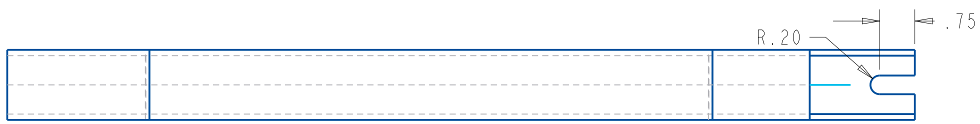

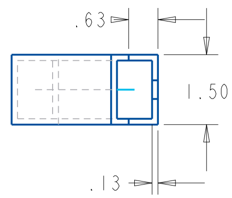

GENERAL TOLERANCES
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NOTE: IF POSSIBLE, BEND THE TUBE TO THESE DIMENSIONS,
OTHERWISE, CUT THE TUBES AND WELD BACK TOGETHER
TO FORM ANGLES SHOWN

TITLE				
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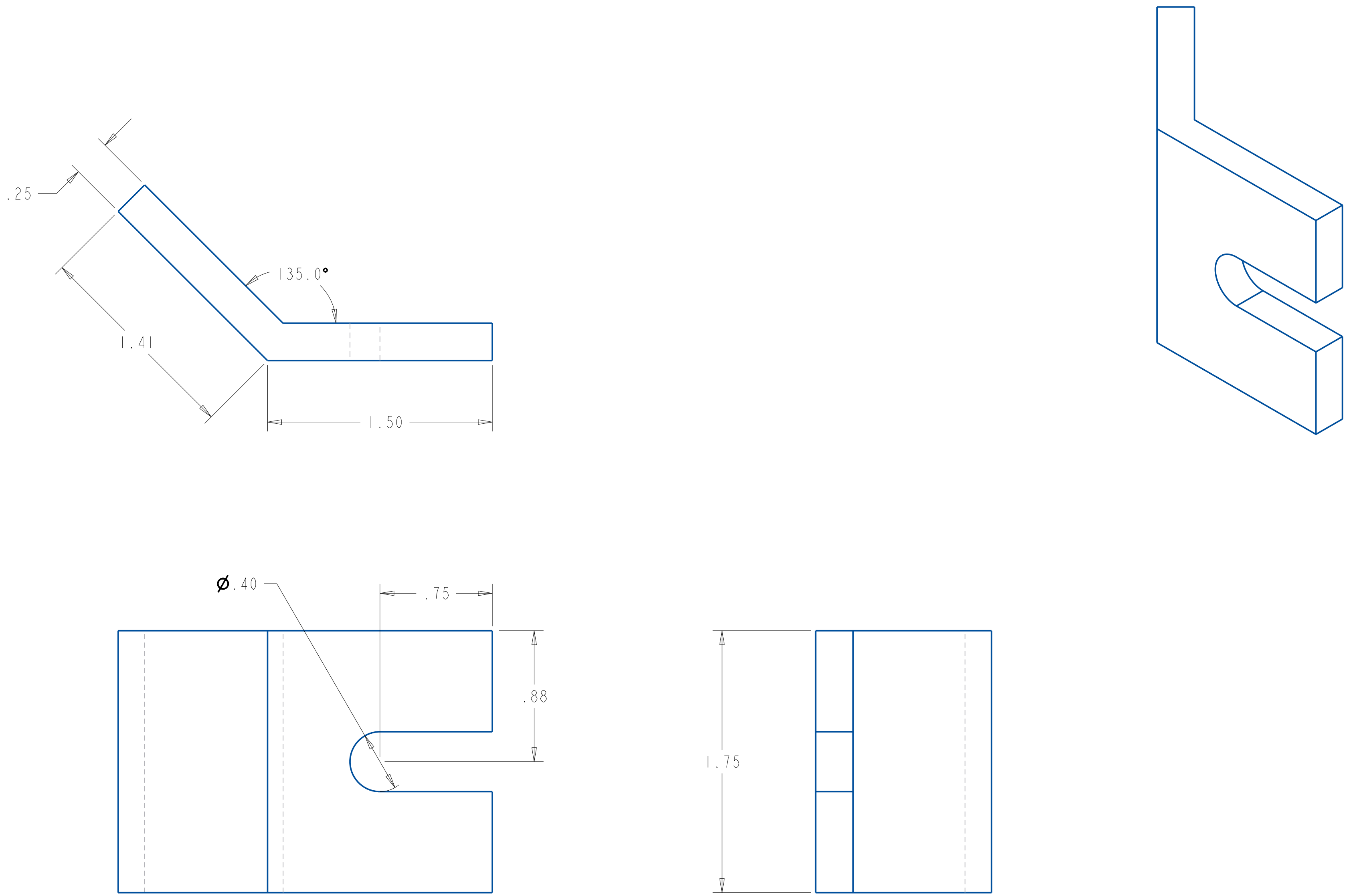

GENERAL TOLERANCES
.XX +/-.01
.XXX +/-.005

TITLE: REAR_FLANGE			
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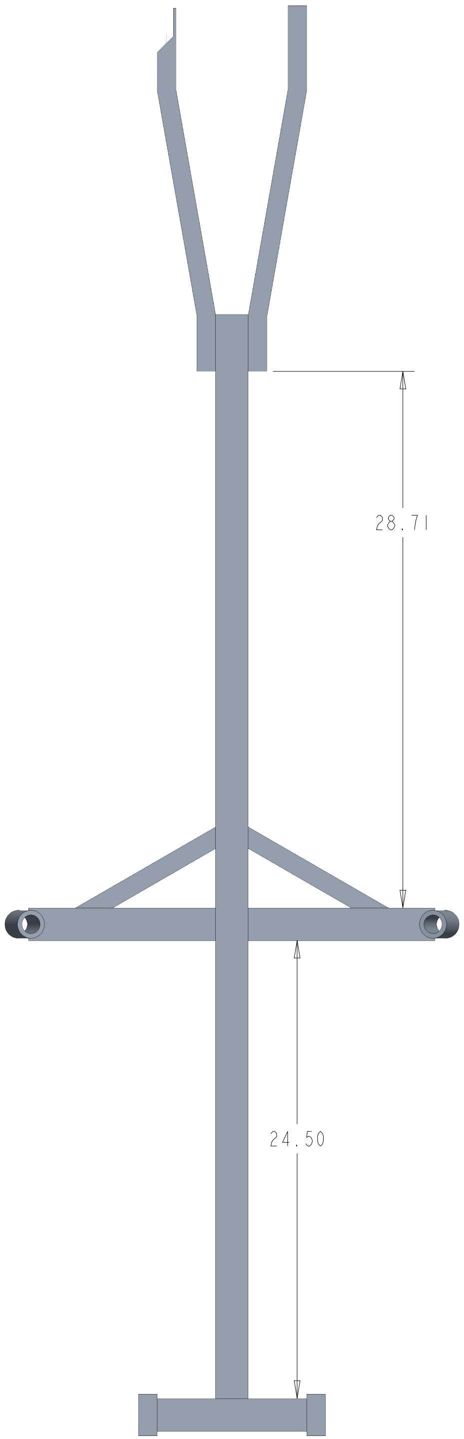
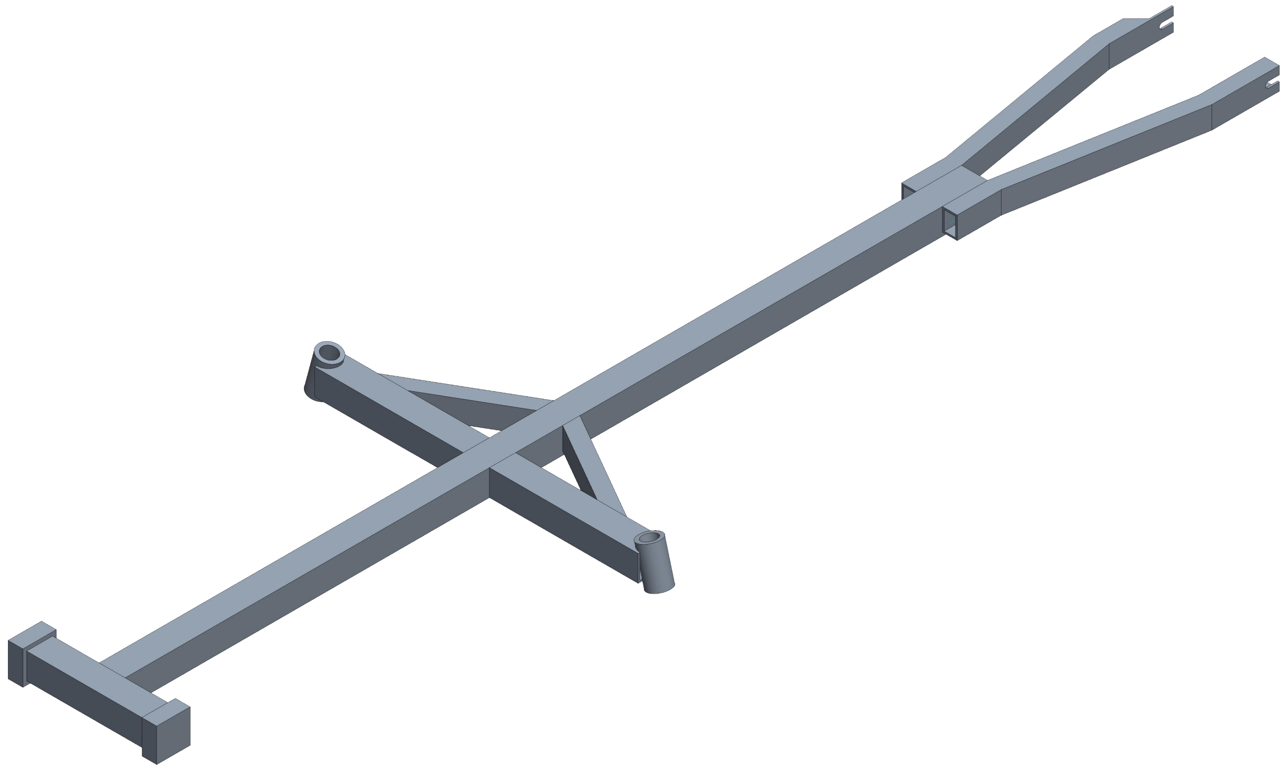
MATERIAL: ALUMINUM	DRAWING SIZE: C	SHEET: 1 OF 1	DATE: 12/16/18
UNITS: INCHES			





GENERAL TOLERANCES
.XX +/-.01
.XXX +/-.005

TITLE TANK_ASSEMBLY				
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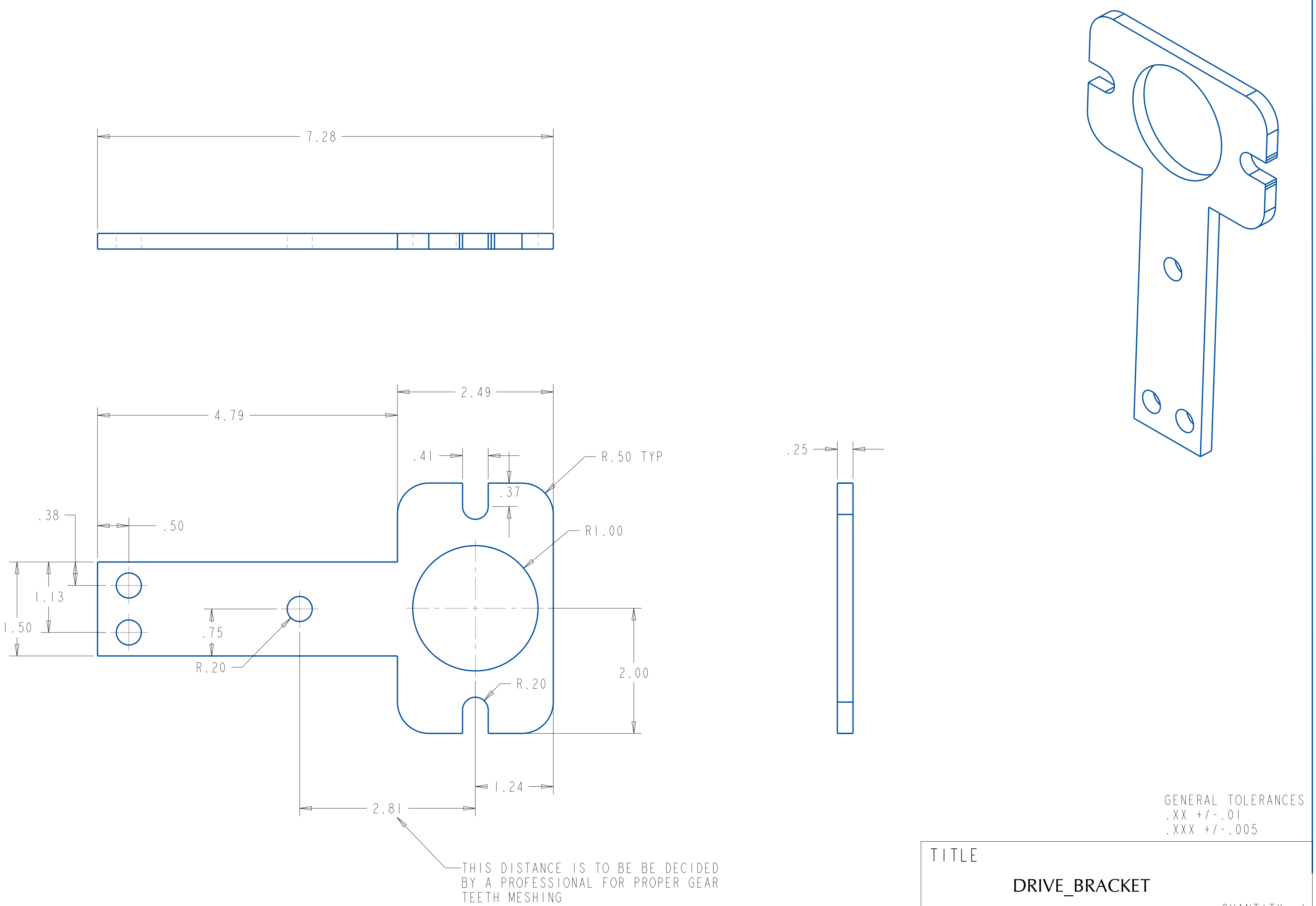
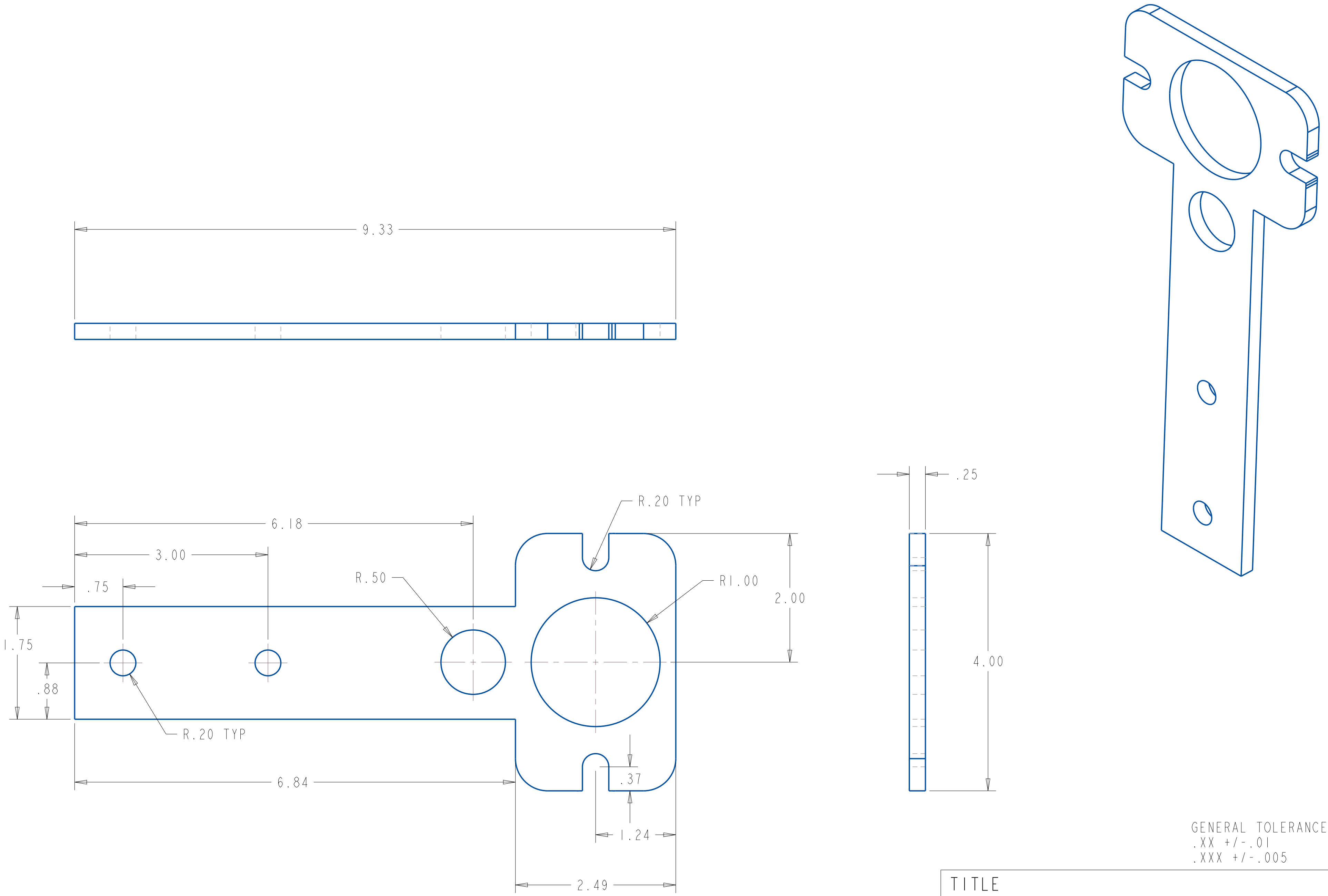
UNITS INCHES	MATERIAL ALUMINUM	DRAWING SIZE C	SHEET 1 OF 1	DATE 12/17/18



GENERAL TOLERANCES
.XX +/-.01
.XXX +/-.005

TITLE				
DRIVE_BRACKET			QUANTITY: 1	
	SCALE 1.000	DRAWN BY TIM WILLIAMS		DRAWING NO. 8
UNITS INCHES	MATERIAL ALUMINUM	DRAWING SIZE C	SHEET 1 OF 1	DATE 12/16/18



GENERAL TOLERANCES
.XX +/-.01
.XXX +/-.005

	TITLE REGEN_BRACKET_1			
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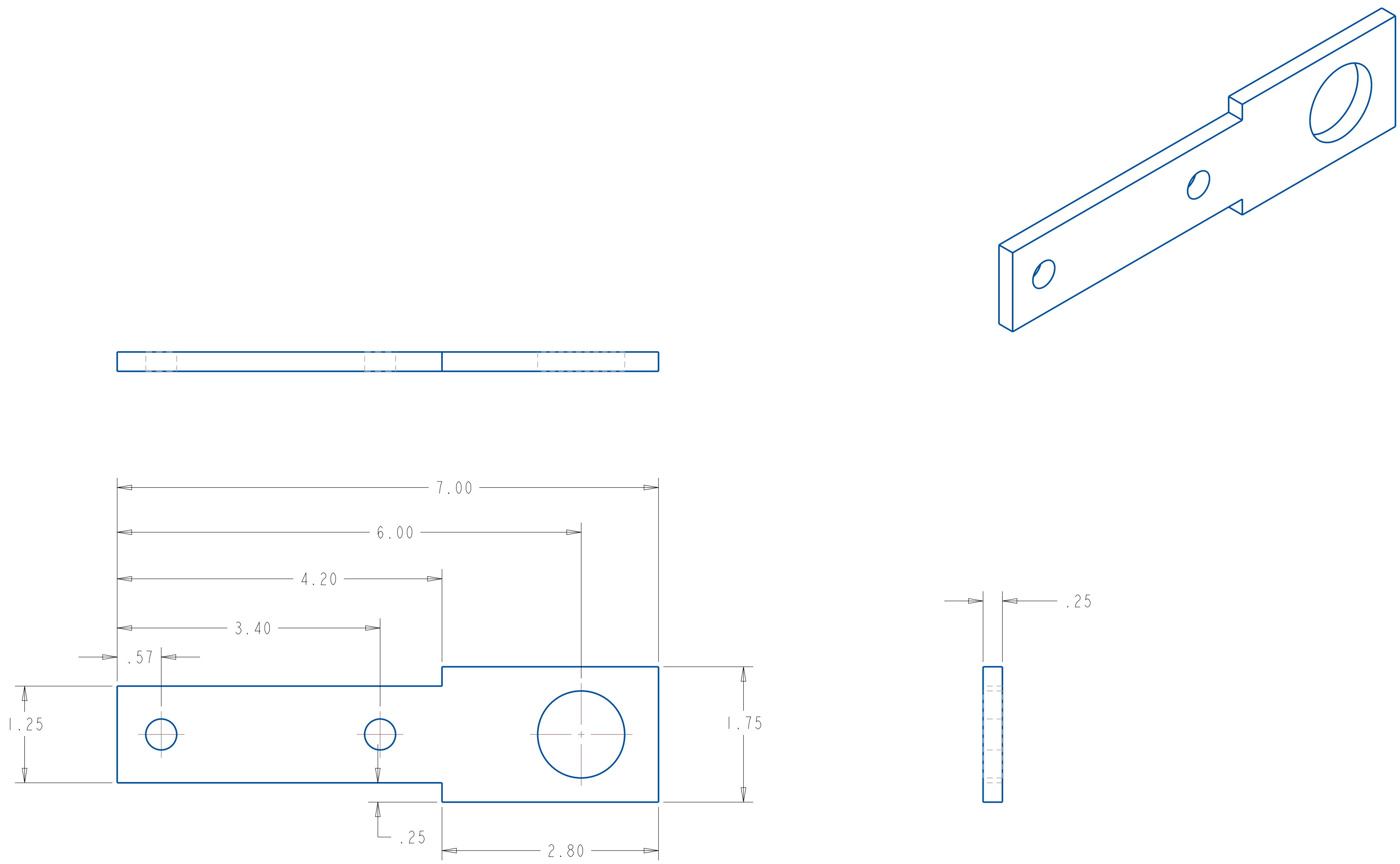
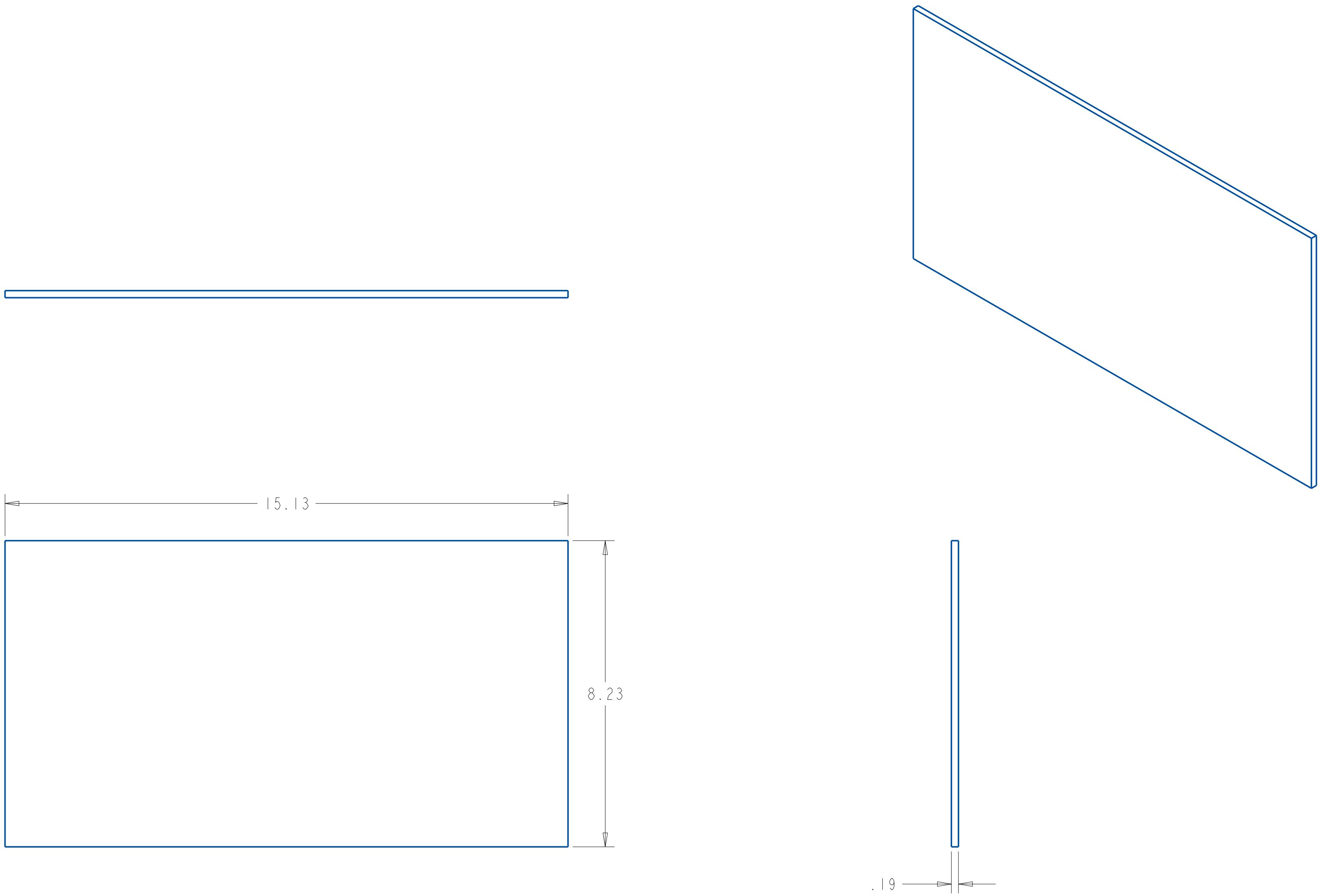
UNITS INCHES	MATERIAL ALUMINUM	DRAWING SIZE C	SHEET 1 OF 1	DATE 1/31/19



GENERAL TOLERANCES
.XX +/-.01
.XXX +/-.005

TITLE REGEN_BRACKET_2			
SCALE 1.000	DRAWN BY TIM WILLIAMS		DRAWING NO.
MATERIAL ALUMINUM	DRAWING SIZE C	SHEET 1 OF 1	DATE 1/31/19

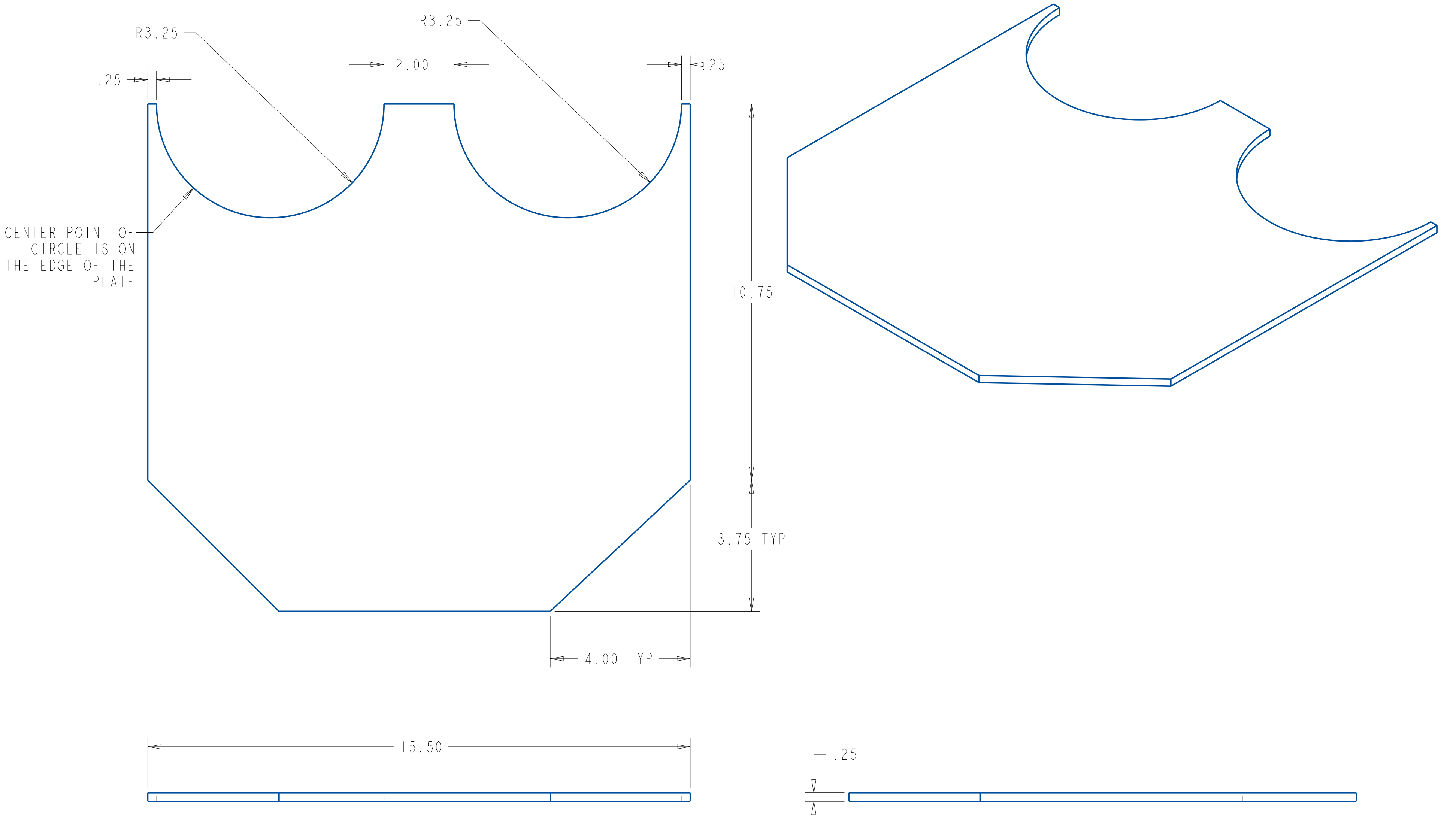
UNITS INCHES



GENERAL TOLERANCES
.XX +/-.01
.XXX +/-.005

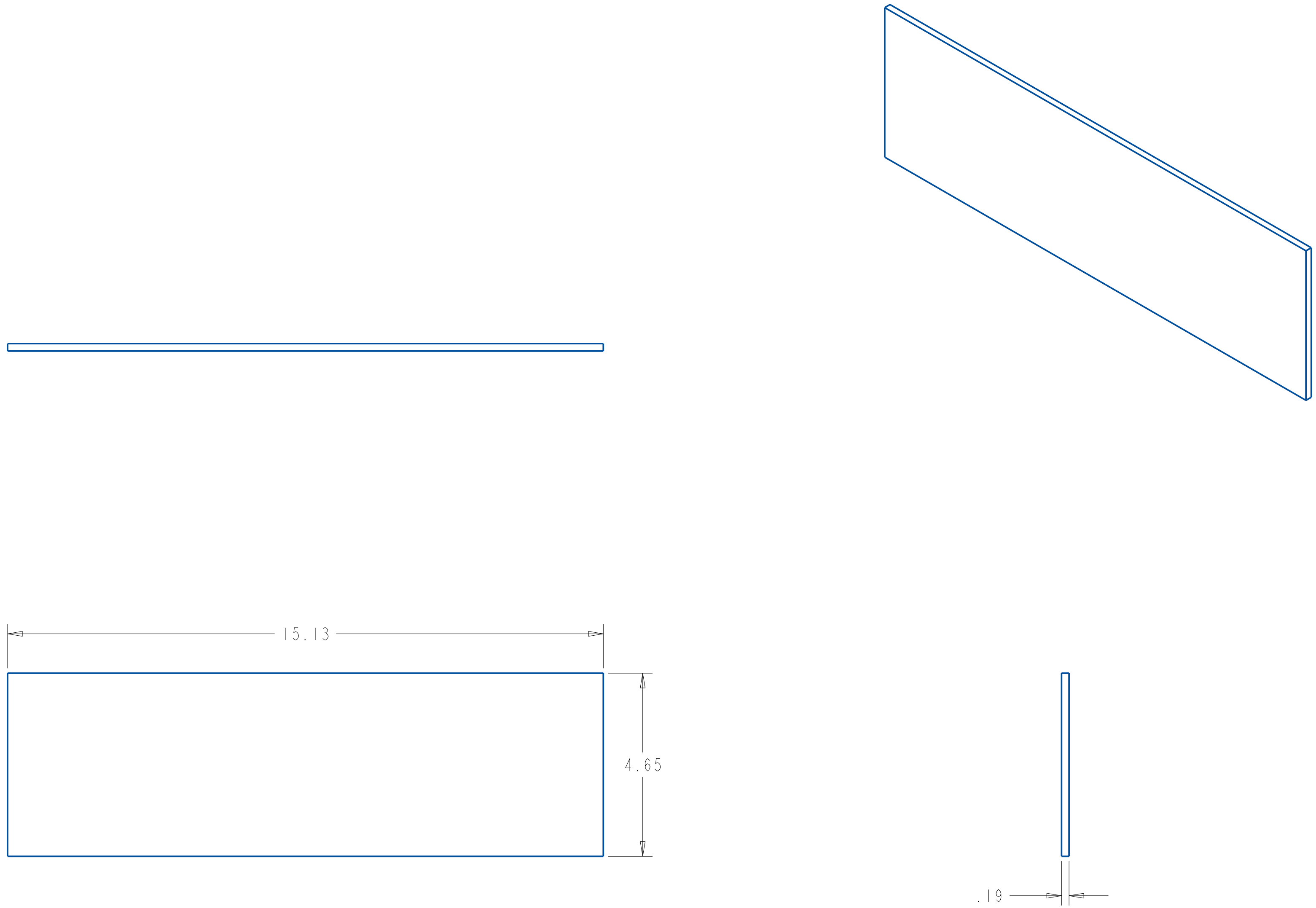
TITLE TANK_BACK			
SCALE 0.500	DRAWN BY TIM WILLIAMS		DRAWING NO. 5
MATERIAL ALUMINUM	DRAWING SIZE C	SHEET 1 OF 1	DATE 12/17/18

UNITS INCHES



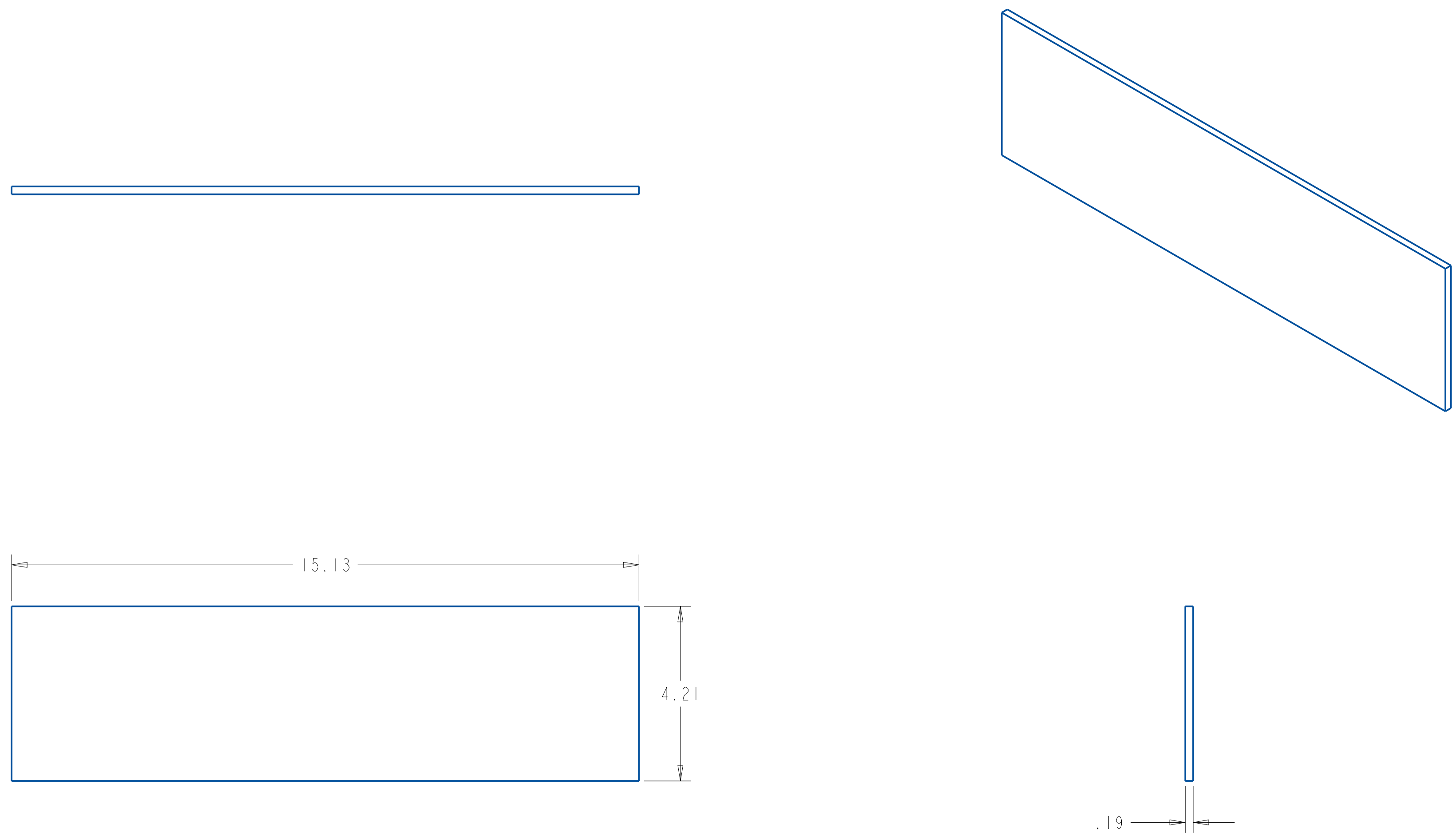
GENERAL TOLERANCES
.XX +/-.01
.XXX +/-.005

TITLE: TANK_BOTTOM				
SCALE: 0.500		DRAWN BY: TIM WILLIAMS		DRAWING NO.: 1
UNITS: INCHES	MATERIAL: ALUMINUM	DRAWING SIZE: C	SHEET: 1 OF 1	DATE: 12/17/18



GENERAL TOLERANCES
.XX +/-.01
.XXX +/-.005

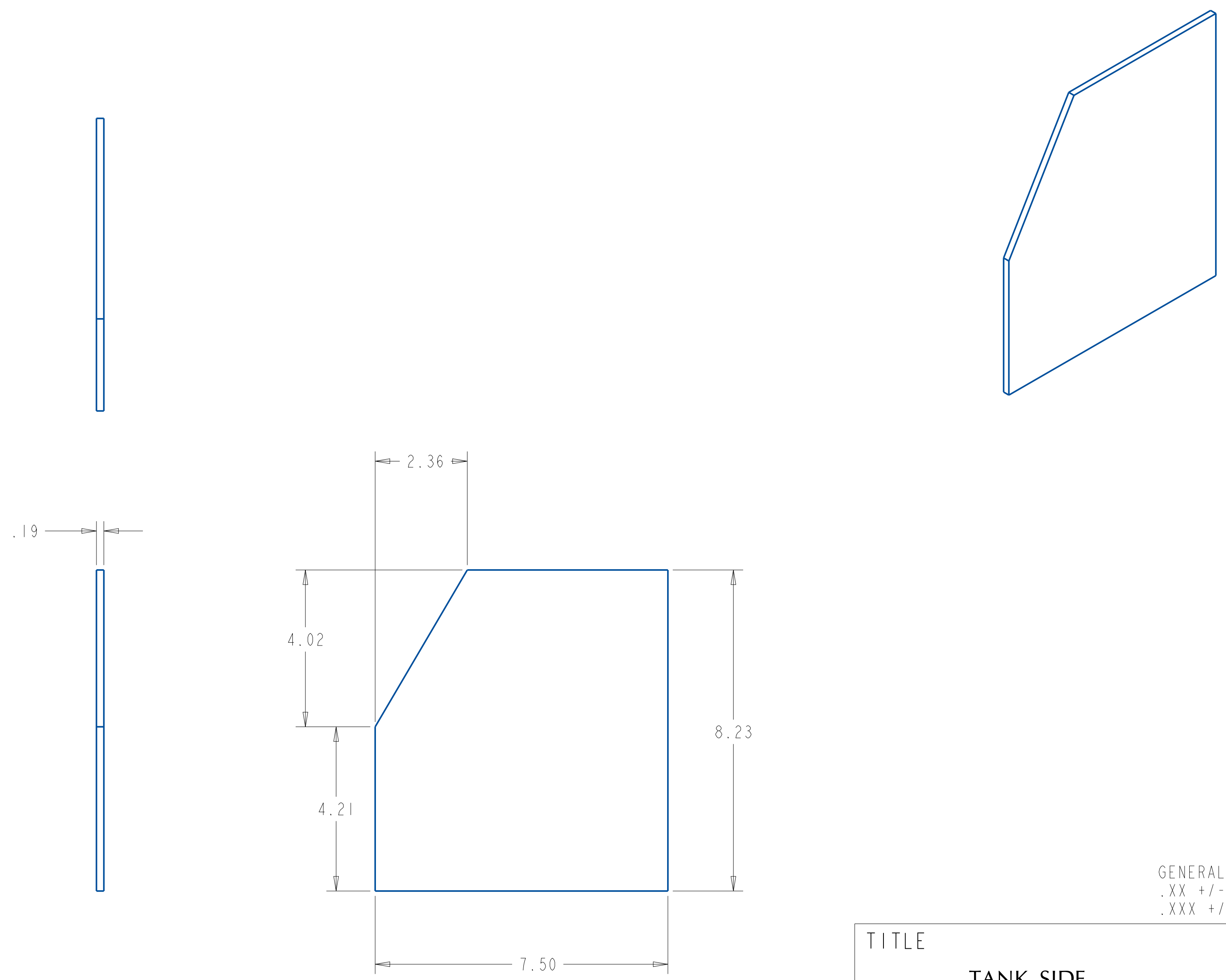
TITLE TANK_DIAGONAL			
SCALE 0.500	DRAWN BY TIM WILLIAMS		DRAWING NO. 4
UNITS INCHES	MATERIAL ALUMINUM	DRAWING SIZE C	SHEET 1 OF 1	DATE 12/17/18



GENERAL TOLERANCES
.XX +/-.01
.XXX +/-.005

TITLE TANK_FRONT			
SCALE 0.500	DRAWN BY TIM WILLIAMS		DRAWING NO. 3
MATERIAL ALUMINUM	DRAWING SIZE C	SHEET 1 OF 1	DATE 12/17/18

UNITS INCHES



GENERAL TOLERANCES
.XX +/-.01
.XXX +/-.005

	TITLE TANK_SIDE			
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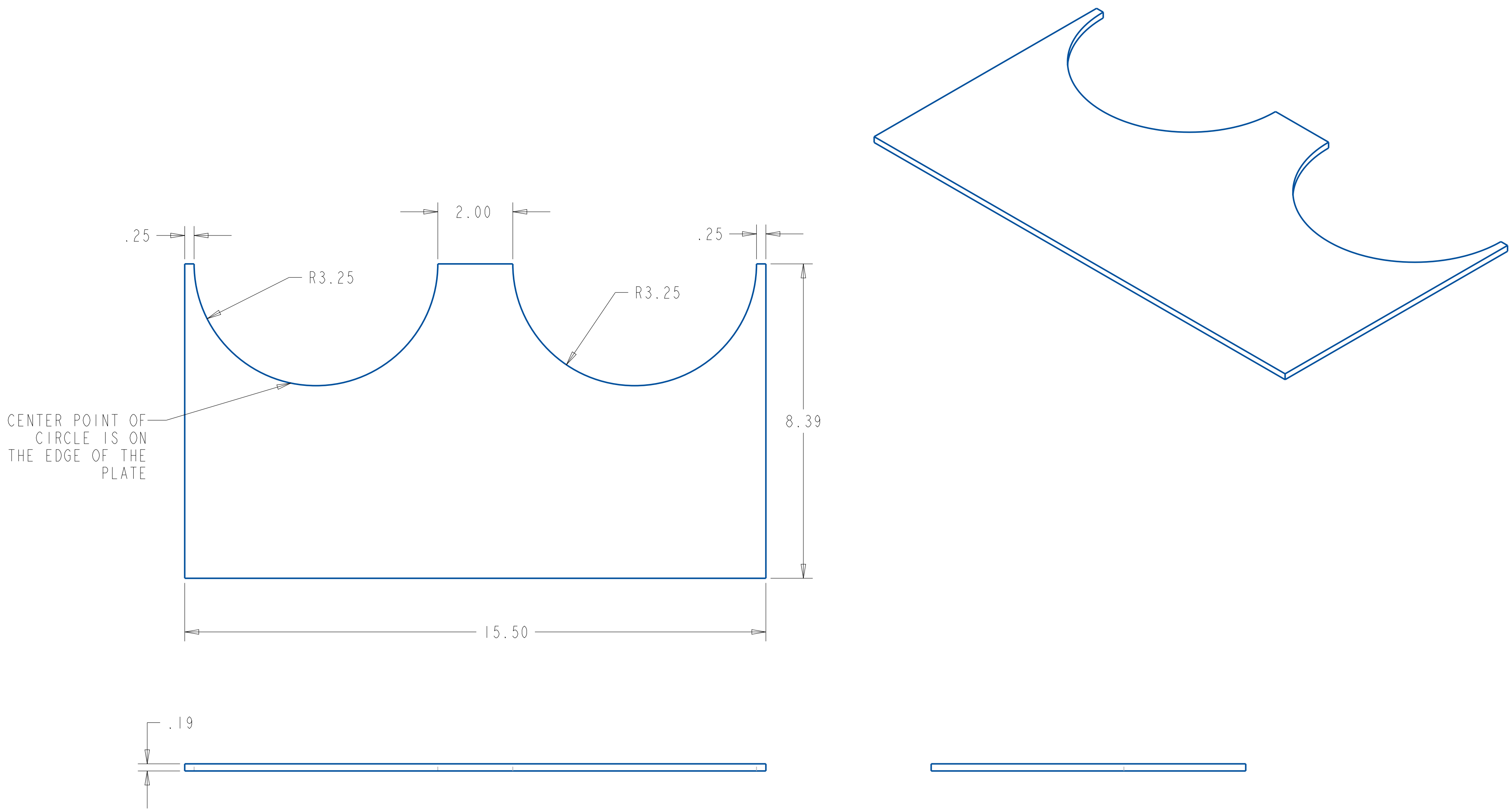
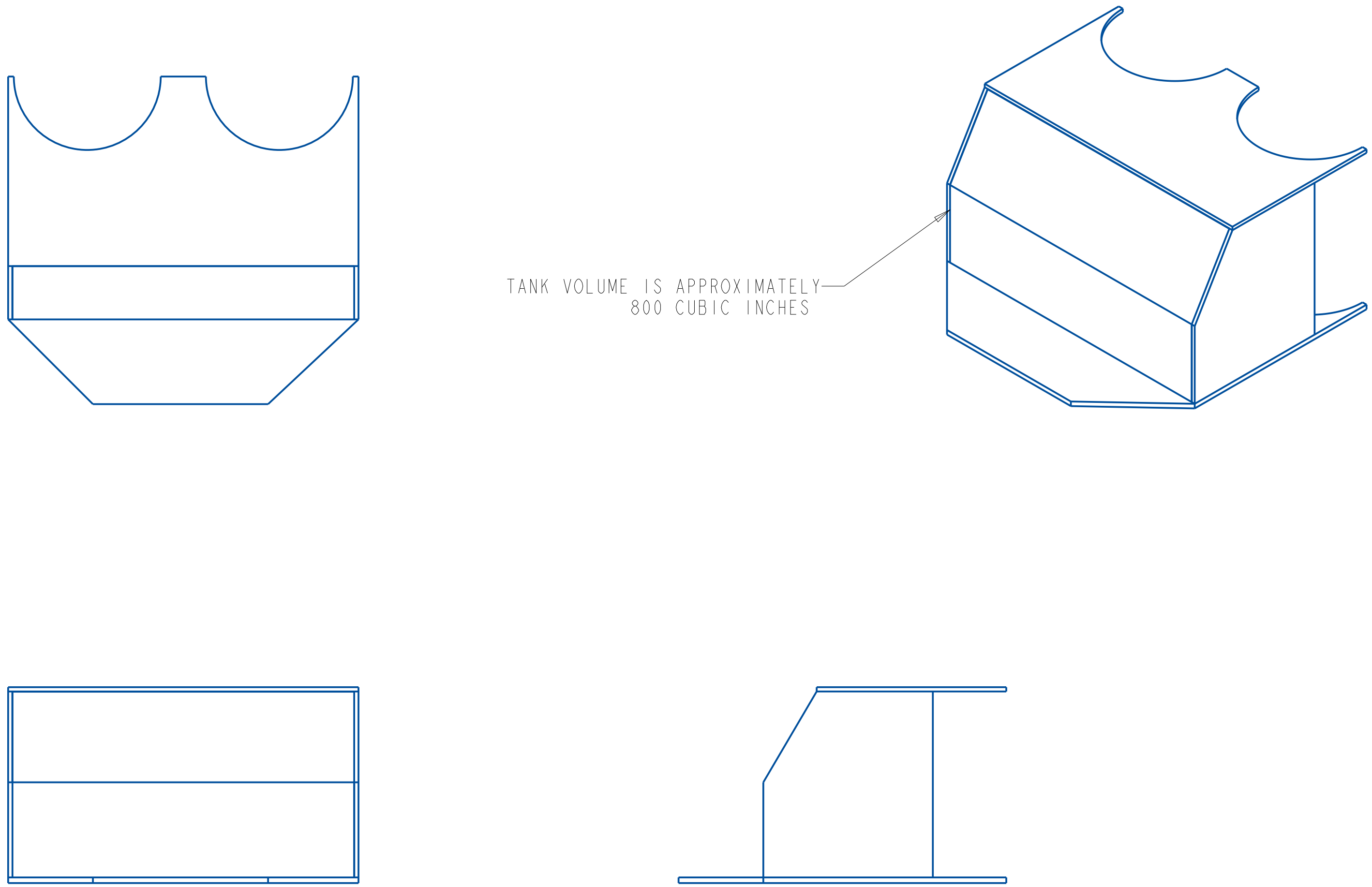
UNITS INCHES	MATERIAL ALUMINUM	DRAWING SIZE C	SHEET 1 OF 1	DATE 12/17/18



GENERAL TOLERANCES
.XX +/-.01
.XXX +/-.005

TITLE: TANK_TOP			
SCALE: 0.500	DRAWN BY: TIM WILLIAMS		DRAWING NO.: 6
MATERIAL: ALUMINUM	DRAWING SIZE: C	SHEET: 1 OF 1	DATE: 12/17/18

UNITS: INCHES



GENERAL TOLERANCES
.XX +/-.01
.XXX +/-.005

	TITLE TANK_ASSEMBLY			
	SCALE 0.250	DRAWN BY TIM WILLIAMS		DRAWING NO. 7
UNITS INCHES	MATERIAL ALUMINUM	DRAWING SIZE C	SHEET 1 OF 1	DATE 12/17/18

Bibliography

[1] E. Busquets and M. Ivantysynova. “A Robust Multi-Input Multi-Output Control Strategy for the Secondary Controlled Hydraulic Hybrid Swing of a Compact Excavator With Variable Accumulator Pressure”. In: *Proceedings of the ASME/ BATH 2014 Symposium on Fluid Power & Motion Control* (2014), 10.1115/FPMC2014–7859.

[2] B. Carl, M. Ivantysynova, and K. Williams. “Comparison of operational characteristics in power split continuously variable transmissions. Tech. Rep”. In: *Sae technical paper* (2006).

[3] M. Ivantysinova, B.A. Carl, and K.R. Williams. *Power split transmission with energy recovery*. US Patent 20080081724 A1. 2008. URL: https://patents.google.com/patent/US8277352B2/en.

[4] R. Kumar. “A power management strategy for hybrid output coupled power-split transmission to minimize fuel consumption”. PhD Thesis. Purdue University, 2010.

[5] R. Kumar and M. Ivantysynova. “The hydraulic hybrid alternative for toyota prius - a power management strategy for improved fuel economy”. In: *7th International Fluid Power Conference (7. IFK)* Vol. 2 (2010), p. 329–341.

[6] Nicola Nervegna. *Oleodinamica e pneumatica: Sistemi - Vol. 1*. Torino: Politeko, 2001.

[7] NFPA. *18-19-FPVC-Overview-Rules-and-Awards-1*. URL: https://nfpahub.com/wp-content/uploads/sites/4/2017/08/18-19-FPVC-Overview-Rules-and-Awards-1.docx.

[8] Jr. Parker J.F. and V. R. West. *Bioastronautics data book, second edition*. Washington: NASA, 1973.

[9] G.L. Zarotti and R. Paoluzzi. *Oleodinamica*. Roma: CNR Edizioni, 2004.