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DESIGN OF AN ELECTRO-PNEUMATIC GEAR SHIFTER FOR A FORMULA SAE VEHICLE

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Abstract. *This work presents the design of a new gear shifter for a Formula SAE vehicle, developed by the Formula CEM team from the Federal University of Santa Catarina. The team's former gear shifter had proven itself to be unreliable and faulty, compromising the overall performance of the vehicle during the competition. Back's et al PRODIP methodology was applied to the selection and design of the product, relying on boundary conditions and design alternatives supported by mathematical models, benchmark, and experimentation. The authors conclude with a semi-automatic electro-pneumatic device for gear selection and clutch activation. Tests of the mechanism, either in laboratory and on track, are presented and the results are discussed.*

Keywords: *FSAE, PRODIP, Gear Shifter, Pneumatic, Development*

1. INTRODUCTION

Formula SAE (FSAE) is an engineering competition organized by the Society of Automotive Engineers (SAE) that challenges students to conceive, design, manufacture and compete with small formula-style racing cars. Teams spend eight to twelve months designing, building and preparing their vehicles for the competition. These cars are judged on a series of static and dynamic events, including technical inspection, cost, presentation, engineering design, ground performance tests and high performance endurance.

The most used engines in the Internal Combustion (IC) category are those of motorcycles, due to a limitation imposed by the competition rules on engine capacity. Since motorcycles are designed for the rider to shift gears directly in the gearbox with their feet, FSAE teams usually have to design an external gear shift mechanism that can transmit the pilot's hand movement from the cockpit to the rear of the vehicle, where the engine is usually located.

Formula CEM is the FSAE team of the Federal University of Santa Catarina at Joinville Technological Centre. They annually design two cars, IC (Fig.1) and EV (Electric Vehicle) powered. The team has participated in FSAE Brazil for ten years and in 2018 they implemented the XT660 motorcycle engine in their combustion project. Ever since their first competition the external gearshift mechanism was based on a system of levers and cables (to transmit the input given by the pilot in the cockpit to the gear selector shaft) and a clutch pedal, connected by cables to the clutch drive shaft, to cease torque flow in gear shift.

Figure 1. Formula CEM 2019 Project at the Endurance

However, as the team progressed through the competition, pilots and designers reported a lack of reliability, robustness and speed in this design solution. The mechanism requires constant maintenance to readjust the tension of the cables. There is also hysteresis in the system, that is, with the recurrent activation of the shift lever, the response gradually becomes slower, as the lever stroke gradually increases. At the end of the Endurance, the pilot is no longer able to shift gears, as the cables and levers are already loose and present mechanical failures. Thus, this work aims to solve the team's problem by delivering a product that meets the requirements of the customer and engineering.

2. METHODOLOGY

The methodology used in the design and manufacture of the external gearshift mechanism of the Formula CEM team's combustion prototype is the PRODIP. The team has implemented this method in almost all of its projects and it has shown great results related to their overall quality and organization, directly reflecting on the satisfaction of customer requirements (pilots, stakeholders, sub teams).

The design methodology arises from a need to strategically organize the development of a product, from its conception to the post-launch. Since designers have central responsibility for the technical and economic properties of a product, it is essential to have a systematic and defined design procedure that finds good solutions for the target audience. This procedure must, above all, be flexible, capable of being planned, optimized and verified. The methodology includes project phases, strategies, rules and principles to achieve general and specific objectives. However, this systematic process should not detract from the importance of experience and intuition, but rather increase the output and inventiveness of talented designers (Pahl *et al.*, 2007).

PRODIP is a design methodology developed in the mechanical engineering department at UFSC (Back *et al.*, 2008). Its first version was based on the NEDIP (Product Development Nucleus) experience in the design, construction and testing of agricultural machinery prototypes. It takes a similar approach to Pahl *et al.* (2007) and consists in dividing the project into three macro phases: planning, design and implementation.

The purpose of the planning phase is to define product ideas to be developed over a period of time. It also includes project planning, in which development plans for selected product ideas are established. The design phase has four micro phases: the Task Clarification, the Conceptual Design, the Embodiment Design and the Detail Design.

The Task Clarification develops the product specifications according to the customers requirements. The main tools used in this step are the QFD (Quality Function Deployment) matrix, the Mudge diagram and the Morphological matrix. The Conceptual Design aims to explore different design solutions. Each alternative is evaluated technically and economically. The main tool applied in this step is the multi-criteria selection matrix. Among the types of decision matrices is the Pugh matrix. The Embodiment Design specifies the main mechanism dimensions and characteristics in terms of layout, materials and manufacturing processes. The Detail Design consists of the development of the final product and production documentation such as technical drawings, assembly sheets and process sheets.

Finally, the Implementation phase, which consists of production preparation (in which the pilot batch of the product is developed), the launch, when the production is monitored and the quality of the initial batch is monitored, and the validation, which consists of evaluating the product together with users.

Considering that this work is a prototype of a competition team, that is, there is no large-scale production, the PRODIP model was adapted to the reality of the project. In this sense, the work will be organized according to the flowchart in Fig.2.

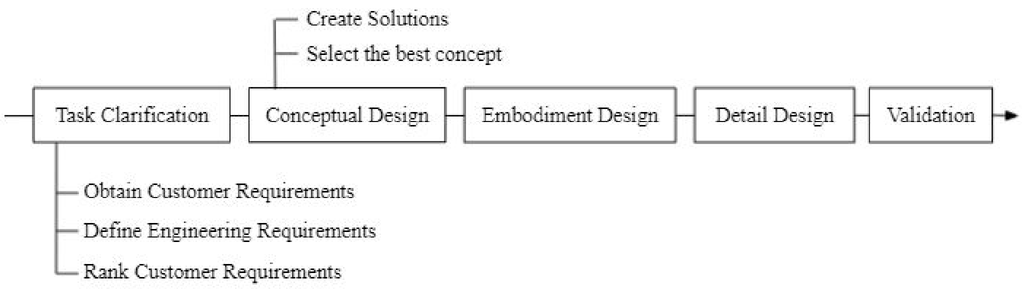


Figure 2. The Design Methodology

The flowchart shows that the large-scale production phases have been eliminated. For example, the planning phase has not been carried out because the team already has a fixed schedule of project milestones and there was no need to make another one. The implementation phase has also been shortened to just prototype validation, since pilot batches will not be produced. In a different perspective, considering that the competition takes as a premise that the vehicle will be later produced on a large scale, it can also be said that the shifter design would encompass all phases of the PRODIP up to the detailed design and the prototype validations would still be part of the design adjustments and not the validation of the final product after the industrialization phase.

Similar works as Chalmela (2017) and Suryavanshi (2017) did not use a design methodology. They directly addressed the product sizing characteristics without defending the choice of the concept in the first place. The works also did not compare the final results with previous projects, nor did they define initial objectives to be achieved. On the other hand, automakers rigidly apply systematic product development methodologies, and many of them share the same nature as PRODIP and Pahl *et al.* (2007) methodology. However, there is no explicit evidence of the use of PRODIP in this specific engineering sector.

3. RESULTS

3.1 Task clarification

The first approach of the design was to interview the main clients of the project: the pilots and the team related to the previous design. Similar needs and suggestions were listed, according to Tab.1.

Table 1. Compilation of customers requirements

Index	Customers Requirements
A	Reliability
B	Increase gear changing speed
C	Simplicity
D	Robustness
E	Comfort
F	Improve track time
G	Ease of maintenance
H	Economically feasible
I	Easy integration with the project

The customer requirements were sorted with the aid of the Mudge Diagram, a tool that allows functions comparisons, in order to sort them by relevance, thus carrying out a systematic analysis of the needs and their implications in the product's result (Rocco and Silveira, 2008). The grades were assigned by the engineering team and the values of each index were added, obtaining a relative score to each costumer need, according to Tab.2.

Table 2. Mudge Diagram

A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**Points**	**Relative Grade**	**Sort**
A	A5	A3	A1	A3	A5	A3	A3	A4	27	27%	A
	B	C1	D4	E2	F3	G2	B1	B2	3	3%	F
		C	D3	E2	F3	G2	H2	C2	3	3%	D
			D	D3	D2	D2	D2	D3	19	19%	E
				E	F3	E2	E3	E4	13	13%	G
					F	F4	F4	F4	21	21%	H
						G	G2	G3	9	9%	B
							H	H2	4	4%	C
								I	0	0%	I

Therefore, the most relevant customers requirements are reliability, improve the track time and robustness. After the interview, the customer needs were translated into technical parameters, which are measurable, called project requirements (or engineering characteristics), listed on Tab.3.

Table 3. Compilation of customers requirements

Engineering Characteristics
Failure Probability (%)
Gear changing speed (s)
Track time (s)
Cost (R$)
Total Weight (kg)
Design time (work days)
Actuation Force (N)

The QFD matrix correlates customer requirements with project requirements, determining the importance of each engineering variable from the perspective of customer needs. For each customer requirement, a correlation score must be assigned between the engineering requirements. For this work, grade 5 is assigned for strong correlation, 3 for medium correlation, 1 for weak correlation and 0 for null correlation. In addition to the grades, a weighting will be assigned based on the results of the Mudge diagram, which ranks customer requirements. In this way, the matrix can reveal the engineering variable that has the greatest impact on customer needs.

Table 4. Simplified QFD Matrix

Customer Importance	Costumer Requirements / Engineering Characteristcs	Failure Probability (%)	Gear changing speed (s)	Track time (s)	Cost (R\$)	Total Weight (kg)	Design time (work days)	Actuation Force (N)
27	**Reliability**	5	0	1	3	1	1	1
21	**Improve track time**	1	5	5	3	3	1	0
19	**Robustness**	5	0	1	3	3	3	3
13	**Comfort**	1	1	3	1	1	1	5
9	**Easy maintenance**	1	0	0	1	1	1	0
4	**Economically feasible**	1	3	3	5	1	1	0
3	**Increase gear changing speed**	0	5	5	3	1	3	3
0	**Easy integration with the project**	1	0	0	1	0	5	0
	Importance Rating Sum (Importance x Relationship)	277	148	220	261	185	155	158
	Relative Weight	20%	11%	16%	18%	13%	11%	11%

According to Tab.4, the failure probability, the cost and the track time are the most critical aspects of analysis and design choice.

3.2 Conceptual design

The conceptual project begins by modeling the product in a functional and abstract way, in the form of functions, structured with the flows that involve the project; and presents compatibility: the input of a function must be associated with the output of the previous function (Rozenfeld *et al.*, 2010). To carry out the relationships between the functions of the product, the FAST method (Function Analysis System Technique) was used (Fig.3), which consists of creating a horizontal diagram, structuring the process under analysis in a logical and systemic way, in search for the best performance in the execution of the functions needed.

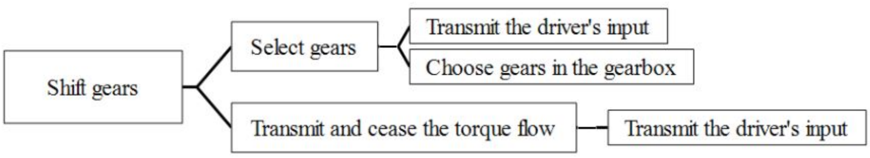


Figure 3. FAST Diagram

The diagram starts from the left with the global function of the project and finishes with the elementary functions. The next step is to find a physical effect for the elementary functions, which through certain behaviors are able to achieve the objective of the present function (Rozenfeld *et al.*, 2010). Each function can present several possible solutions that will be shown in the morphological matrix (Tab.5).

Before evaluating all the solutions listed on Tab.5, an investigation was made to verify the feasibility of implementation. Even though they are all possible to be developed, it is important to consider that an FSAE vehicle aims for low weight to increase its competitiveness. Therefore, heavy components would not comply with the customer requirements of improving the track time (F) and the engineering requirement of minimum Total Weight.

In this sense, it is of the utmost importance to know the stroke and the torque required to shift the gears and to activate the clutch for a brief sizing of the concepts and to discard the ones that has no compliance with the project. As an initial parameter, an experiment was carried out in laboratory with the Fazer 250 engine, as the XT660 was not available at the

Table 5. Morphological Matrix

Elementary Functions		
Transmit driver's input (selecting gear)	Gear changing in gearbox	Transmit driver's input (torque flow)
Lever and push/pull cables (1)	Lever and push/pull cables (6)	Clutch pedal (14)
Lever with a rod (2)	Rod (7)	Hand clutch lever (15)
Lever with pure hydraulic system (3)	Lever with pure hydraulic system (8)	Pneumatic cylinder (16)
Lever with pure pneumatic system (4)	Pneumatic cylinder (9)	Linear actuator (17)
Paddle shifters (Electronic) (5)	Linear actuator (10)	Solenoid actuator (18)
	Solenoid actuator (11)	Hydraulic cylinder (19)
	Hydraulic cylinder (12)	Servo motor (20)
	Servo motor (13)	

time.

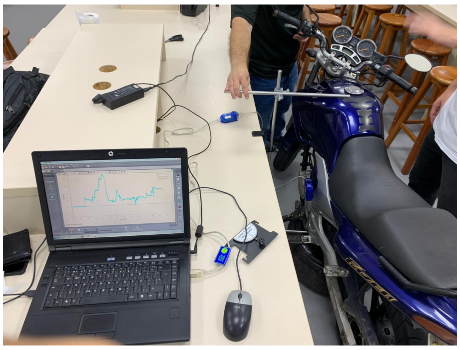


Figure 4. Laboratory Experiment to measure gear shifting stroke and torque

To measure the angular displacement relative to a gear shift, a protractor parallel and adjacent to the lever was installed. To measure the torque required, a digital dynamometer was installed on the levers of the motorcycle according to the experiment in figure 4. In addition, a simple ruler was used to measure the lever arm and then calculate the torque. The results of the experiment are shown in Tab.6.

All the mechanical concepts of Tab.5, such as levers, cables and rods can meet stroke and torque requirements without adding too much weight to the vehicle. On the other hand, a brief research has shown that hydraulic and solenoid concepts have to weigh more than 40 kilograms to meet the same requirements and therefore were not considered in the concept selection.

Table 6. Experiment's results

	Minimum Stroke	Minimum Torque
Gear selector shaft	22º	$8.3\ N \cdot m$
Clutch	45º	$12\ N \cdot m$

A multi-criteria selection matrix (Pugh matrix, Tab.7) was developed to select the conceptual design. The reference design is the former gearshifter mechanism, based on cables, levers and a clutch pedal. The engineering team assigned the scores and tried to remain unbiased toward any particular design.

According to the selection matrix, the concept of pneumatic gearshift mechanism activated by paddle shifters obtained the highest score. This solution would change the former manual transmission to a semi-automatic transmission and according to Naunheimer *et al.* (2011), this class combines the high efficiency of manual transmissions with the ease of operation of a fully automatic transmission.

3.3 Embodiment design

The Embodiment Design began by listing all the possible components of the product (Tab.8), then specifying each one in terms of dimension, materials and manufacture process.

In the experiments carried out in the laboratory, some design requirements were estimated using the Yamaha Fazer 250 engine. Firstly, it must be considered that the XT660 can have even higher parameters due to its greater power and capacity (cc - cubic centimeters), specially the torque needed to actuate the clutch. Considering this, the first sizing began

Table 7. Pugh Matrix

Criteria	Weight	Solution Principles													
		1	**2**	**4**	**5**	**6**	**7**	**9**	**10**	**13**	**14**	**15**	**16**	**17**	**20**
Reliability	27	0	1	1	1	0	1	1	0	0	0	0	1	0	0
Improve track time	21	0	0	1	1	0	0	1	0	0	0	1	1	0	0
Total Weight	20	1	-1	-1	0	0	0	0	1	1	0	1	0	1	1
Robustness	19	1	1	1	1	0	1	1	1	1	0	0	1	1	1
Comfort	13	0	0	0	1	0	0	1	1	1	0	1	1	1	1
Ease of maintenance	9	0	1	1	0	0	0	0	1	1	0	1	0	1	1
Economically feasible	4	0	0	-1	0	0	0	0	-1	-1	0	1	0	-1	-1
Gear changing speed	3	0	0	1	1	0	0	1	0	0	0	1	1	0	0
Simplicity	3	0	1	0	0	0	1	0	1	1	0	1	0	1	1
Overall Weighted Score		39	38	55	83	0	49	83	60	60	0	73	83	60	60

Table 8. Possible components

Components List
Air Tank
Pressure Regulator
Double Action Pneumatic Cylinder
Single Action Pneumatic Cylinder
Rod Ends
Solenoid Valves
Pneumatic Connections Adapters
Pneumatic Hoses
Air Silencer
Hand Clutch for Starting the Engine
Steel Sheet and Tubes for Cylinder Mount
Printed Circuit Board
Wires
Switches
Paddle Shifters

with the pneumatic cylinders. Due to a geometric issue (distance from the ground), previewed in the vehicle assembly (Fig.5), the gear selector axle actuation lever must have a length of approximately 5 cm. Thus, the exchange stroke in the horizontal direction must have a length of at least 2 cm, considering a gear shift angle of 22º. Since the gear shift will be carried out in both directions of the gear selector shaft and the cylinder rod end will be located in the middle of the stroke, the cylinder stroke has to be at least 40 mm. A research in a pneumatic products catalogue revealed that the 50 mm stroke cylinder is the best commercial option and guarantee any stroke difference between the engines.

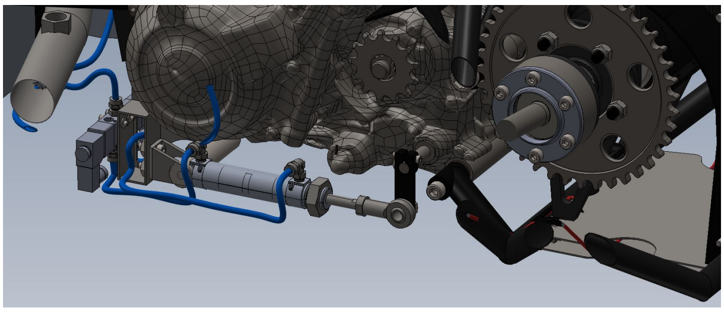
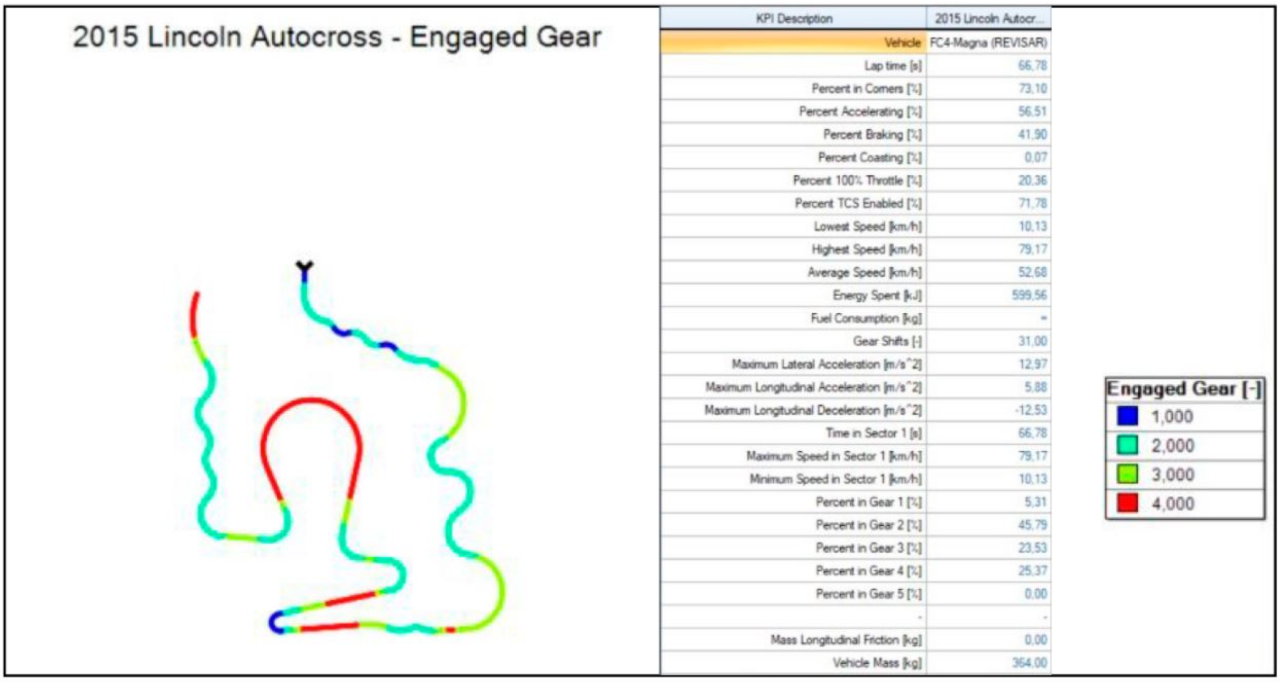


Figure 5. Double Action Cylinder actuating in the gear selector shaft

The torques obtained in Tab.6 will be considered at least 9 and 13.5 N.m for the XT660 and therefore, for the 5 cm and 4 cm lever arms, they are equivalent to a cylinder actuation force of 180 N and 338 N. Considering that the pneumatic tank needs to supply all the fluid necessary for the vehicle to finish the endurance test, the minimum cylinder volume will be considered so as not to oversize the gas tank. A working pressure of 5 bar was also chosen arbitrarily, as it has a good compromise between the theoretical force of the cylinders and the maximum pressure supported by the pneumatic components and the pressure line (10 bar). According to commercial catalogues, the 25 mm diameter cylinder, for both gear selection and clutch disengagement are the ones that can provide that minimum force. In this way, both cylinders are 25 mm in diameter and 50 mm in stroke (with stroke clearance in the clutch cylinder).

The most critical design factor is fluid consumption. It is essential to change gears whenever necessary, but a very large tank cannot be used, as this would add a lot of mass to the vehicle and end up worsening performance in dynamic tests, instead of improving it. To discover how many gear shifts the prototype has to execute to finish the endurance, a simulation in Optimum Lap Software was done using the 2015 Lincoln Autocross Track. The results are shown in Fig.6. Since one track requires 31 gear shifts, 22 tracks (endurance length) would require 682 gear shifts. It is necessary to introduce a safety factor in this result due to the tightness of the system and the geometry factor of the track. This safety factor was considered 1.2 and will increase the system capacity to 820 gear shifts.



KPI Description	2015 Lincoln Autocr...
Vehicle	FC4-Magna (REVISAR)
Lap time [s]	66,78
Percent in Corners [%]	73,10
Percent Accelerating [%]	56,51
Percent Braking [%]	41,90
Percent Coasting [%]	0,07
Percent 100% Throttle [%]	20,36
Percent TCS Enabled [%]	71,78
Lowest Speed [km/h]	10,13
Highest Speed [km/h]	79,17
Average Speed [km/h]	52,68
Energy Spent [kJ]	599,56
Fuel Consumption [kg]	-
Gear Shifts [-]	31,00
Maximum Lateral Acceleration [m/s^2]	12,97
Maximum Longitudinal Acceleration [m/s^2]	5,88
Maximum Longitudinal Deceleration [m/s^2]	-12,53
Time in Sector 1 [s]	66,78
Maximum Speed in Sector 1 [km/h]	79,17
Minimum Speed in Sector 1 [km/h]	10,13
Percent in Gear 1 [%]	5,31
Percent in Gear 2 [%]	45,79
Percent in Gear 3 [%]	23,53
Percent in Gear 4 [%]	25,37
Percent in Gear 5 [%]	0,00
-	-
Mass Longitudinal Friction [kg]	0,00
Vehicle Mass [kg]	364,00

Figure 6. Optimum Lap Simulation

To obtain the necessary compressed air volume, the FluidSim software was used to simulate the electro-pneumatic system with all previously dimensioned components. The simulation is represented in Fig.7. After many trials, the compressed air consumption was higher than the maximum limit. In the most critical case, with a 3 L tank and a pressure of 20 bar, the reservoir was only able to feed 200 gear shifts.

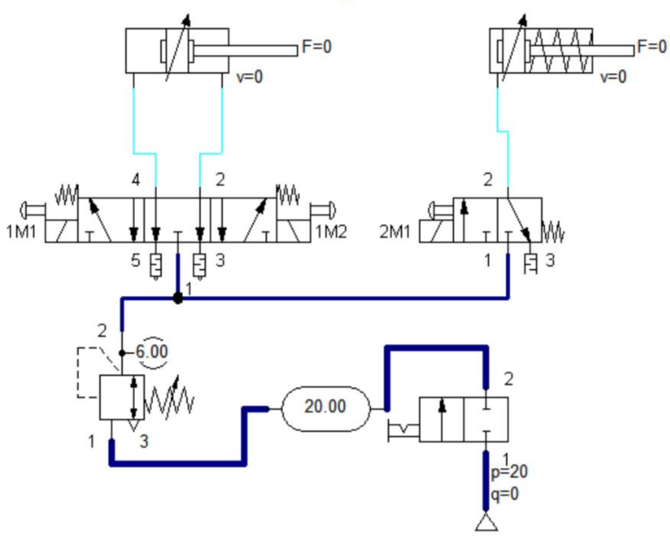


Figure 7. FluidSim Simulation

Therefore, the proposed solution to this problem is the use of an alternative fluid, more compressible than air (store of more mass in a smaller space). The best solution obtained is CO_2, as it is the cheapest and easiest to acquire. Additionally, it's possible to use paintball gas tanks, which have a very affordable price. According to Fig.8 the CO_2 inside the tank under normal conditions (pressure of 60 bar and a temperature of 21.1 ºC) alternates in two states (liquid and vapour). However, due to the high temperatures of the track in competition (more than 35 ºC), the pressure in the reservoir can rise up to 80 bar. This pressure variation will not affect the working pressure, as there is a pressure regulator at the cylinder outlet, but it can damage the orifice seals and thus reduce the tightness.

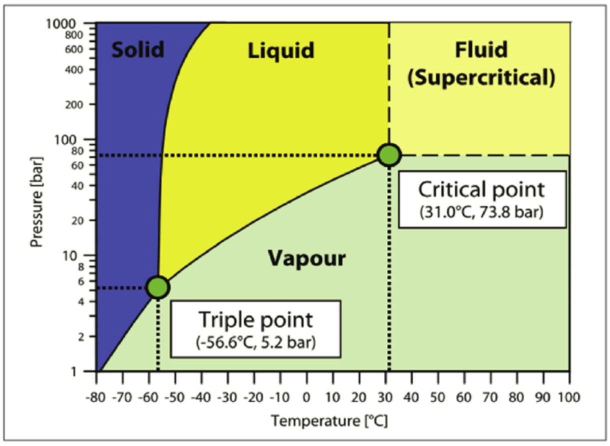


Figure 8. Phase Diagram of CO_2

To discover the volume of CO2 needed to carry out the 820 gear shifts, it is necessary to know the specific volumes of this fluid under the two conditions mentioned, calculate the number of moles of CO_2 needed for each gear shift, obtain the mass of CO_2 from the number of moles, get the mass for 820 gearshifts and get the total tank volume from the specific volume.

Under normal conditions, the specific volume of CO_2 is 0.004742 m^3/kg. Under critical conditions of the track, the specific volume of CO_2 is 0.003 m^3/kg. It is noticeable that the volume occupied in the critical condition is much smaller than in the ideal condition, but it is not the correct pressure to promote the system's durability. Considering CO_2 as an ideal gas, the Clapeyron equation (Eq. (1)) will be used to obtain the number of moles of CO_2 to carry out a gearshift. The shift volume will be considered equivalent to the volume of the actuator's advance chamber, which is larger than the return chamber. This volume is equal to 12271.84 mm^3. In addition, the CO_2 temperature in the actuator (after decompression) will be used. This temperature is actually unknown, but will be considered around 250 K (temperature close to dry ice).

$$PV = nRT, \tag{1}$$

where P is the pressure inside the cylinder (500000 Pa), V is volume of the cylinder advance chamber (0,00001227 m^3), n is the number of moles inside the chamber, R is the universal gas constant (8.31 $m^3\cdot$ Pa /K $\cdot$ mol) and T is the temperature inside the chamber (250 K).

Thus,

$$500000 \cdot 0.00001227 = n \cdot 8.31 \cdot 250 \tag{2}$$

$$n = 0,00295 \tag{3}$$

The molar mass of carbon dioxide is 44 g/mol. The double-acting cylinder only fills half of the stroke on activation, while the clutch's single-acting cylinder fills up completely. Therefore, the mass will be equivalent to three times the number of moles found in the equation 3, which is 0.389 g. Considering 820 gear shifts, the total mass would be 319 g. Under ideal conditions, when the specific volume of CO_2 is 0.0047 m^3/kg, the volume of the reservoir would need to be 0.0015 m^3 or 50 oz. Under critical conditions, when the specific volume is 0.003 m^3/kg, the volume of the reservoir would need to be 0.000957 m^3 or 32 oz.

It is necessary to raise some considerations from the results obtained. The maximum paintball cylinder volume available on the market is 24 oz. Apparently, it appears that the largest tank is not capable of supplying all the gas needed for gear shifting. However, it is noticeable that the weather in which the tank is being filled drastically affects its thermodynamic state, being able to store much more gas than in the ideal condition. During competition, it is very difficult for the fluid temperature to maintain the ideal conditions of 295 K in the reservoir. It will likely have an average temperature of 303 K, causing the reservoir pressure to rise to 70 bar. 820 shifts is also an overestimated value, as well as the number of shifts given by the Optimum Lap software, in which the pilot would shift gears 31 times per lap. The clutch actuator consumes 2/3 of the total fluid mass, as it was assumed that this actuator will be actuated to the end of its stroke (50mm). However, this stroke will be approximately 25 mm, causing the clutch actuator consumption to drop by half, causing a 33 % reduction in total CO_2 consumption. Therefore, the 24 oz tank still represents a secure reservoir to the system and will be the chosen one for the project.

To complete the embodiment design, a 5/3 directional solenoid valve (negative centered) was defined for the gear selector shaft and a 3/2 directional solenoid valve was defined for the clutch actuator, as seen in Fig.7. All the other components were chosen based on the cylinders, tank and valves characteristics.

3.4 Detail design

The Detail Design consist on the development of all the information necessary to manufacture the product. In this work, technical drawings of the cylinders mounting and the valves mounting were made, as well as the process sheets to specify the order of the processes and the specification of the process. Nevertheless, the display of these documents were deprived of this work, as well as the paddle shifter and the electronic devices development. Figure 9 presents the final design of the electro-pneumatic gear shifter.

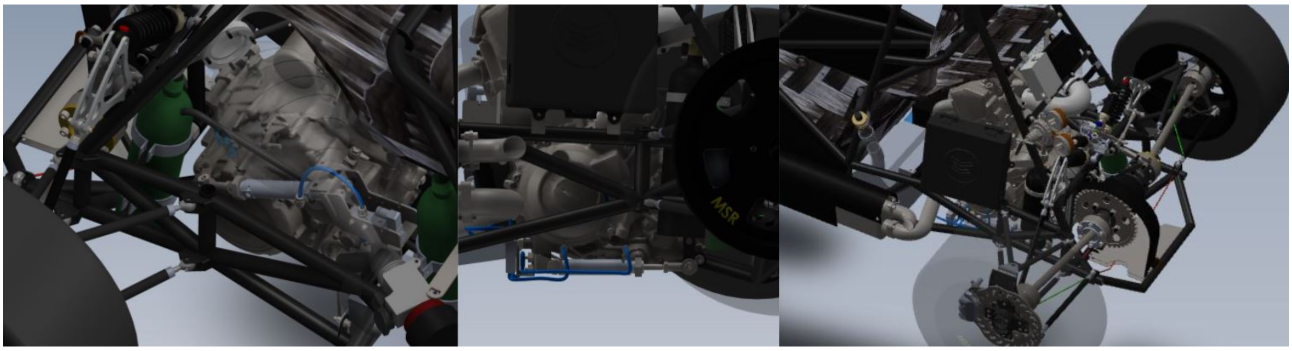


Figure 9. Final Design View: Clutch Actuator, Gear Selector Shaft Actuator, Tank Layout

3.5 Validation

The Validation Step consisted on evaluating the product from the customer's perspective. It is necessary that the product, according to the Task Clarification, presents reliability, improved track time, robustness and comfort compared to the previous project. The first test made with the mechanism was in laboratory, installing the system in a test bench, according to Fig.10. The objective of the experiment was to measure the shift time, as well as the number of shifts that a 24 oz tank can supply. Springs that exert a similar reaction to the activation force of the actuators were installed on the bench. The tests have shown that the electro-pneumatic gear shifter exerts a shift time of approximately 0.4 seconds, measured with a stopwatch. A full reservoir, under these conditions, was able to supply around 850 effective gearshifts, a number even higher than the one calculated.

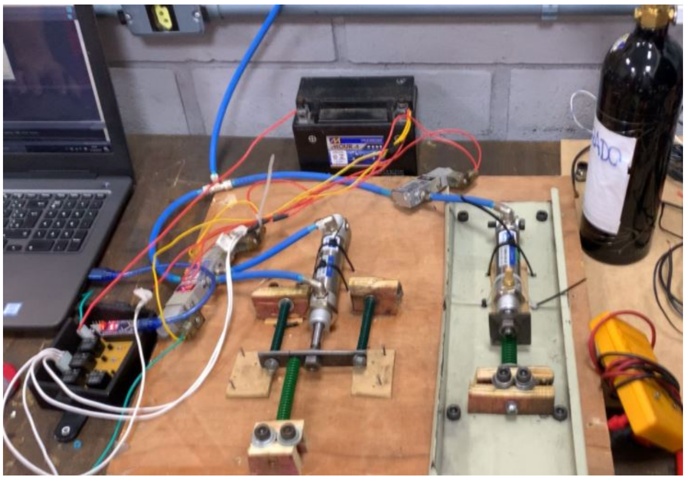


Figure 10. Laboratory Validation

The other validation test consisted on measuring the track time and the shift time with the electro-pneumatic shifter installed in the vehicle, as well as the feedback of the pilots (customers) about the comfort and ergonomics of the new system compared to the former one. Several dynamic tests were carried out to refine the electronics and the pilots' skills. The first ones showed many errors associated to the shifter electronics and, at first, were disappointing in terms of reliability, even though it was really faster and more comfortable to drive compared to the previous system. An analysis of the problem revealed a lack of electromagnetic shielding, as the solenoid valves were constantly activated by interference or not even activated. When this issue was resolved, the new shifter met all customer requirements, both on the test track and in competition. The new average gear shift time was 0.4 seconds in a sample of 40 shifts. It is about 0.6 seconds less than the former shifter based on levers and cables. Track time has decreased by around 10 seconds compared to the same timed circuit in previous years.

The team, as a whole, was very satisfied with the result of the prototype, as the pilot felt more comfortable and less fatigued, the vehicle presented shorter lap times and it was the first time that the team completed the endurance test. That is, it is the most reliable system ever designed by the team. It is important to consider that other changes were made to the vehicle so it is not possible to affirm that the lap time improvement was provided only by the new system. The overall mass of the vehicle, for example, decreased compared to the previous project. Both simulation and dynamic tests have shown improvements of the lap performance. To validate the exact gain of the new design, it would be necessary to install both shifters in the same vehicle to compare the results. However, the previous project was discarded, and this comparison couldn't be done.

4. CONCLUSION

The initial objective of the design was to meet the requirements of reliability, agility (improve the track time) and robustness. All the pilots had the opportunity to test and train with the new mechanism and they all approved, mainly in terms of agility and comfort, as they do not need to take their hand off the steering wheel and can concentrate better on the track. The validation test, in a quantitative aspect, indicates that the design met the initial objective, as the new shifter presented shorter lap times and was able to withstand all the demands placed on it (mechanical and number of changes).

Chalmela (2017) and Kennett (2008) also indicates in their works that this solution not only reduces effort seen by the driver while shifting but also substantially improves the lap times thereby increasing performance during the dynamic events. This work is also another example of how the PRODIP method helped the team to choose the best solution to the problem and organize its development. Suggestions for future work are communication with the engine control unit to cut the ignition during shift in order to take the actuator off the clutch thereby reducing fluid consumption, a gear counter display to guide the pilot if he gets lost in the count, and a fully automatic system study.

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