Potential Solutions
Pneumatic Paddle Shifting

Senior Design Capstone – Team 17

Overall Objective

This project proposes an improved shifting system for Temple Formula Racing's (TFR) racing car. TFR competes annually in the global Formula SAE (FSAE) competition, where more than one hundred universities defend their car designs then race in events such as autocross. The traditional shift lever requires the driver to remove one hand from the steering wheel in critical moments which poses challenges to safety and performance. By moving shifting controls to the steering wheel, the driver can operate all shifting functions while both hands remain on the wheel. Implementing this technology enhances driver focus, vehicle performance, safety, and the team's success.

Currently, TFR uses the stock Honda CBR600RR transmission which utilizes a dog engagement mechanism for changing gears. During a gear change, protrusions on the coupling rings (or "dog rings") rapidly engage or disengage with slots in adjacent gears to change drive ratios. A shift lever controlled by the driver facilitates gear shifting by moving the dog rings into the position of the selected gear through a series of internal and external linkages. A paddle shifting system replaces all external mechanical linkages, (see Figure 1), with actuators operated from the steering wheel, which strengthens driver ergonomics and adds to vehicle performance.

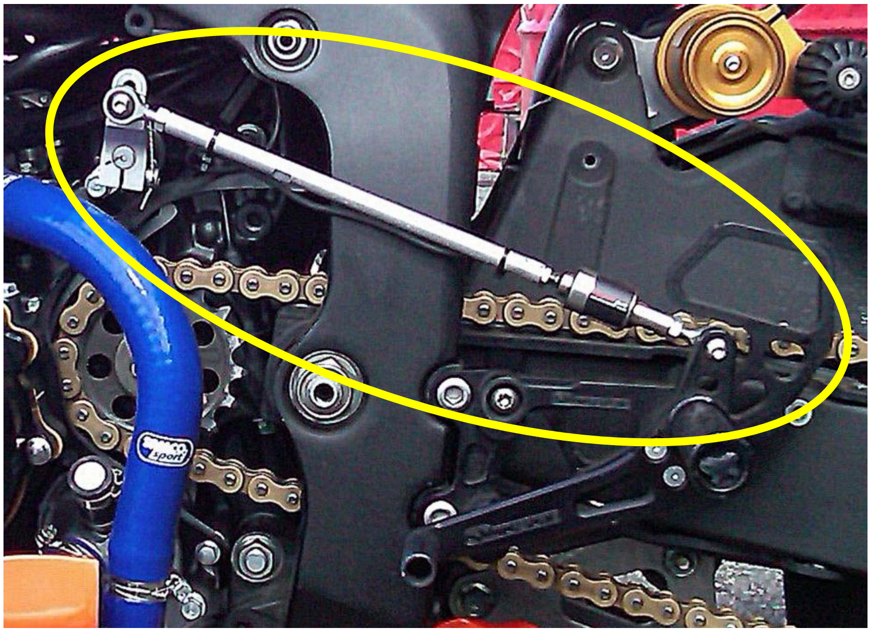

Figure 1 Stock CBR600RR External Shifting Linkage

The main project objective is to create a testing apparatus that replicates motion and forces the shifting mechanism will endure during real driving. The testing apparatus aims to correlate design parameters by collecting data on mechanical and electrical components. The testbench setup includes options for users to attempt manual or automated upshifts and downshifts, with a dashboard providing real-time feedback on the success of each shift based on data processed by a microcontroller.

In summary, the project focuses on constructing a testbench, collecting data on components, and providing valuable insights for Temple Formula Racing on how to successfully integrate a paddle shifting system into their FSAE car in the future.

Potential Solution 1 – Electric Solenoid Shifting

One possible solution to the objectives outlined above is a system in which the lever that is actuated to shift gears is powered completely by electricity. A previous attempt at solving it with this approach was done by Sundge et al. in their paper titled "Design of Gear Shifting Assembly using Paddle Shifters and Electric Solenoid for FSAE vehicles." (Sundge et al., 2022) In this paper, researchers utilized a 12-volt solenoid with an attached arm that would push or pull a lever to actuate a shift.

In this type of system, there would be two inputs, an upshift button, and a downshift button, with the output actuating the solenoid to push or pull the lever, respectively. There would be five primary components: the input buttons, the solenoid, a power source (such as a battery), a relay, and a microcontroller. The input buttons would use a pull-up resistor from the microcontroller, with one side of the button connected to ground, and the other connected to a digital input. When the switch is grounded, a signal would be sent out of a different pin of the microcontroller to the relay. Each switch will control a different solenoid in a 4-way 3 position solenoid, depending on whether the user requests an upshift or a downshift. This relay would control the power source or battery since the signal from the microcontroller wouldn't be strong enough to power the solenoid itself. When the relay receives a signal, it would switch the power source to the solenoid, causing a current to flow through the coil, in turn creating a powerful magnetic field that would be strong enough to move a plunger back and forth. This plunger would be mechanically attached to the lever that is being used for shifting and would generate the necessary amount of force to cause a shift. The force necessary to cause a shift would be found through testing throughout the project's design and research portion.

One of the main drawbacks to this system is that it consumes a massive amount of electrical energy. Since this system's purpose is to be mounted on an FSAE car, in which the battery provides electrical energy for critical tasks, a battery analysis would need to be conducted to determine energy consumption per shift. The batteries that are normally used for FSAE cars range in rating from 80-200 amp hours, so for a perfectly conductive solenoid in which the wire has a resistance of approximately 1 ohm, a 12-volt solenoid would draw 12 amps of current for the length of time it takes for the solenoid to perform the shifting would be continuously compounded by the number of shifts, draining the battery. Additionally, because there are such powerful solenoids generating these huge magnetic fields, there is an electromagnetic interference concern with more sensitive parts, such as the ECU or sensors attached to other parts of the car, which are necessary for vehicle reliability. A further drawback to this system would be the worry of how to manage heat dissipation due to resistive losses, especially through wires conducting a high current. If not managed correctly, the excess heat can also damage other parts of the car, creating further problems. However, one of the main benefits of this system is the lack of complexity. Every single part of the system is powered electrically, meaning there doesn't need to be any intermediary mechanical steps, which could require more sensors and more monitoring equipment to ensure that the system is working properly.

Overall, this potential solution, while simple, does create several issues that will be difficult to overcome in the design process, as outlined above. Above all, the purpose of this project is to make a testbench that the FSAE team will be able to use to design a paddle shifting system for their car, so it will be important to create a testbench that will be similar to what will be viable on the car. Given the critical nature of the battery on the vehicle, the team will most likely avoid using a system that has the potential to drain so much energy from the battery.

Potential Solution 2 – Electro-Hydraulic Shifting System

Hydraulic systems perform repetitive movements or tasks through using a pressurized fluid (Vector). A mechanical force is controlled through the flow and pressure of a hydraulic pump. Hydraulic pumps are necessary as they create a vacuum that forces the liquid into a reservoir and then the mechanical actuation forces the liquid back into the hydraulic system. A hydraulic cylinder or piston converts energy stored in the hydraulic fluid into a linear force (Vector). The pressure and flow of the hydraulic liquid is controlled by a motor. Common applications of hydraulic systems are those with heavy loading, such as hydraulic arms at construction sites, a vehicle's braking system, and a car jack. These liquids have higher viscosity, which correlates to a higher output linear force. The figure below displays a hydraulic schematic for a thermodynamic system. For the paddle shifting system, the paddles would act as switches sending a signal to a microcontroller to activate the pump, motor, and then cylinder for the respective upshift and downshift. The hydraulic system would need electrical components to inform the cylinder when to actuate.

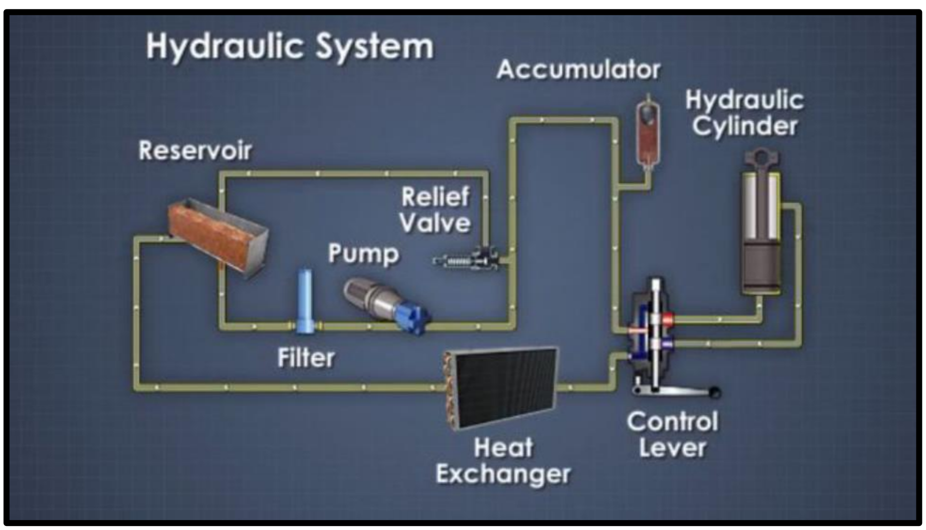

Figure 2 Hydraulic Schematic Example

For industry standard paddle shifting applications, hydraulics are preferred as the working fluid is not compressible, allowing for smooth push and pull movements (source). Pneumatic systems can become jerky as the working gas pressure fluctuates with the movement of the cylinder. If implemented well, a hydraulic system can be lighter than a pneumatic/electric or fully electric one. Compressed oil has a higher capacity to transmit energy (source), thus a smaller bore diameter is required for the same output force. In the automotive industry, a hydraulic paddle shifting system was developed by a company called KAPS to replace the Subaru Impresa's slower H-patter mechanical shifter. Despite the clear advantages to an electro-hydraulic system, previous attempts by other FSAE teams were not found.

The drawbacks that come with an electro-hydraulic system pose a multitude of hurdles for a successful design. Per the FSAE standards, any pressurized system is required to be purchased by a third party to ensure the equipment is safe. Hydraulic actuating systems are more complex than pneumatic or electrical shifting systems due to the extra parts required. The additional pump and motor required to maintain pressure and flow of the hydraulic fluid adds unnecessary weight to the system if components are not designed in-house and manufactured for high performance applications. These additional components add more failure points throughout and could not be optimized for weight savings, an important aspect of the FSAE vehicle design. Hydraulic systems require more expenses to produce and maintain as the fluids require high pressures for operation. The hydraulic fluid itself poses a safety issue as it's highly flammable and under intense pressure. Improper sealing is inevitable especially during the prototyping phase. Sources note that leaks are difficult to completely get rid of, even after replacing gaskets (source), posing an inconvenient mess. Due to the high operating pressure and velocity of the hydraulic piston, any leak could harm those around, bearing a safety hazard for those working closely with the system. The oils also require sufficient filtration to eliminate air pockets that could reduce the working pressure and reliability of the system.

The electro-hydraulic system could optimize the performance-to-weight ratio for paddle shifting. However, due to the constraints of the FSAE competition, these metrics are unattainable. The limitations of the competition make this route would be an unviable option.

Potential Solution 3 – Electro-Pneumatic Shifting System

An electro-pneumatic actuated shifting system can be utilized as a solution to the objective described above. Pneumatic systems involve generating mechanical work from the pressure energy of compressed air or gas. These systems are widely used across various industries. The major components of this specific system are a gas tank, pressure regulator, pneumatic cylinder, and solenoid (Kumar).

A gas tank with high enough capacity to actuate a goal number of shifts must be selected. Paintball gas tanks, typically filled with compressed air, nitrogen, or CO_2, can provide a convenient and lightweight source of pneumatic power. The primary concerns when selecting a tank are cost, shift capacity, weight, pressure requirements, and maintenance. Larger tanks may provide more extended operating times but could also add bulk and weight to the system. A tank which meets pressure and operation requirements while balancing the tradeoff between shift capacity and bulk would be selected.

A pressure regulator is an essential component of this system. The pressure regulator maintains consistent pressure despite fluctuations in input from the gas tank, ensuring the reliability and performance of system components. This component also prevents damage to the cylinder and solenoid from excessive pressure, increasing the system's longevity. Additionally, it optimizes energy consumption by regulating pressure to the minimum level necessary for efficient operation, thus reducing operating costs. The pressure regulator also offers precise control and adjustability over pressure within gas lines, crucial for tuning the shifting system.

The cylinder in this system must be double acting to actuate upshifts and downshifts. A double-acting pneumatic cylinder is a type of pneumatic actuator that uses compressed air to create motion in both directions. Unlike single-acting cylinders, which rely on a single pressure source to move the piston in one direction while using a spring or other mechanism to return it to its original position, double-acting cylinders use air pressure to move the piston in both directions. The bore diameter of the cylinder would be determined using the system's pressure and force requirements.

A four-way, three-position solenoid will be necessary to allow for the cylinder to have up-shift, downshift, and rest positions. Electrical currents will signal the solenoid valves to open in accordance with the shift direction indicated by the driver. An electrical solenoid is preferred to a mechanical solenoid for this application due to the necessity of precise control and rapid actuation (2).

These components will function as part of a system as shown in the figure below.

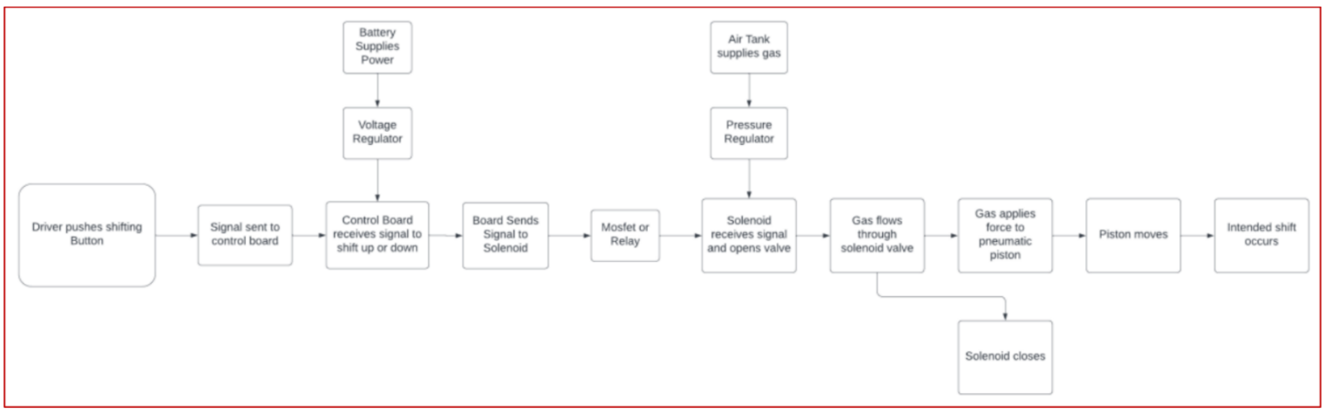

Figure 3 Pneumatic Shifting System Diagram

This system's major drawback is that each gas tank contains a finite number of shifts, so the vehicle can only shift while it lasts. The volume of gas remaining in the tank would have to be closely monitored.

Pneumatic shifting systems, despite their advantages in simplicity, cost-effectiveness, and weight, come with several drawbacks to consider. These include limited precision due to slower response times compared to electronic or hydraulic systems, dependence on a consistent and reliable supply of compressed air which can be prone to leaks and pressure drops, regular maintenance requirements to ensure optimal performance, generation of noise and vibration during operation which may be undesirable in certain environments, lower energy efficiency compared to other systems due to energy losses in compressing air and converting it into mechanical work. The volume of air in each tank is finite, therefore containing a finite number of shifts. As a result, the vehicle can only shift while the gas tank lasts. For safety and performance purposes, the volume of gas contained within the tank must be closely monitored.

Next Steps

Moving forward, the actuation system which best integrates with the needs of Temple Formula Racing will be chosen to design and test. Three options exist, which are electric solenoid actuators, electro-hydraulic systems, and electro-pneumatic systems. The main considerations are potential performance, reliability, mass, packaging, and costs.

Designing a system that meets performance requirements should be possible with all systems. There exists a wide selection of components for all of the proposed solutions. Finding components that are strong and fast enough to successfully shift gears will not pose a challenge.

The single most important element of a racing vehicle is reliability, as finishing a race comes before winning. Each solution faces potential reliability concerns. Both hydraulic and pneumatic systems have a high number of interfacing parts that can fail if improperly installed or maintained. Hydraulic systems deal with excessively high pressures which make them notably questionable for a student lead project. While all systems *can* be implemented successfully, the continuous overturning of leadership in FSAE makes simpler designs more likely to be implemented and passed down each generation.

Considering that the vehicle TFR designs is roughly ~200kg, adding components that weight just a few kilograms threatens a significant decrease in performance. For this reason, the hydraulic system and electric solenoid would not be the best choice as they are constructed of relatively heavy metal components.

Alongside being light, TFR designs its car to be packaged as efficiently and as small as possible. Having the smallest number of parts pushes for the electric solenoid to be a feasible option. However, when accounting for the immense electrical draw this system requires, a larger or additional battery/energy recovery system would need to be developed, adding mass and bulk. While a pneumatic and hydraulic system can have similar overall component sizes, the smaller working pressure in pneumatics allows that system to be more placed with more flexibility. Overall, pneumatics has the most convenient combination of mass and packaging for a contemporary internal combustion FSAE car.

Being a student designed project, costs play a large role in the system selection process. All three options could be designed successfully with a few hundred to one thousand dollar budget. However, selecting components that meet other criteria such as light weight and small quickly increases cost for hydraulic and electrical actuator systems. Most used pneumatic components are already packaged in a reasonable form factor.

Considering all criteria for a success design and implementation, an electro-pneumatic system is the most appropriate option. Pneumatics offer a great ratio of output performance to overall system mass and form factor. While pneumatics are not the most simple systems to install and maintain, documentation can be created to ensure the system is properly used in years to come.

Additionally, the system can be constructed for the same price or less than the other systems and has little maintenance costs.

Citations

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2. Pittman, Richard, et al. 2015, Formula SAE Paddle Shift System: Senior Design II Report.
3. Kumar, Er. Amrit. "Pneumatic System: Definition, Components, Working, Advantages [Notes & PDF]." *THEMECHANICALENGINEERING.COM*, 1 Oct. 2022, themechanicalengineering.com/pneumatic-system/#:~:text=A%20pneumatic%20system%20is%20a%20connection%20of%20various,where%20human%20strength%20and%20accuracy%20are%20not%20enough.
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