# Superkart pneumatic gear shifter

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## Abstract

*This study presents the development and implementation of an automated gear-shifting system for a superkart, utilizing a pneumatic actuator. The primary objective is the automation of sequential gear shifting without using a potentiometer to detect the absolute gear position. Instead, the system employs gear shift sensors that detect gear changes and determine the gear position, maintaining a closed-loop configuration.*

*The methodological approach includes the development of pneumatic, mechanical, and electronic systems, encompassing component selection, design, electronic circuit development, and microcontroller programming. Testing procedures and measurements comparing the efficiency of manual and automated shifting will be presented, focusing on software performance optimization.*

*Key results include successful gear shifting automation, reduced shifting times, minimized driver intervention, enhanced safety, and rapid system responsiveness. Additionally, proposals for further system improvements and upgrades will be presented.*

## 1 Introduction

Superkarts represent an exceptionally popular introduction to the world of motorsport, particularly among young drivers. Due to their relative simplicity and accessibility, they facilitate the rapid acquisition of racing fundamentals and vehicle control. Recent technological advancements in the automotive industry have significantly enhanced vehicle performance and safety, which is particularly evident in motorsport.

Progress in electronics and automation has enabled the integration of complex systems that improve both safety and vehicle performance. Microcontrollers, which serve as the core of modern automation systems, allow precise management of various functions in real-time. Additionally, pneumatic systems, known for their reliability and speed, have proven to be highly suitable for the use in vehicles where rapid response times are critical.

In the context of superkarts, gear shifting is a crucial element that can significantly impact driving performance. Traditional manual shifting systems have limitations, particularly regarding speed and precision. Modern solutions incorporating automated gear shifting via microcontrollers and pneumatic actuators represent a significant advancement in this area.

The aim of this article is to present a project focused on the automation of gear shifting in a superkart, utilizing a microcontroller and a pneumatic system. The project's objective was to enhance safety and reduce shifting times, thereby contributing to improved performance and competitiveness of the superkart on the racetrack. The following sections will detail the theoretical foundations, methods, and results of the project.

## 2 Design

### 2.1 Shifting systems

Shifting systems can be categorized into four types: mechanical, electrical, hydraulic, and electro-pneumatic.

Mechanical shifting utilizes cables, levers, and springs to change gears, similar to how throttle or clutch actuation is executed. This method is highly reliable and allows for an unlimited number of shifts without depleting the battery. Additionally, it is the most cost-effective option. However, it does not support automatic upshifting because it operates independently of electronic control.

Electrical shifting involves a servomotor or magnetic shifter activated by a button to change gears. This system is lightweight and reliable, and it supports automatic upshifting. Nevertheless, it consumes a significant amount of battery power.

Hydraulic shifting employs hydraulic pressure to shift gears, generated by a pump. This method is fairly reliable. Its major drawback is the need to power the pump, which requires a substantial amount of energy. Additionally, the system is quite bulky, and any leakage could pose a fire hazard.

Electro-pneumatic shifting operates on a principle similar to hydraulic shifting but uses compressed air instead of liquid. This method is very reliable, capable of almost instantaneous shifting.

Comparing these four alternatives, electro-pneumatic shifting emerges as the best option and is therefore recommended [1].

### 2.2 Sequential transmission

Sequential gearboxes have long been used in motorcycles and racing vehicles due to their faster shifting and simpler operation compared to traditional H-pattern gearboxes. In sequential gearboxes, gears are changed in a specific sequence. A push of the gear lever upward shifts to a higher gear, while a downward push shifts to a lower gear. These gearboxes are characterized by quicker gear changes, simpler operation, and reduced component wear [2].

Sequential gearboxes operate by changing gears in a predetermined order. On the drive shaft, drive gears for each gear are firmly attached. The output shaft carries a sprocket that transmits the output torque. The drive shaft holds fixed drive gears for each gear, while the driven gears rotate freely around the output shaft. Selectors attached to the output shaft allow axial movement to engage with the driven gears. Their position is determined by shift forks, which are moved by the shift drum. The shift forks move the selectors left and right to engage with the driven gears [2]. The shift drum facilitates the sequential movement of the shift forks, enabling gear changes by using dog clutches to engage gears [1].

Each selector engages with only one gear at a time, preventing damage to gears or shafts due to different rotational speeds. The sequence of shift fork movements with a 60° rotation of the drum includes disengaging the current gear, moving to a neutral position, and engaging the next gear. To engage neutral gear, both shift forks must be positioned in the central position. In motorcycles, the neutral gear is always between the 1st and 2nd gears. This is achieved by the application of a star and spring retainer mechanism that prevents accidental movement of the drum from its designated positions [2].

In our system, the sequential gearbox is integrated into the Yamaha TDM 850 power unit. The gearbox has 5 gears arranged in the sequence 1-N-2-3-4-5.

Due to the high contact pressures during synchronization, this type of gearboxes or the ones with similar shifting methods are only used for either lower torque applications (motorcycles) or in cases where a limited lifespan of the gearbox is not a major concern (racing vehicles) [3].

### 2.3 Pneumatic system

The pneumatic system is a crucial component responsible for actuating the sequential gearbox using 3/2 pneumatic valves and a bidirectional shift actuator. A compact compressor, operating at a voltage of 12V, serves as the source of compressed air. This compressor is mounted on the vehicle and provides the necessary air pressure, which is stored within the tubular frame of the vehicle's chassis. This design allows the system to maintain a reserve of compressed air, which is utilized during gear shifting, thus reducing the compressor's operating time and enhancing efficiency.The system consumes an average of 0.7 liters of air per cycle, which is also the capacity of the air reservoir. The compressor ensures adequate pressure is maintained, with a filling characteristic that allows it to pressurize the system to 10 bar in 14 seconds. This ensures a reliable supply of air throughout the operation.

We opted for this method of energy storage due to space constraints, as it is not possible to install an air reservoir anywhere in the system. Additionally, adding a reservoir would increase the overall weight. Significant deformations of the supporting structure would be required to cause cracks in the system, which will not occur under proper usage.

The compressor's operation is regulated by a pressure switch, ensuring that air pressure remains within the optimal range of 8.5 to 9.5 bar. This pressure range was selected because the valves are rated for this specific pressure. The compressor, which draws 180 W of power from the alternator on the drive unit, serves as the energy source for shifting operations. Additionally, a safety valve is included to prevent over-pressurization, thereby protecting the system's components and ensuring safe operation.

While pneumatic systems typically involve more components like valves and compressors, leading to increased weight, the benefits of our approach are clear when considering performance metrics such as shift time reduction, as highlighted in the comparative studies [4].

The pneumatic system performs two primary functions: gear shifting and throttle blipping. Gear shifting is managed by the bidirectional shift actuator, which moves the shifting mechanism. The blip actuator, a unidirectional pneumatic cylinder, is responsible for increasing engine RPM during downshifts to match the speed of the lower gear, known as rev matching. This process reduces stress on the gearbox and ensures smoother transitions. The engine plays a crucial role in executing gear shifts, not only in controlling engine speed during synchronization but also in ensuring that the transmission torque is free. Integrated powertrain control is necessary to accomplish this task, as described in [5].

The manual shift lever, which remains on the vehicle and operates in conjunction with the pneumatic shifting system, provides an additional layer of control. This setup is illustrated in Figure 1.

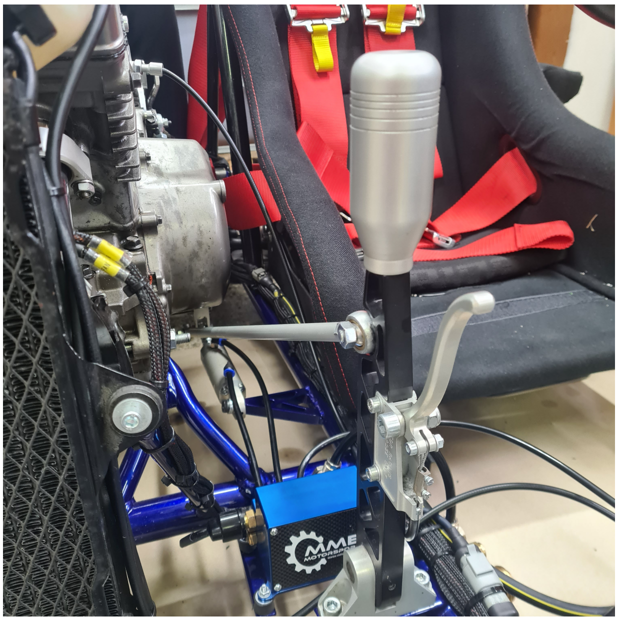


Figure 1: Valve block and shift actuator

### 2.4 Mechanical system

The mechanical system of the superkart consists of several crucial components that ensure the effective operation of the gear shifting mechanism. These components include the steering wheel, the shift sensor housing, various mounts, and actuators.

The steering wheel is designed to provide the driver with a precise control over the vehicle. It is equipped with paddle shifters mounted on the rear side, allowing the driver to change gears without taking his/her hands off the wheel. This setup enhances driving safety and performance by enabling quick and efficient gear shifts.

The gear sensor housing is a component that holds the sensors used to detect gear changes. This housing is securely attached to the vehicle's structure to ensure accurate and reliable sensor readings. The sensors within the housing are aligned to detect the magnet's position on the gear shift mechanism, enabling the system to determine the current gear. Importantly, these sensors detect only the change in gear position, not the absolute gear value.

The shift actuator is a bidirectional pneumatic cylinder designed to precisely control the gear shift mechanism. To select the appropriate actuator size, we measured the shift lever's movement and determined the required stroke length. It was essential to choose an actuator with sufficient force to ensure reliable and quick shifting without damaging the gear mechanism. We measured the force using a hand force meter and utilized the maximum measurement of 150 N. Based on these measurements, we selected an actuator from SMC with a diameter of 25 mm.

The blip actuator operates on the principle of opening the throttle valves in the carburetor by pressing the throttle pedal. The movement is transmitted via a cable that runs through a sheath, ensuring a constant distance between the components. The blip actuator is installed between the throttle pedal and the carburetor, allowing the cable to pass through it. When the actuator is activated, it moves the sheath while the cable remains stationary, effectively opening the throttle valves as if the pedal were pressed.

The magnet holder is made of structural steel and serves as the support for the magnet on the gear shift mechanism. It is welded to a clamp on the gear shift shaft, allowing the magnet to rotate around the shaft during gear shifts. This rotation enables the sensors in the shift sensor housing to detect the magnet's position accurately. The holder includes an M6 thread where an M6x20 mm set screw with a 3 mm diameter magnet is attached. The set screw allows for adjusting the distance between the magnet and the shift sensor, as illustrated in Figure 2.

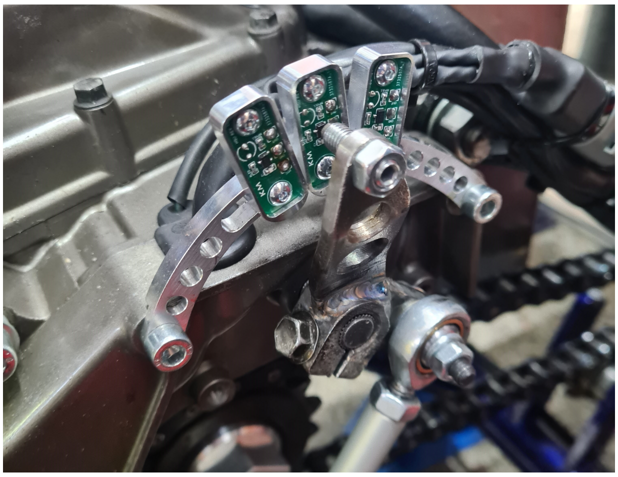

Figure 2: Gear sensors and magnet holder

### 2.5 Electronic System

The power of the system lies in the fact that electronically controlled systems can react much faster and more precisely than a human can [6].

The electronic system is essential for detecting, transmitting, and processing signals necessary for controlling all the components of the gear shifting mechanism. It consists of various electronic components that form the different elements of the control system. The key components of the electronic system are:

- Control Unit (KCU)
- Relay Block
- User Interface
- Gear Sensors

The Control Unit (KCU) is a printed circuit board (PCB) that houses the main controller of the system, an Arduino Nano with an ATMEGA328 microcontroller. The KCU is mounted inside the steering wheel housing to reduce the number of connections to other devices. It monitors input devices via digital signals, reads gear sensor statuses, and tracks analog gauges for system voltage, coolant temperature, and fuel level. The KCU can activate valves in the valve block and the ignition relay during gear shifts. It also handles serial communication with the user interface to display key vehicle data. KCU reads engine RPM by reading frequency of ignition. However, unlike the system described by [4], our system does not take engine RPM into account during the shifting process. The KCU circuit is shown in Figure 3.

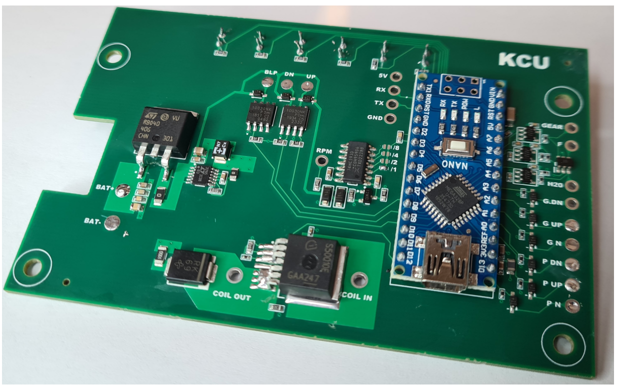


Figure 3: Control unit KCU

The Relay Block is a PCB with five automotive relays, capable of switching loads of up to 20 A. The relays control devices such as the ECU, fuel pump, starter, and ignition coil. Diodes are added to prevent voltage spikes. An NPN transistor (TIP120) activates the ignition relay during shifts.

The user interface, integrated into the steering wheel, provides the driver with the vehicle status and control inputs. It includes:

- LEDs: Indicate critical vehicle parameters like RPM, system failures, and device statuses.
- Switches and Buttons: Control the relays on the Relay Block and input commands for gear shifting, engine starting, and system reset.
- Display: Shows information such as current gear, engine RPM, coolant temperature, fuel level, and system voltage. The Nextion display (NX4832T035) is used.
- Paddle Shifters: Located on the back of the steering wheel, they allow gear shifts without taking hands off the wheel.

Gear sensors provide feedback on the gear mechanism's position. Three sensors detect the positions: center, upshift, and downshift. Magnetic switches are used, with pull-up resistors and LED indicators for proper operation.

This electronic system design ensures accurate and reliable control of the gear shifting mechanism, enhancing the performance and safety of the vehicle. Not only does it give quick response while shifting but also decreases effort of the driver. Implementing such type of shifing system increases the overall performance of the vehicle in race like scenario [7].

### 2.6 Programming

The programming of the gear shifting system was carried out using the Arduino IDE. The program is composed of multiple modules, each performing specific tasks to create the overall control functionality required for gear shifting. Ensuring the program runs in real-time was crucial, given the need for swift and efficient gear changes. Below, we discuss the primary functions related to the gear shifting system. Additional program functionalities are not included in this section. Currently, the system lacks a safety mechanism that monitors engine RPM and prevents shifting under certain conditions. We only restrict shifting to higher than 5th gear and lower than 1st gear.

The main components of the shifting program include the millis function, which is used to track the elapsed time in milliseconds since the program started. This function is crucial for managing timing events without blocking the execution of other code. It returns the number of milliseconds the Arduino has been running and overflows after approximately 50 days, returning to zero. The syntax is millis(). It is used in this sketch to sound an alarm each time the device is reset or switched on [8].

The acquisition and filtering of digital input signals' module acquires input signals from various sensors and filters out noise to ensure accurate readings, which is essential for precise gear shifting. User's timer settings allow the user to set and adjust the timing parameters for gear shifting operations, ensuring customization and flexibility. The initiation of shifting function handles the initial steps required to start the gear shifting process, ensuring all conditions are met before proceeding.

The shifting up function manages the transition to a higher gear, coordinating the disengagement of the current gear and the engagement of the next gear in the sequence. The shifting down function handles the transition to a lower gear, ensuring smooth and precise engagement. The manual shifting function allows for manual intervention in the shifting process, providing the driver with direct control when necessary. The shifting from neutral function manages the process of engaging the first gear from a neutral position, a critical function for starting the vehicle.

The display output to the user interface module is responsible for displaying relevant information on the user interface, keeping the driver informed of the current gear and system status. The loop timing function tracks the execution time of the main loop to ensure that the program runs efficiently and can meet real-time demands.

By closely monitoring and optimizing the execution speed of these functions, the program ensures that the system achieves the shortest possible shifting times, enhancing overall performance.

### 2.7 Measurement Methodology

As part of the system testing on the vehicle, we conducted several measurements, all performed on a stationary vehicle without load on the gearbox and without disturbances that occur during driving. We measured the time for both manual and automated shifting.

Time for manual shifting was measured using a mechanical switch placed under the clutch lever. The switch is activated when the clutch is released and deactivated when the driver presses the clutch. Measurements were recorded using a prototype board with Arduino.

Shifting time with the pneumatic system was measured using additional timers in the main program code that controls the entire system. For up shifting, we measured the time from the deactivation of the relay controlling the ignition coil to its reactivation. For down shifting, we measured the time from the activation of the blip valve to the activation of the sensor.

To accurately assess the impact of the added weight on the vehicle's performance, we measured the mass of the vehicle without the shifting system, which is 162 kg. We then measured the masses of individual components of the manual and automated shifting systems. The mass of pneumatic connectors, hoses, and electrical conductors was neglected as their impact on the overall system mass is negligible. Based on these measurements, we calculated the total mass of the systems and evaluated its impact on the vehicle's performance.

These measurements enable a comparison between manual and automated shifting, which is crucial for evaluating the efficiency and performance of the new system.

## 3 Results

The primary result of this project is the successful automation of sequential gear shifting without a potentiometer for detecting the absolute gear position. Automation was achieved using a pneumatic actuator and gear sensors that detect shifts to determine the gear position.

We developed a pneumatic system, mechanical components and electronic components. The entire system is managed by a program that processes input signals and executes actions in real-time for successful shifting. The steering wheel assembly is shown in Figure 4, illustrating the current state of the vehicle. Special attention was given to the optimization of the program code. Using this microcontroller, we achieved the shortest possible execution time for one loop, which is 0,49 ms. This is the best result achievable considering hardware limitations and available optimization technologies.

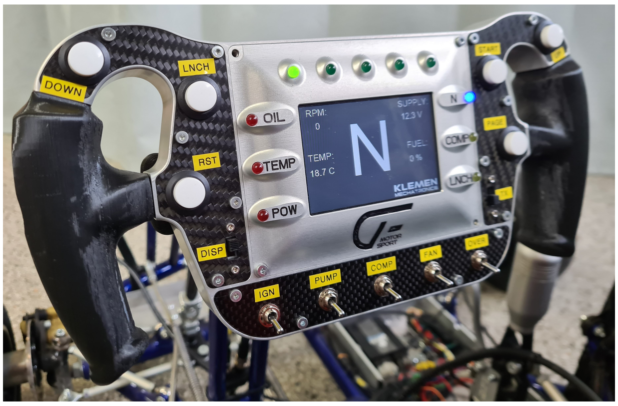


Figure 4: Finished steering wheel

Based on the shifting time measurements, we can compare manual and automated shifting systems. Manual shifting to a higher gear took on average around 621 ms, while shifting to a lower gear took on average around 525 ms. The automated shifting system demonstrated significantly better results. The average time needed for shifting to a higher gear with the system was 135 ms, a considerable improvement over manual shifting. Even more pronounced is the improvement in shifting to a lower gear, where the average shifting time was just 93 ms. These results clearly indicate that the automated shifting control system provides much faster and more efficient gear changes, enhancing vehicle performance.

With the installation of the new shifting system, the total vehicle weight increased from 163.13 kg to 168.46 kg. Although the weight increase negatively affects vehicle's performance, it is negligible compared to the improvements in shifting times.

## 4 Conclusion

The implementation of the pneumatic actuator and sensors for gear detection without a potentiometer in our automated shifting system demonstrates that it is feasible to detect gear changes using sensors that recognize only the change rather than the absolute gear position. This advancement not only reduces the shifting time but also minimizes the potential for human error, thereby enhancing driver consistency and vehicle reliability. The ergonomic design of the steering wheel was emphasized to ensure that the driver maintains full control of the vehicle, which is crucial for achieving optimal performance on the racetrack.

Despite the clear benefits of the developed system, there are areas for improvement. One significant challenge encountered was the occasional failure of the gearbox to stay in gear, leading to incorrect gear displays on the user interface. This issue arises due to the current method of detecting gear changes. Addressing this problem through more reliable detection methods could enhance the system's performance to match those using potentiometers.

The speed of the program loop is critical to the system's correct operation. Faster execution times improve the system's responsiveness and the accuracy of the timers within the code. Although the current system operates reliably, future development should consider using a more powerful microcontroller to enable real-time operation and support more complex functions.

The comparison of shifting times highlights the substantial advantage of the automated system. Manual shifting times averaged 621 ms for higher gears and 525 ms for lower gears, whereas the automated system achieved significantly faster times of 135 ms and 93 ms, respectively. This improvement translates to a considerable reduction in total shifting time during a single lap of approximately 10 shifts, decreasing from 5.7 seconds to 1.1 seconds. This 4.6-second reduction allows for longer acceleration periods or later braking, ultimately leading to faster lap times.

In conclusion, the developed system significantly improves shifting performance, enhances safety by allowing two-handed steering during shifts, and offers a considerable reduction in lap times. Despite the identified challenges and limitations, the system is reliable and suitable for racetrack use, with clear pathways for future enhancements to increase reliability and functionality.

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