Development of a mechatronic transmission control system for the drivetrain of the K71 Project

by

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A dissertation submitted in full satisfaction of the requirements for the degree of Magister in Mechatronic Engineering in the Faculty of Engineering, the Built Environment and Information Technology of the Nelson Mandela Metropolitan University

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I, Alexander Nörtemann, 213508869, hereby declare that the dissertation, *Development of a mechatronic transmission control system for the drivetrain of the K71 Project* for the degree of *Magister in Mechatronic Engineering*, is my own work and that it is not previously been submitted for assessment or completion of any postgraduate qualification to another university or for another qualification.

Port Elizabeth July 11, 2014

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Copyright statement

Abstract

The tractive force has to be interrupted during a gear-shifting operation in a manual vehicle transmission, leading into a decrease of speed while changing gears during the acceleration process. Therefore in a racing application, the shifting time has to be as short as possible so that the required performance of a racing car can be achieved. The following dissertation describes the development of a transmission control system to enable gear changes within a manual gearbox, which was designed for the Formula Student racing series. Various solutions were developed on the basis of reviewed literature, technical data of components and experiences of Formula Student teams. Following this, a comparison of the concepts by means of a utility analysis identified the pneumatic actuation of selector forks to be the most suitable concept. This was mainly due to the expected shifting time, the weight, and its advantageous energy supply requirement. After the selection of the actuators and the position sensors, the system was implemented into the drivetrain to check the fitment and the technical feasibility. To draw conclusions regarding the shifting time and to prove the functionality of the system, an open test bench was constructed. Additionally, the hardware and software had to be developed to enable the test run. After the manufacturing and assembling of the test bench, the optimal settings for the test run were determined. By comparing the achieved shifting time of alternative solutions, an improvement in the driving performance of a Formula Student race car is probable.

Keywords:

Shifting system, Shift-by-wire, Tractive force interruption, Formula Student, Shifting time

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First I want to thank all the employees from the Faculty of Engineering for their support and cooperation. Particularly I would like to mention Prof. Dr.-Ing. U. Becker and Prof. T. van Niekerk. Due to their tireless support and their confidence placed in me, they contributed significantly to the success of this project. A big thank you goes to Gregor Lasser for his assistance and his soldering skills. Last but not least I want to thank my parents for their love and support.

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Nomenclature

Abbreviations

Abbreviation	*Meaning*
AC	Alternating current
ADC	Analog-digital converter
AMR	Anisotropic magnetoresistive
ATZ	Automobiltechnische Zeitschrift (Magazine for automotive technology)
BMW	Bayrische Motorenwerke (Bavarian Motor Works)
BUS	Binary Unit System
CAD	Computer Aided Design
CPU	Central processing unit
EEPROM	Electrically erasable programmable read-only memory
IFBW	Institut für Fahrzeugbau Wolfsburg (Institute for Vehicle Manufacturing Wolfsburg)
K71	Internal name for a motorbike engine from BMW
LED	Light-emitting diode
LVDT	Linear variable differential transformer
MISO	Multiple input single output
NPN	Type of a bipolar transistor
RAM	Random-access memory
SCK	Serial clock
SMD	Surface mounted device

Abbreviations

Abbreviation	***Meaning***
SRAM	Static random-access memory
USART	Universal synchronous and asynchronous serial receiver and transmitter

Symbols

Symbol	***Unit***	***Meaning***
b_{abs}	$[^{kg}/_{h}]$	Absolute fuel consumption
d	$[mm]$	Diameter
F	$[N]$	Force
F_a	$[N]$	Axial force
F_t	$[N]$	Tangential force
F_{tef}	$[N]$	Effective tractive force
F_{tid}	$[N]$	Ideal tractive force
F_z	$[N]$	Tractive force
h	$[mm]$	Piston stroke pneumatic cylinder
I	$[A]$	Current
I_{ex}	$[A]$	Existing current
i_n	$[1]$	Transmission ratio
n	$[^{r}/_{min}]$	Engine speed
n_i	$[^{r}/_{min}]$	Input speed
n_o	$[^{r}/_{min}]$	Output speed
n_{max}	$[^{r}/_{min}]$	Maximum engine speed
n_P	$[1]$	Possible amount of movements
P	$[W]$	Power
p	$[Pa]$	Pressure
p_A	$[Pa]$	Pressure resistance pressure accumulator
p_C	$[Pa]$	Operating pressure pneumatic cylinders
P_{dis}	$[W]$	Power dissipation
P_{max}	$[W]$	Maximum power
R_{min}	$[\Omega]$	Minimum resistance value
T	$[Nm]$	Torque
T_i	$[Nm]$	Input torque

Symbols

Symbol	***Unit***	***Meaning***
T_{max}	$[Nm]$	Maximum torque
T_o	$[Nm]$	Output torque
t_{shift}	$[s]$	Shifting time
U	$[V]$	Voltage
U_L	$[V]$	Operating voltage of LED
U_MC	$[V]$	Output voltage microcontroller
U_R	$[V]$	Voltage drop at resistor
v	$[{}^{km}/{}_{h}]$	Speed
V	$[m^3]$	Volume
V_A	$[m^3]$	Capacity pressure accumulator
V_{Cn}	$[m^3]$	Stroke volume pneumatic cylinder

Greek symbols

Symbol	***Unit***	***Meaning***
α	[°]	Inclination angle of selector gate
η_e	[1]	Efficiency of the drivetrain

1 Introduction to the study

1.1 Introduction and background

Various student teams from technical universities compete against each other in the racing series Formula Student. The objective is not only to develop the fastest car, but construction and performance is evaluated as well, taking into consideration the financial planning, and the sales arguments of the teams. The aim of the project is the acquisition of practical experience and application of theoretical knowledge provided in lectures [17].

Corresponding to the objectives stated above, the task of the K71 Project is the development of a specified drivetrain for Formula Student applications. The development is based on the existing K71 [1] engine from the motorcycle manufacturer BMW [20]. The engine was customized by several modifications in order to meet the requirements of Formula Student applications. To take advantage of the modified power unit, the gearbox was modified in order to supply the driving wheels with the required tractive power [42]. During gear changes in the gearbox, the tractive force needs to be interrupted, leading to a decrease of vehicle speed during the shifting time. The discontinuity in the torque flow thus affects mainly the acceleration process. Consequently the shifting time will have to be as short as possible, depending on how fast the dog rings [2] can take up their positions. In order to enable shifting operations with the optimized gearbox of the K71 Project, a shifting system is required to position the dog rings.

[1] Internal name of the used engine given by the manufacturer.

[2] Components in the gearbox to engage and disengage the spur gears.

1.2 Overall aim, objectives and declaration of the study

Aim

The aim of the study is to develop a mechatronic transmission control system to enable gear changes in the optimized gearbox of the K71 Project. The system being developed aims to improve the dynamic driving properties of a Formula Student racing car. Furthermore, the system must be capable of assisting the driver during a shifting operation. The development is the next step towards completing the drivetrain of the K71 Project.

Objectives

Primary research objective

The primary research objective is the development of a mechatronic transmission control system to position dog rings inside the gearbox of the K71 drivetrain, so as to enable gear changes. To reduce the tractive force interruption during a shifting operation, the system should guarantee a short shifting time. Another significant characteristic is the weight of the system. Furthermore the energy requirement of the system must be taken into consideration.

Secondary research objective

In order to achieve the primary objective of this study, the following secondary objectives were defined:

- To undertake studies of frequently used shifting systems.
- To develop concepts which enable gear changes in the K71 gearbox.
- To compare possible solutions in order to find a suitable system which meets the requirements of a Formula Student application.
- To select the actuators and the sensors for the system.
- To construct the shifting system by means of the available CAD data of the K71 drivetrain.
- To construct an open test bench in order to test the functionality of the system.
- To develop the necessary hardware and software for the test bench.
- To test the system on the test bench

Declaration of the study

The focus is on developing the shifting system based on the available CAD data of the drivetrain, as the development of the engine and gearbox housing has not yet been finalized. Since the housing of the drivetrain could change in future developments, the preparation of technical drawings for the shifting system is not included in this dissertation.

1.3 Brief literature review

In the following section a brief literature review of transmissions connected to internal combustion engines is given. In this context, another consideration is the tractive force interruption. Furthermore, a compilation of sources dealing with the gear linkage and actuation principles of gearboxes is provided.

1.3.1 Transmissions and combustion engines

According to Trzesniowski [46] and Naunheimer *et al.* [41], a gearbox is a necessity in the adaption of power from an internal combustion engine to the demands of a vehicle. A gearbox can be divided into two main components:

- Speed converter: Adjusts the speed of the drivetrain (mechanic or hydrodynamic clutch)
- Torque and Speed converter: Torque and speed are converted by different gear ratios i_n. (Range change or continuously variable transmission)

Various types of gearboxes are utilized, although in racing applications, manual range change gearboxes are mainly used [46]. The gearboxes transfer the torque by different meshed spur gear pairs which can be selected by the driver.

1.3.2 Tractive force interruption

The importance of a short tractive force interruption is described by Trzesniowski [46] and can also be deduced from Wright [50]. While the gears in a manual gearbox are changing, the tractive force needs to be interrupted to relieve the loads acting on the gearwheels. This allows mainly the disconnection of the current gear pair, and the gentle selection of the following one.

While this is happening, no torque can be transferred so the speed of a race car is reduced momentarily during the acceleration process. Therefore, engineers are attempting to shorten the shifting time, leading to the optimisation of mechanical components. Furthermore, semi- or fully-automated systems are used to enable faster gear changes. These systems may use actuators to carry out the gear selection and/or methods to interrupt the tractive force more precisely.

1.3.3 Gear linkage

According to Trzesniowski [46] and Naunheimer *et al.* [41], a distinction is made between inner and external shifting elements. Inner shifting elements are components inside the gearbox which enable a shifting operation. Extern shifting elements are used in the transfer of the force from the driver to the inner shifting elements. These parts are amongst others, a shift lever, shafts and joints to transfer the force and/or push and pull cables. To facilitate the shifting operation, the shift lever should be located close to the steering wheel [46]. Consequently, the necessary force to operate the lever and the movement range have to be taken into consideration. By using a mechanical system, a compromise has to be made between a short movement of the lever, and the force required to actuate it [46] [41]. Furthermore, the efficiency of the mechanical system to transfer the force is often less than 70%, according to Naunheimer *et al.* [41] .

As stated previously, actuated systems are an option. These systems are also called "shift-by-wire" [46] [41]. The development ensures more design freedom in terms of the positioning of the control elements, and the possibility of simplifying the handling. Furthermore, automated operations are possible; for example, a shifting operation at a defined engine speed [41]. Disadvantages of actuated systems can also be found in the literature. Malfunctions of these systems can result in serious damage to mechanical parts in the drivetrain, or can jeopardize the driving stability of a vehicle. Thus safety measures are needed to prevent malfunctions. Safety measures which can be found in the literature are, for instance, mechanical linkages which prevent two gear pairs from being engaged at the same time, or redundant position sensors [41].

1.3.4 Actuation principles of gearboxes

A compilation of theoretical possibilities to realise a shifting actuation can be found in the book by Trzesniowski [46]. The options are an electric, hydraulic or a pneumatic actuation. However, the focus is on the explanation of a hydraulic actuation by the use of a rotary actuator and mechanical components. Wright [50] also describes the system stated above, and mentions the use of hydraulic linear actuators furthermore. The hydraulic cylinders are able to position the shifting elements directly. In consequence, the inner shifting elements can be simplified. A hydraulic actuation in Formula Student applications is furthermore shown in an ATZ[3] article [27]. The system described consists of a hydraulic linear actuator which actuates a shift lever. The shift lever is mounted on a shaft to convert the linear movement into a rotary movement similarly to the rotary actuator mentioned above. The detailed description of the system and the achieved shifting time makes it a relevant reference source. Another report shows a pneumatic shifting system in a Formula Student application. It operates similarly to the hydraulic system shown in the ATZ magazine, using a linear pneumatic actuator [44]. The master‘s thesis of Binder [19] describes the development of a shifting system powered by a servomotor. A further possibility is electric actuation using a linear solenoid [45] [15]. Apart from these sources which deal with the actuation of shifting systems in gearboxes, general pros and cons of different actuation principles can be gathered from Croser *et al.* [26], Merkle *et al.* [39] and Gerke [29]. Further information can also be found in the technical data given by the manufacturers of components. To enable a comparison between possible actuation principles, the information will have to be grouped under various concepts, as stated in Section 1.4.2.

1.4 Methods and materials

The aim of this study, as stated previously, is to develop a mechatronic transmission control system to enable a gear change in the optimised gearbox of the K71 Project. In order to reach the objectives, a secondary study and a primary study will be carried out.

During the studies, research material will be obtained through library facilities of the Nelson Mandela Metropolitan University and from the Ostfalia University in Wolfsburg, Germany. Further information will be acquired utilizing the Internet.

[3] Magazine for automotive technology

1.4.1 Secondary study

Prior to the development of the system, information from Formula Student teams will be collected with regard to the systems they use to enable gear changes as well as their experiences. Further information about shifting systems in gearboxes and advantages of different actuation principles are obtained from published literature. Sources dealing with the actuation of dog rings in racing applications are, for instance, the books "Rennwagentechnik" (Race Car Technology) [46] and "Formula 1 Technology" [50].

The acquired information will be used to define the requirements for a shifting system. Furthermore, the material will be grouped together in various concepts. Additional concepts will be developed regardless of their existence in the field of application. This is intended to collect a wide scope of possible solutions.

1.4.2 Primary study

The primary study deals with the selection of a suitable concept and its development in order to improve the dynamic driving properties of a Formula Student racing car. The concept selection is intended to be undertaken by means of a utility analysis. The components for the actuation will have to be selected afterwards. For this purpose, technical data will have to be collected and reviewed with regard to the range of application. The same applies to the selection of position sensors. An overview of possible sensors in automotive applications is furthermore given by H Wallentowitz *et al.* [35]. If necessary, different concepts can repeatedly be compared in a utility analysis.

After the actuators and sensors are selected, the system will be implemented in the K71 drivetrain. This is necessary to ensure the technical feasibility of the transmission control system in connection with the K71 drivetrain. The construction work will be undertaken using the program "Catia" and the available CAD data of the K71 drivetrain. Furthermore, 3D data of some components can be obtained from the manufacturers. During the construction process, the permissible operating parameters of the components will have to be taken into consideration.

To demonstrate the advantages of the system and to verify its functionality, the system will be tested on an open test bench. For this purpose, the test bench will be developed with the program Catia. On the test bench the gearbox will be powered by a DC motor. By changing the operating voltage of the motor, the speed of the gearwheels can be regulated if necessary. The manufacturing of mechanical parts will be done in the workshops of the Nelson Mandela Metropolitan University.

To run the system on the test bench, the hardware and software needs to be developed. For the development of the circuit board, the CAD application KiCad will be used. The circuit board will be printed and assembled using own resources. The Open-Source-Software "Eclipse" will be used for the development of the control software. Extensive documentation is available for this application [1].

As mentioned above, the system will be tested on the test bench after the assembly and the connection of the components.

1.5 Scope and significance of the study

While executing shifting operations with conventional gearboxes during acceleration, the speed of vehicles decreases due to the necessary tractive force interruption [46]. The effect mentioned above is also noticeable in Formula Student applications. Various types of actuated shifting systems were developed to ensure a quicker positioning of the dog rings [46] [50] [45] [27] [44] [19], as the time of the tractive force interruption depends on how quickly the dog rings can take up their positions. The many development projects in Formula Student applications aim to leave the original engine housing (which is usually a part of a conventional motorbike engine) in its original shape. This constraint limits the number of possible solutions. The aim of the K71 Project is to develop a drivetrain based on an existing motorbike engine. The various changes to the drivetrain also include a new engine housing. This offers more design freedom for a gear-shifting system, which will be developed in this dissertation. Following this, a system will be developed, which will provide an advantage in terms of shifting time, system weight and energy requirement. Therefore the study will attempt to make a valuable contribution to possible gear-shifting systems in Formula Student applications.

1.6 Structure of the research

The research will be structured as follows:

Chapter one: Introduction to the study will present the background of the study as well as the problem statement. The aim of the study as well as the research objectives will be stated thereafter. The literature review which follows will provide a compilation of sources used for the research. Additionally, the methods used will be described. Thereafter the scope and the significance of the study will be presented. The chapter will end with an overview of the structure of the dissertation.

Chapter two: Fundamental basics of the transmission will describe the function of a mesh gearbox[4] as well as the basics of a transmission in connection with internal combustion engines. Furthermore inner shifting elements of the standard K71 engine will be explained. The impact of a tractive force interruption during a shifting operation will be shown as well. To provide the basis for the development of a shifting system for the K71 drivetrain, the modified gearbox of the K71 drivetrain will be presented thereafter.

Chapter three: Concept development will show the development of the basic system, and the requirements for a shifting system therefor will be described. Possible concepts will be shown and evaluated in a utility analysis. The necessary components will be selected thereafter. The chapter will end with the implementation of the shifting system in the K71 drivetrain, used to show the technical feasibility of the system.

[4] Common type of gearbox used in motorsport and motorbike applications.

Chapter four: Hardware will deal with the development of the hardware to enable the test run on a test bench. The requirements for this will be defined. Based on this, the functional architecture of the hardware will be specified. This will lead to the selection of the components and the preparation of the circuit board.

Chapter five: Software will focus on the development of the software for the test bench. This will also be based on the presentation of the requirements. By means of the state machine, the basic functions of the software will be shown. The flow chart of the shifting system will be explained thereafter to clarify the software design and the program sequence.

Chapter six: Test bench will provide the construction of the open test bench to enable the functional testing. The construction will be based on the shifting system developed in chapter three. For the sake of clarity, only the finished design and the features of the components will be shown.

Chapter seven: Application on the test bench will describe the assembly of the components and their interconnection. Furthermore, the necessary settings will be shown as well as the functions of the software. The chapter will end will the determination of the optimal settings for the test bench, and the achieved shifting times.

Chapter eight: Summary will summarise the previous chapters. In particular, the results of each chapter, what was achieved, and the limitations of the study will be presented. The chapter will end in showing further development potential of the gear-shifting system.

2 Fundamental basics of the transmission

2.1 Introduction

The following chapter presents the basics of the dissertation. They are necessary to understand the following calculations and construction steps. For that purpose, the construction of the standard gearbox which is integrated in the engine block gets explained. Especially the function of the standard gear-shifting system is described in this section. Further on, the necessity of a transmission which is connected with a combustion engine is clarified. Another topic is the impact of the tractive force interruption during a shifting operation.

The modified gearbox which will be used in the K71 drivetrain is shown at the end of this chapter. This is the basis for the development of the transmission control system.

2.2 Standard K71 transmission

The gearbox of the K71 engine is integrated in the engine block. Figure 2.1 shows this unit with the crank shaft and the lower engine case. In Figure 2.2 the gearbox layout is shown.

The torque is transferred from the crankshaft by a straight-toothed spur gear to the basked of the wet multi-plate clutch. To provide vibration damping, torsional dampers are used. They enable a twisting motion of the gear wheel (1) relative to the clutch basket (2) [3].

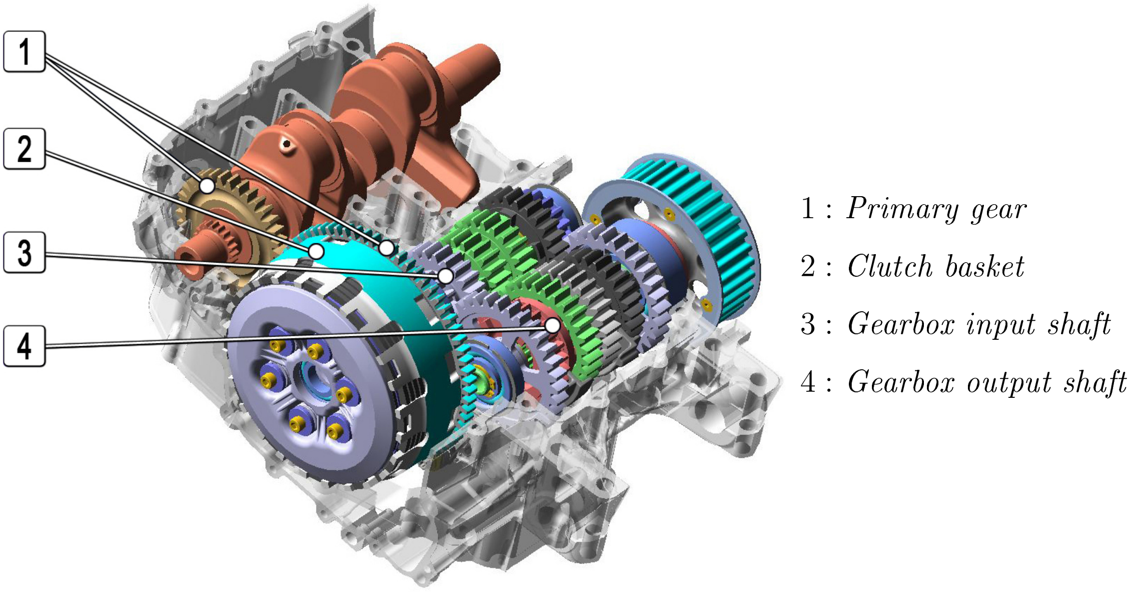


Figure 2.1: K71 standard transmission [4]

The gearbox is a single-stage, sequentially shifted six-gear mesh gearbox which operates without synchronization. The gear shafts (3)(4) are arranged crossways behind the cylinders on one level [1]. On the gear shafts, straight-toothed spur gears are located. The selectable gear ratios are realized by six different gear pairs. The lubrication is provided by the engine oil, which is transferred by spray nozzles or by the drilled out gearbox input shaft to the lubrication points. To realize a final drive, a synchronous belt is used. It connects the gearbox output shaft with the driving wheel [3].

2.2.1 Gearbox layout of the K71 engine

To clarify the function of a mesh gearbox, the gearbox layout of the standard engine is shown in Figure 2.2. The layout is similar to the optimized gearbox, which is shown in Section 2.5.

[1] Transverse gearbox [46]

To enable selectable gear ratios, one gear wheel is connected in an interlocking and/ or force fitting manner on a gear box shaft [2] (5). The mating gear [3] (6) is located on a bearing on the opposite gear shaft, which makes the gear wheel twistable.

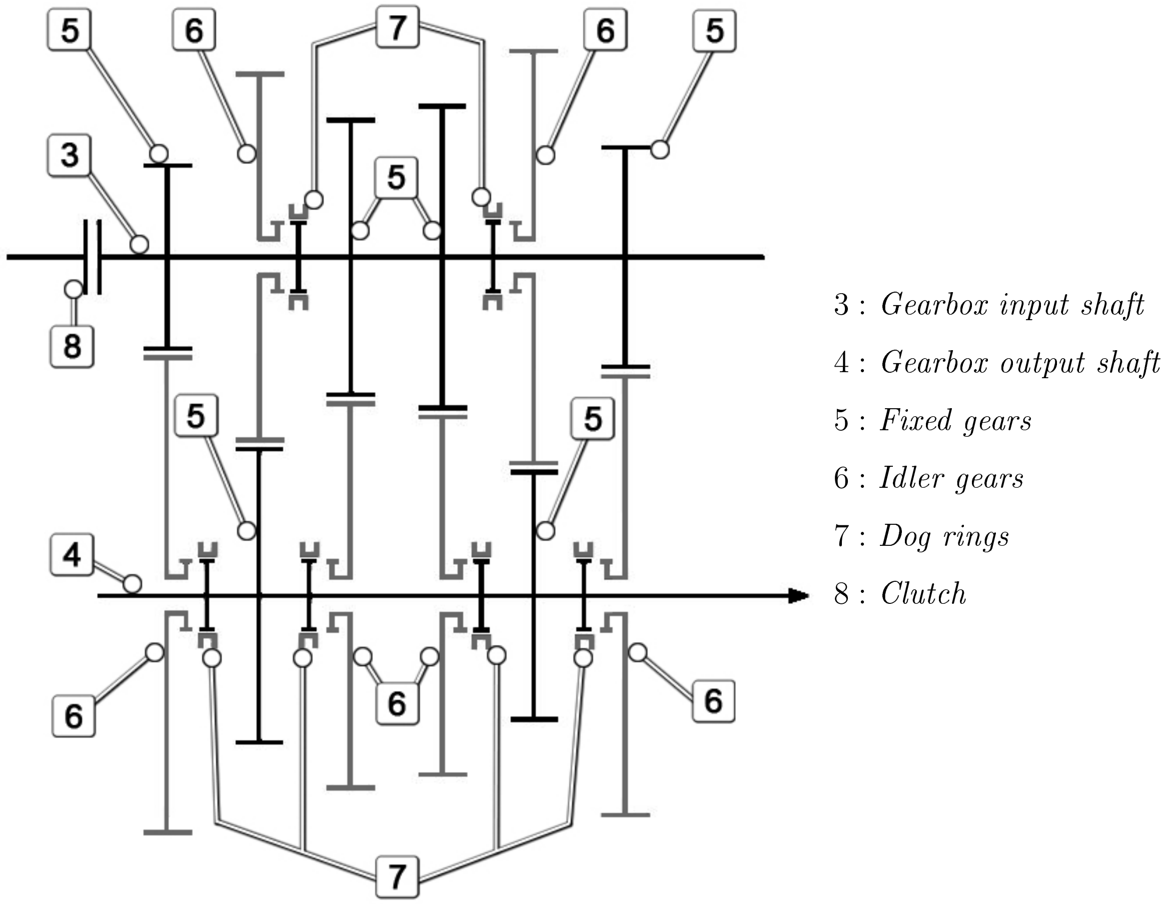


Figure 2.2: Standard K71 gearbox layout [42]

The dog rings (7) are mounted non-rotatable but allow axially movement. By moving the claws of the dog rings into the cutouts of the idler gear, a ratio can be selected and engaged to the shaft.

[2] Fixed gear
[3] Idler gear

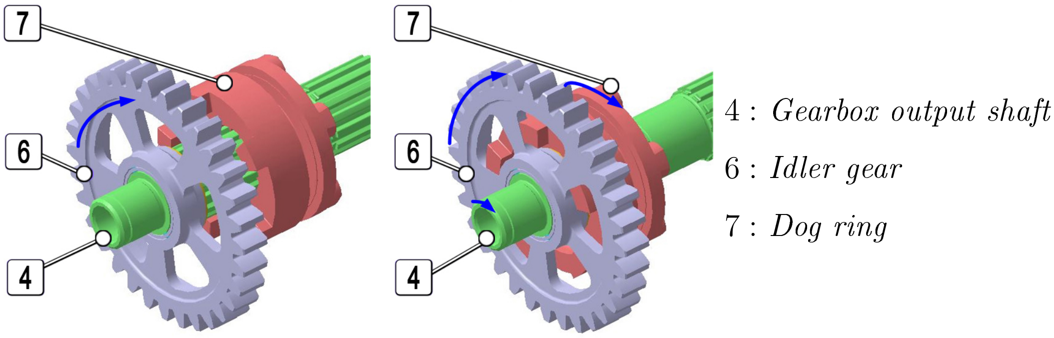


Figure 2.3: Principle of a mesh gearbox [4]

2.2.2 Gear-shifting system of the K71 engine

The standard K71 engine has a mechanical, sequential shifting system. The following figure shows the CAD image of the component.

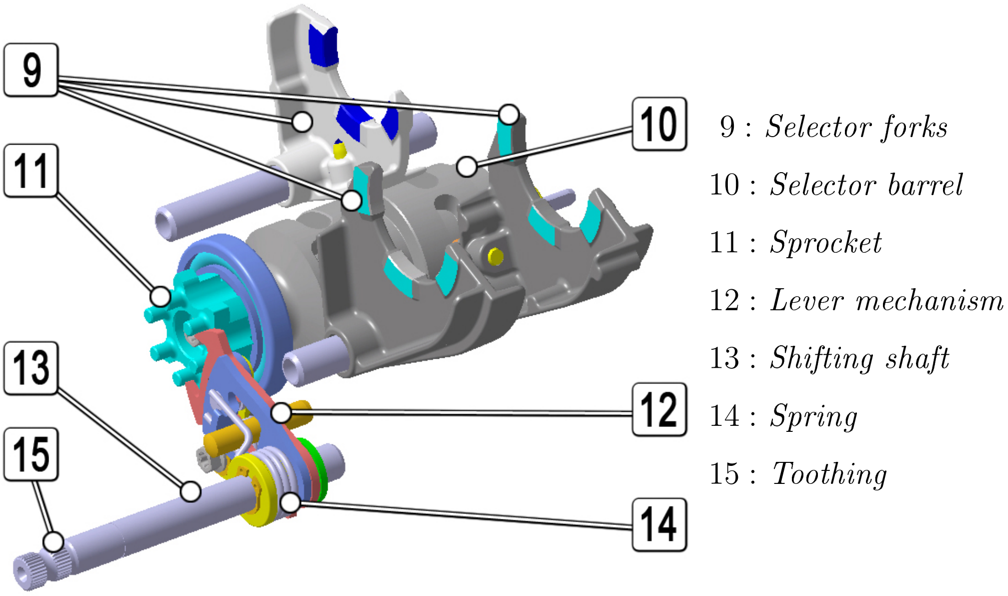


Figure 2.4: Standard K71 gear-shifting system [4]

The axial movement of the dog rings are enabled by axial moveable selector forks (9), which are controlled by a twistable selector barrel (10). A lever mechanism (12) ensures the positioning of the selector barrel in the required rotation angle, by turning the shifting shaft (13) which reaches outside of the gearbox housing. To hold the selector barrel in the selected position, a locking mechanism is used. A spring (14) moves the shifting shaft in its original position. A toothing structure (15) is located at the end of the shaft, where a shifting lever is mounted in a form-locking manner. To do a shifting operation, the shift lever is moved up and down.

The grooves of the selector barrel are designed to get the following gear-shifting sequence: 1-N-2-3-4-5-6

2.3 Basics of vehicle transmissions connected with combustion engines

A transmission is necessary due to the difference between the tractive force of a combustion engine to the tractive force demand of a vehicle. This fact will be clarified in this section.

2.3.1 Power characteristics of a combustion engine

The engine characteristics of a combustion engine can be described by two diagrams: The torque/speed curve at full load and, calculated from these values, the power curve.

These curves show the following disadvantages of combustion engines:

- No torque is available on start-up
- P_{max} is reached at a certain rotational speed of the engine

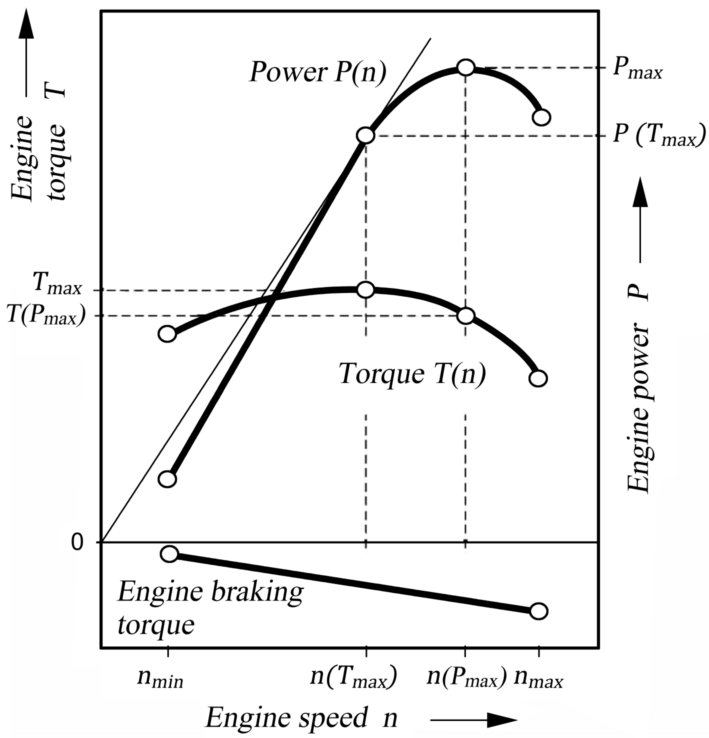


Figure 2.5: Performance diagram of a combustion engine [41]

Furthermore the fuel consumption depends on the operating point on the engine map [41]. Figures 2.5 and 2.6 are showing the diagrams mentioned above.

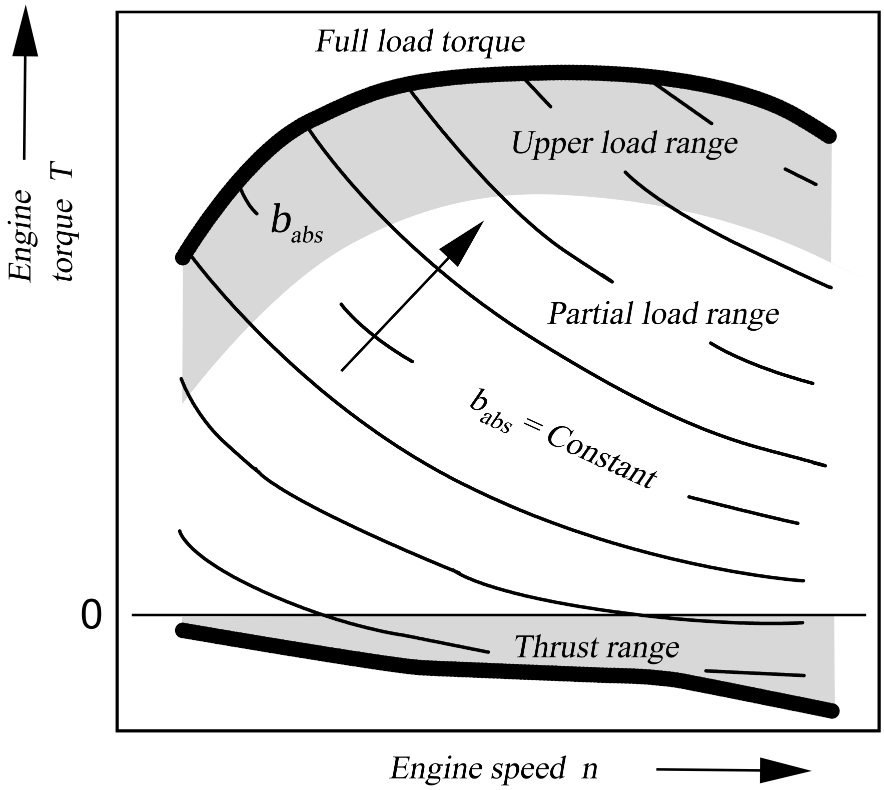


Figure 2.6: Fuel consumption diagram of a combustion engine (b_{abs}= absolute fuel consumption $^{kg}/_{h}$) [41]

2.3.2 Tractive force demand of a vehicle

The tractive force demand of a vehicle can be described by the tractive force hyperbola. The curve is generated by an ideal driving machine which has the same power output throughout the whole engine speed range.

A distinction is drawn between the ideal tractive force which is described by the following equation and the effective tractive force which can be calculated by Equation 2.2.

$$F_{tid} = \frac{P_{max}}{v} \tag{2.1}$$

$$F_{tef} = \frac{P_{max}}{v * \eta_e} \tag{2.2}$$

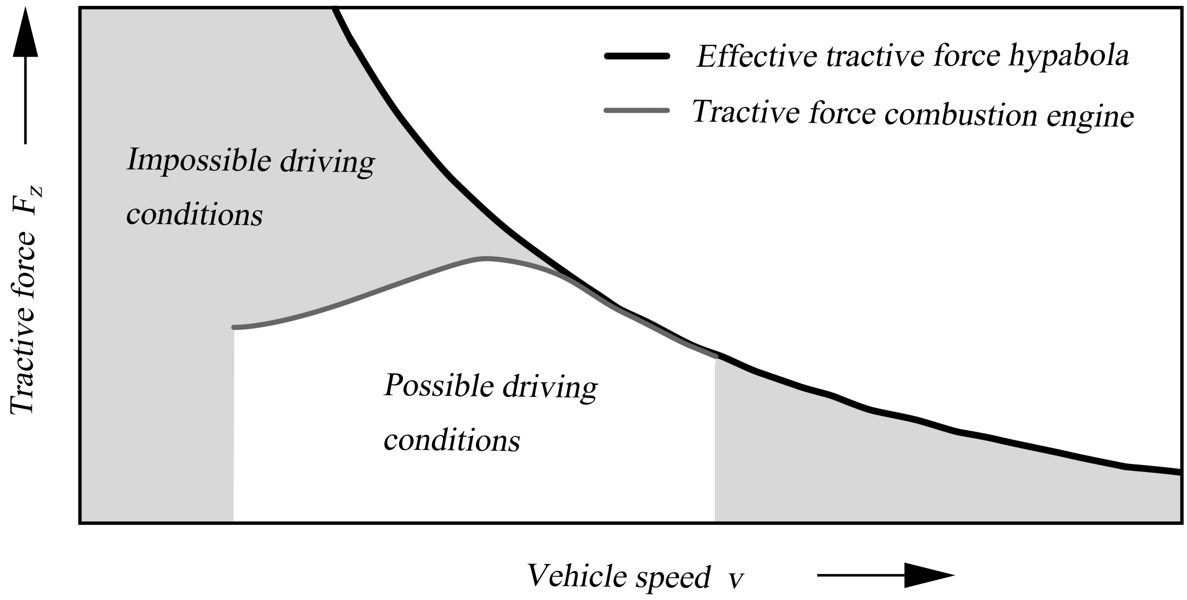


Figure 2.7: Tractive force of a combustion engine compared to the demand of a vehicle

As shown, the effective tractive force takes the efficiency of the drivetrain into account. Figure 2.7 shows the tractive force of the K71 engine, which is used in the motorcycle model F800, compared to the tractive force demand of the same motorcycle. The comparison is made under the assumption, that the torque of the engine is transferred by a constant gear ratio. The shaded areas are marking the impossible driving conditions and showing the disadvantages of a combustion engine. [41] [46]

2.3.3 Task of a transmission

The task of a transmission is, to adapt the tractive force of the engine so that it comes close to meet the demand of the vehicle. A transmission consists of the following components:

- **Speed converter:** Adjusting the speed of the drivetrain in relation to the engine speed. In case of a speed difference, the power difference is converted into heat (mechanic or hydrodynamic clutch).
- **Torque and speed converter:** Torque and speed are converted by different gear ratios i_n. The following equations are showing a constant power on the driving

wheels, if a loss-free power transfer is assumed. (range-change or continuously variable gearbox).

$$\frac{T_o}{T_i} = i_n \tag{2.3}$$

$$\frac{n_i}{n_o} = i_n \tag{2.4}$$

This leads into the following main functions of a vehicle transmission:

- Enable the start off
- Power adaption
- Power transfer

Figure 2.8 shows the tractive force demand of the above mentioned motorcycle in comparison with the tractive force of the K71 engine, which is connected to a four gear transmission [41] [46].

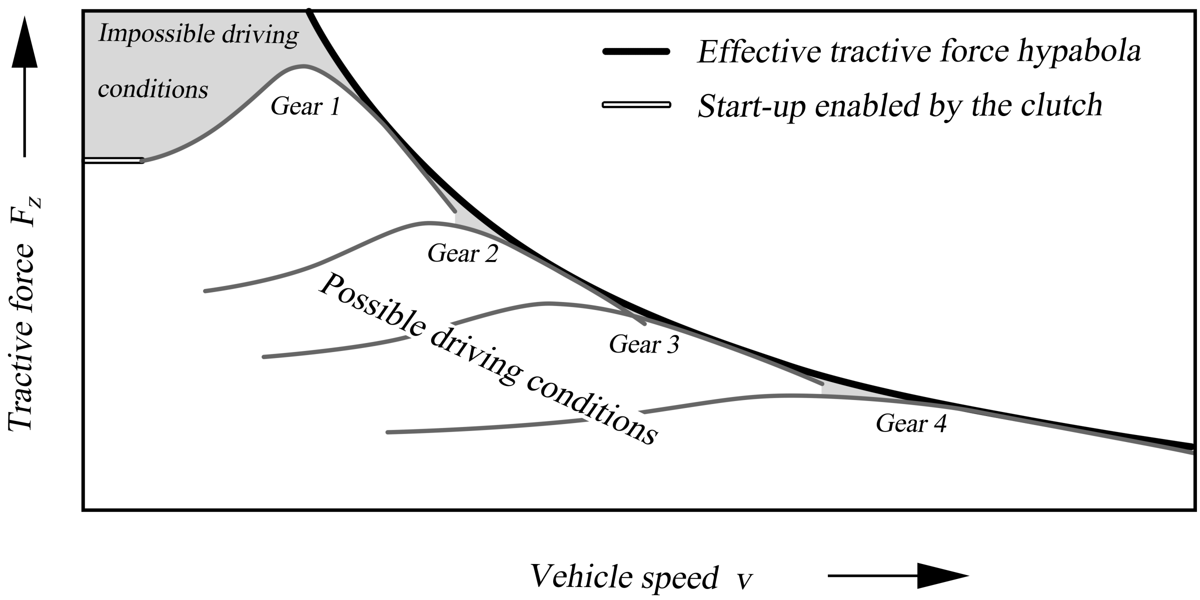


Figure 2.8: Tractive force of a combustion engine connected to a transmission

2.4 Tractive force interruption

As described in the introduction, it's necessary to interrupt the tractive force during a shifting operation when using a manual gearbox. This interrupts the torque acting on the gear wheels and disconnects the dog rings. The effects of a tractive force interruption are very noticeable during an acceleration process. As shown in Figure 2.9, the torque interruption causes a decrease of speed. The time of the torque interruption can also be described as the shifting time. The time depends, among other factors, on how fast the dog rings can take up their position [46].

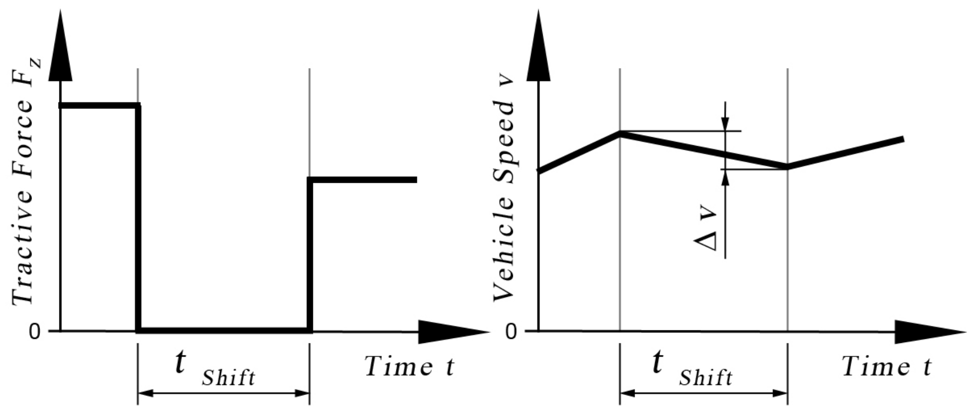


Figure 2.9: Tractive force interruption [46]

2.5 Modified gearbox of the K71 drivetrain

Due to several modifications on the standard K71 engine, a changed power characteristics can be expected as well as a changed tractive force provided by the engine. Furthermore the tractive force demand of a Formula Student race car differs from the demand of a motorcycle. Therefore, the standard gearbox of the K71 engine was modified. Figure 2.10 shows the component with the other torque-transmitting parts of the modified K71 drivetrain.

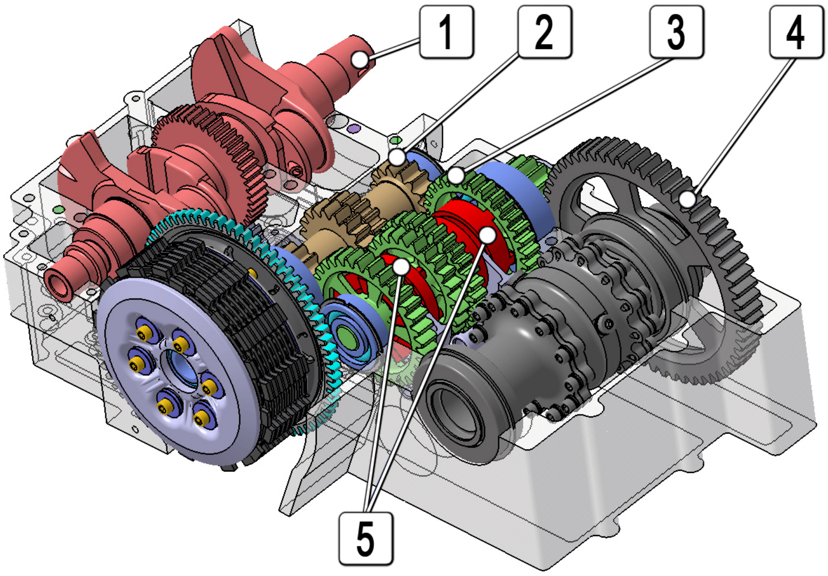
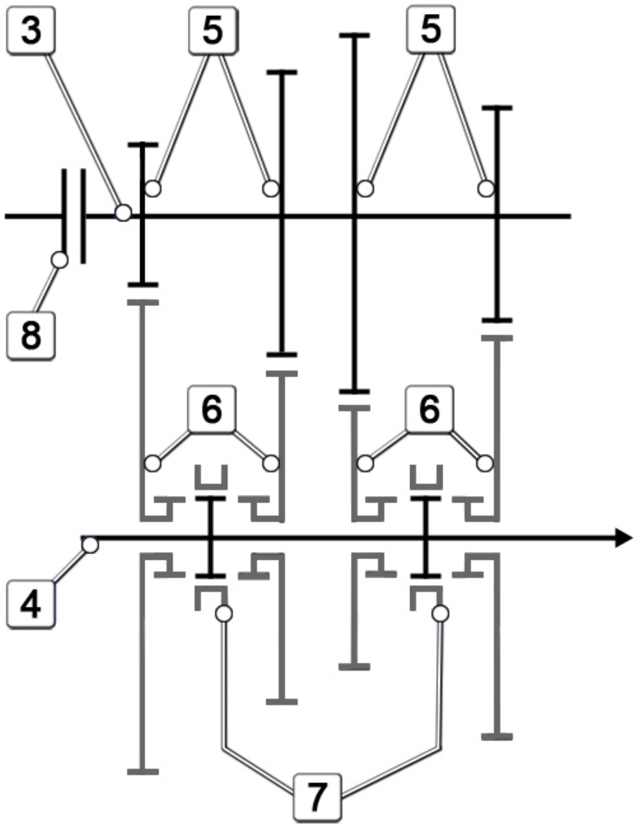


Figure 2.10: Torque-transmitting parts of the K71 drivetrain

The functionality is similar to the standard gearbox, shown in Section 2.2. Figure 2.11 shows the layout of the modified gearbox. As shown, the gearbox is a four-gear mesh gearbox. The fixed gears are located on the gearbox input shaft.



3 : *Gearbox input shaft*

4 : *Gearbox output shaft*

5 : *Fixed gears*

6 : *Idle gears*

7 : *Dog rings*

8 : *Clutch*

Figure 2.11: Modified gearbox layout [42]

2.6 Summary

The purpose of this chapter was to present the basics of the dissertation. Therefor the function of a mesh gearbox was explained by means of the description of the standard K71 gearbox. Furthermore the inner shifting elements of the gearbox were explained, since these parts are often used in Formula Student shifting systems. By comparing the tractive force of a combustion engine with the demand of a vehicle, the necessity of a transmission in connection with a combustion engine was clarified. This was followed by explaining the effects of a tractive force interruption during a shifting operation. At the end of this chapter, the modified gearbox of the K71 drivetrain was shown and especially the layout, hence the shifting system will be based on the modified gearbox.

3 Concept development of the shifting system

3.1 Introduction

This chapter describes the development of the basic system. To find a suitable concept, the requirements of a transmission control system are defined with regard to the range of application. Furthermore, possible concepts are evaluated in a utility analysis. After the determination of the concept, the necessary components for the actuation are selected, taking into consideration the operational parameters. This is followed by the selection of sensors for the position detection. These steps are the basis for the implementation of the components in the K71 drivetrain, shown at the end of this chapter.

3.2 Requirements of a shifting actuation

Due to the range of application, the transmission control system must ensure an effective transfer of the engine torque to the driving wheels. As described in the introduction, this leads into the need of a short shifting time [1] and therefore a short position timing of the dog rings. Another important parameter is the weight of the system. The weight of a vehicle has a big influence on dynamic driving properties. In this context, the centre of gravity of the drivetrain has to be mentioned. It is beneficial to locate the centre of gravity as low as possible to reduce the pitching and rolling of the race car. Furthermore it should be located near to the driver‘s position, which is near the crankshaft of the K71 engine. By that, the mass distribution can be reduced to the centre of gravity of the vehicle [42]. The energy supply needs to be considered as well, it can be provided by the engine or by an energy storage device.

Another requirement, which does not directly affect the driving properties of a vehicle, is the package of the transmission control system. This is not only essential to allow the fitting of the system. The optimal arrangement of following components has to be considered as well. Furthermore the system has to provide the robustness required in a racing application. In this context, the operational safety has to be mentioned. Due to the difference in rotational speed of the spur gears on the gearbox output shaft, it is essential to ensure that only one dog ring is engaged at one time. Therefor sufficient position accuracy has to be provided under all conditions.

The maintainability is another criterion, as parts need to be checked or exchanged after certain intervals. Unlike the application in a production vehicle, the comfort and the acoustic properties are less important, as long as no unreasonable burden of the driver occurs.

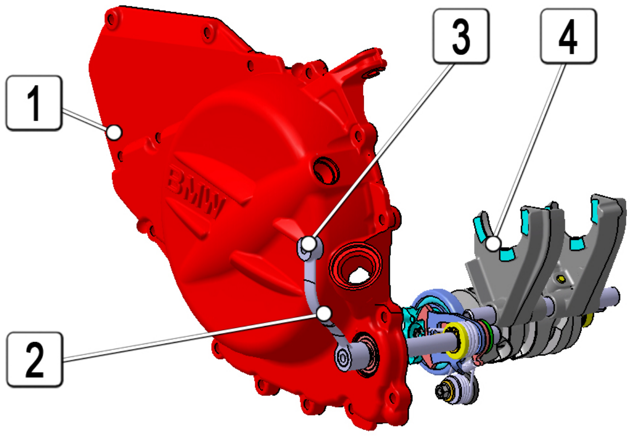
[1] Time of the tractive force interruption.

3.3 Concepts of shifting systems

3.3.1 Concept 1: Mechanical shifting system

One possibility to do shifting operations is the usage of a purely mechanic system. This concept is not suitable to be developed, as the aim of this thesis is to develop a mechatronic system. Nonetheless this concept is shown to enable a comparison between the mechanical system and other solutions.

The mentioned concept operates sequentially with a selector barrel as described in Section 2.2.2. The selector barrel gets turned by the shifting shaft, which is actuated by mechanic components. These components enable a force transfer from the shift lever which is actuated by the driver, to the lever mounted on the shifting shaft. The transfer can be realized by a system consisting of levers and joints or by the usage of a push-pull cable[2]. Figure 3.1 shows the principle of the shifting system.



1 : *Clutch cover*

2 : *lever*

3 : *Fastening point push-pull cable*

4 : *Standard shifting system*

Figure 3.1: Mechanic shifting system

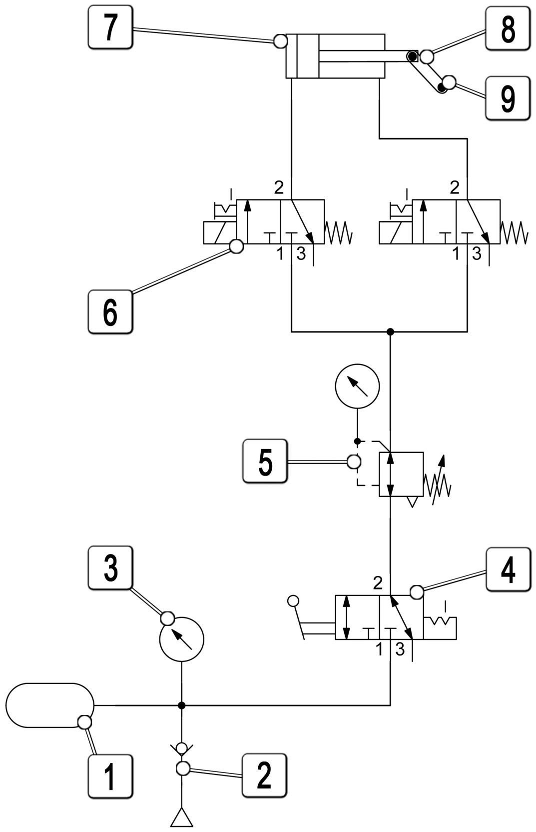
The concept allows the reuse of the standard engine block. By the usage of the selector barrel it‘s impossible to engage two dog rings with the spur gears. This increases the operational safety, furthermore this concept can be considered to be quickly realizable and

[2] Flexible cable, which is used to transfer pulling and pushing forces.

cost effective. Negative to note is the assumed shifting time. It depends on how fast the driver can do the shifting operation. Furthermore the shifting process is uncomfortable, as the driver has to operate the shifting system with the required force. Additionally there is no possibility to realize automated shifting operations at a defined engine speed. By the usage of mechanical components to transfer the force, a compromise has to be made between package, weight distribution and an ergonomic arrangement of the control elements.

3.3.2 Concept 2: Pneumatic actuation of the shift lever

In this concept the shifting system is actuated by a double-action pneumatic cylinder. The concept is used for example by the WOB-Racing Team of the Ostfalia University in Germany. By using this system, the engine block can stay in its standard shape. Figure 3.2 shows the pneumatic circuit diagram of the concept.



1 : *Pressure accumulator*

2 : *Air supply*

3 : *Pressure gauge*

4 : *Manual on-off valve*

5 : *Pressure regulator with gauge*

6 : *2x electrical 3/2 way valve*

7 : *Double-action pneumatic cylinder*

8 : *Shift lever*

9 : *Shifting shaft*

Figure 3.2: Circuit diagram of a pneumatic actuation of the shift lever

The energy for the pneumatic actor is stored in a pressure accumulator (1). A pressure regulator (5) mounted behind the accumulator provides the pneumatic components with the required working pressure. The pneumatic cylinder (7) which is moving the shift lever, is controlled by two 3-2 way valves (6). The shift lever turns the shifting shaft of the mechanical system [3] inside the gearbox. Depending on the dimensioning of the pressure accumulator, other components in the drivetrain can be actuated pneumatically. The WOB-Racing team for instance is using pneumatic components to actuate the clutch and the air box as well.

Advantageous is the energy supply by a pressure accumulator, therefor no energy has to be supplied by the engine. Furthermore useable pressure accumulators can be considered to be light weight. According to the experience of the WOB-Racing team, the time of the

[3] Shown in Figure 2.4.

torque interruption is about 100 ms. A disadvantage, however, is the limited amount of shifting operations depending on the accumulator capacity.

3.3.3 Concept 3: Electric actuation of the selector barrel

Another opportunity to move the selector barrel is the usage of an electric motor, which drives the selector barrel directly. As a result, the lever mechanism and the shifting shaft are no longer required[4]. A control device has to set the correct position of the selector barrel. To provide the needed amount of torque, a reduction gear can be used.

With an electrical shifting system, assuming an appropriate generator, unlimited shifting operations can be enabled. Another option is an energy storage device which is capable to power the shifting system through the whole race. Also a combination of both options is possible. By removing the shifting shaft and the lever mechanism, the engine block has to be modified. Moreover the selector barrel has to be fixed in the selected position till the next shifting operation. The development of a clutch actuation, at a later stage of the K71 Project, has to be considered as well. The required force to actuate the clutch depends on a number of factors. According to the experience of the WOB-Racing Team, the amount of force is about 180 N. This could lead into big and heavy actuators.

3.3.4 Concept 4: Electric actuation of the shift lever

A linear solenoid can be used with the standard mechanical parts[4] to move the selector barrel and engage gears. The actuator consists of two separated coils (2/3) and a plunger (1). The plunger moves in a linear direction depending on the energized coil. A transistor (4) operates the coils. Figure 3.3 shows the section view of a linear solenoid.

[4] The parts are shown in Figure2.4.

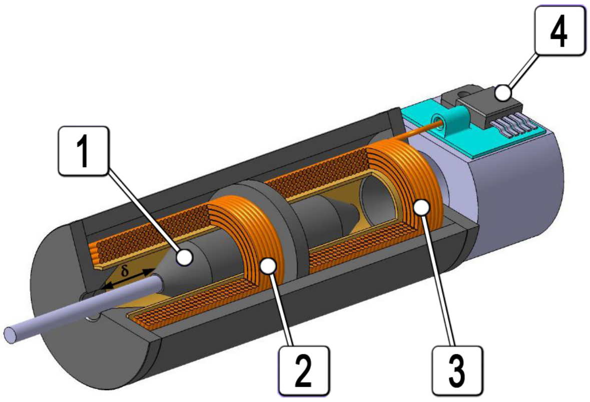


Figure 3.3: Section view of a linear solenoid [45]

Figure 3.4 shows an installed linear solenoid sold by the company ProShift. The actuator is part of an aftermarket shifting system for motorbikes.

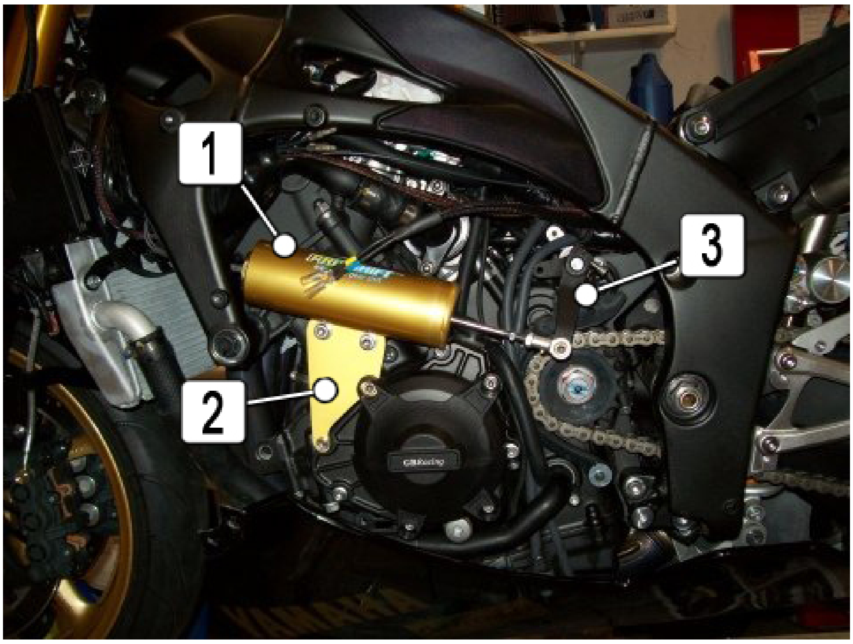
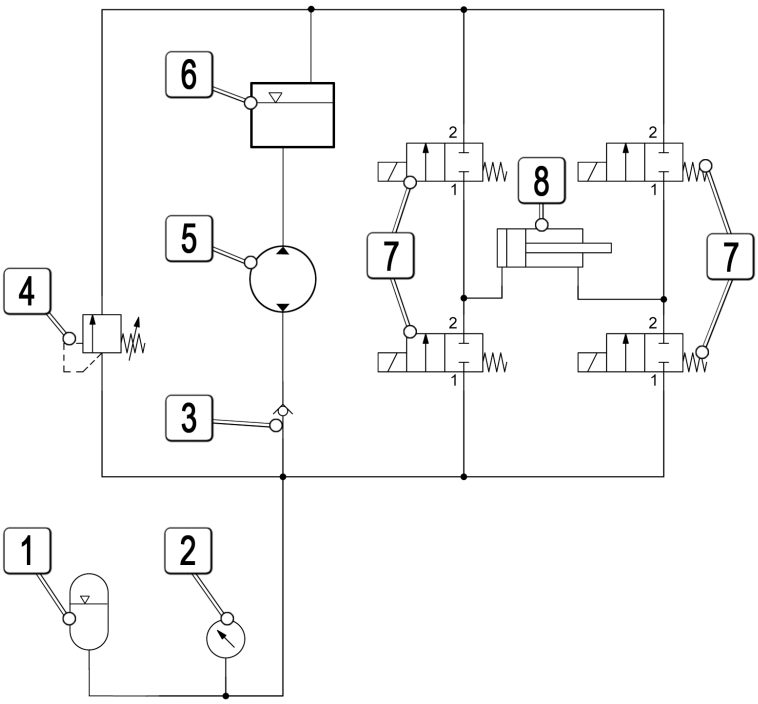


Figure 3.4: Installed solenoid in a motorbike [16]

Due to the reuse of the mechanic components inside the gearbox, the system can be easily implemented in the drivetrain. By that, the operational safety can be increased as well. The possibilities to supply the system with energy are already described in Section 3.3.3. As described in the mentioned section, the possibility of a clutch actuation will have to be checked as well.

3.3.5 Concept 5: Hydraulic actuation of the shift lever

The fifth concept consists of a hydraulic cylinder, which actuates the standard mechanical components in the gearbox [5]. In some circumstances, the engine oil can be used as a hydraulic fluid. However in that case, a filter has to be installed to protect the hydraulic components against particles. Furthermore the oil will have to be cooled. As an example for a hydraulic shifting system, the system from the Formula Student Team of the RWTH-Aachen University in Germany is shown in Figure 3.5. The hydraulic energy is stored in a pressure accumulator (1). As soon as the pressure falls below a pre-set value, an electric hydraulic pump (5) switches on. To reduce internal leakage, the hydraulic cylinder (8) is actuated by four 2/2 way valves (7).



1 : *Hydraulic accumulator*
2 : *Pressure sensor*
3 : *Non-return valve*
4 : *Pressure relief valve*
5 : *Pump*
6 : *Hydraulic tank*
7 : *2/2 way valve*
8 : *Hydraulic cylinder*

Figure 3.5: Circuit diagram of a hydraulic actuation of the shift lever [27]

[5] Shown in Figure 2.4.

The actuation of the clutch isn't shown in the diagram. It also operates hydraulically. Advantageous is the high power density of hydraulic actors. Therefore, a short shifting time can be estimated on one hand and light weight actuators with a good package on the other hand. The disadvantage is the reduction of driving power when the hydraulic pump is powered by the engine. Furthermore the weight and the needed space for the pump and other components have to be considered.

3.3.6 Concept 6: Hydraulic actuation of the selector forks

In addition to the previous concept, it's possible to power the selector forks directly by a hydraulic system. To be able to use the system, the engine block has to be modified. Each hydraulic cylinder will move one selector fork, which is enabled by a good position capability of hydraulic actuators. The fact that no energy is needed while keeping a gear engaged is another advantage of the actuators. By driving the selector forks directly, mechanical components can be reduced. This results in a lower weight of the system as well as a reduction of friction loss. A negative factor is the high requirement in terms of the accuracy of the control system, since the selector forks are controlled separately. A wrong movement of the selector forks can cause mechanical damages on the gearbox or blockade the driving wheels. Figure 6.1 shows a possible circuit diagram of the above mention shifting system, derived from the fifth concept.

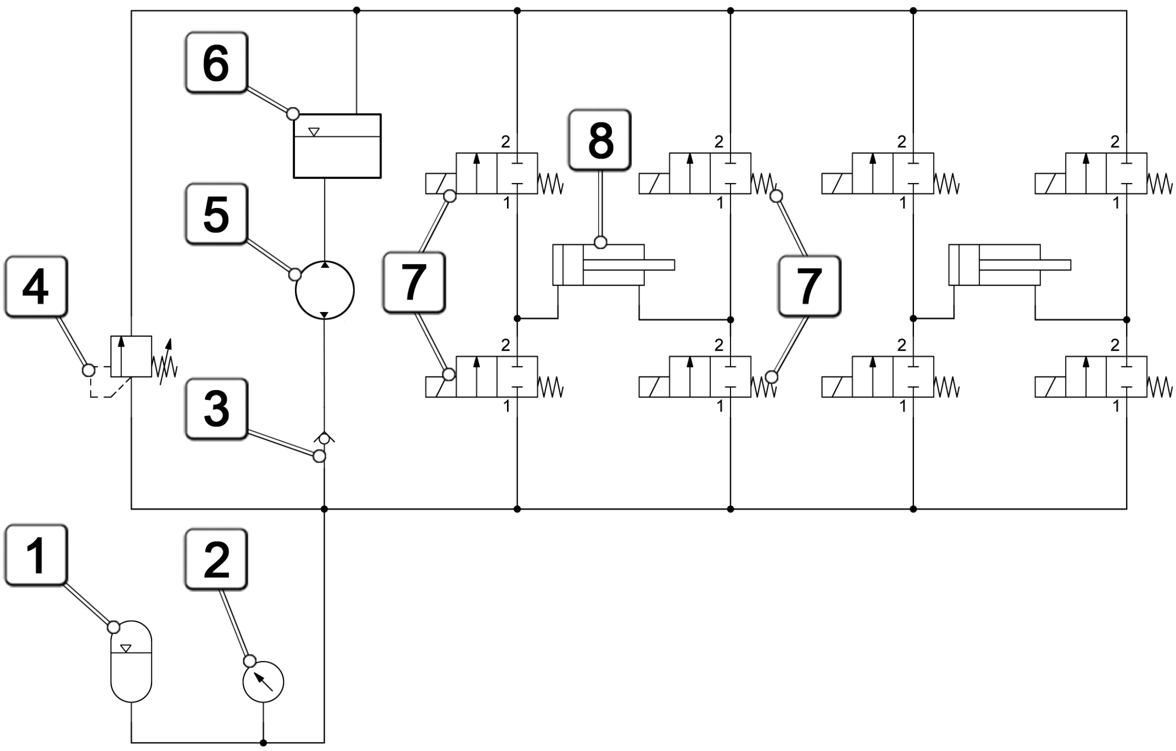


Figure 3.6: Circuit diagram of a hydraulic actuation of the selector forks

1 *Hydraulic accumulator;* 2 *Pressure sensor;* 3 *Non-return valve*

4 *Pressure relief valve;* 5 *Pump;* 6 *Hydraulic tank;* 7 *2/2 way valve*

8 *Hydraulic cylinder*

3.3.7 Concept 7: Pneumatic actuation of selector forks

A direct actuation of selector forks with pneumatic components combines the advantages of the energy supply by a pressure accumulator with the reduction of mechanical components to transfer the force to the selector forks. As the actuators are powered by a compressible working fluid, problems can occur in terms of the positioning of the selector forks. Therefore in this concept, two pneumatic cylinders are used to move one selector fork. Figure 3.7 shows how two pneumatic cylinders are able to position the selector fork. The pneumatic circuit diagram is shown in Figure 3.8.

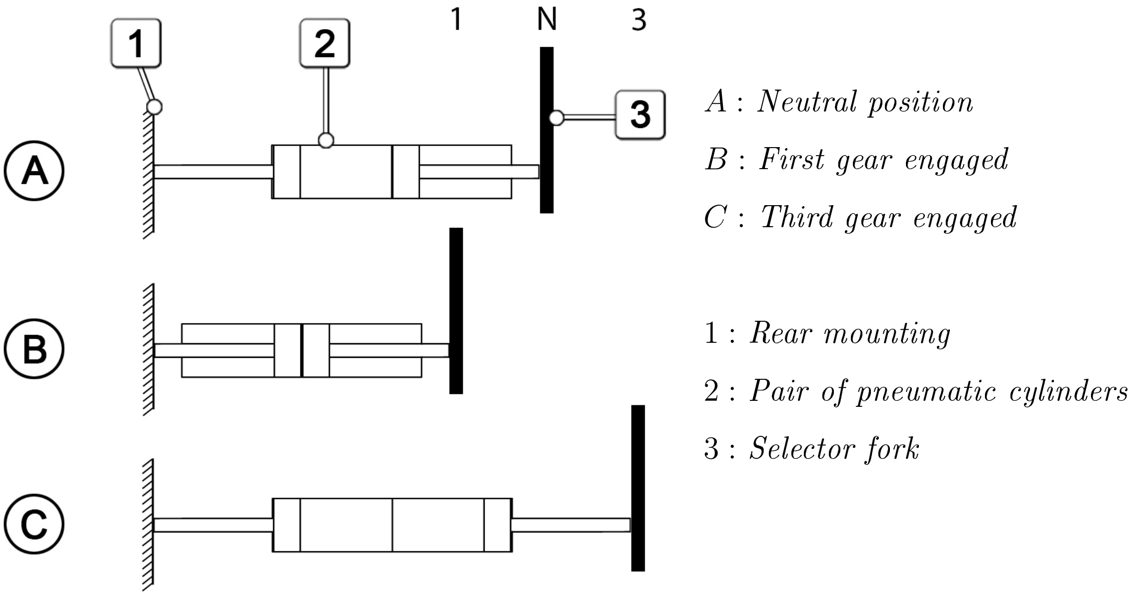


Figure 3.7: Principle of a pneumatic actuation of the selector forks

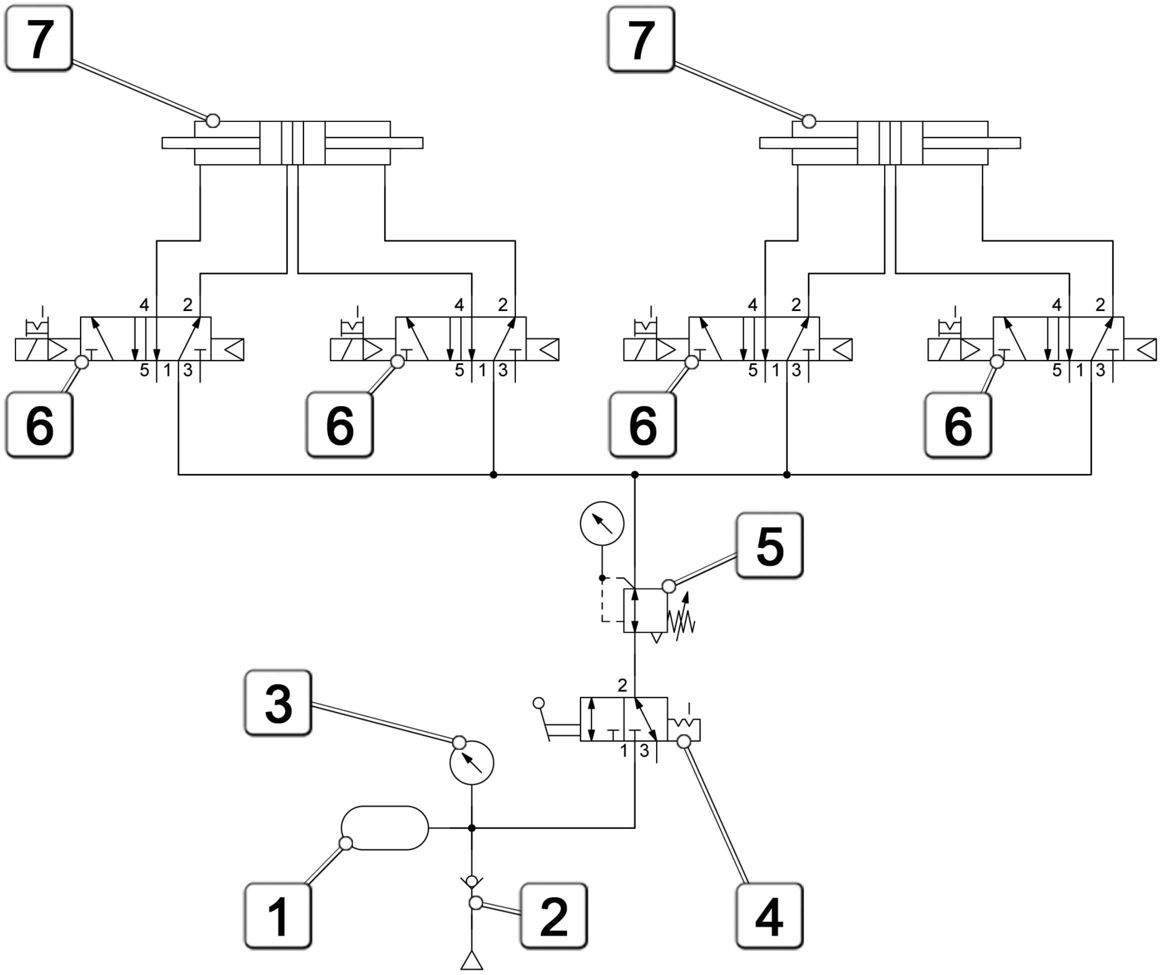


Figure 3.8: Circuit diagram of a pneumatic actuation of the selector forks
1 *Pressure accumulator;* 2 *Air supply;* 3 *Pressure gauge;* 4 *Manual on-off valve;* 5 *Pressure regulator with gauge;* 6 *5/2 way valves;* 7 *Pairs of double acting pneumatic cylinders*

By the usage of a pneumatic system, no energy needs to be supplied while keeping the selector forks in their position. A disadvantage is the operational safety, which is also described in Section 3.3.6, as a wrong movement of the selector forks has to be prevented.

3.4 Utility analysis

In the following utility analysis, the above mentioned concepts were evaluated in different criterions by using ranking points.

Evaluation	***Ranking points***
Very good	10
Good	8
Satisfactory	5
Sufficient	3
Insufficient	1

Table 3.1: Ranking points of the utility analysis

The criterions were weighted differently depending on their relevance for the development of a transmission control system. Factor ten was used for a very high importance whereas factor one stands for insignificant.

Relevance	***Factor***
Very high	10
High	8
Medium	5
Low	3
Very low	1

Table 3.2: Relevance factors of the utility analysis

In the utility analysis, the achieved ranking points of the concepts were multiplied by the factor of the relevance for each criterion. The results are sub points which each concept received in different criterions. The sub points of each concept were added together to the total score. The concept with the highest total score is therefore the most suitable concept and got developed in this thesis.

Table 3.3 shows the utility analysis for the different concepts mentioned in Section 3.3.

Evaluation criterion	**Factor**	**Co. 1**	**Co. 2**	**Co. 3**	**Co. 4**	**Co. 5**	**Co. 6**	**Co. 7**
Shifting time	10	40	70	60	50	90	100	80
Weight	10	80	70	90	50	60	80	100
Usability	10	50	80	80	80	80	90	90
Energy supply	10	100	90	80	80	80	80	90
Space requirement	8	48	64	72	72	56	56	64
Operational safety	8	80	64	56	64	48	40	48
Maintainability	7	70	56	63	63	42	35	49
Development effort	4	40	36	32	36	28	24	28
Costs	3	30	27	24	27	21	18	21
Total score		548	567	547	542	495	503	570
Ranking		3	2	2	5	6	4	1

Table 3.3: Utility analysis of the shifting system

3.4.1 Explanation of the evaluation

Shifting time

The shifting time is an important criterion for the selection of the right concept; therefore it got factored into the utility analysis with a very high relevance. In this criterion, the hydraulic actuation of the selector forks is rated best. A low amount of mechanical components transfer the force to the selector forks, compared to the other systems. Therefore a lower amount of parts and weight have to be accelerated during a shifting operation. A reduction of friction can be expected as well. Furthermore the high power density of hydraulic actors was considered [39].

The time of the tractive force interruption of concept fife is about 60 ms, according to the log data of the RWTH-Aachen University [27]. The concept was evaluated with nine points.

The pneumatic components in concept two and seven were simulated with the design software from the manufacturer Festo. Frictionless and without any counterforce, both concepts would be able to shift up in about 40 ms. However in this simulation, the movement of the pneumatic actuators was considered only. The hole shifting time of concept two is, according to the experiences of the WOB-Racing Team, about 100 ms. Taking into account the lower amount of mechanical components to transfer the force in concept seven, the system got a better ranking than the second one.

To evaluate the shifting time of concept three, the know-how of the Bodensee Racing Team [6] was considered. There, a shifting system as described has been developed. The position timing of the actor is about 100 ms. Nonetheless the time of the tractive force interruption can be estimated to be a bit longer.

To power the shift lever with a linear solenoid, it‘s possible to use systems developed for motorbike engines. Two companies selling these systems are the Kliktronic Ltd and the ProShift Technologies Ltd. The company Kliktronic was unable to provide test results to show the shifting time or the position time of the actor. The company ProShift made a test bench result available. The tested motorbike is a Suzuki GSXR1000 which was also fitted with a control unit to interrupt the ignition. This enables an upshift without using the clutch.

[6] Formula Student team of the HTWG University in Konstanz, Germany.

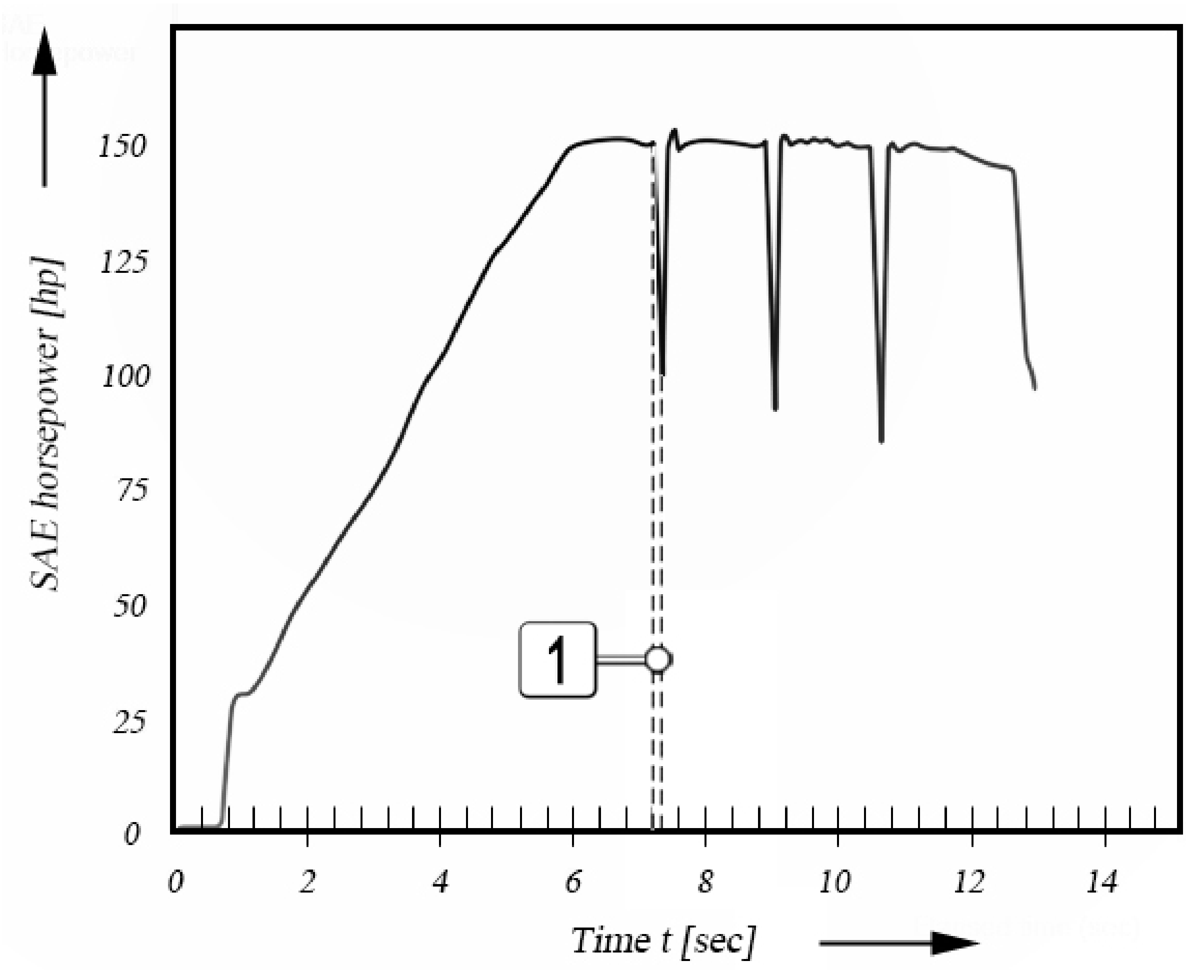


Figure 3.9: Test bench result Suzuki GSXR1000 equipped with the ProShift Gearshifter [15]
1 *Shifting time* $t_{shift} \approx 200\,ms$

Figure 3.9 shows the edited result, as the original graph wasn‘t available in a suitable quality. The original graph is shown in the appendix 8.6. The shifting time can be estimated, due to the elapsed time from the beginning of the drop of power (beginning of the tractive force interruption), to the point when the power is setting in again (end of the tractive force interruption). The required time for the fastest shifting operation (1) is about 200 ms and therefor longer than the other mechatronic concepts.

The mechanical shifting system was rated worst in this criterion. Since it can be assumed that a driver won't be able to shift faster than the mechatronic solutions mentioned above.

Unfortunately no login data was available for a mechanical system in a Formula Student application.

Weight

The weight of mechanical parts can be estimated with the CAD data of the K71 drivetrain. The concepts which are using a lever to turn the shifting shaft are using mechanical components inside the gearbox to transfer the force to the selector barrel [7]. The weight of the original mechanical components, which are located inside the gearbox, is about $5\,kg$.

According to an ATZ report, the system weight of the hydraulic actuation shown in concept five is lower than $3\,kg$ [27]. Which different components are included in the system weight couldn't be found out. Therefor the weight of the hydraulic components was assumed to be just below $3\,kg$. Taking the weight of the mechanical components inside the gearbox into account, the total weight of the system is $8\,kg$.

The concept four also weights about $8\,kg$ including the ProShift shifting system and the mechanical components. Not included in the weight is a bigger generator or an electrical storage device. These components might be necessary. Furthermore a clutch actuation is not included in the weight. Therefore, concept four got a lower ranking than the fifth concept.

The electric motor which drives the selector barrel directly, as described in concept three, was better evaluated. The weight of the mechanical components is reduced by about $0,3\,kg$ due to the removal of the shift lever and the lever mechanism. Furthermore the actors for the selector barrel and the clutch weight about $0,8\,kg$ [8]. Therefore the total weight of the concept is about $5,5\,kg$. Not included in the weight is a bigger generator or an electrical storage device. Furthermore the chosen clutch actuation isn't capable to disconnect the clutch completely. During a shifting operation in a lower gear, other arrangements have to be made to interrupt the torque flow in the gearbox.

[7] Shown in Figure 2.4.

[8] According to the Bodensee Racing Team.

To estimate the weight of the pneumatic shifting system of concept two, the known components of the shifting system used by the WOB-Racing Team were considered. The total weight of the system is about $6,9\,kg$. The components of the clutch actuation increase the weight by $100\,g$.

Since no Formula Student team was using a shifting system like it is described in concept seven, the suitable components had to be chosen and the required mechanical parts had to be designed to estimate the weight. The total weight of the concept is about $4,7\,kg$. Not included is the clutch actuation. The weight reduction compared to the second concept is based on the reduction of mechanical components to transfer the force to the selector forks.

The weight of the mechanical shifting system was estimated as well. The weight which is assumed is about $6\,kg$, this affects the ranking accordingly. Not included in the weight is the clutch actuation.

The hydraulic system which powers the selector forks directly comes to a total weight of about $6\,kg$. The reduction of mechanical components compared to concept five was significant for the estimation.

Usability

The criterion usability evaluates the impact of the usage of a concept while driving. Hence the shifting operation with a mechanical system has to be performed quickly and with the needed force, the usability got evaluated with five points. Apart from that, a too short shifting operation cause shifting errors. Therefor the driver has to focus on the shifting operation to recognize, whether a gear is engaged or not.

The other described systems are using actors to engage the gears. Therefor these systems were better evaluated. The best rating in this criterion was received by the concepts, which power the selector forks directly. They allow the driver to skip gears.

Energy supply

Another important criterion is the energy supply of the concepts. The energy can be supplied by the engine or by an energy storage device. The mechanical shifting system comes out best in this criterion, since no negative impact on the technical data of the vehicle is caused by the energy supply. However energy has to be supplied by the driver.

The pneumatic concepts were evaluated with nine points, as no energy needs to be supplied by the engine. Also the energy storage device, which is used for example by the WOB-Racing team, weights about $0,8\,kg$ and can therefore be considered to be light.

A lower amount of single pints was given to the hydraulically and electrically powered concepts. The storage capability of hydraulic energy is limited, therefor the energy for these concepts will have to be supplied by a hydraulic pump [39]. The electrical shifting systems need to use engine power or an energy storage device to supply the system with the needed energy. A hybrid system is also possible. Whereby it is assumed that, compared to a pneumatic system, the storage of electrical energy increases the vehicle weight markedly higher.

Space requirement

In the criterion space requirement, the electrically actuated concepts come out best. The requirements on cable routing are lower compared to pneumatic or hydraulic systems. Furthermore the pneumatic concepts have the disadvantage of the necessary pressure accumulator and valves. The hydraulic concepts got a lower amount of points in this criterion, as these concepts need further components like a hydraulic pump, a radiator or a hydraulic tank. The lowest amount of points was given to the mechanical shifting system. Since a compromise has to be made between an ergonomically positioning of the shift lever and the space requirement of the force transmitting parts of the concept.

Operational safety

The prediction of the operational safety of the concepts is difficult. Nevertheless it‘s an important criterion in motorsport applications. A malfunction can cause shifting errors or destroy the gearbox. This criterion gets more significant, as the gearbox and the shifting system are prototypes, whereby some sources of error can be expected. The operational safety depends on the complexity of the concept, secondly on the susceptibility of the individual components and the control unit.

The mechanical shifting system was rated best in this criterion. The force is transferred by visible mechanical components. If developed properly, malfunctions can be considered to be almost impossible.

The actuation with a linear solenoid was evaluated with eight single points as electrical wiring is used to transfer the energy to the actor. Furthermore the mechanical components in the gearbox only allow one gear pair to be engaged.

The pneumatic components have a lower operational safety. The system is more complex and consists of more components. Furthermore the pneumatic hoses have to be laid carefully to prevent them from being damaged. A leakage can lead into a failure of the shifting system.

The lowest amount of single points was given to the hydraulic shifting system which powers the selector forks directly. First because of the complexity of the concept and secondly because of the high amount of components which can cause failures. Furthermore, leakages in hydraulic components can cause pollution and have a higher risk of accidents compared to pneumatic systems [39].

Maintainability

The complexity of the concepts influences, among other things, also the maintainability of the system. Due to the reasons mentioned in Section 3.4.1, the mechanical shifting system got the full amount of points. Furthermore, a high maintainability can be predicted when an electric powered system is used. Because of the higher complexity, the pneumatic and hydraulic systems got a lower ranking.

Development effort and costs

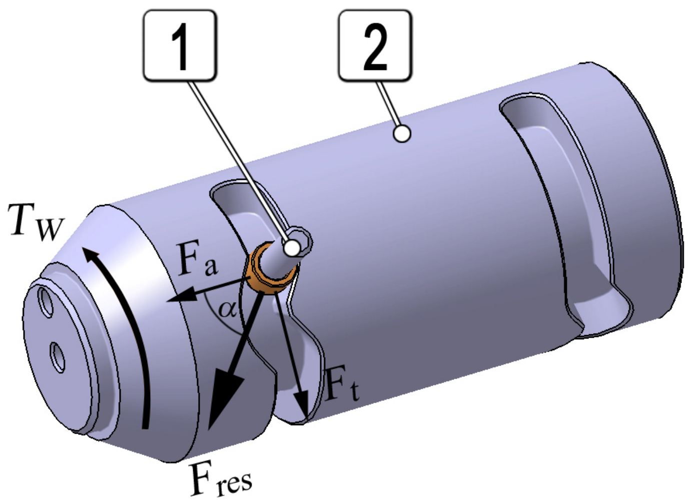
The criterions development effort and the costs of the concepts are given a relatively low weighting compared to other criterions due to the usage in motor sport applications. The highest amount of points in this criterion is given to concept one, the mechanical shifting system. The highest development effort and cost is predicted by using a hydraulically operated system which drives the selector forks directly.

3.4.2 Conclusion of the utility analysis

The utility analysis indicates concept seven, the pneumatic shifting system with directly driven selector forks, to be the most suitable concept. During the analysis technical data had to be estimated or is based on information of several Formula Student teams and companies, which are unable to be verified under reasonable circumstances. Therefor the significance of the analysis gets reduced. Furthermore the weighting of the different criterions was estimated, here again it‘s difficult to determine, what kind of importance has to be attached in the racing series. However the shifting system which is described in concept seven is seen to have a high potential, according to the reasons mentioned in Section 3.3.7 and 3.4.1. Therefor the concept shall be developed in this thesis.

3.5 Selection of the pneumatic cylinders

To choose suitable pneumatic cylinders, the movement range of the selector forks has to be considered. According to the available CAD data, the selector forks need to move 5 mm in each direction. Furthermore, the pneumatic cylinders must provide sufficed force to connect and disconnect the gear pairs as quickly as possible. As described in Section 2.2.2, the selector barrel in the standard gearbox gets turned to do a shifting operation. The assumed amount of torque on the standard selector barrel is 8 Nm. This value is higher than the measured one. However it can be expected, that shifting operations can be done safer and quicker with more powerful components. Assuming a force transfer without friction, the torque of 8 Nm can be converted into the necessary force for the pneumatic cylinders, based on the geometry of the selector barrel. Figure 3.10 shows the forces acting on the selector barrel during a shifting operation.



1 : *Bolt of the selector fork*

2 : *Selector barrel*

Figure 3.10: Forces acting on the selector barrel

The tangential force F_t results from the torque on the selector barrel and the diameter of the point of applied force on the selector barrel. The diameter of the applied force is, according to the CAD data of the standard selector barrel, 49 mm. The tangential force is calculated by Equation 3.1.

$$F_t = \frac{2 \cdot T_W}{d_W} \tag{3.1}$$

$$F_t = 326,5N$$

- F_t: Tangential force
- T_W: Torque
- d_w: Diameter of the point of applied force

The force which is moving the selector forks to engage the gears is the axial force F_a. This results from the force parallelogram shown in Figure 3.10 as follows.

$$F_a = F_t \cdot tan(\alpha) \tag{3.2}$$

According to the CAD data, the inclination angle of the selector gate α is 34°. In this way, the axial force can be determined.

$$F_a = 220,2N$$

- F_a: Axial force
- α: Inclination of the selector gate

As shown, the required piston force is $F_a = 220,2N$. A suitable pneumatic cylinder is the "ADVC 25-5-I-P-A" from the company Festo, which will be used in the shifting system.

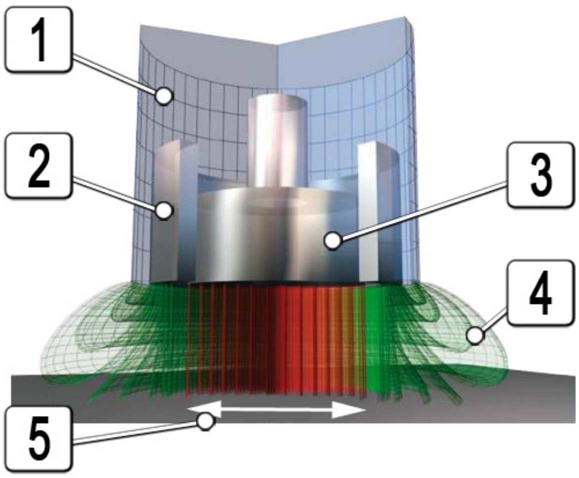
3.6 Selection of the position sensors

3.6.1 Requirements

To select an appropriate sensor system, the requirements are getting defined. The sensors have to detect the positions of the selector forks. For this purpose, a sufficient accuracy is required as well as an adequate signal quality. Furthermore the sensors have to be resistant against the operating conditions. If not, the operating conditions have to be improved by a suitable construction. Other important parameters are the space requirement of the sensor and the weight. This includes adjustments to the design of the shifting system to enable the usage of a sensor concept. Unlike in a series application - taking into account the costs - the durability can be shorter, as long as a sufficient durability exists.

3.6.2 Concept 1: Capacitive sensors

During the capacitive distance measurement, an alternating current runs through the sensor element. A conductive surface is placed on the opposite, which forms a kind of plate capacitor. It‘s capacity is depending on the distance of the sensor element to the conductive measuring surface. The capacity is determined by measuring the amplitude of the alternating voltage [8]. Figure 3.11 shows the principle of the capacitive sensor.



1 : *Housing*
2 : *Protective ring*
3 : *Capacitor*
4 : *Field lines*
5 : *Measuring spot*

Figure 3.11: Capacitive sensor [9]

This type of measurement is used for applications requiring a high accuracy. The sensor "CS10" of the manufacturer Micro Epsilon in connection with the controller "CapaNCDT6019" is an example for this measurement method. The controller is needed to convert the alternating voltage to an analog signal, depending on the distance of the sensor to the measuring surface. Due to the measuring method, soiling can affect the measuring quality, as it can cause a change of dielectricity. As a result of the nonlinear dependency between the distances of the measuring surface to the determined alternating voltage, a large sensor element has to be used. Since the determined alternating voltage depends on the size of the sensor element. In this case, the required measurement range is $10\,mm$ for each selector fork, this leads to the needed sensor diameter of $60\,mm$. Moreover the conductive surface on the opposite has to have a diameter of at least $57\,mm$ [9].

3.6.3 Concept 2: Linear potentiometers

Inside the housing of a linear potentiometer, a sliding contact tapes the current from a resistor. Figure 3.12 shows a possible circuit of a potentiometer which operates as a voltage divider.

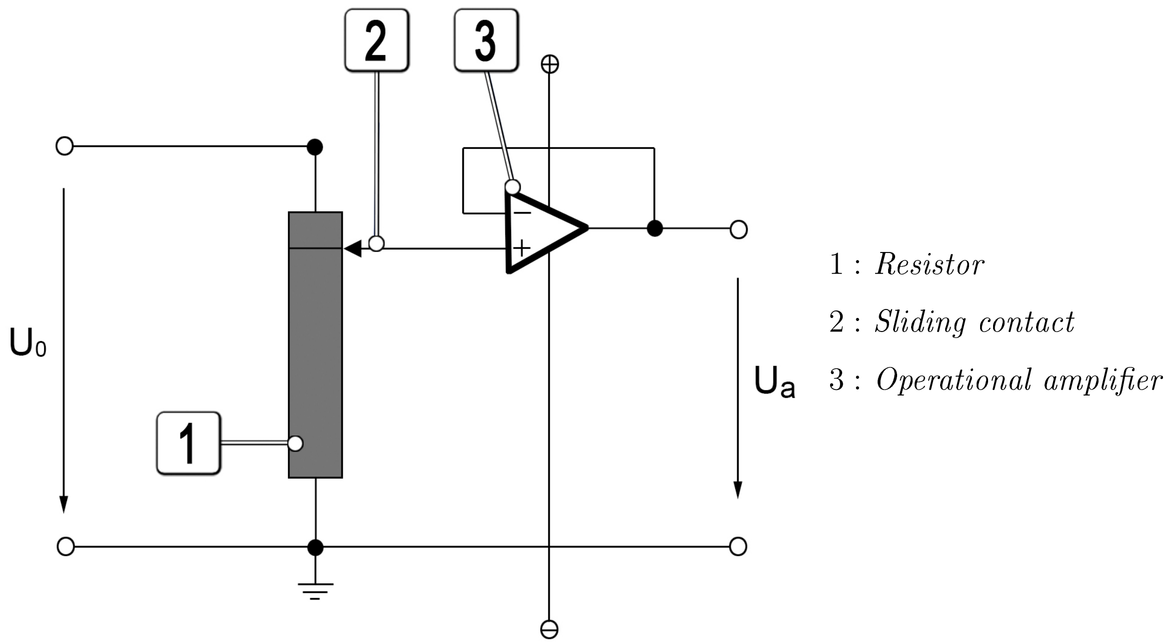


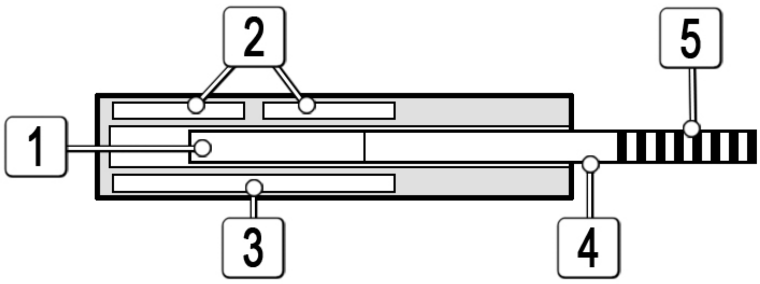
Figure 3.12: Electrical circuit of a potentiometric sensor [33]

For the position detection, the sliding contact is connected to the measuring object and moves depending on its position. A constant reference voltage U_0 is applied on the resistor. By moving the sliding contact, the potential U_a changes linearly, which is tapped by an operational amplifier [35][33]. A possible linear potentiometer is the model "SLS 095/40" from the manufacturer Penny and Giles [30]. The disadvantage of this sensor concept is the required connection of the slider and the resistor, which causes mechanical wear. Furthermore the slider can lift of the resistor due to strong shocks. Advantageous is the linear output signal as well as the oil and soiling resistance, as long as no foreign objects pass the sealing of the sensor housing. Figure 3.13 shows the sensor described above.

Figure 3.13: Linear potentiometer [30]

3.6.4 Concept 3: Inductive sensors

Another opportunity is the position detection with an inductive sensor (LVDT [9]). Inside the sensor element, a sliding core moves depending on the position of the measuring object. Next to the sliding core, three coils are located. The primary coil is supplied with a constant alternating voltage. The voltage is transmitted to the two secondary coils. The signal on the secondary coils is depending on the position of the sliding core [38]. Figure 3.14 shows the principle sketch of the sensor.



1 : *Soft magnetic core*
2 : *Secondary coils*
3 : *Primary coil*
4 : *Core extension*
5 : *Rod*

Figure 3.14: Inductive sensor [34]

The sensor "DTA-10-D-CA" in connection with the controller "MSC-710", supplied by the company Micro Epsilon, is used for the utility analysis [11]. Advantageous is a con-

[9] Linear variable differential transformer

tactless position measurement, therefor the sensor runs nearly without friction and wear. Furthermore the measurement quality is not depending on soiling, as long as no dirt ingresses into the housing.

3.6.5 Concept 4: Eddy current sensors

The eddy current sensor consists of a coil which is integrated in the sensor element. An alternating current of high frequency is running through the coil which creates an electromagnetic field. The sensor is designed so that the field lines can escape the sensor and induce eddy currents in an electro conductive measurement object. These eddy currents counteract the coil field. The AC resistance is increasing; the closer the measuring object is located to the sensor. By detecting the phasing as well as the amplitude, the position of the measurement object can be determined [14][38].

For the utility analysis, the eddy current sensor "U15" in connection with the controller "DT 3010-M" from the company Micro Epsilon shall is used. Unlike capacitive sensors, only electro conductive dirt affects the measurement quality. Due to the measurement principle, the sensors must have a certain diameter to cover the required measuring range. The sensor "U15" has a measuring range of 15 mm and a diameter of 37 mm. Moreover, the detected measuring surface has a diameter of 111 mm. Therefor surrounding electro conductive parts can have a disturbing influence on the measurement quality [10].

3.6.6 Concept 5: Laser sensors

Laser sensors work according to the triangulation principle. To measure the distance of an object, a diode inside the sensor element emits a laser beam, which gets reflected by the surface of the measurement object. The reflected beam hits the receiving element in a specific angle. Depending on the distance of the received laser beam to the diode, the distance between sensor and object can be calculated. Figure 3.15 shows the principle of a laser sensor.

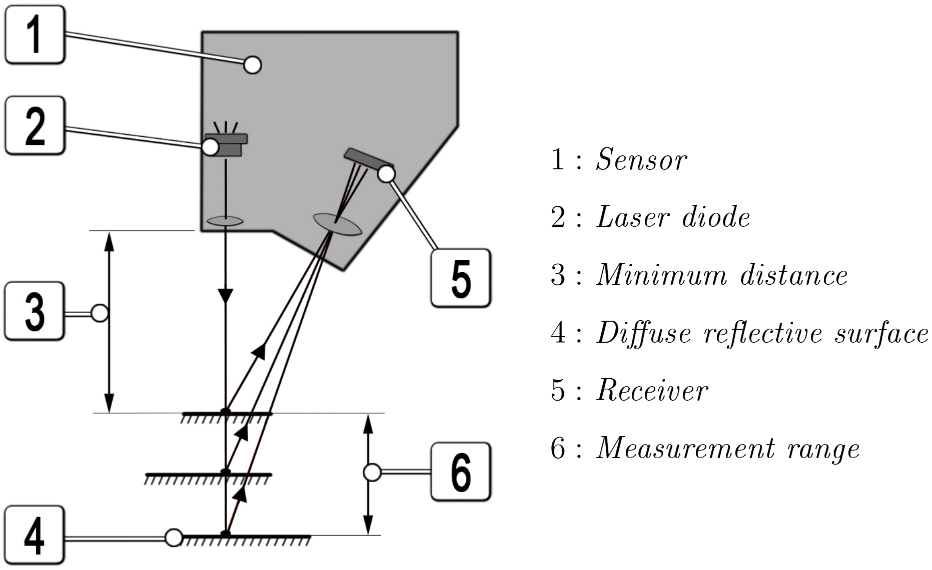


Figure 3.15: Laser sensor [35]

An example for the described measurement system is the sensor "ILD1402-10SC" from the company Micro Epsilon. Disadvantageous is the vulnerability to contamination, which can lead into a falsification of the measuring results. Furthermore the sensor has a low temperature resistance of $50\,°C$ [13].

3.6.7 Concept 6: Magnetoresistive sensors

The chosen magnetoresistive sensor type is the "AA-746" from the company Sensitec. It consists of a material, which electronic resistance is depending on the direction of the magnetic field as well as on the strength. This effect is also called AMR effect (anisotropic magnetoresistive). The sensor consists of two Wheatstone bridges, which are positioned at 45° from each other [31]. In the concept one sensor is placed on each pneumatic cylinder. The pistons of the pneumatic cylinders are magnetic. By measuring the magnetic field it‘s possible, to detect the position of the pistons. For this purpose, a suitable signal processing unit has to be developed. Advantageous is the small size of the sensor chips. Furthermore the measurement is contactless. The signal quality was tested with a sensor glued on one of the pneumatic cylinders. A signal noise of $2\,mV$ was measured with an output signal of $1-7\,mV$. This puts the usage of the above described sensor system into question.

3.6.8 Concept 7: Magneto-inductive sensors

The magneto-inductive measurement system consists of a sensor element and a magnet which is mounted on the measurement object. To measure the strength of the magnetic field, a magneto-resistive material [10] inside the sensor is used. Furthermore eddy currents are generated in the sensor, as described in Section 3.6.5. By combining the two non-linear measurement methods, a linear signal can be generated [7]. As an example for the utility analysis, the sensor "MDS-45-M12-CA" from the company Micro Epsilon will be used [12]. The necessary electronics for the signal processing is integrated in the sensor element, which is oil resistant. Disadvantageous is, due to the measurement principle, the impact of ferromagnetic materials near the sensor and also behind the magnet. The measurement quality can also be influenced by ferromagnetic soiling or external magnetic fields [7].

3.6.9 Utility analysis

The sensor concepts were compared with a utility analysis. The process is described in Section 3.4. Table 3.4 shows the results of the analysis.

3.6.10 Explanation of the evaluation

Accuracy

The criterion accuracy evaluates the measuring accuracy of the sensors. Each concept got the full amount of points, as every sensor provides more than sufficient accuracy for the

[10] The electronic resistance of the material changes depending on the external magnetic field.

Evaluation criterion	Factor	Co. 1	Co. 2	Co. 3	Co. 4	Co. 5	Co. 6	Co. 7
Accuracy	10	100	100	100	100	100	100	100
Resistance/ measurement quality	10	70	90	80	70	50	40	60
Space requirement	9	45	72	63	36	54	81	72
Weight	8	48	72	56	40	48	56	64
Durability	7	63	56	63	63	56	56	64
Costs	7	42	63	56	42	49	63	63
Total score		368	453	418	351	357	403	422
Ranking		5	1	3	7	6	4	2

Table 3.4: Utility analysis of the sensor concept

application in the shifting system.

Resistance/ measurement quality

The criterion resistance and measurement quality is an important criterion, therefor it got included into the utility analysis with the factor ten. The resistance of the sensor concept against the operating conditions was evaluated as well as the current measurement quality under these conditions.

The capacitive sensor got seven points, as oil and soiling can cause a change of the dielectricity. Thereby the measurement can be influenced. The same applies for the eddy current sensor, as ferromagnetic soiling can affect the measurement quality.

The linear potentiometer was rated best in this criterion. The movement of the selector forks is transmitted by a moveable rod, which reaches into the sensor housing. Therefore soiling and oil don‘t influence the measurement, as long as no foreign object ingresses into housing.

The same principle applies for the inductive sensor; however this sensor is only heat resistant up to $80\,°C$. Thus this concept was evaluated with eight points.

Concepts based on the detection of magnetic fields are disadvantageous in this criterion, as foreign magnetic fields can influence the measurement quality. This is especially important, as the magnetic material in the pneumatic pistons or on the selector forks would be located close to each other. In addition to this, the concept of the magneto-resistive sensor was tested in combination with a pneumatic cylinder. As described in Section 3.6.7, the measured signal amplitude was very low and a high signal noise was noticed. Therefor this concept got four points in this criterion.

Furthermore the negative impact of soiling got considered in the evaluation of the magneto-inductive sensor concept.

The shown optical position measurement was evaluated with five points. Firstly oil and soiling can influence the measurement quality; secondly the sensor is temperature resistant up to $50\,°C$, which is insufficient for the field of application.

Space requirement

Another important criterion is the space requirement of the concepts. The concept of the eddy current sensor was rated worst, due to the large diameters of the sensor and the required measuring surface. The same applies for the capacitive sensor; however the diameter of the required measuring surface is a bit smaller. The concept of the laser sensor was evaluated with six points, due to the dimensions of the sensor as well as the necessary minimum distance of $20\,mm$ to the measurement object. The linear potentiometer and the magneto-inductive sensor have favourable dimensions. This allows the arrangement of these sensors next to the pneumatic cylinders. Additionally these concepts don‘t require an extern signal processing unit. Therefore these concepts were evaluated with eight points.

The highest rating in this criterion is received by the magneto-resistive sensor concept. The sensor chip has very low dimensions and can be glued on the pneumatic cylinders.

Weight

In the criterion weight, the linear potentiometer was rated best. The sensor weighs 16 g. However the total weight is considered to be a bit higher, as a mounting bracket has to be developed. The heaviest concept is the eddy current sensor, which weighs 567 g, whereby the signal processing unit is the heaviest part of the sensor concept. The weight of the magneto-resistive sensor chip was not considered, as the chip is very light. The signal processing unit, which has to be developed, was estimated to a weight of 50 g.

Durability

The durability of each concept is more than sufficient; therefore nearly every concept was evaluated with nine points. Only the laser sensor can fall out earlier, as the laser diode has a finite useful life of about 20000 operating hours. The linear potentiometer has a limited lifetime as well, due to the wear of the sliding contact and the resistor. However the manufacturer predicts a lifetime of 100 million strokes. Therefore, these concepts were evaluated with eight points, due to the sufficient but limited durability.

Costs

In terms of costs, the comparably affordable priced concepts, like the linear potentiometer or the magneto-inductive sensor, were evaluated with nine points. The sensor chip of the magneto-resistive sensor concept costs about 370 R, whereby four sensor chips are needed. The required signal processing unit was considered to cost about 500 R. Therefor this concept got the same amount of points.

The most expensive concept is the capacitive sensor. The price for the sensors and controller is about 18000 R.

Conclusion of the utility analysis

The utility analysis suggests the linear potentiometer to be the most sufficient concept for the usage in the transmission control system. However the concept has some disadvantages, it is satisfying in any criterion. Moreover the resistance and the measurement quality, as well as the space requirement are advantageous. Therefore this concept goes into action.

3.7 Implementation of the shifting system in the K71 drivetrain

To meet the demands, such as operational safety, maintainability and space requirement; the individual components and their position had to be adapted during the construction. However, for the sake of clarity, only the finished design and the features of the different components are explained in this section. Figure 3.16 shows the current design of the torque transmitting parts of the drivetrain with the available concept of the engine housing, as well as the implemented shifting system. The mechanical parts of the shifting system are shown in Figure 3.17.

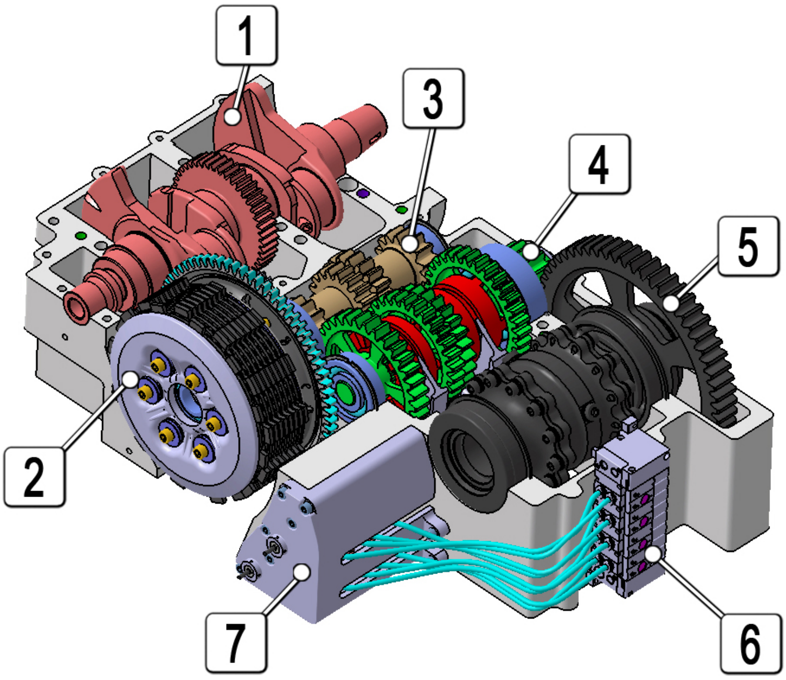


Figure 3.16: Implemented shifting system

1 *Crankshaft;* 2 *Clutch;* 3 *Gearbox input shaft;* 4 *Gearbox output shaft;*

5 *Differential;* 6 *Valve terminal;* 7 *Cover pneumatic cylinders*

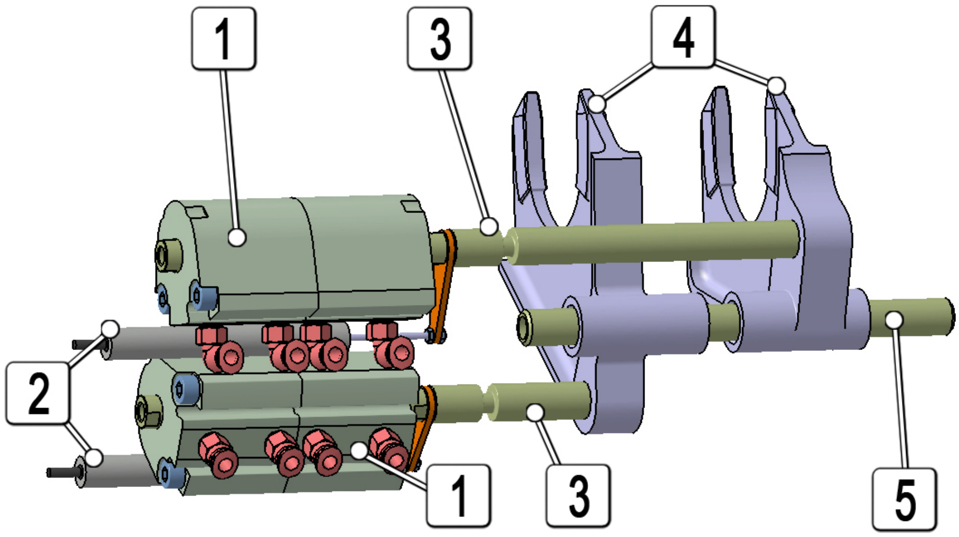


Figure 3.17: Mechanical parts of the shifting system

1 *Pneumatic cylinders;* 2 *Potentiometers;* 3 *Shifting rods;*

4 *Selector forks;* 5 *Guide for the selector forks*

3.7.1 Valve terminal

The valve terminal is mounted on the backside of the engine housing, as enough installation space is available. Furthermore, the valves are easily accessible, which facilitates maintenance work. On the back side of the valve terminal, buttons are mounted to operate the valves without the control system. This enables shifting operations for function testing. According to the experiences of the WOB-Racing Team, it is preferable to mount the pressure accumulator on the opposite of the clutch. The appropriate arrangement of the pneumatic houses is favoured by the position of the valve terminal. The displacement of the centre of gravity (as a result of the position of the terminal at the back of the engine housing) is negligible due to the low weight of the valves ($264\,g$). Figure 3.18 shows the above mentioned component.

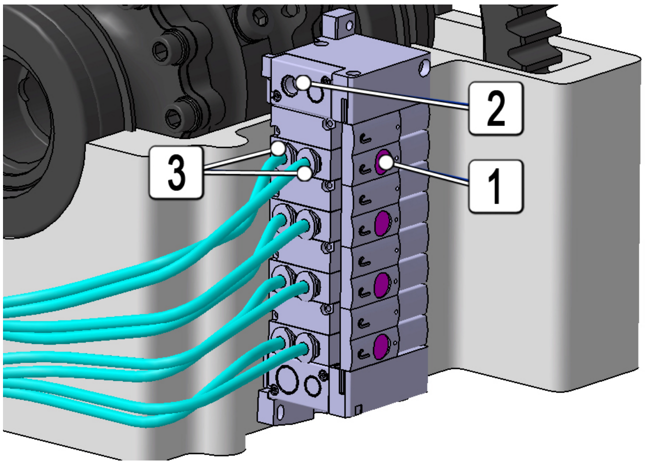


Figure 3.18: Valve terminal of the shifting system

1 *Buttons for manual operation;* 2 *Air supply;*

3 *Connections for the pneumatic cylinders*

3.7.2 Pneumatic hoses

The pneumatic hoses are installed on the outside of the engine housing. It is important to prevent them from touching the moveable parts of the suspension or the drive shafts. Furthermore the houses need to be fixed in their position but still have to allow the pneumatic cylinders to move.

3.7.3 Cover of the pneumatic cylinders

The shown cover is an example, based on the available CAD data of the K71 drivetrain. The designed cover is separated from the clutch cover to enhance the maintainability. The component protects the pneumatic cylinders and the linear potentiometers from soiling. Furthermore, the pneumatic cylinders and the linear potentiometers are mounted on the back side of the cover. To ensure the required position accuracy of the pneumatic cylinders, the cover is aligned by positioning elements shaped like sleeves (3). The material of the cover is an aluminium alloy. Steel sleeves (2) are located inside the cover to mount the pneumatic cylinders. Due to the shape of the pockets and the design of the piston rod, a turning of the pneumatic piston during the mounting is prevented. Figure 3.19 shows the cover of the pneumatic cylinders.

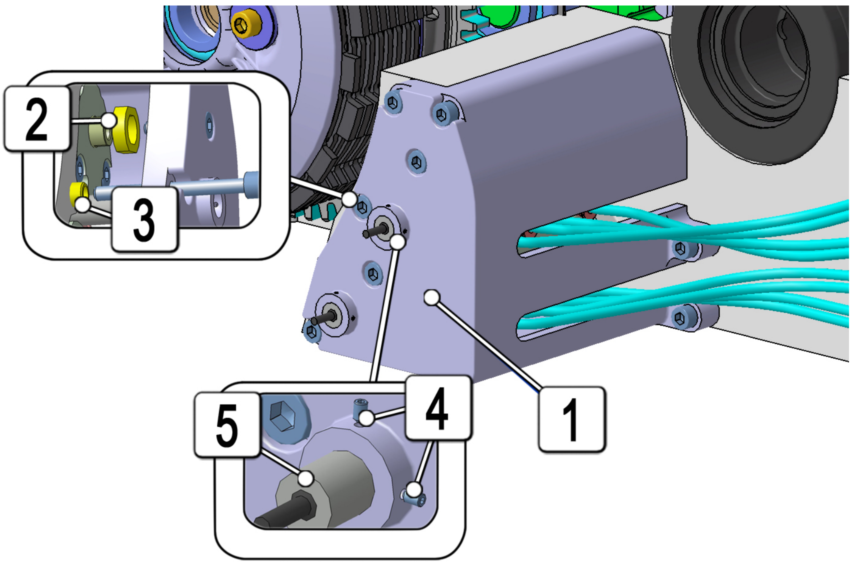
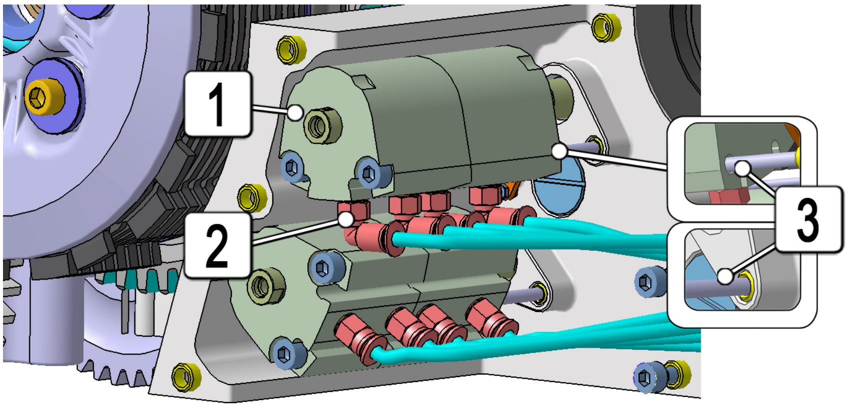


Figure 3.19: Cover of the pneumatic cylinders
1 *Cover;* 2 *Sleeves of the pneumatic cylinders;* 3 *Positioning elements;*
4 *Fixing of the potentiometer;* 5 *Potentiometer*

3.7.4 Pneumatic cylinders

The housing of the pneumatic cylinders (1) is edited in order to improve the space requirement of the parts. Tapped holes are provided to screw the cylinders together. The cylinders located next to the engine housing have a hole to take up steel pins (3). The pins are moveably mounted in fitting holes located in the engine housing. This is necessary to prevent the moveable pneumatic cylinders from rubbing against other components. Figure 3.20 shows the edited pneumatic cylinders.

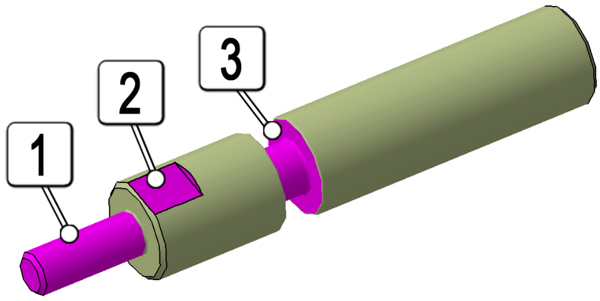


1 : *Pneumatic cylinder*
2 : *Connections*
3 : *Pins*

Figure 3.20: Pneumatic cylinders of the shifting system

3.7.5 Shifting rods

The shifting rods allow the transmission of force from the piston rods to the selector forks. The shifting rods are screwed into the internal thread of the piston rods. Pockets (2) are provided to use a wrench for the mounting. To seal the holes of the shifting rods in the engine housing against oil leaks, a groove is provided to mount piston seals used in hydraulic cylinders (3). At the back side of the shifting rods, an M5 internal thread connects the shifting rods with the selector forks. Figure 3.21 shows the above mentioned component.



1 : *External thread*

2 : *Pocket for the wrench*

3 : *Groove for the sealing*

Figure 3.21: Lower shifting rod of the shifting system

3.7.6 Selector forks

The design of the selector forks is based on the geometry, constructed during the previous gearbox development [42]. One of the selector forks is shown in the below figure.

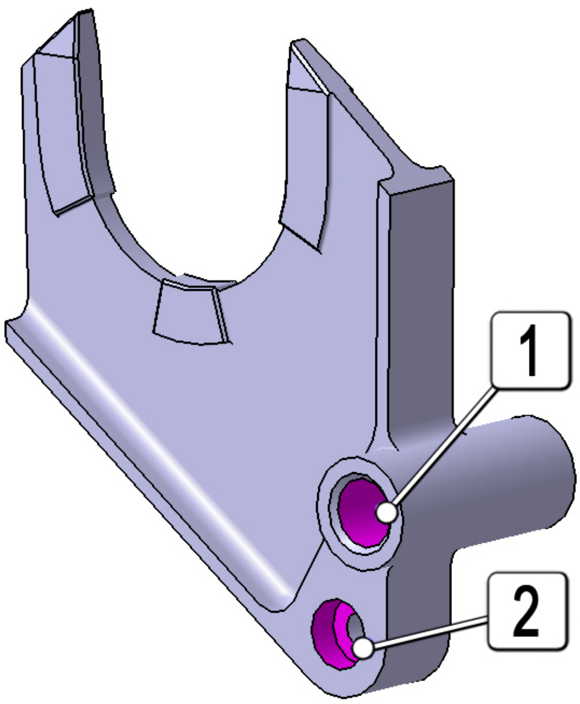
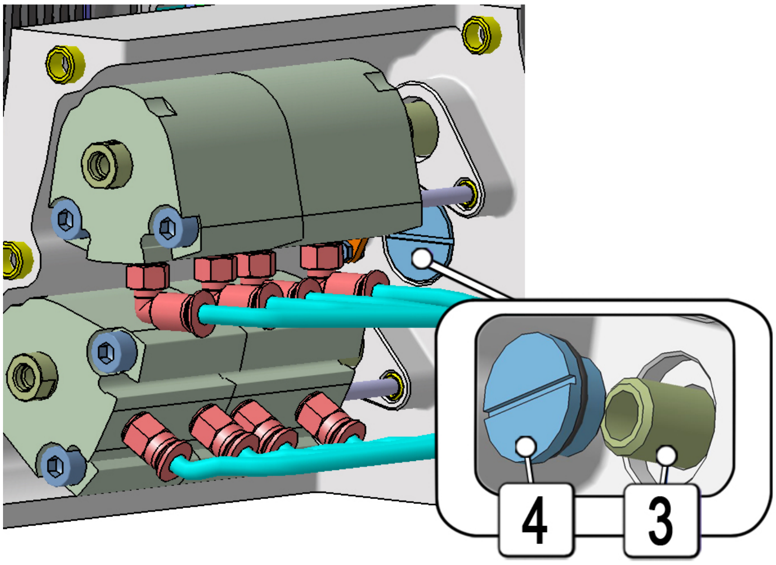


Figure 3.22: Selector fork of the shifting system

1 *Axial guidance;* 2 *Mounting of the shifting rods*

To allow the axial movement but to prevent the selector forks from tilting, a fitting hole (1) in the selector forks and a matching rod (3) is provided. This allows the selector forks to slide on the rod during a shifting operation. To mount the components, the rod is inserted in the engine housing. The necessary hole for the rod is sealed by a screw plug with integrated O-ring (4). Figure 3.23 shows the construction.



1 : *Screw plug*

2 : *Rod for axial guidance*

Figure 3.23: Guide of the selector forks

3.7.7 Potentiometer

As shown in Figure 3.19, the linear potentiometers are mounted on the cover of the shifting system. The sliding rod (3) which moves the sliding contact inside the potentiometer, is connected with the shifting rod (5). Figure 3.24 shows the construction.

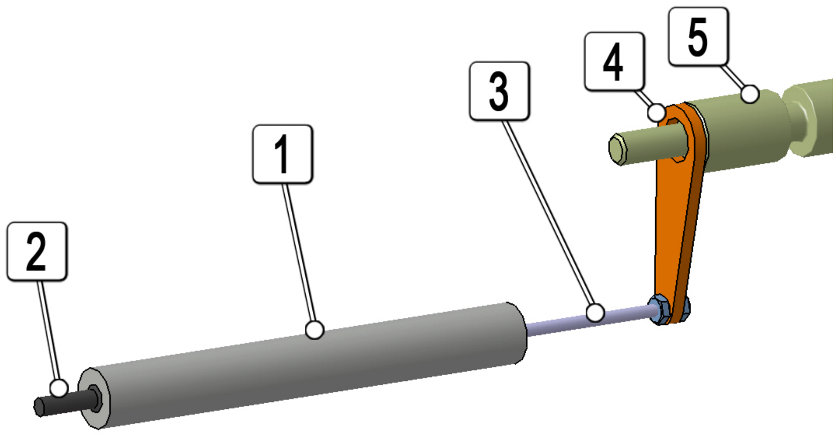


Figure 3.24: Implemented linear potentiometer of the shifting system
1 *Housing;* 2 *Cable connection;* 3 *Sliding rod;*
4 *Connection to the shifting rod;* 5 *Shifting rod*

3.8 Summary

After defining the requirements of a shifting system in Formula Student applications, different concepts were shown which had been developed in advance. The concepts are driven either by pneumatic, hydraulic or electric actuators. Some concepts are based on a simple actuation principle and the usage of mechanical components to transfer the force from the actuator to the selector forks. In other concepts, the selector forks are driven directly, which leads into a more complex system. Nevertheless these concepts were expected to be in general advantageous in terms of shifting time and weight of the system. A mechanical system was also described to allow the comparison against the actuated systems. The concepts were compared in a utility analysis, whereas a direct pneumatic actuation of the selector forks was found to be the most suitable concept. Based on this, the necessary force of the actuators was calculated and the pneumatic cylinders were selected. To find a suitable sensor concept, several concepts were again compared in a utility analysis, which resulted in the usage of linear potentiometers. The main reasons for the choice are the resistance of the sensors against the operating conditions as well as the advantageous space requirement. At the end of this chapter, the implementation of the shifting system in the K71 drivetrain is described. As a result, the technical feasibility and the space requirement of the components could be shown.

4 Hardware for the test bench

4.1 Introduction

As shown in Section 1.2, the developed system shall be tested on a test bench. Therefor the hardware for the test bench needs to be developed, which is explained in this chapter. The first step of the development is, to define the requirements. On this basis, the functional architecture of the hardware is specified. This is followed by the selection of the components and preparing of the circuit diagram. The diagram is used to print the circuit board, which is the mechanical support of the electrical components.

4.2 Requirements

The hardware has to provide the necessary components for the data acquisition, processing and the electrical actuation of the valves. This includes components for the data input to allow the user to initiate a shifting operation. Furthermore additional options have to be provided to adjust the settings of the control software. The operator should also be able to access the status data of the system. Another requirement is the monitoring, to protect the gearbox or to ensure the driving stability in case of malfunctions. This also includes components for the processing of the measurement results from the linear potentiometers. To ensure a short shifting time, the hardware needs to operate quickly.

4.3 Functional architecture

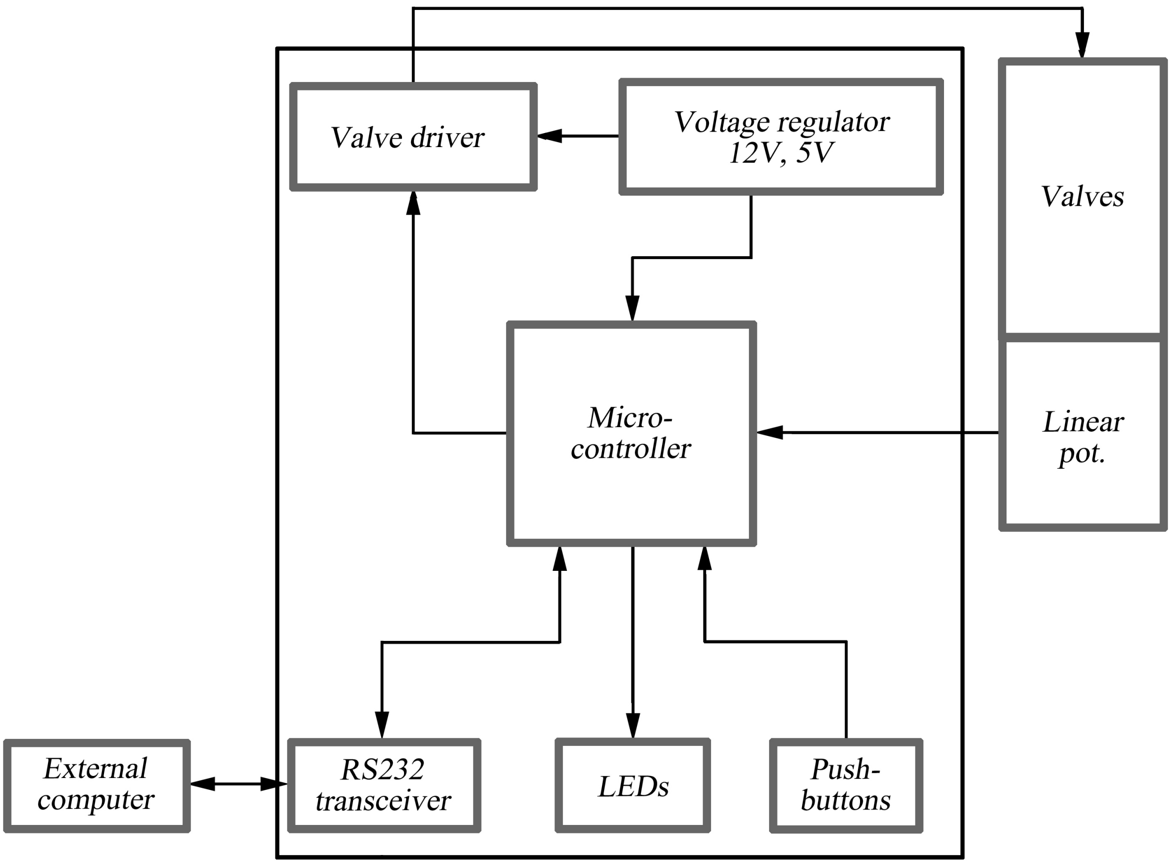


Figure 4.1: Functional architecture of the hardware

Figure 4.1 shows the functional architecture of the hardware. The main component is the microcontroller which executes the software program. Furthermore integrated storage possibilities allow to save data on the chip. Additional components in the microcontroller enable the connection of hardware peripherals.

To actuate the valves, a valve driver is necessary. This component supplies the coils of the valves with the required electric power, as soon as an electrical signal from the microcontroller is received.

As described in Section 3.6.10, the position of the selector forks is detected by linear potentiometers. To use the signals from the linear potentiometers in the microcontroller, an analog-digital converter is necessary. The shown functional architecture assumes an analog-digital converter integrated in the microcontroller.

Pushbuttons on the circuit board allow the command inputs "shift up" and "shift down". LED‘s [1] are provided for function testing during the development of the control software.

In order to have more possibilities for command input and also to display the operating conditions of the transmission control system, an external computer shall be connected to the hardware. To do so, an RS232 transceiver is used to enable the communication between the microcontroller and the external computer by means of a serial interface.

4.4 Component selection

4.4.1 Microcontroller

The chosen microcontroller is the "ATmega8A-AU" from the company Atmel. The microcontroller is in-system programmable. Therefore the chip doesn‘t have to be removed from the hardware board during the programming [24]. Figure 4.2 shows the essential components in the microcontroller for this application. They are getting explained below.

[1] Light-emitting diode

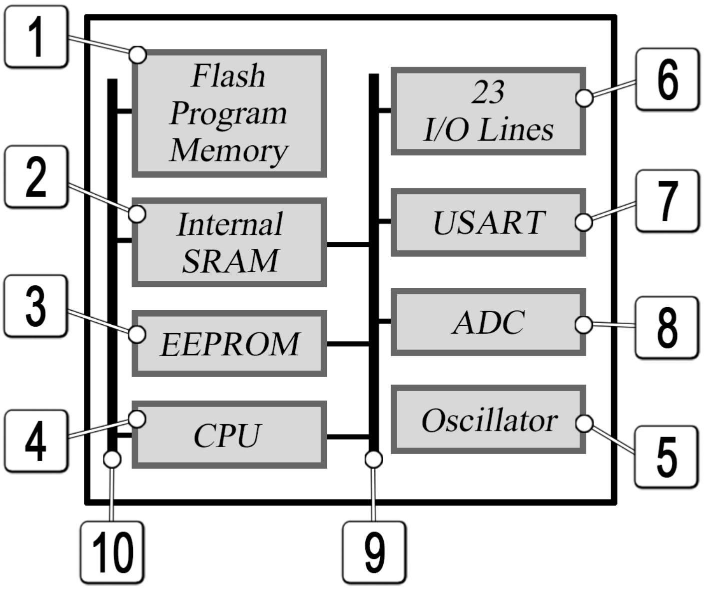


Figure 4.2: Microcontroller architecture [48]

The program of the transmission control system is stored in the flash memory. A capacity of 8 $kByte$ is provided for this purpose. The memory can be rewritten up to 10000 times.

To save variables as well as the processing state of a program function, the SRAM memory (2) is provided. It is a volatile memory.

Data which needs to be kept after the operating voltage is switched off, is saved in the EEPROM (3). This memory has a capacity of 512 $Byte$.

The CPU (4) is the central processing unit of the microprocessor. It is used for the processing of the program and to perform logical operations.

The system cycle can be provided by the integrated oscillator (5). For this purpose, four possible frequencies (1,2,4 and 8 MHz) can be set. In addition, the microcontroller can be operated with an external oscillator. By that, a frequency up to 16 MHz is possible.

In order to be connected with external peripherals, the microcontroller has 23 digital input- output lines (6).

By means of the USART interface [2], data can be transferred either synchronous or asyn-

[2] Universal Synchronous and Asynchronous serial Receiver and Transmitter

chronous by a data line.

To receive analog signals, an integrated 8-chanal analog-digital converter is provided (8), which has an accuracy of 10 bit.

The microcontroller consists of two separated BUS systems. To exchange data with the integrated periphery, the data bus (9) is provided. The address bus (10) is used to exchange machine instructions with the CPU (Harvard architecture) [48][24].

Table 4.1 shows the technical data of the microcontroller.

Characteristic	***Rating***
Flash [$kbytes$]	8
EEPROM [$bytes$]	512
SRAM [$kbytes$]	1
Max. i/o pins	23
Fmax [Mhz]	16
Vcc [V]	$2,7 - 5,5$
A/D chanels TQFP	8 10 bit

Table 4.1: Technical data ATmega8A-AU [24]

4.4.2 Valve driver

Two Darlington transistor arrays are used as valve drivers. They consist of seven NPN Darlington pairs. Each Darlington pair is connected to a free-wheeling diode (1). Therefor the induction voltage, generated when the applied voltage is switched off, can dissipate [25]. Figure 4.3 shows the logical diagram of the component as well as the connections.

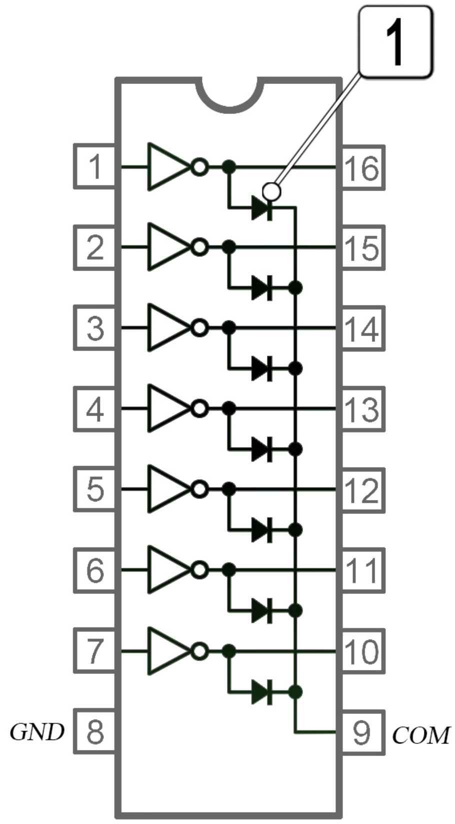


Figure 4.3: Valve driver of the hardware [25]

As shown in the diagram, the component can be described as an array of NOT gates. If a voltage is applied to an input connector (Connector: 1-7), the corresponding output connector (Connector: 9-16) is switched to ground. The following table shows the technical data.

Characteristic	***Rating***
Output sustaining voltage $[V]$	$-0,5 \ - \ 50$
Output current $[mA/ch]$	500
Input voltage $[V]$	$-0,5 \ - \ 30$
Clamp diode reverse voltage $[V]$	50
Clamp diode forward current $[mA]$	500

Table 4.2: Technical data ULN2003AFWG [25]

4.4.3 RS232 transceiver

The used MAX232 transceiver has two channels. Hence the extern computer shown in Figure 4.1 can only detect $12\,V$ signals, a driver (1) is used. The function of the component is to generate $12\,V$ signals out of $5\,V$ signals, which are sent by the microcontroller. The receiver (2) consists of a Schmitt Trigger, which has a threshold voltage of $1,3\,V$ and a hysteresis of $0,5\,V$. It allows to convert $12\,V$ signals, coming from the serial interface of the computer, to $5\,V$ signals. They can then be captured by the microcontroller. The transceiver is inverting, a high level input is converted to a low level output and vice versa [36]. The following figure shows the logical diagram of the component. Table 4.3 gives information on the technical data.

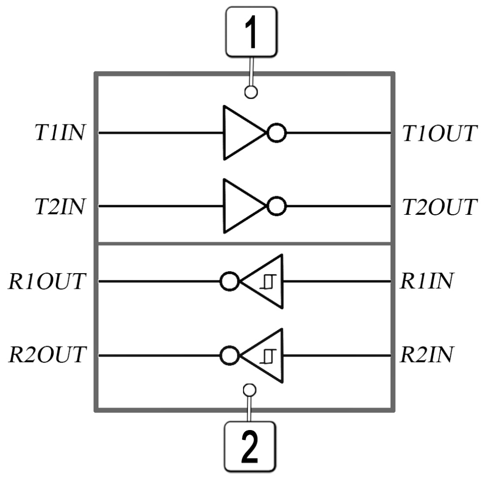


Figure 4.4: RS232 transceiver of the hardware [36]

Characteristic	*Rating*
Supply voltage [V]	$4,5 - 5,5$
High-level input voltage (T1IN, T2IN) [V]	$min\ 2$
Low-level input voltage (T1IN, T2IN) [V]	$max\ 0,8$
Receiver input voltage (R1IN, R2IN) [V]	$+/- 30$
Driver high-level output voltage (T1OUT, T2OUT) [V]	$min\, 5, typ\, 7$
Driver low-level output voltage (T1OUT, T2OUT) [V]	$typ\ -7, max\ -5$
Receiver high-level output voltage (R1OUT, R2OUT) [V]	$min\, 3,5$
Receiver low-level output voltage (R1OUT, R2OUT) [V]	$max\, 0,4$

Table 4.3: Technical data MAX232 transceiver [36]

4.5 Circuit diagram

In this section, the circuits of the different components are explained separately.

4.5.1 Microcontroller

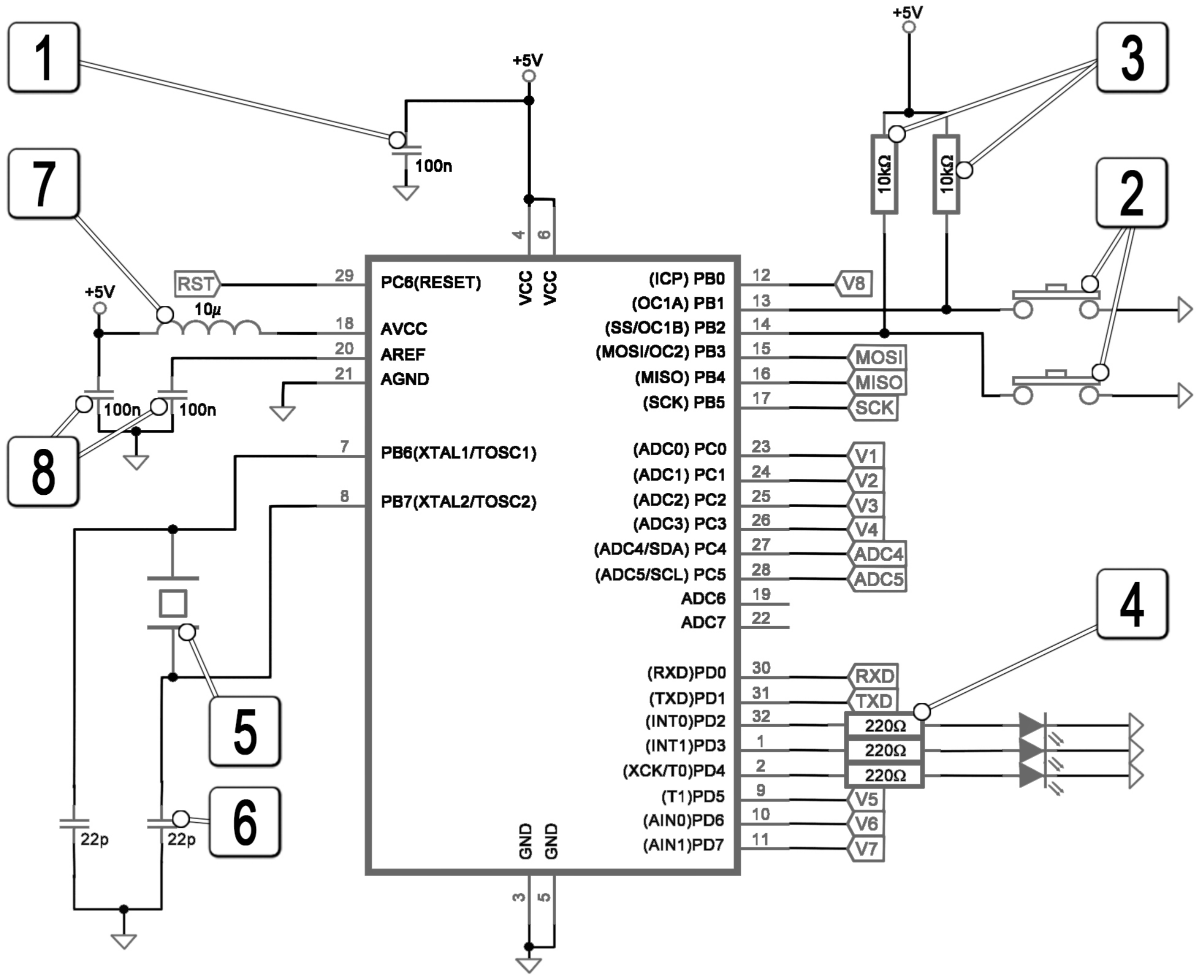


Figure 4.5: Circuit of the microcontroller

The microcontroller is supplied with voltage via the connectors 4 and 6. A capacitor with a capacity of $100\,nF$ is used to smooth the voltage (1).

To control the valves of the pneumatic system, the pins 12, 23-26 and 9-11 are defined as digital outputs. They are connected with the valve drivers.

Two push buttons (2) for the commands "shift up" and "shift down" are located on the connectors 13 and 14, which are defined as digital inputs. A voltage of $5\,V$ is applied to each pin till a button is pressed. Resistors (3) are used to prevent a short circuit.

The pins 15-17 are the connectors for the programming interface, shown in Figure 4.9 [23].

To enable the position measurement, the linear potentiometers are located on the connectors 27 and 28. The connectors are defined as inputs for the analog-digital converter.

The communication between an extern computer and the microcontroller is provided by the pins 30 and 31. They are defined as input (connector 30) and output (connector 31) of the USART [3] transmitter. Therefor they can be connected to the RS232 transceiver, shown in Figure 4.7.

The LEDs which are used for function testing are located at the digital outputs 32,1 and 2. Series resistors with $220\,\Omega$ protect the LEDs against overvoltage (4).

The pins 3 and 5 are the ground connections of the microcontroller.

To operate the chip with the maximum frequency of $16\,MHz$, the clock frequency is generated by an extern quartz crystal (5). Two capacitors (6) enable the oscillation of the quartz. The circuit and the necessary capacity of the capacitors is taken from the datasheet of the microcontroller [24].

The pins 18 and 21 are the power supply of the analog-digital converter. The analog input signals are protected against the influence of electromagnetic waves by means of a coil and a capacitor [24]. The reference voltage for the analog-digital converter is applied at the connector 20. A capacitor with $100\,nF$ (9) is used for smoothing the voltage.

To reset the microcontroller after the programming, the pin 29 is used for the reset command. This port is connected with the programming interface, shown in Figure 4.9.

4.5.2 Valve driver

Each valve driver controls four valve coils. To switch the transistors in the valve driver, a $5\,V$ signal from the microcontroller is applied to the particular input port (I1-4). The valve driver closes the circuit to operate the coils, by switching the corrisponding output

[3] Universal Synchronous and Asynchronous serial Receiver and Transmitter

connector to ground (O1-4). To avoid electromagnetic interferences, the free inputs (I5-7) are connected to ground [28]. Figure 4.6 shows the connections of the valve driver.

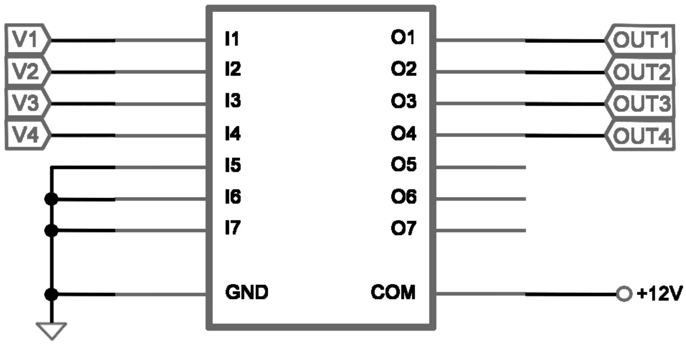


Figure 4.6: Circuit of the valve driver

4.5.3 RS232 transceiver with DB9 connector

To operate the RS232 transceiver (1), the shown circuit is provided as described in the datasheet of the component [36]. The ports for the data input (2) and output (3) are connected with the corresponding pins of the DB9 connector (4). To measure the signal, the voltage is compared against the signal ground applied at pin 5. The data flow control of the serial interface is not provided, as a low data amount can be assumed. Therefor the other pins of the connector aren‘t required.

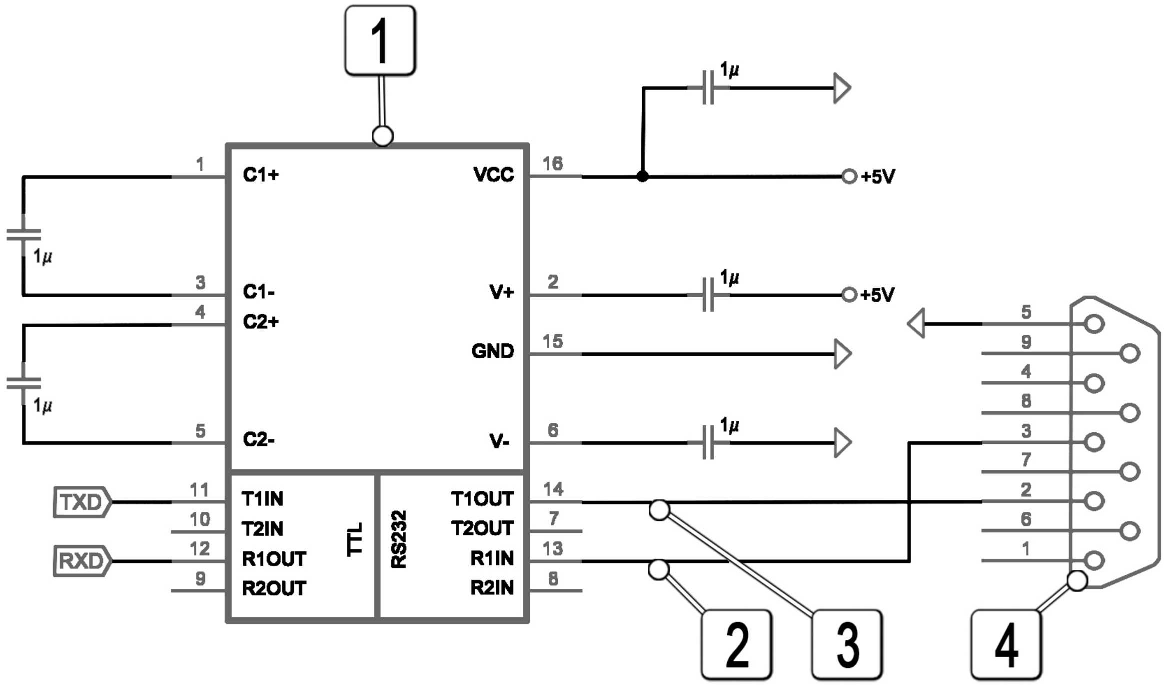


Figure 4.7: Circuit of the RS232 transceiver

4.5.4 Voltage regulator

The hardware is supplied with an input voltage of $12\,V$. Certain components of the hardware require an operation voltage of $5\,V$. To supply these components, a voltage regulator (1) is used. Smoothing capacitors provide a constant voltage level (2). The power supply is indicated by an LED connected to a series resistor (3).

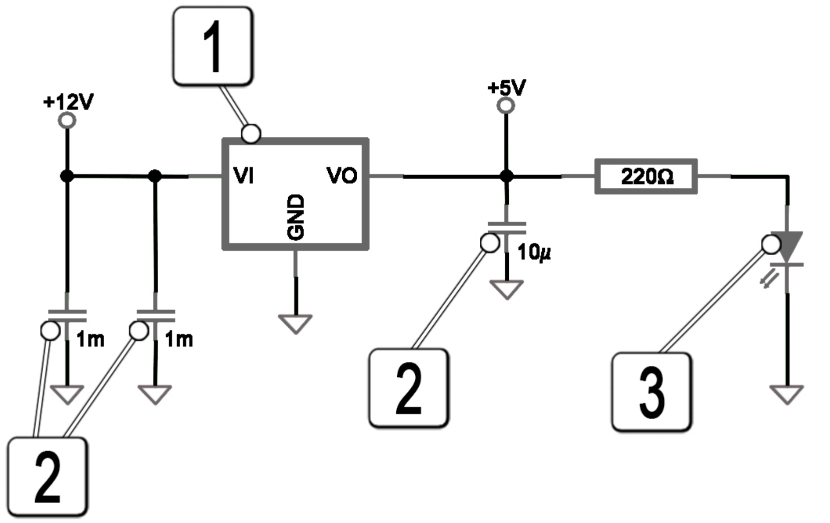


Figure 4.8: Circuit voltage regulator

4.5.5 Programming connector

In order to program the microcontroller, a programmer has to be connected with the hardware. Therefor a programming connector (1) with the shown circuit is necessary. The circuit is taken from the following datasheet [23]. The connections (MISO/SCK) and (MOSI) as well as the reset conductor (RST) are connected with the microcontroller.

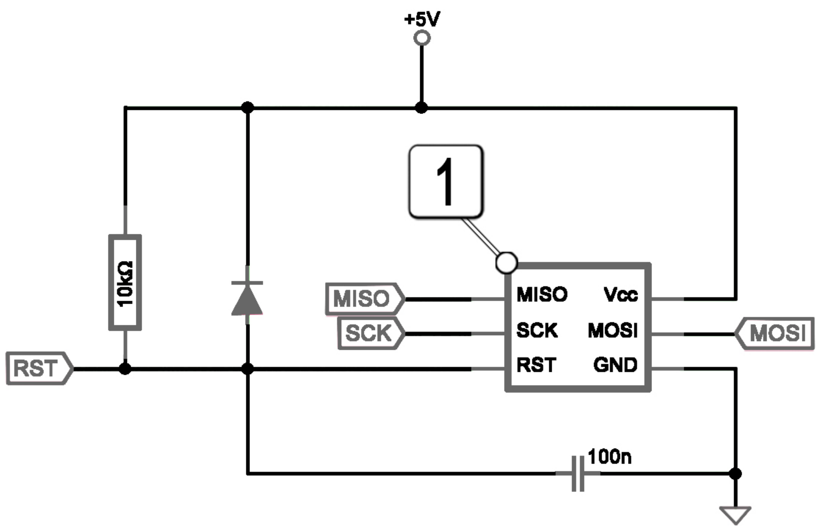


Figure 4.9: Circuit of the programming connector [23]

4.5.6 Dimensioning of the resistors

The dimensioning of one series resistor is explained as an example. The position of the resistor is shown in the following figure.

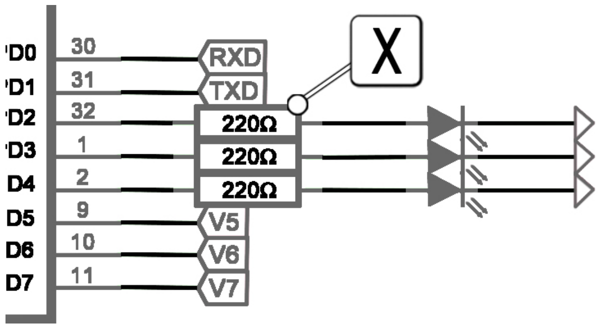


Figure 4.10: Position resistor

The dimensioning of the other resistors on the circuit board is done accordingly, the results are displayed in Table 4.5. Table 4.4 shows the input parameters of the calculation.

Characteristic	***Rating***
SMD-LED red	
Operating voltage $[V]$	2
Current $[mA]$	30
SMD resistor	
Max. power dissipation $[mW]$	100
Resistance value $[\Omega]$	220

Table 4.4: Input parameters dimensioning of the resistor

The necessary voltage drop to reach the operating voltage of the LED is calculated as follows.

$$U_R = U_{MC} - U_L \tag{4.1}$$

- U_R: Voltage drop at the resistor
- U_{MC}: Output voltage of the microcontroller

- U_L: Operating voltage of the LED

$$U_R = 5\,V - 2\,V$$

$$U_R = 3\,V$$

The minimum resistance value is calculated from the current and the necessary voltage drop at the resistor.

$$R_{min} = \frac{U_R}{I} \tag{4.2}$$

- R_{min}: Minimum resistance value
- U_R: Voltage drop at the resistor
- I: Current

$$R_{min} = \frac{3\,V}{30\,mA}$$

$$R_{min} = 100\,\Omega$$

The chosen resistance value for all series resistors of the LEDs is $220\,\Omega$. For the dimensioning of the resistors, the maximum power consumption has to be considered as well. Therefore, the existing current is calculated, when using a resistor with a value of $220\,\Omega$.

$$I_{ex} = \frac{U_R}{R_{ex}} \tag{4.3}$$

$$I_{ex} = \frac{3\,V}{220\,\Omega}$$

$$I_{ex} = 13,64\,mA$$

The power dissipation at the resistor results from the following formula.

$$P_{dis} = U_R \cdot I_{ex} \tag{4.4}$$

$$P_{dis} = 3\,V \cdot 13,64\,mA$$

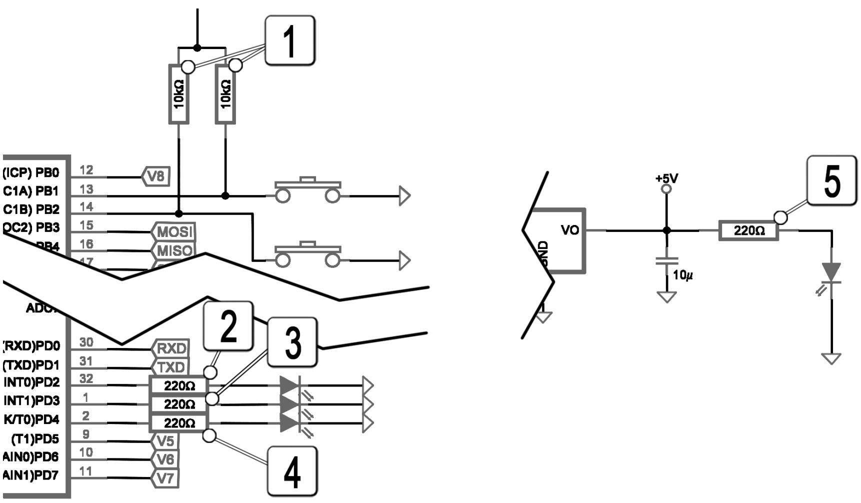
$$P_{dis} = 40,92\,mW$$

As shown, the calculated power dissipation is lower than the maximum power dissipation of $100\,mW$, as displayed in Table 4.4. Therefor the resistor is adequately dimensioned. The calculation results of the other resistors are shown in the following table. Figure 4.11

shows the positioning of the resistors. The pull-up resistors are excluded from the calculations, as the bush buttons where taken from a car radio. Therefor no technical data for the push buttons was available and the resistance values had to be estimated.

Characteristic	***LED red***	***LED green***	***LED yellow***
Operating voltage $[V]$	2	2,2	2,1
Current $[mA]$	30	25	30
SMD Resistors			
Max. power dissipation $[mW]$	100		
Resistance value $[\Omega]$	220		
Calculation results			
Voltage drop at the resistor $[V]$	3	2,8	2,9
Minimum resistance value $[\Omega]$	100	112	97
Existing current $[mA]$	13,64	12,73	13,18
Existing power dissipation $[mW]$	40,92	35,64	38,22

Table 4.5: Summary dimensioning of the resistors



1 : *Pull-up resistors*

2 : *LED red*

3 : *LED yellow*

4 : *LED green*

5 : *LED green*

Figure 4.11: Positioning of the resistors

4.6 Circuit board

The double-sided circuit board has the material description "FR4". The top and the bottom layers consist of 35 μm thick copper (1). The non-conductive layer in between is made out of epoxy resin and glass-fibre (2) [5]. Figure 4.12 shows the section view of the circuit board.

Figure 4.12: Section view of the circuit board

The electronic components are placed on the circuit board, so that an overlapping of the conductor paths is avoided. The following figures show the front- and back-side of the circuit board.

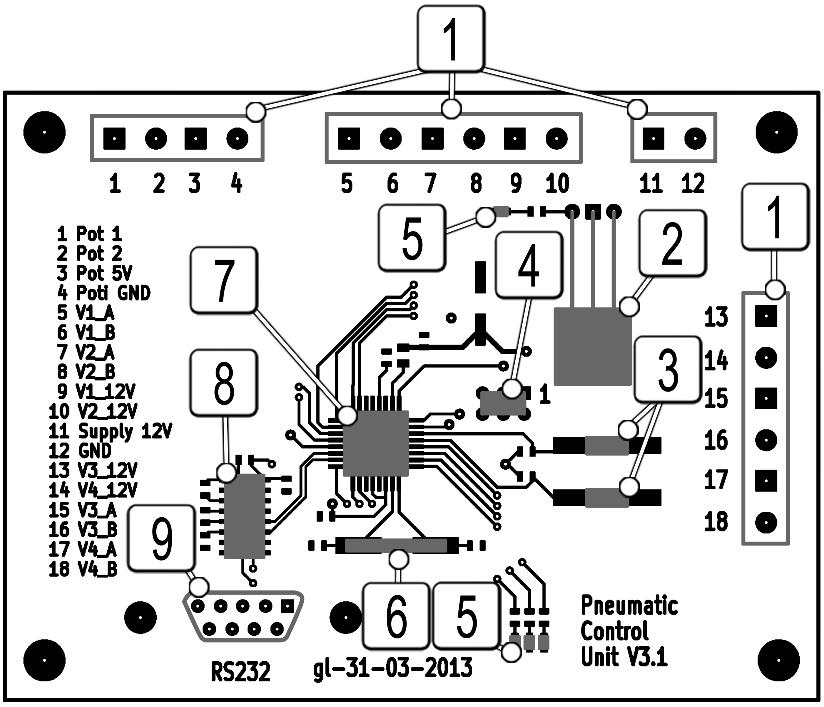


Figure 4.13: Front-side circuit board

1 *Connector block;* 2 *Voltage regulator;* 3 *Push-button;* 4 *Programming connector;* 5 *LEDs;* 6 *Oscillator;* 7 *Microcontroller;* 8 *RS232 transceiver;* 9 *DB9 connector*

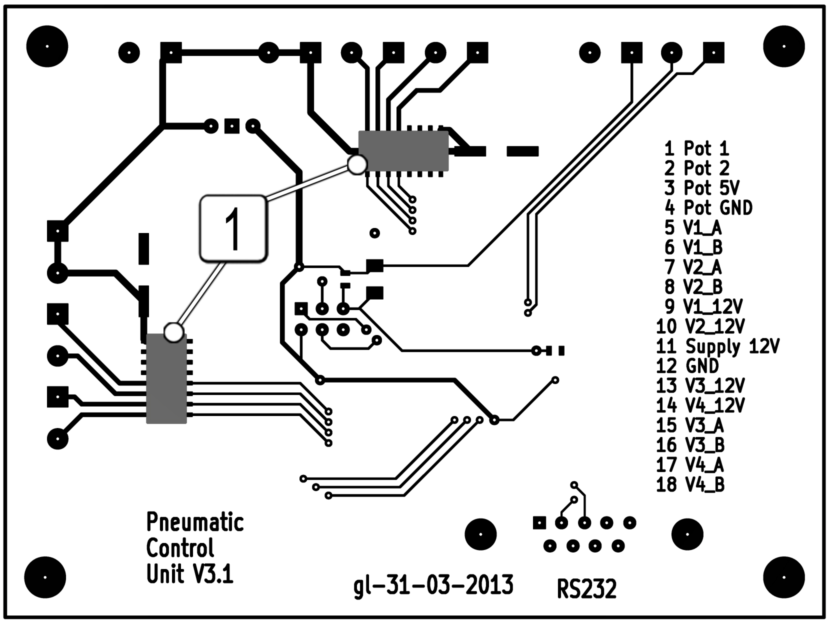


Figure 4.14: Back-side circuit board

1 *Valve driver*

4.6.1 Dimensioning of the conductor paths

The conductor paths are oversized due to the manufacturing tolerances. The chosen widths are shown in the following table.

Conductor type	*Conductor width [mm]*
Signal conductor	0, 254
Power supply	0, 508
Conductor to the valve coils	0, 762

Table 4.6: Conductor paths widths of the circuit board

The dimensioning of the conductor path, which connects the valve drivers with the valve coils, is shown as an example. The manufacturers of circuit boards provide guidelines for the dimensioning, depending on the thickness of the conductive layer. Table 4.7 shows an extract of this data.

Conductor paths widths [mm]	***Current carrying capacity [A]***
$0,1$	$0,5$
$0,2$	1
$0,5$	2
1	4
$1,5$	5

Table 4.7: Current carrying capacity of conductor paths with a copper sickness of $35\,\mu m$ [6]

The current which is required to power the valve coils is $0,084\,A$ [22]. The chosen widths of the conductor paths are $0,762\,mm$. As shown, the applied current strength is much lower than the current carrying capacity.

4.6.2 Production of the circuit board

Due to the costs, the circuit board was produced with non-professional methods. Even though these methods are similar to the professional manufacturing process.

First the board layout shown in Section 4.6 was printed by a conventional office printer on a transparent foil. The conductive paths were printed black, the isolating areas remained clear. After that, the printed layout was placed on the photoresist coated circuit board and got exposed. In the next step, the board was developed. In this process, the board was placed in a high concentrated caustic soda. There the photoresist got removed in the exposed areas. The following etching process removed the copper in the exposed areas. Finally the board was cleaned and equipped with the necessary components. Figure 4.15 shows the production process.

Figure 4.15: Production process of a circuit board

4.7 Summary

The purpose of this chapter was to describe the development of the hardware for the test bench. Based on the defined requirements at the beginning of the chapter, the functional architecture of the hardware was specified. This was followed by the component selection. Based on the technical data of the components, the circuit diagram was developed with the program KiCad. Additionally, the dimensioning of the resistors on the circuit board was explained as well as the dimensioning of the conductor path. The chapter ends with the explanation of the production process of the circuit board.

5 Software for the test bench

In this chapter, the software of the test bench is explained. At first the requirements are defined. This is followed by explaining the basic functions of the software based on the state machine. Furthermore the flow chart of the shifting system is shown to explain the software design and the program sequence. For the sake of clarity, only the essential functions for the shifting system are described.

5.1 Requirements

The software has the task, to execute shifting operations initiated by the operator. For this purpose, the command input needs to be processed and the positions of the selector forks needs to be detected. As only one dog ring can be engaged at one time, it is important to recognize whether a dog ring is engaged or not. Therefor the voltage values of the potentiometers need to be compared with previous set values, which define whether a gear is engaged or not. On this basis electrical signals have to be sent to the valve drivers to move the dog rings in the required position. Another important aspect is to provide safety measures and to verify the accuracy of the measured potentiometer values. It is also important to enable the communication of the shifting system with the extern computer. Furthermore the user should be allowed to change certain parameters of the control system.

5.2 Basic functions

Based on the state machine of the software, shown in Figure 5.1, the basic functions of the control software are explained.

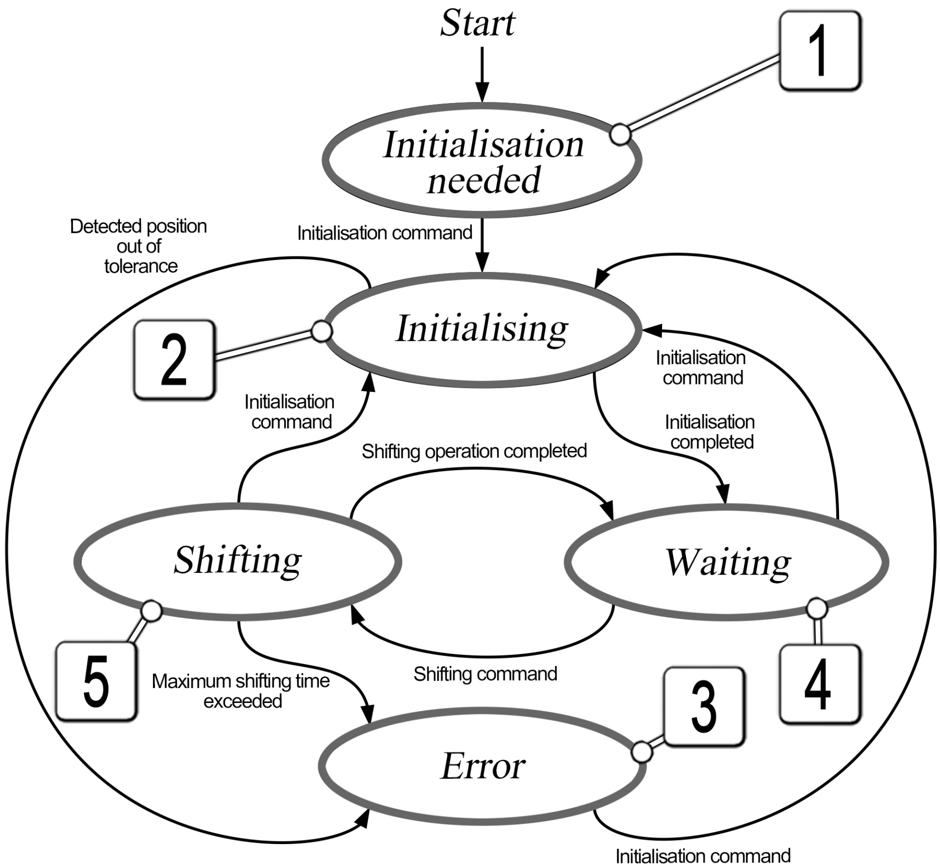


Figure 5.1: State machine of the software

After starting the software, the system is waiting for the initialization command (1). The command can be made by the first press of one of the push buttons or by the initialization command on the extern computer. During the initialization (2), the valve coils are energized to move the selector forks in the defined neutral position. Figure 5.2 shows the positions of the pneumatic cylinders in the neutral position.

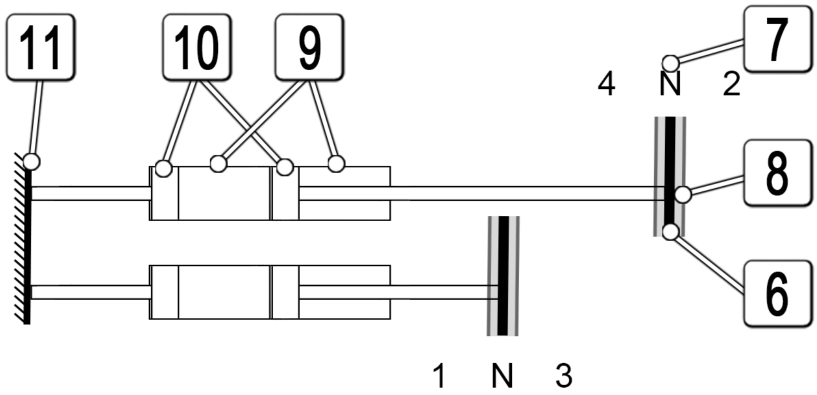


Figure 5.2: Defined neutral position of the shifting system

6 *Selector fork;* 7 *Neutral position;* 8 *Range of tolerance*

9 *Pneumatic cylinder;* 10 *Pneumatic piston;* 11 *Rear mounting*

After the selector forks (6) are moved into the neutral position (7), the measurement values of the potentiometers are compared with target values, set in the shifting system. Therefore the accuracy of the linear potentiometers can be verified. If the measured values are outside of the range of tolerance (8), the shifting system switches in the error state (3). After a successful initialization, the system state is changed in the waiting mode (4). In this mode, a shifting operation can be made. Another initialization can be started was well.

A shifting operation can be executed either by a command input on the extern computer or by pressing a push button on the circuit board. This changes the state of the system into the shifting mode (5). As an example, Figure 5.3 shows a shifting operation from the first to the second gear.

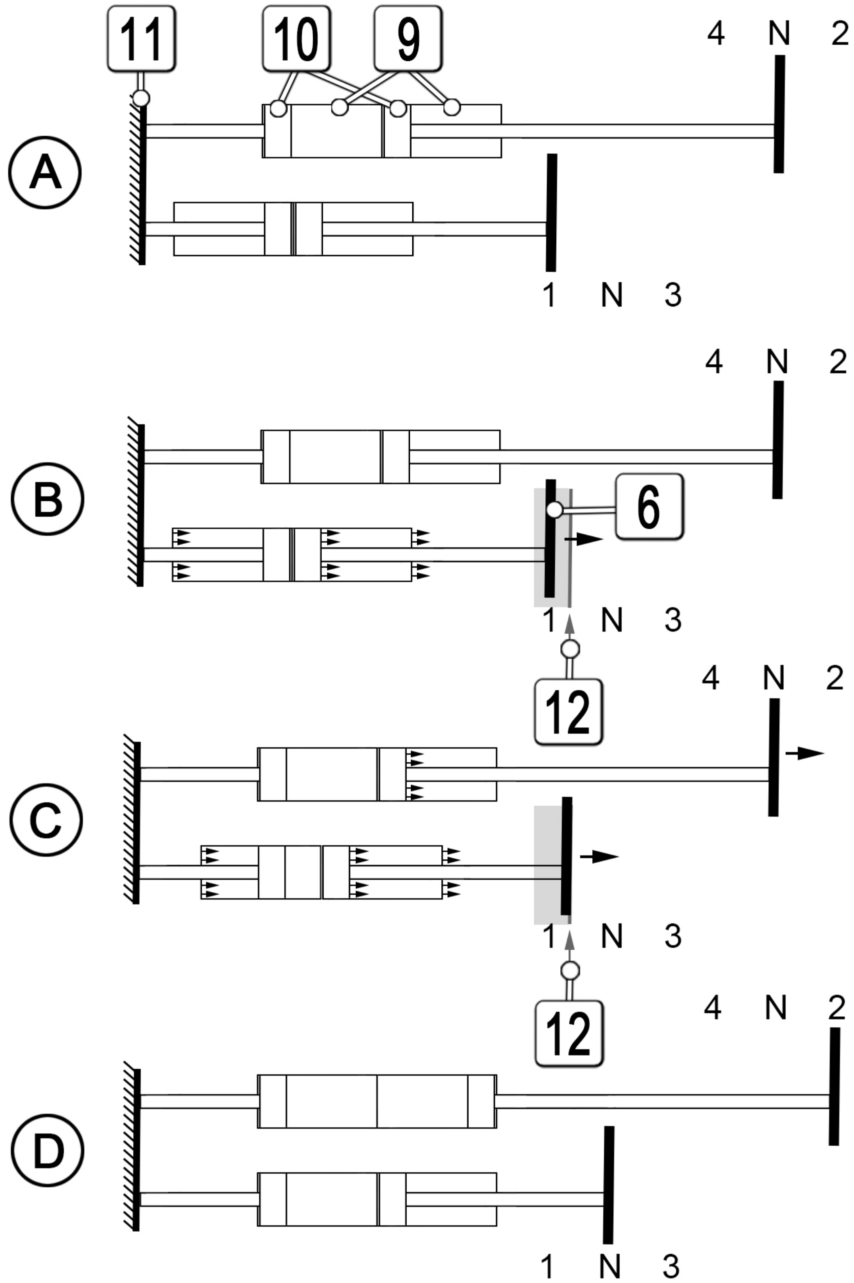


Figure 5.3: Process of a shifting operation

6 *Selector fork;* 9 *Pneumatic cylinder;* 10 *Pneumatic piston*

11 *Rear mounting;* 12 *Threshold value: Gear engaged*

At the beginning the first gear is engaged (A). This is recognized by the control software due to the measured position of the selector forks. As only one dog ring is allowed to be engaged at one time, the marked selector fork (6)(B) is moved towards the neutral position. A set threshold value of the potentiometers detects, whether a dog ring is engaged or not (12)(B). As soon as the selector fork passes the threshold value, the opposite dog ring can be moved into the second gear (C). Another threshold value set in advanced detects, when the selector fork has reached the end position (D). By means of this position, the shifting time can be calculated. In the following step the shifting system is switched in the waiting mode again.

As described above, the software changes in the error mode, when the initialization wasn‘t successful. Furthermore the error state is reached, when the maximum shifting time exceeds a certain value. Another shifting operation is impossible in the error state. By means of a successful initialization, the system can be changed in the waiting mode again.

5.3 Flow chart of the shifting system

By means of a flow chart, the software design and the program sequence is explained. Figure 5.4 shows the flow chart of the program. Firstly the microcontroller is initialized (1). In this process, the variables in the EEProm are read. Furthermore the in- and output lines of the microcontroller are defined and the timer is initialized. To run certain program flows independently from one another, the program is split up into different time cycles. Time-critical tasks are executed every $1\,ms$ (2) whereas other tasks are executed every $100\,ms$ or $500\,ms$ (3) (4). The serial interface is handled with every program sequence (5).

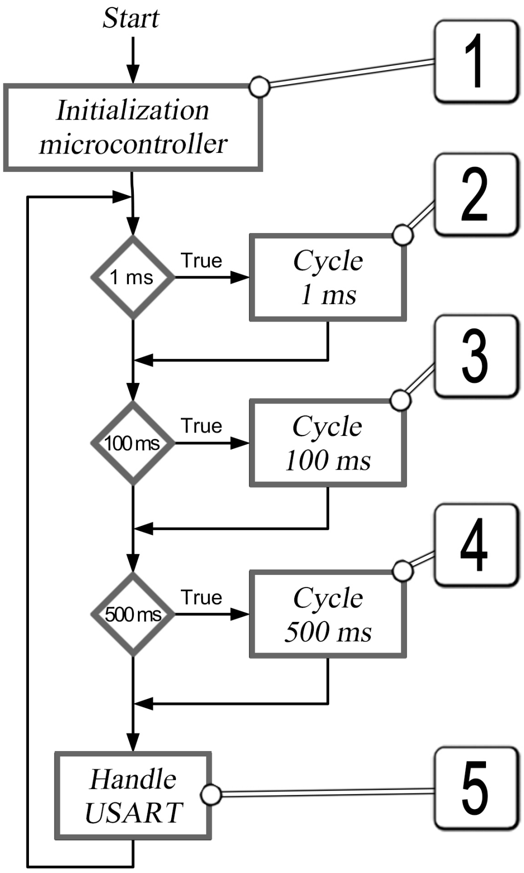


Figure 5.4: Flow chart of the software

5.3.1 First time cycle

Every millisecond, the voltage values of the potentiometers are read (1). By comparing these values with the values defining, whether is gear is engaged or not, the status of the dog rings can be determined and the current gear is calculated (2). Furthermore the statuses of the push buttons located on the circuit board are read. If a gear is selected by the extern computer (Figure 5.4 No. 5) or by the push buttons, the status of the shifting system is changed into the shifting mode. When the shifting system is in the shifting mode, the shifting process is started (4).

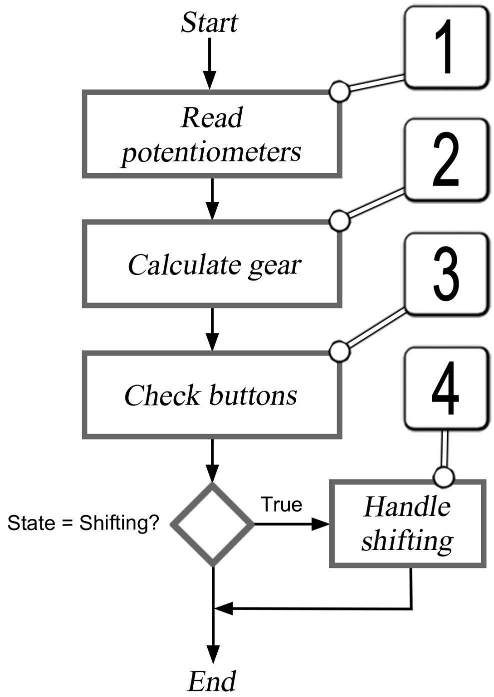


Figure 5.5: Flow chart of the 1 ms cycle

Handle shifting process

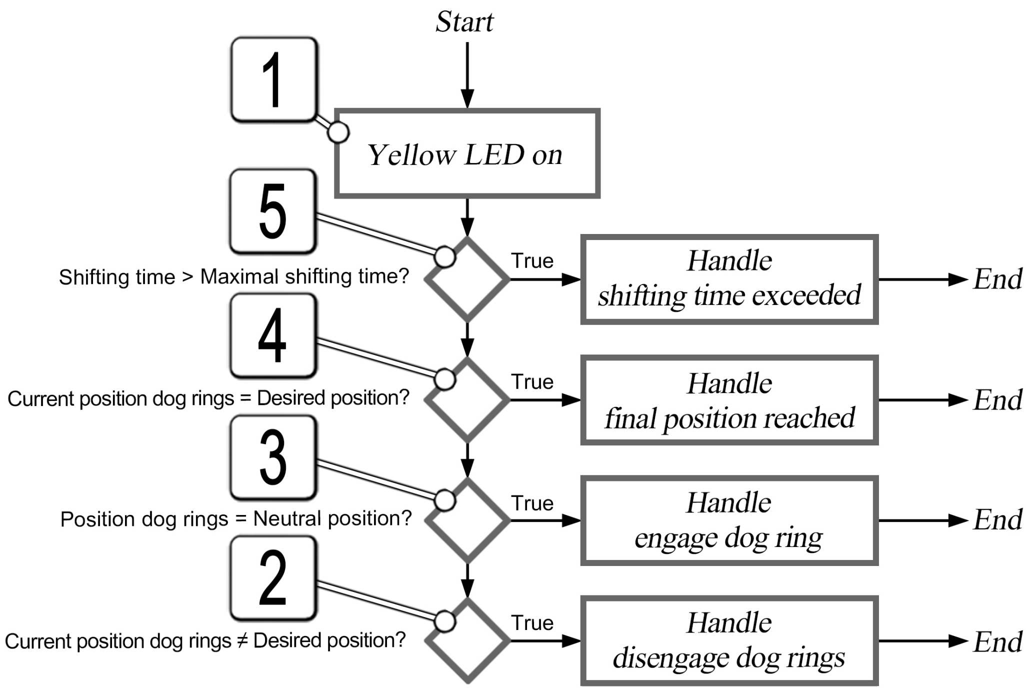


Figure 5.6: Flow chart of the shifting process

Figure 5.6 shows the flow chart of the shifting process. At the beginning, the yellow LED on the circuit board is switched on (1). If the position of one selector fork is not in the desired position for the selected gear, the valve coils are energized so that each selector fork would be moved into the neutral position (2). As soon as both selector forks are in the neutral position range and no torque can be transferred by the dog rings, the dog ring who engages the required gear is moved into the spur gear (3). When the measured values of the potentiometers are in the desired position for the selected gear (4), the state of the shifting system is changed in the waiting mode. Furthermore the yellow LED and the valve coils are switched off. The last step is to display the shifting time on the extern computer. In case that the shifting time overruns a value set as the maximum shifting time (5), the system is set in the error mode. The yellow LED is switched off and the red LED lights up. Additionally an error message is send to the serial interface of the extern computer.

5.3.2 Second time cycle

Each 100 ms, the positions of the dog rings displayed on the computer are updated (1). The same applies for the valve status (2), as the data transmission with the serial interface requires time. Furthermore the initialization command is queried (3).

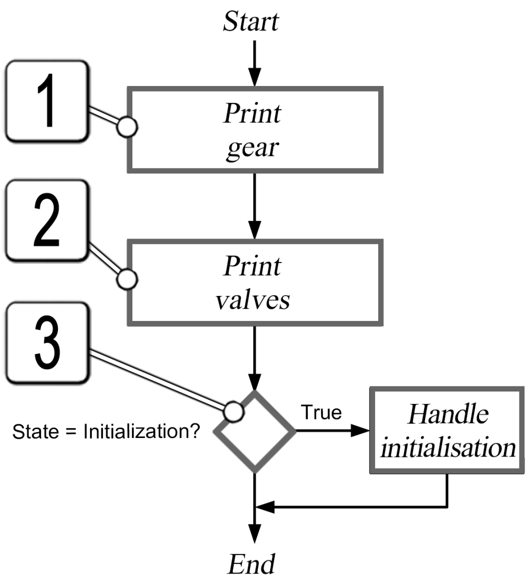


Figure 5.7: Flow chart of the 100 ms cycle

Handle initialization process

When the initialization process is started, the yellow LED is flashing with 5 Hz (1). Furthermore the valves are actuated to move the dog rings into the defined neutral position (2)(3). The system waits 1000 ms to give the dog rings time to reach the neutral position (4). The voltage values of the potentiometers are checked, if they are outside of the set range of tolerance. If so, the shifting system is switched in the error mode (5). The red LED lights up and an error message is send to the serial interface (6).

If the measured values are inside the range of tolerance, the status is displayed on the extern computer (7). Furthermore the yellow LED is switched off (8) and the state of the shifting system is switched in the waiting mode (9).

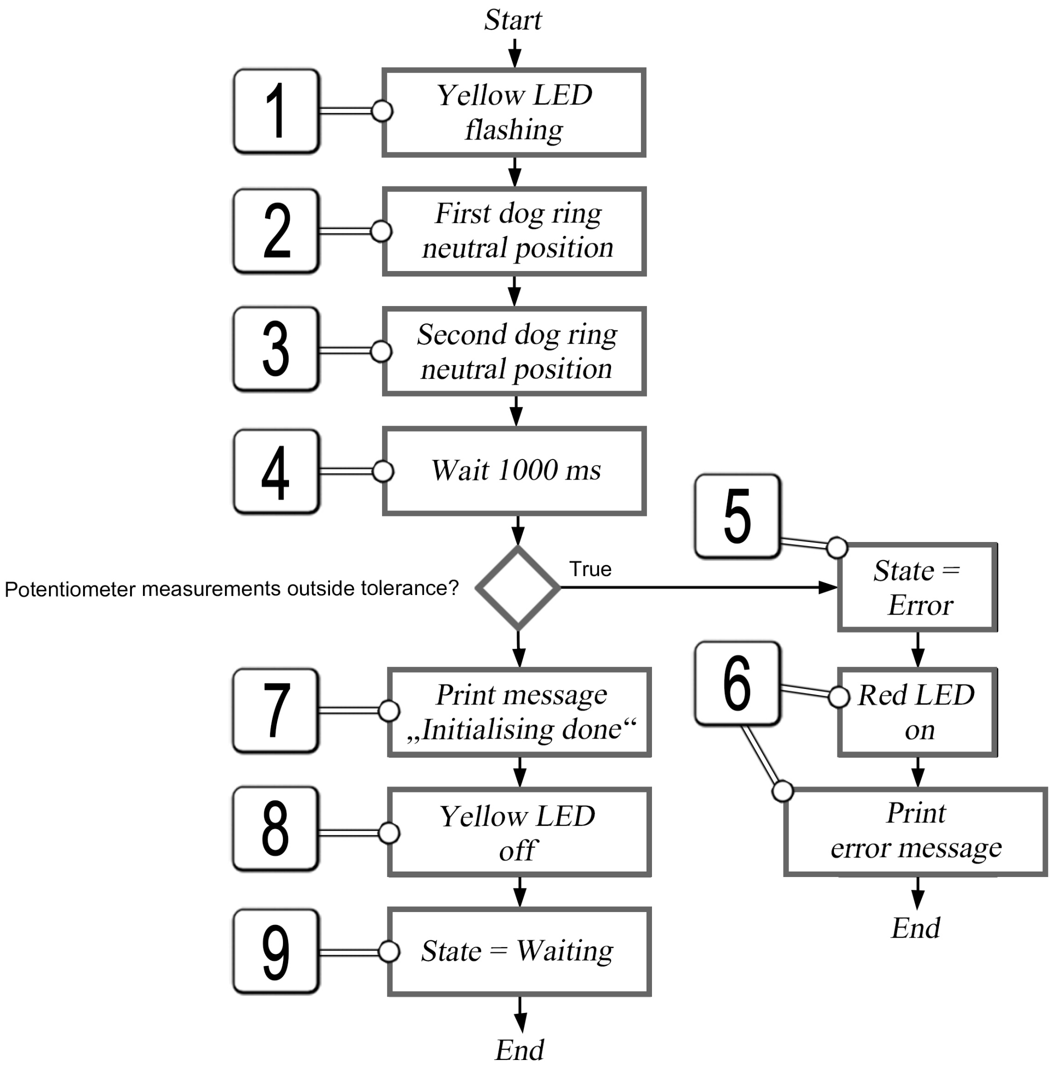


Figure 5.8: Flow chart of the initialization

5.3.3 Third time cycle

In the third time cycle, the green LED is toggled (1). This is to see, whether the microcontroller still executes the program. Furthermore the potentiometer measurements displayed on the extern computer are updated (2). This ensures a better readability. Furthermore the free storage of the RAM memory integrated in the microcontroller is updated on the extern computer (3). Therefor it can be noticed, when the storage capacity is exhausted.

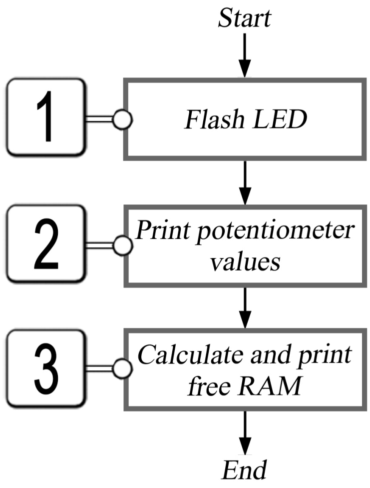


Figure 5.9: Flow chart of the 500 ms cycle

5.4 Summary

To enable the test run with a test bench, the software had to be developed. Based on the developed hardware shown in chapter four and the shifting system shown in Section 3.3.7, the requirements of the software were defined. An important aspect was to provide safety measures to prevent malfunctions. To explain the software, the basic functions were shown based on the state machine. The following flow charts were used to explain the software design and the program sequences.

To allow the software to run certain program flows independently from one another, the program was split up into different time cycles. Implemented safety measures are measurement values which detect the end positions of the pneumatic cylinders as well as values detecting the neutral position during an initialisation process. Therefor the accuracy of linear potentiometers can be verified with each shifting operation and even more precisely during the initialisation process.

6 Construction of the test bench

6.1 Introduction

In this chapter, the constructive design of the test bench gets explained. The construction is based on the shifting system shown in Section 3.3.7. As proposed in Section 1.2, an open test bench had to be constructed. The following figure shows the CAD model of the developed test bench. The construction work was done with the CAD program Catia.

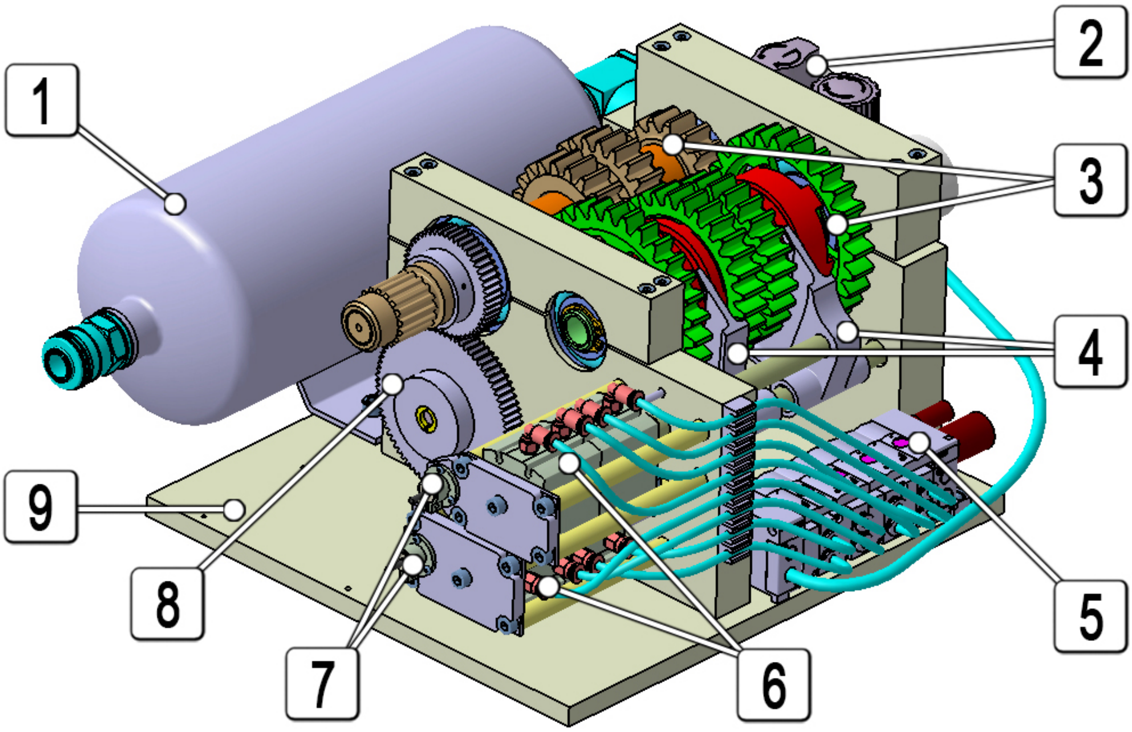


Figure 6.1: Test bench

1 *Pressure accumulator;* 2 *Compressed air preparation;* 3 *Gear shafts*

4 *Selector forks;* 5 *Valve terminal;* 6 *Pairs of pneumatic cylinders*

7 *Linear potentiometers;* 8 *Drive;* 9 *Holes for the circuit board*

6.2 Pressure accumulator

The energy to power the pneumatic components is stored in a pressure accumulator. Therefore the test bench can be operated without an extern pressure supply. The accumulator has a capacity of two litres, the maximum pressure is limited to 16 MPa. In order to fill the pressure accumulator, the pneumatic connector located at the backside is used.

6.2.1 Dimensioning of the pressure accumulator

To show the sufficient dimensioning of the pressure accumulator, the possible amount of shifting operations is calculated. The input parameters for the calculation are shown in Table 6.1.

Characteristic	***Symbol***	***Rating***
Pressure pneumatic cylinders $[MPa]$	p_C	6
Piston diameter pneumatic cylinders $[mm]$	d_P	25
Piston stroke pneumatic cylinders $[mm]$	h	5
Pressure resistance pressure accumulator $[MPa]$	p_A	16
Capacity pressure accumulator $[l]$	V_A	2

Table 6.1: Imput parameters dimensioning of the pressure accumulator

As shown, the calculation assumes a pressure of $6\,MPa$ to drive the pneumatic cylinders.

The basis for the calculation is the law of Boyle-Mariotte. It states, that the pressure of ideal gases p is inversely proportional to the volume V, assuming a constant temperature and amount of substance.

$$p \cdot V = const. \tag{6.1}$$

In the case of the pneumatic shifting system, two states are assumed. In the first state, the pressure accumulator is filled to its maximum capacity. In the second state, the air escapes completely in a different chamber, where the pressure is $p_C = 6\,MPa$. The air volume in the second state needs is calculated

$$p_C \cdot V_2 = p_A \cdot V_A \tag{6.2}$$

$$V_2 = 5,33\,l$$

The air volume V_2 is used to fill all the pneumatic components of the shifting system, furthermore it is used to power the pneumatic cylinders. The air volume to power the pneumatic cylinders V_C is calculated as shown in Equation 6.3. Simplified just the volume of pressure accumulator is assumed to be filled, as is has a much bigger volume than the other pneumatic components.

$$V_C = V_2 - V_A \tag{6.3}$$

$$V_C = 3,33\,l$$

To calculate the possible amount of movements with the pneumatic cylinders, the stroke volume of one pneumatic cylinder V_{Cn} is calculated.

$$V_{Cn} = \frac{1}{4} \cdot \pi \cdot d_P^2 \cdot h \tag{6.4}$$

$$V_{Cn} = \frac{1}{4} \cdot \pi \cdot (25\,mm)^2 \cdot 5\,mm$$

$$V_{Cn} = 0,00245\,l$$

The possible amount of movements n_P results from the following equation.

$$n_P = \frac{V_C}{V_{Cn}} \tag{6.5}$$

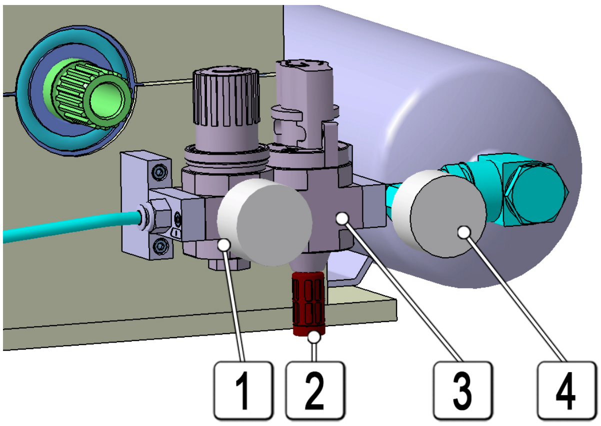
$$n_P = 1360$$

For each shifting operation, two pneumatic cylinders are moved. An exception is the shifting operation from the neutral position to engage a gear and vice versa. Therefore, about 679 shifting operations can be assumed. The filling of the other pneumatic components, such as pneumatic hoses, valves and the air preparation was excluded in the calculation. However, due to the high amount of calculated shifting operations, the capacity of the pressure accumulator can be considered to be appropriate.

6.3 Pressure monitoring and compressed air preparation

To show the pressure in the pressure accumulator, a manometer is installed (4). Furthermore the compressed air has to be prepared to be used in the shifting system. The compressed air preparation consists of a manual on-off valve to disconnect the pneumatic components from the pressure supply and vent them for maintenance work. The function principle is based on a 3-2 way valve. A silencer (2) is installed to reduce noise during venting.

Additionally a pressure regulator (1) is provided, which is mounted behind the on-off valve. It is used to adjust the required working pressure, which is between 3 and 6 MPa. The current working pressure is shown in the integrated manometer. Figure 6.2 shows the components of the compressed air preparation.



1 : *Pressure regulator with manometer*

2 : *Silencer*

3 : *On-off valve*

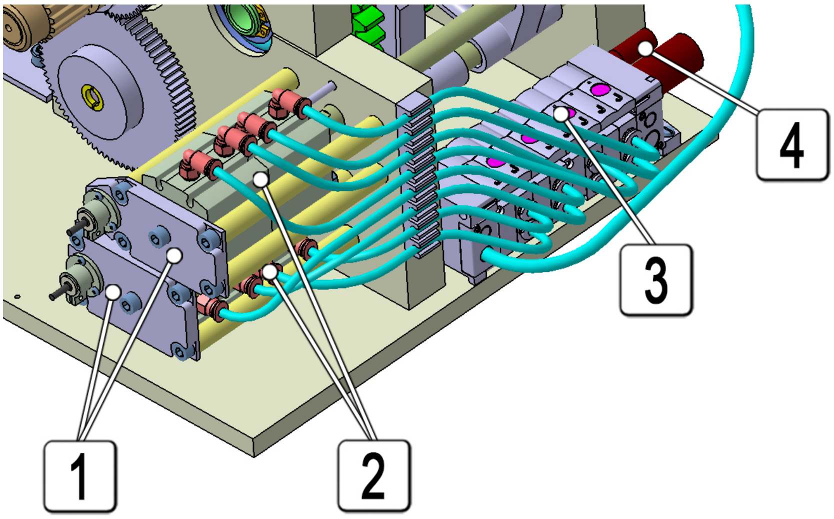
4 : *Manometer pressure accumulator*

Figure 6.2: Compressed air preparation of the test bench

6.4 Shifting system of the test bench

The shifting system is based on the same principle, as the one which is implemented in the drivetrain, shown in Section 3.7. Therefor this section deals only with the features that are different from the one mentioned above.

One difference is the valve terminal, which is equipped with silencers (4) to reduce the noise of escaping air. Furthermore the housing of the pneumatic cylinders (2) isn‘t machined, as enough space is available. Hence the risk of soiling is low compared to the usage in the drivetrain, a cover for the pneumatic cylinders isn‘t provided. In order to mount the pneumatic cylinders and the linear potentiometers, mounting brackets are used (1). The following figure shows the shifting system of the test bench.



1 : *Mounting brackets*

2 : *Pneumatic cylinders*

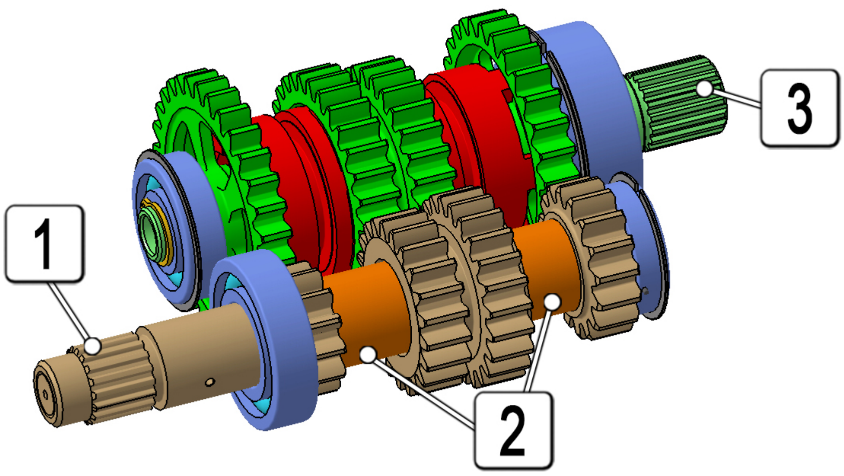
3 : *Valve terminal*

4 : *Silencer*

Figure 6.3: Shifting system of the test bench

6.5 Gearbox

To reduce the costs of the test bench, the standard gearbox of the K71 engine is used to test the shifting system. By removing the pinion of the third and fourth gear from the gearbox input shaft (1), the standard gearbox gets the same layout as the modified four-gear gearbox. Spacers (2) are holding the remaining pinions on the gearbox input shaft in position. Figure 6.4 shows the gearbox of the test bench.



1 : *Input shaft*

2 : *Spacers*

3 : *Output shaft*

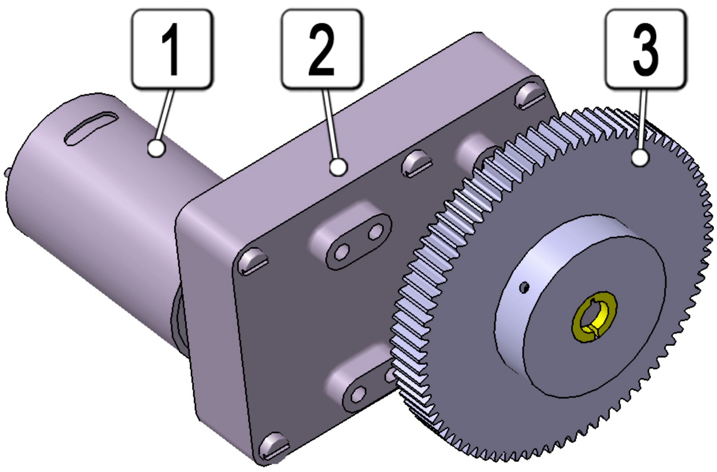
Figure 6.4: Gearbox of the test bench

6.6 Drive

In order to do shifting operations, the gearwheels need to be set in a turning motion. This is enabled by a direct current motor (1) with a flange-mounted gearbox (2). The torque is transferred by a gear pair from the drive to the gearbox input shaft. Due to the usage of a direct current motor, the speed of the gearwheels can be adjusted by changing the voltage to power the motor. This is advantageous as the test bench is an opened construction. By a low speed of the gearwheels, oil can be prevented to splash. Table 6.2 gives information on the technical data of the drive. The following figure shows the CAD model of the component.

Characteristic	***Rating***
Operating voltage [$V\ DC$]	24
Torque [$^{kg}/_{cm}$]	16
Speed without load [rpm]	160
Number of teeth spur gear on the motor	$Z_1 = 80$
Number of teeth spur gear on the gearbox	$Z_2 = 50$
Maximum speed of the input shaft [rpm]	256

Table 6.2: Technical data of the drive for the test bench



1 : *Direct current motor*

2 : *Gearbox housing*

3 : *Spur gear*

Figure 6.5: Drive of the gearbox

6.7 Summary

In this chapter, the construction of the test bench was explained. As proposed, the gearbox is not covered by a housing to facilitate maintenance work. Furthermore a high speed of the gearbox shafts is not required for function testing. To power the pneumatic components, the energy is stored in a pressure accumulator. This enables the test run without an extern pressure supply. The gearbox consists of the standard K71 gearbox to reduce the costs. In order to get a four gear gearbox similar to the one which will be used in the K71 drivetrain, the third and fourth gear where removed. A DC motor is used to set the gearwheels in a turning motion.

7 Application on the test bench

7.1 Introduction

The following chapter deals with the application of the system on the test bench. From the suggested assembly of the components and their connection to the first commissioning. Furthermore additional functions of the shifting system are explained. The chapter ends with the determination of the optimal settings for the test bench and the average shifting time under these conditions.

7.2 Partial assembly

Before the first commissioning, the test bench needs to be partially assembled. To simplify the assembly, the components are split-up into modules, which are pre-assembled in advance. The first module (1) is the electric motor connected to the left mounting bracket of the gearbox. The shifting rods are mounted on the shifting forks. They form the second module (2). The third module (3) consists of the pneumatic cylinders in connection with the linear potentiometers and the mounting brackets. After the assembly of the modules, the second module can be embedded in the mounting brackets of the gearbox. Then, the other pre-assembled components can be connected to these parts. After the fit and free movement of the pneumatic components is validated; the gearbox output shaft (6), the pressure supply (7) and the valve terminal (5) can be mounted as well as the circuit board (8). Figure 7.1 shows the assembly of the test bench.

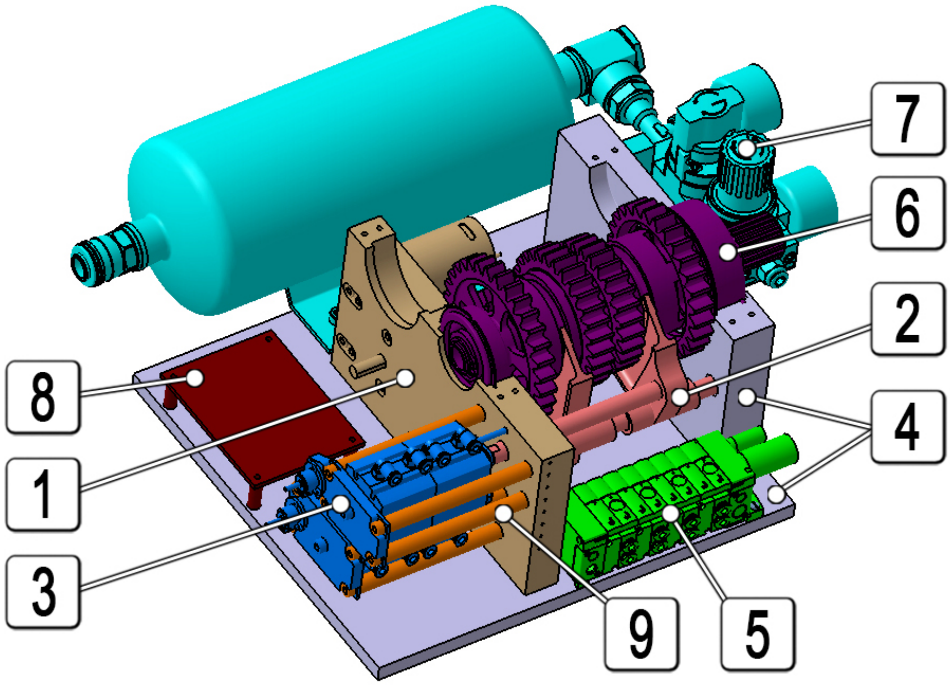


Figure 7.1: Partial assembly of the test bench

1 *First module;* 2 *Second module;* 3 *Third module*

4 *Right mounting bracket with base plate;* 5 *Valve terminal*

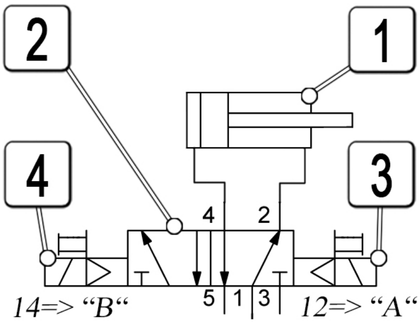
6 *Gearbox output shaft;* 7 *Pressure supply;* 8 *Circuit board*

After the mounting of the gearbox output shaft, it is advantageous to check the free movement of the shifting system again. The next step is the connection of the valve terminal with the hardware and the pneumatic cylinders. These steps are explained in the next section.

7.3 Connection of the components

The correct connection of the components is important, as the connections are set in the control software. The legend printed on the circuit board shows the names of the connectors. The first and second are the connectors for the sliding contacts of the linear potentiometers. They are marked with "Pot 1" and "Pot 2". The first potentiometer ("Pot 1") detects the position of the dog ring, which engages the first and third gear. The connections three and four are the voltage supply of the potentiometers. The connectors for the valves are numbered consecutively, running from "1" to "4". Furthermore the two different coils of the valves are marked on the hardware with "A" and "B". The connections "A" on the circuit board energize the corresponding valve coils of the valve terminal, which are marked with the number "12" (3). "B" are the connections for the valve coils "14" (4). As described in Section 4.4.2, the electric circuits of the valve coils are closed by switching the corresponding connector to ground. Therefor the hardware connectors for the coils "A" and "B" need to be connected with the ground lines of the valves.

The pneumatic cylinders are connected to the valves, so that the energisation of a valve coil "A" contracts the corresponding pneumatic actuator and vice versa. The following figure illustrates the connections of one valve (2) and the corresponding pneumatic cylinder (1). The connections of the entire pneumatic components is shown in Figure 7.3.



1 : *Pneumatic cylinder*

2 : *Valve*

3 : *Valve coil "12"*

4 : *Valve coil "14"*

Figure 7.2: Circuit of the valves and pneumatic cylinders

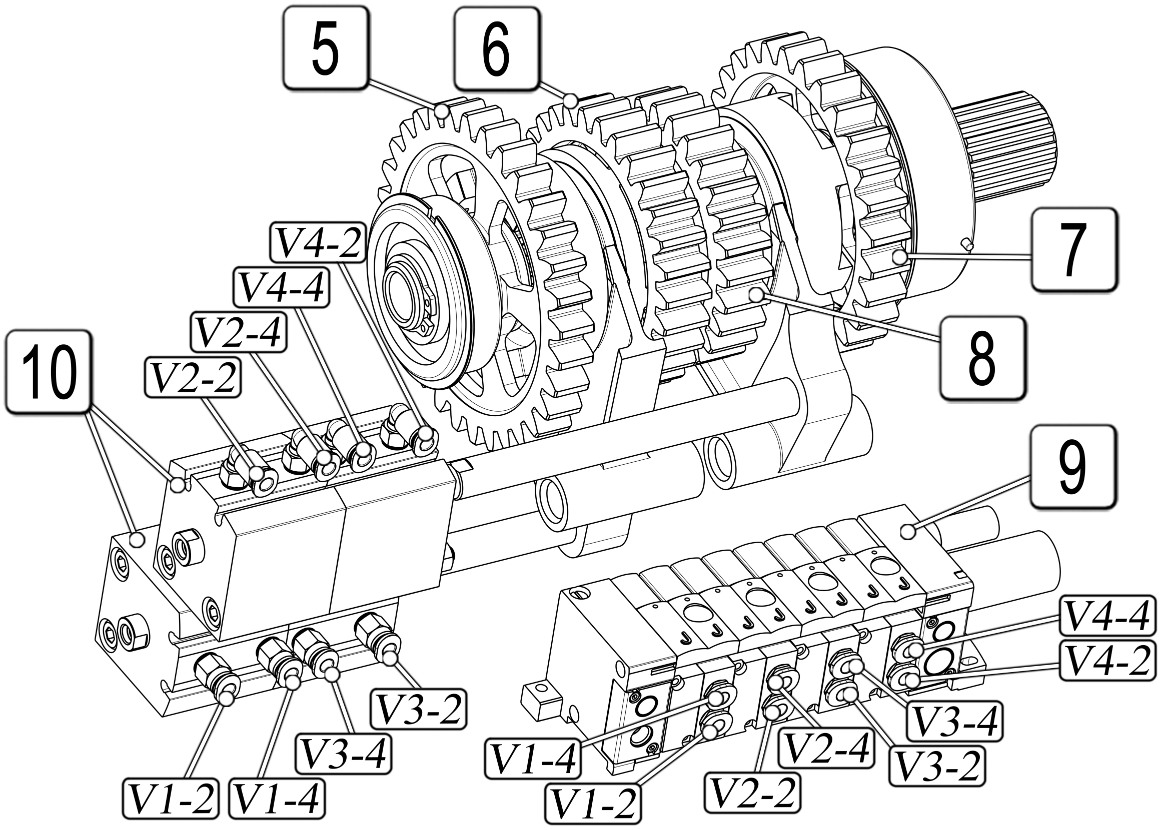


Figure 7.3: Connections of the pneumatic components

5 *First gear;* 6 *Third gear;* 7 *Second gear*

8 *Fourth gear;* 9 *Valve terminal;* 10 *Pairs of pneumatic cylinders*

7.4 First commissioning

To operate the shifting system, the DB-9 connector is connected to the extern computer and the power supply of the hardware is switched on. After calling up the serial interface, the terminal window is generated by entering "reset". Figure 7.4 shows the terminal window.

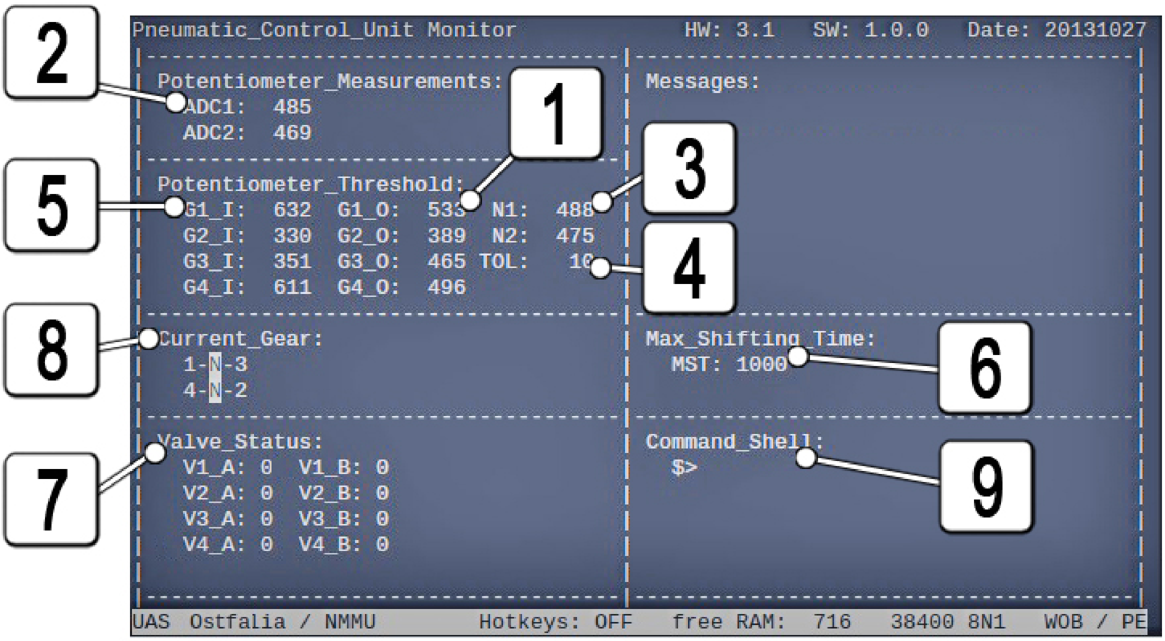


Figure 7.4: Terminal window

1 *Thresholds gear engaged;* 2 *Current potentiometer measurements*

3 *Thresholds neutral position;* 4 *Tolerance neutral position*

5 *Thresholds gear completely engaged;* 6 *Maximal shifting time*

7 *Valve status;* 8 *Current gear;* 9 *Command shell*

As described in Section 5.1, the control system is only enable to engage a gear, when the other gear wheel isn‘t currently engaged. Therefore the voltage values of the potentiometers need to be set, which define whether a dog ring is engaged or not (1). To set the thresholds, the dog rings are moved into the gears, so that the gears are engaged completely. By turning the engaged gear and moving the dog ring carefully out of the gear wheel, the position can be determined when the gears are just getting engaged. The current measurement values of the potentiometers are shown in the terminal (2). After the values of each gear are determined, a certain tolerance needs to be set due to the gaps in the mechanic components. In this example, the tolerance is about $1\,mm$. The following table shows the threshold values of each gear.

Gear	*Measured thershold*	*Thershold with tolerance*
1	563	533
2	419	389
3	435	465
4	526	496

Table 7.1: Threshold values first commissioning of the test bench

The threshold values of Table 7.1 are programmed into the shifting system. The command to set the value of the first gear is for example "G1_O set 533".

As described in Section 5.2, the measured values of the potentiometers are checked during the initialization process. Therefore the potentiometer values for the neutral position of the selector forks need to be set. To do so, the selector forks are moved by hand into the neutral position. In this example, the values of the neutral positions are set with the command inputs "N1 set 488" and "N2 set 475" (3). As the measured values can be slightly different each time, a tolerance is set. The tolerance for this example is 10 bits, which is set with the command input "TOL set 10" (4). Accordingly, the measured voltage values during the initialization process can very up to +/– 10 bits of the values set in the columns "N1" and "N2".

Other threshold values which need to be defined are the values detecting, if a gear is completely engaged (5). These values are necessary to calculate the shifting time. To measure these positions, the gears are engaged completely by moving the dog rings into the gears. Before setting these values, a tolerance is necessary as well. In this example, the chosen tolerance is 10 bits. The command input to set the shown threshold of the first gear is "G1_I set 632". The maximum shifting time (6) to determine shifting errors or measurement errors of the potentiometers, is set with the command "MST set [shifting time]". In this example, the shifting time is set to 1000 ms.

After the definition of the necessary values, the first initialization process is started to move the dog rings in the defined neutral position. If successful, the shifting system can be operated. To do so, the gearbox input shaft is mounted. For the first operation, it is recommended that a helper turns the gearbox input shaft while the operator executes shifting operations with the command input "gear set [x]"[x = 0 - 4]. If the potentiometer thresholds are set correctly, the gearwheels can be turned without getting stuck. After that, the test bench can be operated with the electric motor.

7.5 Additional functions

The additional functions of the shifting system are helpful for the operation. The command "hotkey" brings the transmission control system in the hotkey mode. In this mode, the gears can get engaged while pressing the numbers of the gears on the keyboard [0 - 4]. By the command "x" the hotkey mode is switched off. For maintenance work or to test the coils of the valves separately, the different coils can be switched on and off by the command input "V[n]_[C] set [x]".

[n] : Valve number

[C] : Coil A or B, see Figure 7.2

[x] : 1 = on / 0 = off

The status of each coil is shown in the terminal (7). As described in Section 4.3, the shifting system can also be operated without an extern computer by using the push buttons on the circuit board. As shown in Section 5.2, the first key press after the supply voltage is switched on, brings the shifting system in the initialization mode.

7.6 Operation and test results

The objective of the test is to find out the optimal settings for the test bench. Furthermore the possible shifting time shall be determined under these conditions. The speed of the gearbox input shaft is fixed for the testing. Therefor changeable settings are the potentiometer values defining, whether a dog ring is engaged or not. As described in Section 7.4, the threshold values [1] are set with a certain tolerance. By reducing the tolerance, the shifting time should decrease as the selected gear can be engaged earlier. However a reduction of tolerance increases the risk to engage two gear pairs at one time. This can lead into serious damage, as described in Section 3.3.7. A further possibility to influence the shifting time is to adjust the operating pressure. By increasing the pressure, the shifting time should be reduced due to stronger actors. However by increasing the operational pressure, the energy consumption increases as well. Furthermore the mechanical stresses of the pneumatic cylinders need to be considered, as the residual energy of the pneumatic pistons in the end positions can damage the actors. To find the optimal settings for the system, the above mentioned parameters are changed separately. The shifting time can be read from the terminal window after each shifting operation. To collect enough data for accurate test results, the shifting system did five upshifts from the first to the fourth gear and five downshifts from the fourth to the first gear. This results into 30 shifting operations with each setting. Table 7.2 shows the impact of the variation of the operational pressure on the shifting time. During the test, the tolerance of the potentiometers was set to the voltage value of 30. Table 7.3 shows the average shifting time while the tolerance of the potentiometer threshold values was changed. The operating pressure for the test was set to 6 bar.

[1] Shown in Table 7.1

***Pressure** [bar]*	***Avg. shifting time** [ms]*
1	–
2	147
3	78
4	73
5	67
6	62
7	61
8	61

Table 7.2: Correlation between the operational pressure and the shifting time

***Tolerance** [$ADCvalue$]*	***Appr. tolerance** [mm]*	***Avg. shifting time** [ms]*
40	$1,3$	65
30	1	62
20	$0,7$	63
10	$0,3$	62

Table 7.3: Correlation between the threshold values and the shifting time

As shown in Table 7.2, an increase of the operational pressure doesn‘t influence the shifting time noteworthy, once the pressure is above 6 bar. The increase of the shifting time below 3 bar can be explained by the operation principle of the valves, which are operating according to the servo principle. To ensure a quick switching of the valves, the pilot air supply shouldn‘t fall below 3 bar [22]. After reducing of the pressure to 1 bar, the valves couldn't operate timely, which resulted in an overrun of the shifting time set to 1000 ms.

The variation of the threshold tolerances doesn‘t have a noteworthy impact of the shifting time. However increasing the tolerance to any value isn‘t useful, as these values would overrun the values of the neutral position. Due to the measurement results, an operational pressure of 6 bar and a tolerance of 30 is considered to be suitable for the test bench. The expected shifting time is therefore about 62 ms.

Due to the differences of the shifting system on the test bench, compared to the usage in the K71 drivetrain and the differing operating conditions, the shifting time might be slightly different in the drivetrain. One difference is the weight of the moveable parts of the system, which is higher on the test bench as the parts where manufactured from conventional steel. This increases the inertia forces during a shifting operation. Another aspect is the required sealing for the holes of the shifting rods in the drivetrain, shown in Section 3.7.5. These parts are not mounted on the test bench and will increase the friction loss during a shifting operation. The different operating conditions result from the speed of the gearbox input shaft. As shown in Section 6.6, the maximum speed of the gearbox input shaft on the test bench is $256\,rpm$, whereas the speed of the shaft in the drivetrain will vary mostly between $1554\,rpm$ and $5699\,rpm$. These values are calculated from the primary gear ratio of $1,93$ and the expected engine speed range of $3000\,rpm$ to $11000\,rpm$ [42].

7.7 Summary

The aim of this chapter was to proof the function of the system as well as to determine the possible shifting time on the test bench. Prior to the testing, the assembly of the components was explained as well as their connection according to the developed hard- and software. The first commissioning was explained thereafter. In this section, the functions of the shifting system were explained as well as the suggested way to set the operational parameters. This is followed by the determination of the optimal settings for the test bench and the shifting time under these conditions. The average shifting time was $62\,ms$. At the end of the chapter, the differences between the operation on the test bench to the usage in the drivetrain were shown.

Therefor it can be deduced, that the test results do not necessarily represent the usage in the drivetrain. The main differences are the lower speed of the gearwheels, the missing sealing of the holes for the selector rods as well as the weight of the moveable parts of the shifting system on the test bench.

8 Summary

8.1 Introduction

The last chapter provides an overview of the dissertation in which the previous chapters are summarised, and the achievements and the limitations of the study are discussed. The chapter ends by showing some prospects for future development.

8.2 Overview of the research

In the racing series Formula Student, students from technical universities compete against each other with their developed racing cars. To gain experience in the development of drivetrains, the K71 Project from the Ostfalia University in Wolfsburg deals with the development of a specified drivetrain for Formula Student applications. The drivetrain consists of a four-gear mesh gearbox. This type of gearbox is also often used in other racing applications. While gears are being changed in the gearbox, the tractive force needs to be interrupted. This leads to a decrease of vehicle speed during shifting operations. The time of the tractive force interruption depends, amongst other things, on how quickly the dog rings can be positioned.

The primary objective of the dissertation was to develop a transmission control system to enable shifting operations in the K71 drivetrain. To improve the dynamic driving properties of a Formula Student race car, the system had to allow a short shifting time. Other relevant characteristics were the weight of the system and the energy supply requirement of the shifting system. In order to reach the primary objective, the secondary objectives were defined as follows:

1. To undertake studies of frequently used shifting systems.
2. To develop concepts which enable gear changes in the K71 gearbox.
3. To compare possible solutions in order to find a suitable system which meets the requirements of a Formula Student application.
4. To select the actuators and the sensors for the system.
5. To construct the shifting system by means of the available CAD data of the K71 drivetrain.
6. To construct an open test bench in order to test the functionality.
7. To develop the necessary hardware and software for the test bench.
8. To test the system on the test bench

Prior to the development of the system, literature was reviewed mainly to gain knowledge about the gear linkage and actuation principles of gearboxes. Thereby the first research objective could be addressed. The reviewed literature can be found in the first chapter.

In the second chapter, the fundamentals of the study are shown. At first, the function of a mesh gearbox is explained. After this, the necessity of using a transmission with an internal combustion engine is explained. Also relevant is the section about the impact of interruptions in the tractive force during an acceleration process. After this, the K71 drivetrain and the gearbox layout were shown; hence the shifting system is based on this information.

Chapter three deals with the development of the basic system. The requirements are listed and the concepts of shifting systems are described. These systems were developed beforehand according to the reviewed literature, and the experiences of Formula Student teams. A utility analysis was used to compare the concepts and showed that a pneumatic actuation of the selector forks was the most suitable concept. Although it wasn‘t expected to be the fastest one, it was considered to be quick enough for the application. Other reasons for the selection were the reduction in the number of inner shifting elements, which leads into a lower weight of the system and a reduction of friction loss. Additionally the pneumatic system requires no energy from the engine, which is an advantage. After the selection of the actuators according to the required movement range and the necessary force, the sensors were chosen again by means of a utility analysis. In terms of accuracy, space requirement and resistance against the operating conditions, the concept of using linear potentiometers suited the requirements best. Furthermore, having a linear output signal is advantageous. As shown in the defined objectives, the shifting system was constructed according to the available CAD data of the K71 drivetrain. The construction is precisely described in chapter three, to show the technical feasibility.

In order to test the shifting system, the hardware and software for the test bench had to be developed. The hardware is described in chapter four. The development was undertaken by means of the program KiCad. The design included components not only to provide the basic functions, but which also allowed communication with an external computer. By that, the user is able to change the settings of the software and also to view the current status of the shifting system. On this basis, the software for the test bench was developed, which is shown in chapter five. The provided safety measures verify the accuracy of the linear potentiometers. The program was divided into different time cycles thereby allowing certain program flows to run independently of one another. Furthermore the software calculates the shifting time, which is very useful as it allows the capabilities of the shifting system to be demonstrated.

The construction of the test bench was the next step, with the objective of enabling the functional testing of the shifting system. The details are described in chapter six. To reduce costs, the standard gearbox of the K71 engine was used for the test bench. By removing two gears, it was possible for the standard gearbox to have the same layout as the optimised gearbox from the K71 drivetrain. A pressure accumulator allows the system to operate without an external pressure supply. As the gear wheels need to be set in rotation, a DC motor was provided for this.

Chapter seven deals with the functional testing of the shifting system, which is the concluding objective. Prior to the functional test, the assembly and the interconnection of the components were explained, as well as the functions of the control system. To determine the optimal settings of the shifting system, several settings and their influence on the achieved shifting time were tested. The average shifting time with the optimal settings was $62\,ms$. Therefore the final objective was achieved. At the end of this chapter, the differences between the operation on the test bench and the operation in the drivetrain were shown. This is important, as the test results are not necessarily a true representation of the functioning in the drivetrain.

8.3 Main findings

During a shifting operation in the gearbox of the K71 drivetrain, the tractive force needs to be interrupted. This leads into a decrease of vehicle speed during the shifting time. The shifting time depends on how fast the dog rings can take up their positions. Therefore a shifting system for the drivetrain should ensure a quick positioning of the selector forks.

As mentioned in chapter three, various types of shifting systems exist, which use mechanical shifting elements inside the gearbox to transfer the force from an actuator to the selector forks. This leads to frictional losses. Furthermore, these parts need to be accelerated during shifting operations and additionally, they add weight to the drivetrain. An alternative solution is the direct actuation of selector forks with pneumatic cylinders. This will reduce both the weight and frictional losses caused by the mechanical components. Another advantage is that the energy required to power the system can easily be stored in a pressure accumulator. Because of the way the system in the K71 drivetrain was implemented, the technical feasibility could be demonstrated.

The test run on the test bench, described in chapter seven, shows an average shifting time of $62\,ms$. As described, the result doesn‘t necessary reflect the operation in the drivetrain, due to the different operating conditions. Nevertheless by comparing the developed system with other concepts shown in Section 3.3, the system can be considered to the dynamic driving properties of a Formula Student racing car positively. Firstly due to the low weight of the system which is expected to be about $4,7\,kg$. Secondly due to the fact that the system requires no energy to be supplied by the engine. Assuming a shifting time of about $62\,ms$ in the K71 drivetrain, the developed system would also be beneficial in terms of a short tractive force interruption. Additionally the actuated system is capable of assisting the driver during a shifting operation, being easier to operate than a manual system. It can thus be concluded that the aim of the study could be achieved.

8.4 Contributions of the study

The dissertation has contributed towards the available options of shifting actuations in Formula Student applications, and racing applications in general. The pros and cons of different actuation principles were set out. Additionally, the development of an alternative shifting system could be described, which is based on the direct actuation of selector forks by pneumatic cylinders. Apart from that, the presented development of the hardware and software for the test run provides the basis for the control system of the drivetrain, which could be implemented at a later stage of the K71 Project. As a result, the study contributed significantly to the completion of the K71 drivetrain.

8.5 Limitations of the study

One limitation of the study is the selection of the shifting system concept. A variety of concepts were compared in a utility analysis. Therefore technical data of the concepts had to be estimated or is based on information from Formula Student teams and companies. However, this data could not be readily verified. Furthermore, the weighting of the different criteria had to be estimated, and again, it was difficult to determine what level of importance to attach to the different criteria in Formula Student applications. Therefore the selected and developed shifting system, which does appear to have a number of advantages, may not in fact be the most suitable one.

An additional limitation is the operational safety of the system. As no mechanical linkage is provided between the selector forks, two dog rings can be engaged at the same time. This can lead to serious damage of the gearbox, or can cause instability of the racing car while driving. Therefore safety measures and control functions are included in the software to prevent malfunctions. Despite these arrangements, the possibility of malfunctions cannot be ruled out completely. Consequently, this dissertation ends with some indications of the potential for further development of the shifting system. Most important is the need to improve the operational safety.

8.6 Future prospects

In order to use the advantages of the shifting system in the K71 drivetrain, further development steps are necessary. These are listed below.

- Long-term test:

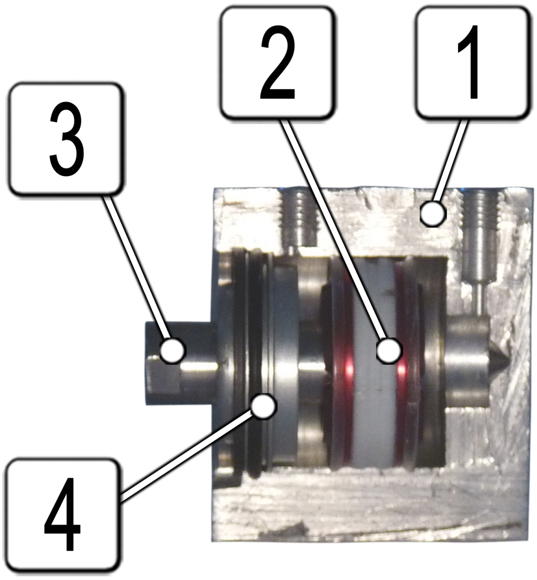
  The shifting system was tested on the test bench to show the functional capability. To improve the reliability of the system further, a long-term test is advisable, which will allow weak points of the prototype to be detected. The system can therefore be improved before it is used in a racing car.

- Adaption of the hardware and software for the use in a Formula Student racing car:

  The control system needs to be adapted for the use in the drivetrain. This includes the automatic interruption of the torque flow to the gearbox in case of malfunction. Furthermore, the hardware and software need to be capable of interacting with the specific control systems used in the racing car.

- Optimization of the pneumatic cylinder housing:

  As shown in the dissertation, the pneumatic cylinder housing (1) will have to be machined in order to improve the space requirement of the parts. Another possibility is to design a new housing for the pneumatic cylinders. Figure 8.1 displays a cut-open pneumatic cylinder to clarify the improvement possibilities of the housing.



1 : *Housing*

2 : *Piston*

3 : *Piston rod*

4 : *Cap*

Figure 8.1: Cut pneumatic cylinder

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Appendix

A. Test bench result Pro-Shift Gearshifter

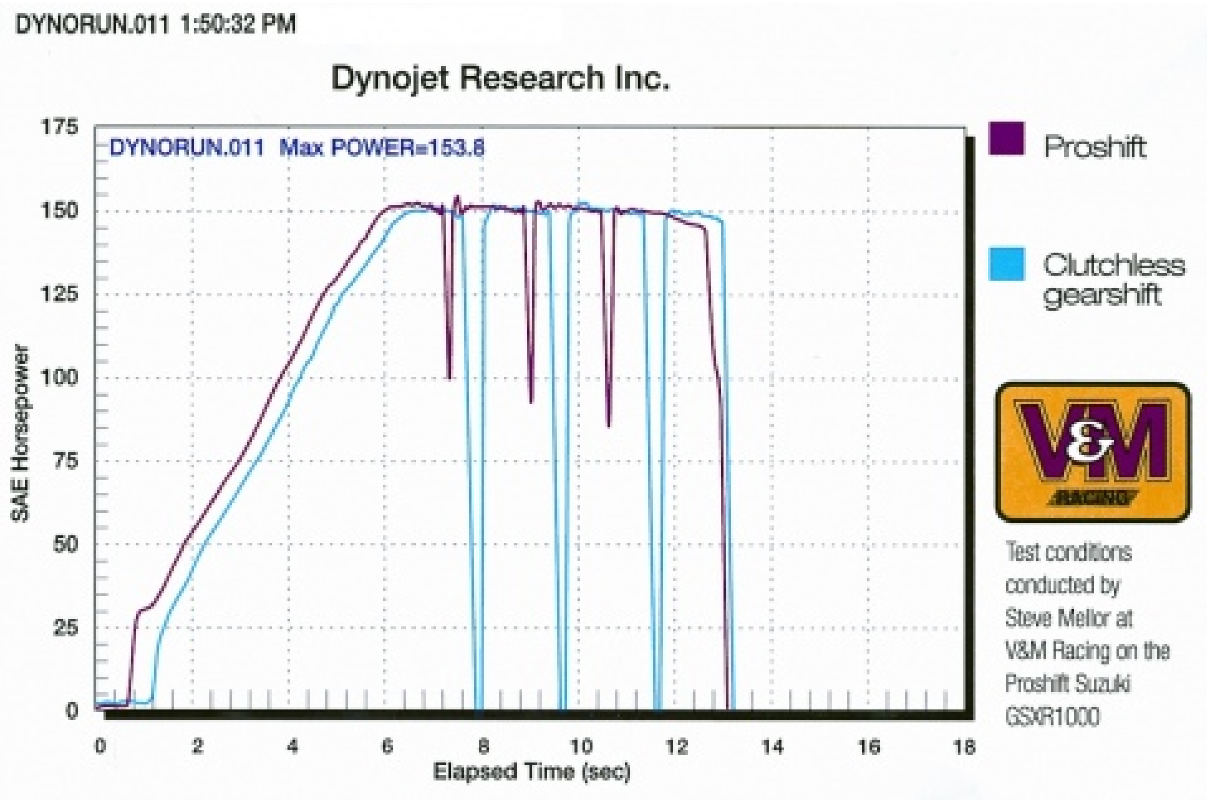

Figure 8.2: Test bench result Suzuki GSXR1000 equipped with the Pro-Shift Gearshifter [15]