VM450 & VE450 Summer 2016
Capstone Design Project

Demonstration and Testbench for Electronic Controlled Clutch:
Final Report

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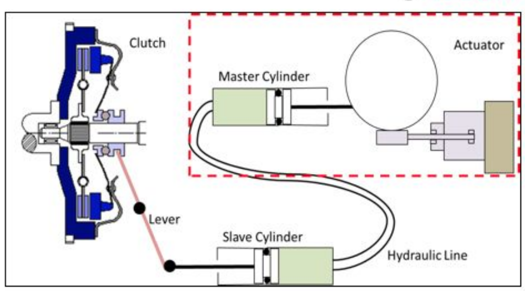

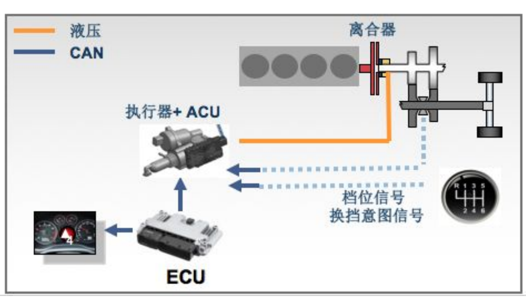

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Executive Summary

For manual transmission cars, drivers have to press the pedal to disengage the clutch in order to shift gears. This step brings many problems: the time to press the pedal needs to cooperate with the gear shift; in a traffic jam, drivers have to press the pedal for countless times; the hybrid car still does not have manual transmission system because of the clutch issues. With the invention and development of electronic controlled clutch (e-Clutch) system in car industry, it is possible to replace the traditional clutch system and give the same experience to those drivers who still use manual transmission cars. The advantages include: saving fuel during coasting, stall prevention, gear shift assistance and pedal free shift. The whole system proposed by UAES includes the clutch controlling part and engine management system (EMS). For the controlling part in this capstone design, building the full size system and demonstrating the basic eclutch function should be focused. UAES will use it to conduct further testing, such as cooperation with engine; or different manual transmission gearbox.

The team and UAES concluded several customer requirements on 3 different aspects: properties; manufacturing process and main usage. The testbench should be durable; easy to manufacture; the cost should be low; the system should correctly monitor the movement of the clutch and fulfill the functionality of eclutch. The engineering specifications with the target value for each requirements were also generated, including: lifespan; percentage of customized machined part; change to the original transmission system; money spend; size of the testbench; range and resolution of the sensor; response time and stability.

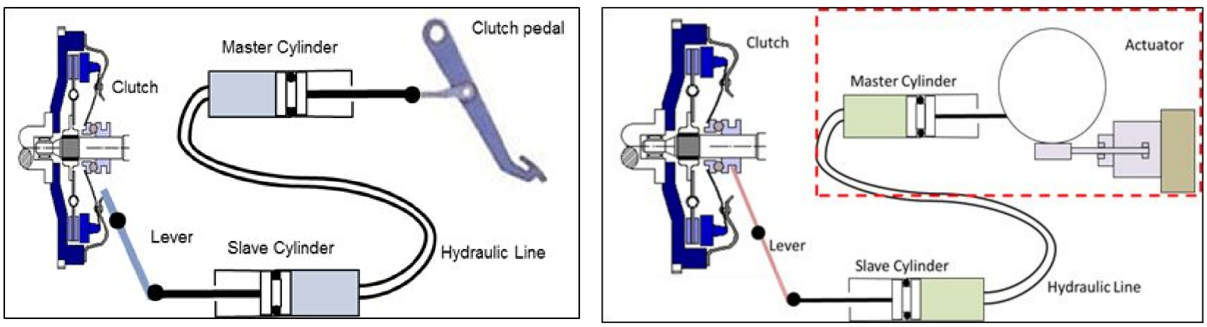
The e-Clutch system can be achieved in 4 stages. First stage is the driving intention detection. The sensor assembled at the gear lever will detect the gear position and changing intention. Second stage is the driving mechanism. After the controller receive the signal, it will drive the motor to push the hydraulic cylinder with a gear system. Third stage is the clutch performance. When the force from the hydraulic cylinder exerts on the release bearing of the clutch, it will engage or disengage automatically; a sensor assemble at the clutch will also monitor the performance. Fourth stage is the testbench. The testbench build for supporting the whole system; it will be used for demonstration and future development.

The validation plan is made to test the functionality of the prototype. After the experiments, the test results are compared with the engineering target value. The comparison indicates the prototype sufficiently satisfies the customer needs. For physical properties, it is durable and can withstand large load; it cost less but is very safe to use. During the manufacturing process, less components are added, and make the assembly method more user-friendly. Most importantly, the prototype can fulfill the main usage, the sensor can precisely detect the driving intention, and the driving mechanism can successfully engage the clutch. The response time is less than the target value. In conclusion, the e-Clutch system meet customer goals, and the testbench is ready for demonstration and further developments.

1.Problem Description & Introduction

1.1 Overview of Electronic Controlled Clutch System

Traditionally, as for vehicles with manual transmission (MT), they always have clutch pedals and when drivers want to change gears, they need to press the pedal in advance. Only after they successfully declutch can they shift gear lever. To make the operation of changing gears easier, UAES developed an electronic controlled clutch (e-clutch) system. In the e-clutch system, we replace the traditional clutch pedal with an actuator, which can control the clutch automatically based on the car’s states and driver's’ intention (Figure 1.1).



(a) (b)

Figure 1.1 Schematic representation of two different clutch systems: (a). traditional clutch system with pedal; (b) e-clutch system[1]

Through the replacement, the e-clutch system can realize 4 major functions. First, drivers do not need to step on and control the clutch pedal. This can greatly reduce jerk during the gear shift, especially when the cars are in a low speed and low gear situation. Secondly, the system can help the drivers in the stop and go process. It is very common that new drivers are facing difficulties in this process because they are not familiar with the amount of time they should use to release the pedal. Therefore, with the help of the e-clutch system, they do not need to worry about this problem. Besides, drivers also face difficulties when they need to start at a hill. It is very dangerous of the hill starting since it may lead to engine stall or car sliding. Using the new system, we only need to control the brake and gas pedals, which can significantly reduce the operation complexity. Finally, the system can declutch when the driver releases the gas pedal. In that way, the car can roll longer without limits from the engine and saving fuel.[1][2]

1.2 UAES Proposed E-clutch System

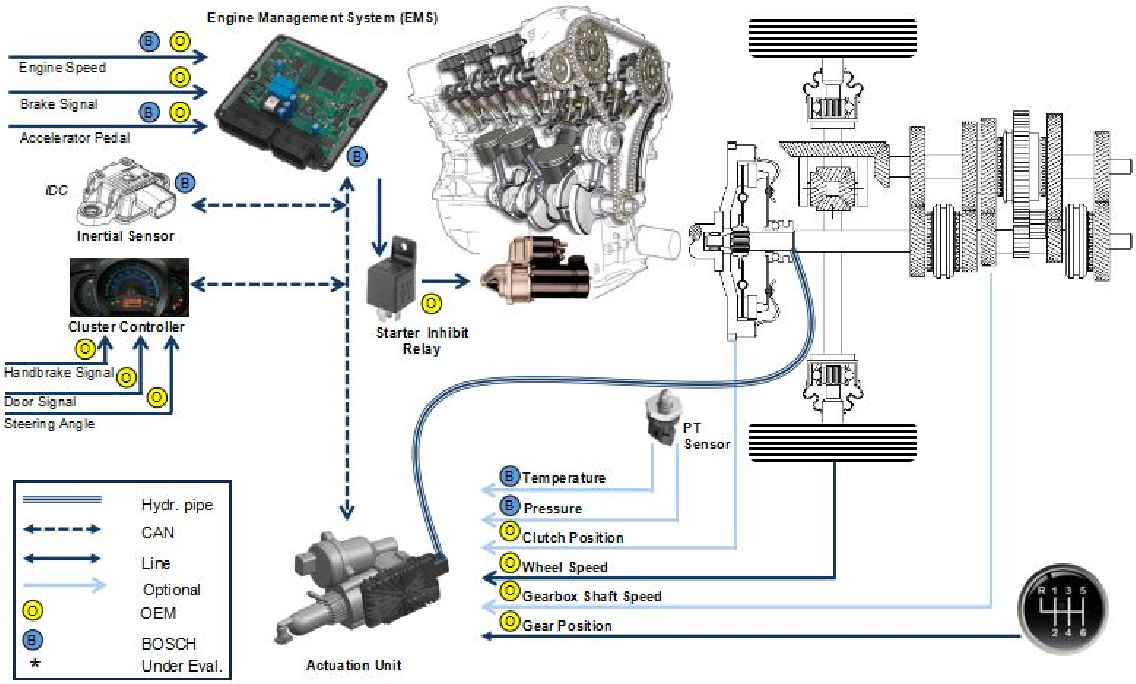


Figure 1.2 Overall structure of e-clutch system

The figure above illustrates the overall structure of the e-clutch system proposed by UAES. The right part is the automatic clutch control system, which contains the actuation unit, clutch system and the gearbox. The actuation unit consists of a controller and an actuator. The controller will be able to read the information of temperature, pressure, current clutch position, wheel speed, gearbox shaft speed and gear position. Based on these data the microprocessor of the controller will predict the driving intention of changing gears and generate corresponding signals to instruct the actuator. Then the actuator can actuate the movement of the clutch to satisfy the need of changing gears. In addition, the actuation unit can be further used to interact with EMS designed by UAES, which means the actuation unit can receive the information of engine speed, brake and acceleration pedal position from the EMS and transmit the information of driver's intention of changing gears to the EMS as well.

1.3 Expected Outcome & Initial Design

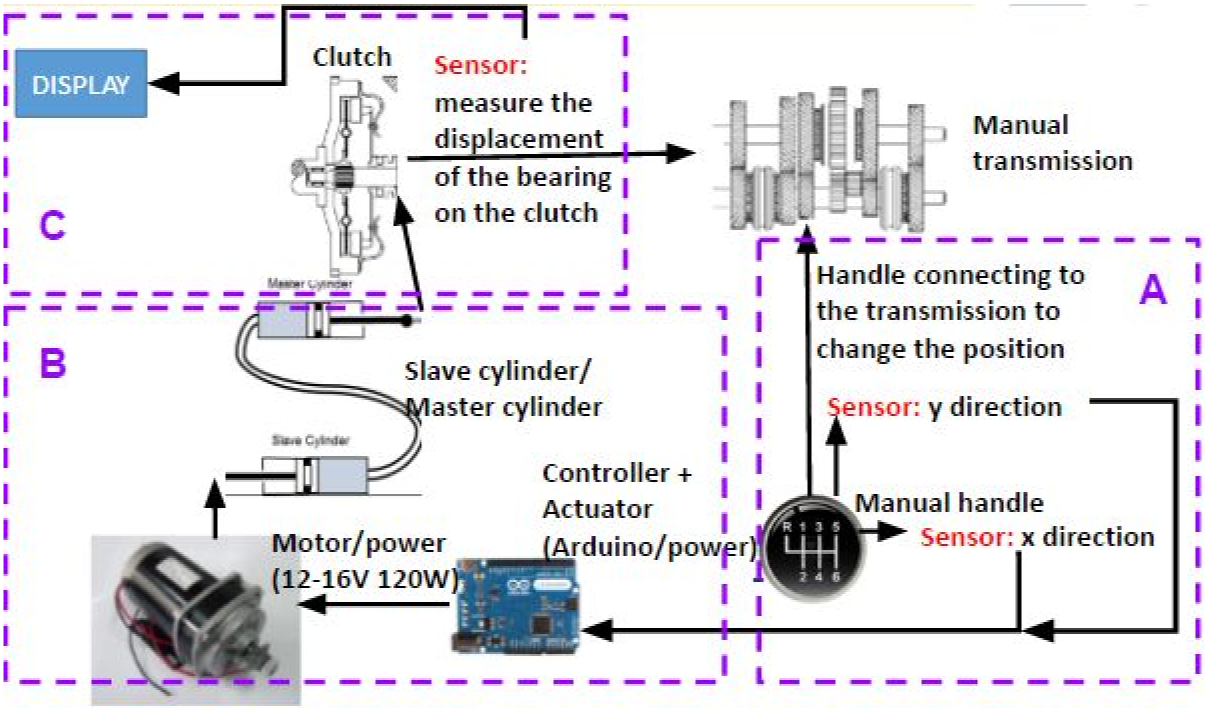


Figure 1.3 Initial team design of the control system proposed for this project

In this semester, our project will be focused on the automatic clutch control system, which does not include the interaction with EMS. For our initial approach to deal with this project, the structure can be divided into 3 stages. Stage A can detect the gear position and predict the driver's intention of changing gears. Stage B will use the Arduino and the motor to control the movement of the clutch. Stage C can detect the clutch position to check whether the process of changing gears is complete. In order to test this e-clutch system, we will build a testbench, which contains the e-clutch system as well as the gearbox.

Therefore, our expected deliveries are a testbench which includes a transmission with gear lever, a clutch with hydraulic circuit and an e-clutch actuator, an electronic controller for the e-clutch actuator and the corresponding software.

2. Information Sources

2.1 Literature Review

Literature review for this project was conducted. From the database, the chart below shows that there are many papers and researches related to the automatic clutch control system, and the number is increasing during recent years. Here are some numbers of how many literatures can be found in different database search engines: Web of Science (283); Engineering Village (509); IEEE(2041); ACM(86704). [3,4,5,6]

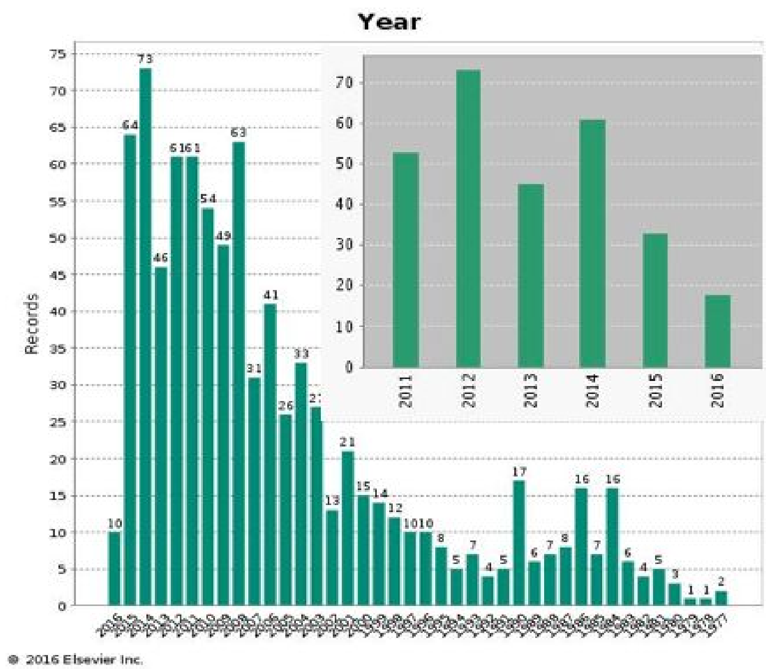


Figure 2.1 Chart for number of paper published annually [3]

Generally speaking, China, US, and Japan are the countries that have most of the papers and research experience in this area. From the literature review, 23 papers are from US, 141 papers are from China, 22 papers are from Germany and the rest are from other countries.

From the literature, the researchers are focusing on topics such as electronic controlled clutch, engine clutch control algorithm during mode change and integrated powertrain control of gearshift on twin clutch transmission. In addition, the test methods selected in these days are still case by case study, MATLAB/Simulink test and (PID) mechatronic control. The researchers have already contributed and solved many topics including auto adjustment of engine clutch during mode change, dual-clutch transmission and development of electronic controlled clutch. Next steps for the researchers would be to design the integrated system and set up the testbench for this e-clutch.

2.2 Patent Search Overview

Patents in US and China were reviewed. Several patents related to electronic controlled clutch were found and listed in Table 2.1. Two of the most related patents are introduced in detail in the following.

Table 2.1 Summary of the results of patent search [7,8,9,10]

Company	Title	Patent Number
Automotive Products plc, England	Electronic clutch control system	US 4561530
Dana Corporation, USA	Electronic clutch control mechanism for a vehicle transmission	US 5562192
Automotive Products plc, England	Electric clutch actuator	US 4865173
Dongguan Lianlong Science and Technology Ltd, China	Automatic clutch control system	CN 201703254 U

2.3 Review of Benchmark and Related Product

a) US4865173: Electric Clutch Actuator

In this patent, an electric actuator used to engage and disengage the clutch is described and introduced.

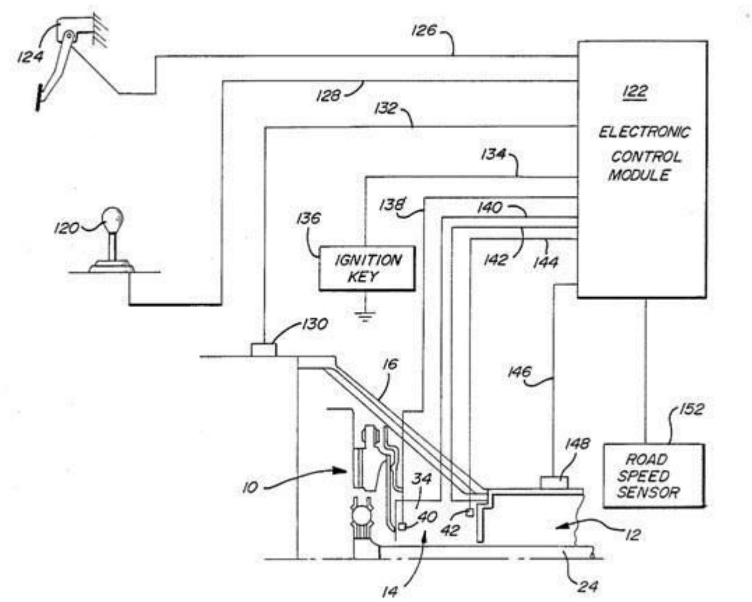


Figure 2.2 Sketch of the solution described in US 4865173 [9].

As described in the patent and shown in Figure 2.2, the clutch pedal is eliminated. The signal to engage and disengage the clutch is generated by pressure on lever 120. If the signals received from the throttle position sensor 124, engine speed sensor 130, gearbox input speed sensor 148, and road speed sensor 152 are compatible with the requested engage or disengage action, then proper control signal will be transmitted to motor 34 to drive the screw member that placed concentrically around the clutch shaft. The screw member will move the release bearing to control the clutch.

This patent requires the actuator unit to be sized so the actuator can be placed within the housing of the clutch. In addition, the installment of annular armature assembly concentrically around the clutch shaft is also required. As a result, the solution described in this patent needs a lot of modifications on the clutch shaft and within the clutch housing. Furthermore, the original hydraulic clutch control unit through the clutch pedal is eliminated, which is also not desirable according to customer need of preserving original manual transmission parts as much as possible.

b) CN201903254U: Automatic clutch control system

As illustrated in Figure 2.3, this automatic clutch control system is designed to simplify the process of changing gears of a car with manual transmission. This overall system contains a controller and an actuator. These two parts are connected to each other. The controller is responsible for receiving car speed signal, input shaft speed signal, brake signal, acceleration pedal position signal and gear lever position signal. The microprocessor of the controller will predict the driving intention and generate corresponding signals to instruct the actuator. The actuator consists of a motor that can drive the hydraulic pump and the pump can control the movement of the clutch to satisfy the need of changing gears.

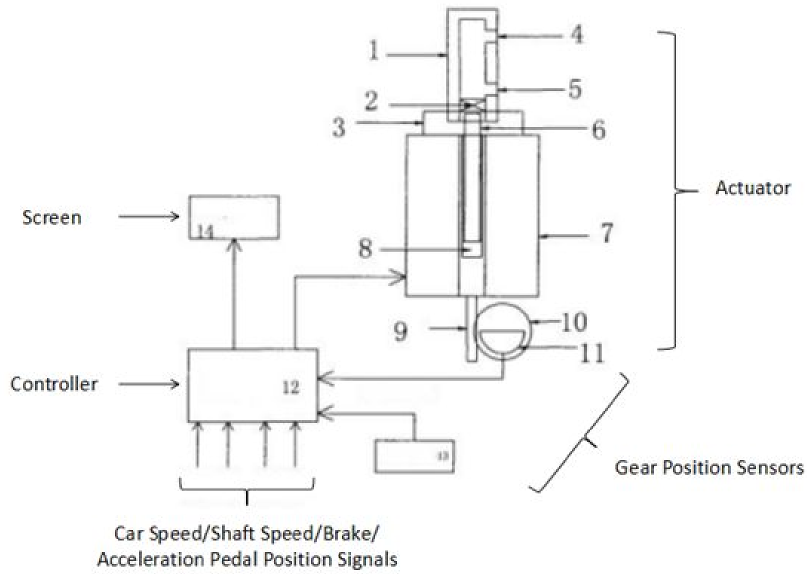


Figure 2.3 Sketch of the solution described in CN 201903254 U [10]

The product described in this patent does not require many modifications on the original manual transmission system. The new automatic controller is connected in parallel with the original clutch control mechanism. The driver can choose whether to use the automatic clutch controller or the original clutch control mechanism. However, the controller does not check whether the signals from sensors agree with the clutch engage or disengage request. Furthermore, the controller can only receive signals from the EMS and cannot interact with it.

Summary

The ultimate goal of this project is to construct a testbench that can be used to develop and demonstrate the function of e-clutch, and the e-clutch is able to interact with the EMS (send and receive signals). In this way, the e-clutch system is an integrated part of the automobile, instead of a foreign system the added on the car. Although, at the starting stage of this project, the solutions described in these patents, especially the second one, seems sufficient, there are still needs of an e-clutch system that can automatically control the clutch and communicate with EMS.

3. Customer Requirements and Engineering Specifications

3.1 Customer Requirements & Engineering Specifications

From the description of the UAES research team and meeting with Dr. Yang Xiao, the customer needs were agreed and reordered in the following steps: properties, manufacturing process and main usage. The purpose of this testbench is to set up a system which can automatically control the clutch and measure the movement of release bearing. The detailed requirements are listed in the following table:

Table 3.1 Summary of customer requirements from different aspects

Property	Manufacturing process	Main usage
Durable testbench	Easy to manufacture	Monitor the movement of release bearing
Safety	Fewer modifications to the original system	Identify position of gear lever
	Cost	Automatically control the clutch
	Reasonable size for testing	Consistent performance

First of all, UAES wants a durable testbench for a one-to-two-year system development. Hence, two engineering specifications were set for this needs: life span and minimum load. The life span is the lifetime of the testbench, which should also be compared with the research development time in order to get a reasonable criteria value. The minimum load for the testbench is important because all the transmission system and control system are set on the table. The larger load the table can hold, the smaller risk the table will fracture or break within the life span. The safety issue also needs to be considered because power supply for the electronic controlling part are needed in the project. The maximum voltage provided should be less than 12 Volts but high enough to power the motor and controlling units.

Another concern is during the manufacturing process of the e-clutch system and the testbench. If the product wants to be user-friendly and popular, it should be easy to operate and the system structure should be concise. In this background, UAES wants their e-clutch and the testbench has following features: easy to manufacture; fewer modifications to the original auto parts; low cost and reasonable size. Therefore, the engineering specifications generated for these needs are clear. In order to makes the manufacture process easier, two solutions are available: reduce the percentage of the customized machined parts and number of the parts added to manual transmission system. These solutions can also help reduce the cost to make the product more attracting. The reason for constraining the size of the testbench is that if the bench is too large, the transmission system is obviously not correctly organized and not efficient when operating the test system.

The main usage of this e-clutch system and its testbench is obviously the most critical customer requirement. The functions of whole system include: monitoring the movement of the release bearing; identifying the position of gear lever; and automatically control the clutch. These main functions are the most important and valuable customer requirements that need to be satisfied. Therefore, several engineering specifications are concluded and different sensors are added to fulfill these functions. In order to monitor the entire movement of the release bearing on the clutch, the range of the sensor should be comparable with the range of the bearing movement. The resolution of the sensor is also important because of the accuracy consideration. For example, if the driver wants to change the gear lever, the sensor should accurately read the position change, even when the value changed is small. In addition, to get a promising result on how clutch works after building the automatically controlling system, the resolution of the sensor at the release bearing is also worth noticing. For the controlling system, in order to give users smooth gear lever transition experience, the response time of the control system and the time needed for the hydraulic system to engage the clutch are critical. In this project, the power of the motor, and the response time of the hydraulic system and its efficiency need to be considered, in order to reduce the response time after the users change the gear lever. The consistent performance can not be neglected. After setting up the system and building the testbench, the test will be conducted and recorded. The system should give a stable performance in order to fulfill the customer requirements. The repeated success rate should be highlighted and continuously improved.

The engineering specifications are then developed further. In order to get a clear goal for the final deliverables, several target values are set for different specifications. For durability, the lifespan of the testbench is set to at least 1-2 years, which is proposed by UAES. After searching and gathering information from different vendors, the weight of the manual transmission system (gearbox, clutch) are estimated to be about 40 kilograms, hence to maximize the load that the testbench supports, the target value should be at least 50 kilograms. During the process of the manufacturing, the percentage of the customized machined part should be minimized and the number of additional parts added to the original part also be minimized. The target value set for the percentage is 10%. The cost should obviously be minimized, and value should be less than 15,000 RMB. The size of testbench is another key factor when designing and manufacturing the bench, and the size should be constrained within 2m*2m*1.5m. When considering the main usage of the automatic controlled system, as mentioned before, actual size of the manual transmission system that will be used in this project still needs to be considered. As a result, the range of the sensor is still to be decided before determining which system to purchase; however, the resolution of the sensor should be maximized, which the target value of the minimum increment of the position sensor would be less than 0.05-0.1mm. For stability, the repeat success rate during the test should be greater than 95%. In addition, for safety concern, the power supply for the electronic control part and for motor should be less than 12V.

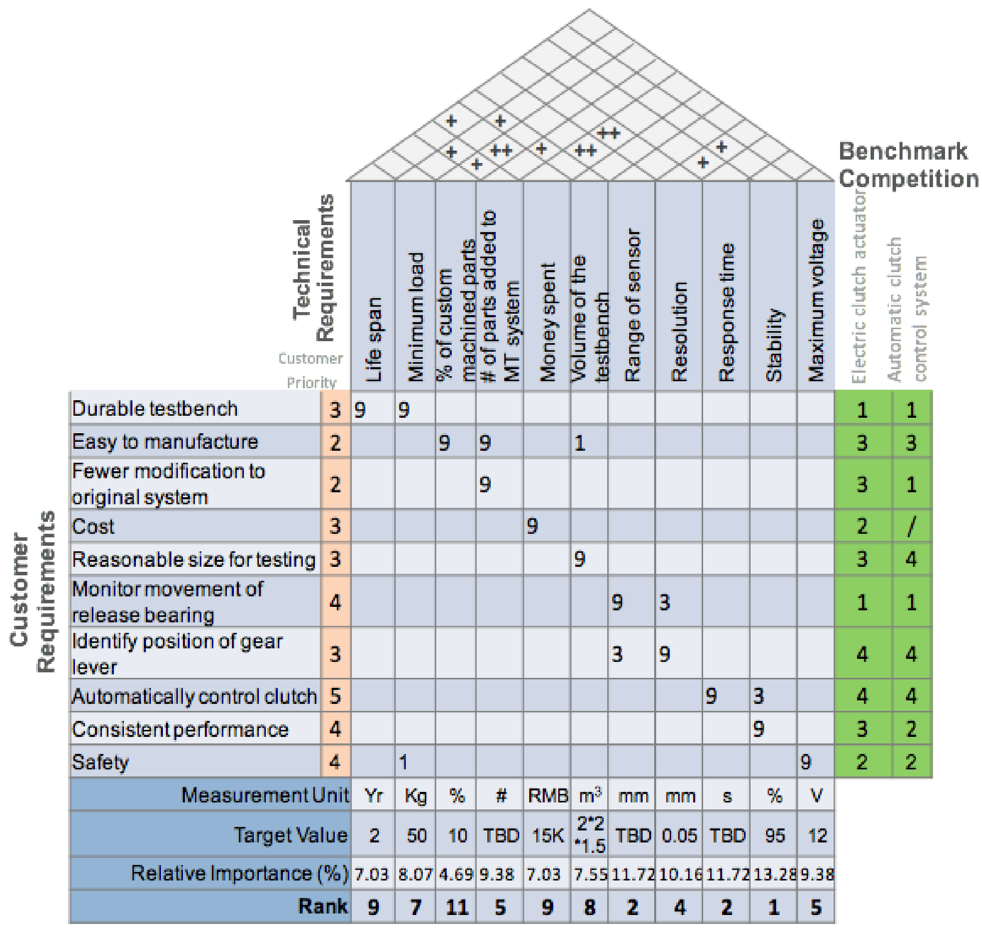
Table 3.2 summarizes all the detailed customer needs and corresponding engineering specifications designed for these needs. In addition, the target values developed for these specifications are also listed in the following table:

Table 3.2 Summary of customer requirements, engineering specifications and its target value

Customer Needs	Engineering Specifications	
Durable testbench	Life span comparable with production development time	1-2 yr.
	Minimum load	>50 Kg
Easy to manufacture	% of custom machined parts	<10%
	# of parts added to original MT system	<60
Fewer modifications to the original system	# of parts added to original MT system	<60
Cost	Money spend	<15k RMB
Reasonable size for testing	Volume of the testbench	2m*2m*1.5m
Monitor the movement of release bearing	Range of displacement sensor	x,y [-45°, 45°]
	Resolution	0.5°
Identify position of gear lever	Range of displacement sensor	x,y [-45°, 45°]
	Resolution	0.5°
Automatically control the clutch	Response time	0.5s
Consistent performance	Stability	>95%
Safety	Maximum voltage for the control system	<= 12 Volts

3.2 QFD Development

A Quality Function Deployment (QFD) is utilized to transform user demands into design quality by correlating customer requirements with engineering specifications. Figure 3.1 shown below is the QFD chart design for this project, and the detailed explanation will be given after:



Customer Requirements	Customer Priority	Life span	Minimum load	% of custom machined parts	# of parts added to MT system	Money spent	Volume of the testbench	Range of sensor	Resolution	Response time	Stability	Maximum voltage	Electric clutch actuator	Automatic clutch control system
Durable testbench	3	9	9										1	1
Easy to manufacture	2			9	9		1						3	3
Fewer modification to original system	2				9								3	1
Cost	3					9							2	/
Reasonable size for testing	3						9						3	4
Monitor movement of release bearing	4							9	3				1	1
Identify position of gear lever	3							3	9				4	4
Automatically control clutch	5									9	3		4	4
Consistent performance	4										9		3	2
Safety	4		1									9	2	2
Measurement Unit		Yr	Kg	%	#	RMB	m^3	mm	mm	s	%	V		
Target Value		2	50	10	TBD	15K	2*2*1.5	TBD	0.05	TBD	95	12		
Relative Importance (%)		7.03	8.07	4.69	9.38	7.03	7.55	11.72	10.16	11.72	13.28	9.38		
Rank		9	7	11	5	9	8	2	4	2	1	5		

Figure 3.1 QFD chart for e-clutch control system

First, priority of customer requirements needs to be determined. After discussing with UAES, customer requirements are ranked in order of importance and priority values (1-5) are assigned to them, where 5 means the most critical requirements:

1. Automatically control clutch (5)
2. Consistent performance (4)
3. Monitor movement of release bearing (4)
4. Safety (4)
5. Identify position of gear lever (3)
6. Reasonable size for testing (3)
7. Cost (3)
8. Durable testbench (3)
9. Fewer modification to original system (2)
10. Easy to manufacture (2)

The correlations between the customer requirements and engineering specifications are quantified by a value with range {blank, 1, 3, 9}. Blank indicates no relationship; 1 indicates a weak relationship; 3 indicates a medium relationship; 9 indicates a strong relationship. The correlations between engineering specifications and its source customer requirements are assigned a value of 9, indicating a strong relationship between them. Besides, sensor range and resolution are correlated with monitoring movement of release bearing and identify position of gear lever. Automatically control clutch has a medium relationship with stability. As a result, the correlations are rated as 3. Minimum load and safety, volume of the testbench and easy to manufacture both have a weak correlation.

Importance weights for engineering specifications are calculated by summing all multiples of customer priority and correlation value. Importance weights are normalized to become relative importance. Then all engineering specifications are ranked based on the relative importance. According to the QFD, the three most important engineering specifications are stability, response time and range of sensors.

The correlations of engineering specifications are also analyzed and represented by a value with range {blank, +, ++, -, --}. Blank indicates unrelated; + indicates medium positive; ++ indicates strong positive; - indicates medium negative; -- indicates strong negative. Main potential trade-offs are money and sensor performance.

Two benchmarks are evaluated according to the customer requirements. From the result, their performances both need some improvement and lack some function required by the customer.

4. Concept Generation

4.1 Overview

After the stages of the project being determined, the corresponding sub-systems (which is also known as the sub-functions) are discussed. Notice that there are several limitations for project concept generation. One is that the gearbox type is given and not much modification can be made to this part. In addition, the Arduino board is a popular controller, and in this project, it will be selected as the controlling system. The sub-function for stage A is to detect driver's intention, and the sensors will be used to fulfill the goal. The sub-function for stage B is to process the signal and drive the hydraulic system. The initial concept for this function is to design a motor and driving mechanism which can push the hydraulic cylinder to engage and disengage the clutch. The sub-function for stage C is to measure the results, and the sensor is selected in this part as well. The sub-function for stage D is to design a sturdy testbench which can support the whole system and conduct the experiment.

4.2 General Function Structure

The purpose of the this morphological analysis is to determine the relationship between each sub-functions and find the possible correlation among them. In addition, the energy flow, signal flow, and material flow are used to express the relationship more clearly.

First, the general structure is created to represent the most critical goal for the whole projects, as shown in the Figure 4.1. The main function is to automatically control the clutch when changing the gear lever. The input flow includes material flow: suitable location for performance testing; signal flow: driving intention, change of gear ratio; energy flow: driver's operation, power supply. After run through the main function, which acts like a black box at this time, the output flow would include signal flow: performance results, stability; energy flow: actual reaction for releasing bearing.

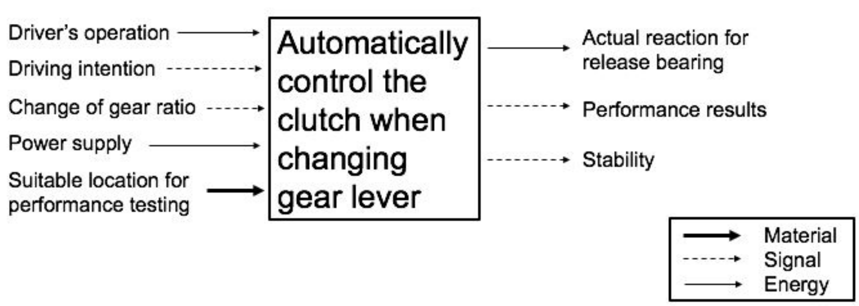


Figure 4.1 General function structure

4.3 Detailed Function Structure with Decomposition

Then, the function structure is further developed, as shown in Figure 4.2. The general function, i.e. the “black box”, are divided in several detailed sub-functions based on the previously determined stages. The first detailed function in the structure is the detection of driving intention. The input signal flow is telling the change of gear lever and the position of gear lever. The input energy flow would be driver’s operation. After going through this detailed sub-function, the output will then come to the next detailed sub-function, which consists of two parts: controller and driving mechanism. The input includes an additional energy flow: 12V power supply. The output also includes two parts, the output energy flow is to engage/disengage the clutch; and the signal flow is to give the results to the next detailed sub-function. The third sub-function is performance measurement and display. The output signal flow is stability and performance results. The last detailed sub-function is the testbench designed for the whole system, it provides material flow to all other detailed functions described above. The function of testbench is to provide location for all different kinds of experiment and demonstration.

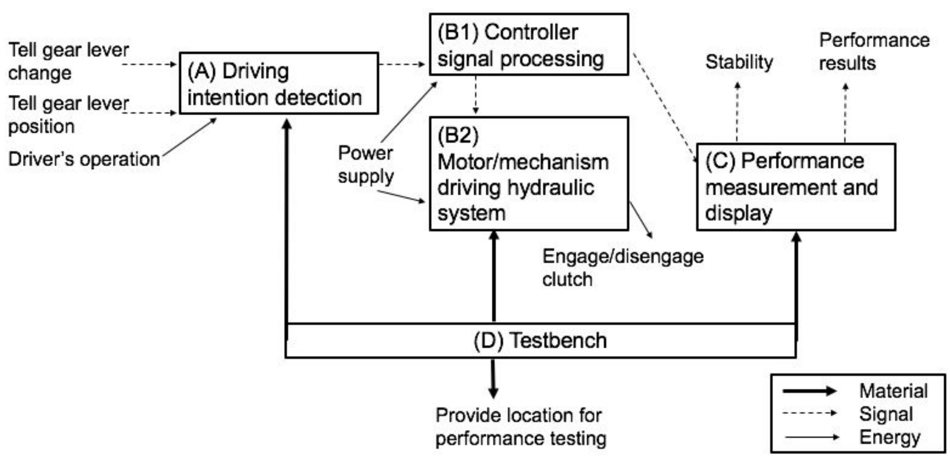
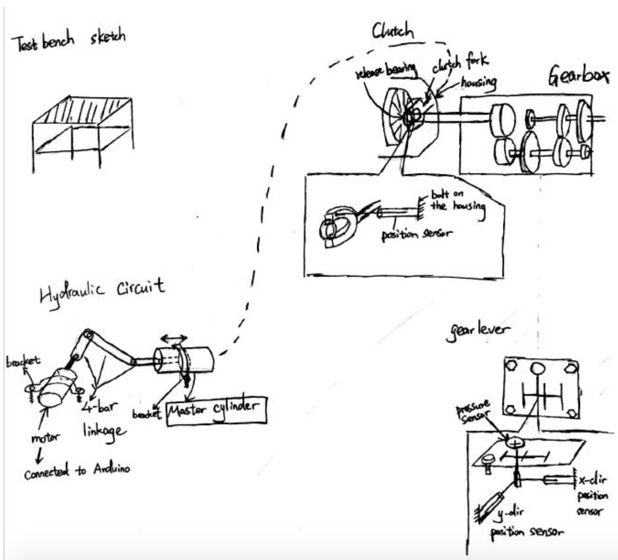


Figure 4.2 Detailed function structure (with stage decomposition)

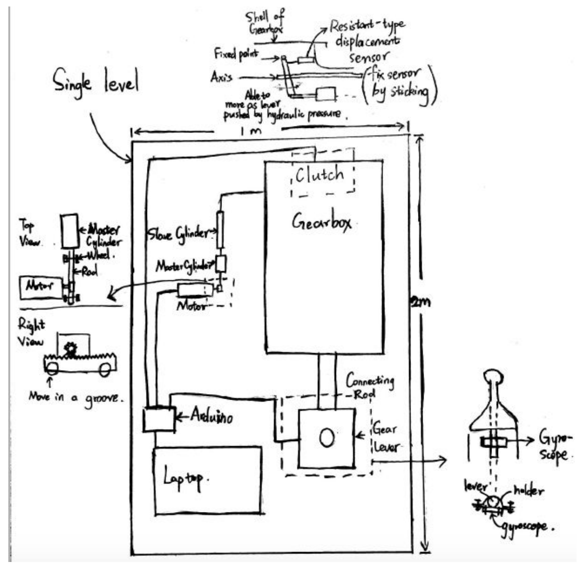
After the morphological analysis, these 4 sub-function mentioned in the overview can be confirmed, which are driving intention detection, controller & driving mechanism, performance measurement, and testbench. Then the brainstorming for concept design and concept selection are performed in the team to choose the best design for this project.

4.4 Brainstorming

Each team member generates the detailed design for the whole system, focusing on the sub-functions described before. The five unique designs are shown in the following figure. Notice that these concept diagram are hand scripts; the CAD model will be generated after the team determine the concept for each sub-function. The detailed description for each design will be included in the section 5.



(a)



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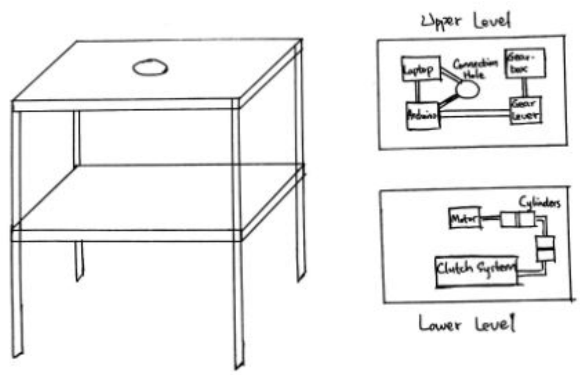
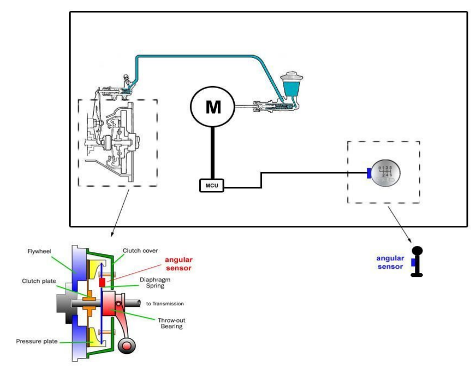


(c)



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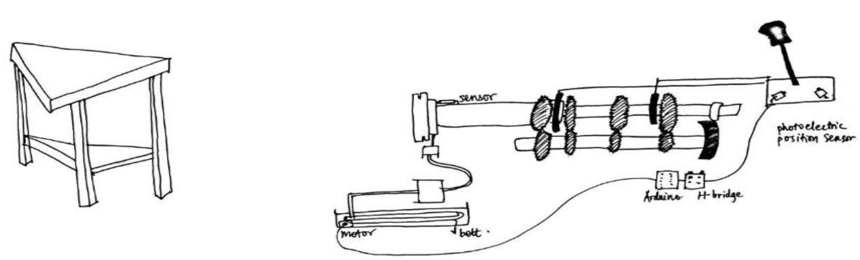


(e)

Figure 4.3 Five different initial designs for e-Clutch system

5. Concept Selection Process

5.1 Introduction of Weighted Scoring Matrices

In order to choose the best solution for each sub-function, every unique concept is compared with each other to choose the best one. The criteria used in the selection process is based on the customer requirements.

First, the customer requirements which are related to specific sub-function are chosen, then these requirements are the criteria to evaluate the design. In addition, these criteria are ordered in the category of property, manufacturing, and main usage. For different sub-functions, the weight percent for each category is different. For example, as shown in Figure 5.1, the selected customer requirements for the testbench are listed by their categories. These categories are assigned the weight percent first. Then, the requirements in the same category have their own weight percent. The final weight percent is the multiplication of the two weight percent.

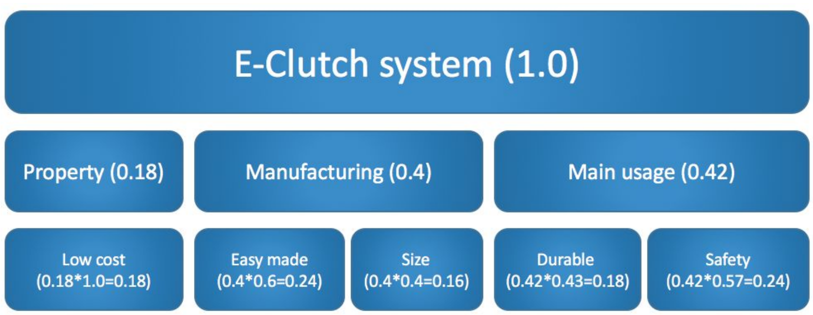


Figure 5.1 Direct assignment of weight percent for criteria

After the weight percent of each criteria is determined, the score of each design can be determined. For example, as shown in Figure 5.2, for each criteria, the design has its own score, the weighted score is the multiplication of the raw score and the weight percent. The total weighted score of one design is the sum of all criteria. Using this method, all the criteria and weight percent for each sub-function can be determined and the best design for each sub-function can be selected.

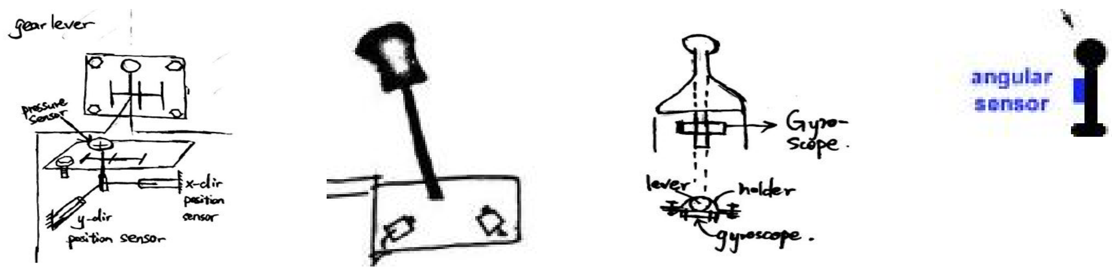
Criteria	Weight (%)	Rectangular Single level	Rectangular Double level	Triangular Double level
Durable testbench	18	7		
Ease of manufacturing	24			
Low cost	18			
Reasonable size	16			
Safety	24			
	Weighted Sum	126	0	0

18*7=126

Figure 5.2 Weighted value calculation method for each criteria

5.2 Selection of Sensor on Gear Lever

For sensor on the gear lever, the detailed design and the weighting matrix are shown in the following figure and table:



(a) (b) (c) (d)

Figure 5.3 Sensor assembled at the gear lever. (a) Resistance-type displacement sensor; (b) Photoelectric sensor; (c) Gyroscope; (d) Angular sensor

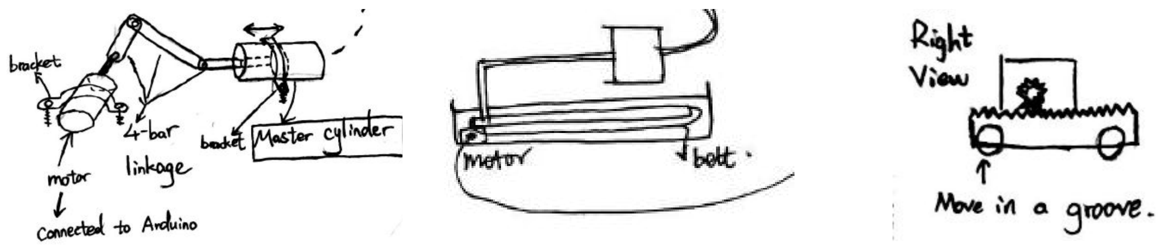
Table 5.1 Scoring matrix of different type of sensor at gear lever

Criteria	Weight (%)	Resistance-type Displancement Sensor	Photoelectric Sensor	Gyroscope	Angular Sensor
Durable	4.5	8	3	6	6
Fewer modification	12.5	2	5	8	8
Low cost	10.5	6	3	8	8
Reasonable size	12.5	7	8	8	8
Identify position of gear lever	42	6	8	5	6
Consistent performance	18	8	3	7	7
	Weighted Sum	**607.5**	**597.5**	**647**	**689**

The possible sensor that can be used at the gear lever are: resistance-type displacement sensor, photoelectric sensor, gyroscope, and angular sensor. All these sensors can detect the change of gear lever. The advantage of resistance-type displacement sensor is durable and having consistent performance. The disadvantage is that due to its size, there are several modification needs to accomplish before assemble the sensor to the gear lever. For photoelectric sensor, it is good for detecting the distance and the size is reasonable; however, it is relatively expensive. Gyroscope sensor is suitable to assemble on the gear lever, and the price is reasonable, but noticing that the sensor has some problem when detecting the instant position of gear lever due to its function. When comparing with angular sensor, the properties of the sensor meet nearly all the criteria for gear lever, especially for less modification, small size and lower price. It is easy to attach the sensor on the lever, and can detect the movement of the gear lever and tell the instant position. After evaluation each concept, the team decide that the angular sensor is the best solution to detect the change of gear lever.

5.3 Selection of Driving Mechanism

The next important sub-function is the mechanism to drive the hydraulic system to engage or disengage the clutch. Three unique designs are developed and compared as shown in the following figure:



(a) (b) (c)

Figure 5.4 Sensor assembled at the gear lever. (a) Four-bar linkage; (b) Rolling belt; (c) Gear transmission

Table 5.2 Scoring matrix of different type of driving mechanism

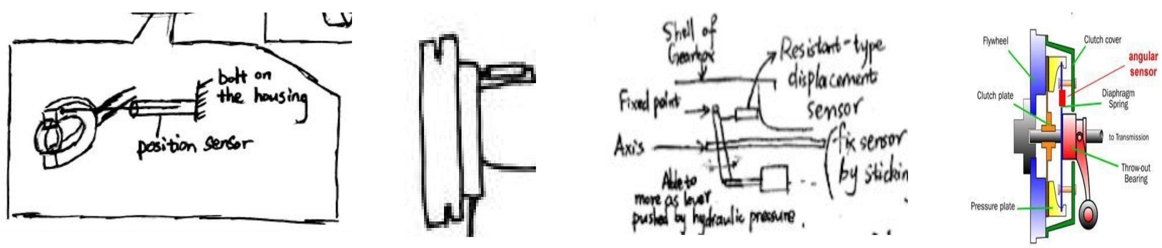
Criteria	Weight (%)	Four-bar linkage	Rolling Belt	Gear transmission
Durable	7.5	5	7	7
Ease of manufacturing	10.5	5	5	5
Fewer modification	10.5	8	5	8
Low cost	7.5	8	5	5
Reasonable size	10.5	8	4	6
Automatically control clutch	20	8	8	8
Consistent performance	20	6	8	8
Safety	10	8	8	8
	Weighted Sum	**678**	**637**	**689.5**

For the four-bar linkage design, the mechanism is made of aluminum bar and joints are connected using the screws and bearings. When the motor rotates, the mechanism turns the rotational movement to horizontal movement and push the master cylinder in order to engage the clutch. For the rolling belt design, the slot is made to constrain the direction of belt transport. The belt transforms the rotational movement from the motor to horizontal movement. The last design is the gear transformation. When the motor is on, the gear will rotate on the rack, and the rack will push the hydraulic cylinder to engage and disengage the clutch.

Compared among these three different designs, the weighting metrics is also shown in Table 5.2. The four-bar linkage design is suitable to control the clutch and the cost is low; however, it is not easy to manufacture and the performance may not be always consistent. The advantage of the rolling belt is that it has a good performance and it is safe to control. The disadvantage would be that the size may be relative large and it also needs a lot of modification. The gear transmission also need some modification, but it needs less machining process, and it can have a great performance when controlling the clutch. In addition, the performance is consistent and the size is reasonable. As a result, the gear transmission will be selected as mechanism to drive the cylinder to engage the clutch.

5.4 Selection of Sensor at Clutch

In addition, the sensor is needed to monitor the movement of release bearing of the clutch to examine the engagement of the clutch. Different types of the sensor are listed below, along with the weighting matrix:



(a) (b) (c) (d)

Figure 5.5 Sensor assembled at the gear lever. (a) Resistance-type displacement sensor; (b) Photoelectric sensor; (c) Gyroscope; (d) Angular sensor

Table 5.3 Scoring matrix of different type of sensor at gear lever

Criteria	Weight (%)	Resistance-type Displancement Sensor	Photoelectric Sensor	Gyroscope	Angular Sensor
Durable	4.5	8	3	6	6
Fewer modification	12.5	2	5	8	8
Low cost	10.5	6	3	8	8
Reasonable size	12.5	7	8	8	8
Monitor release bearing	42	8	7	7	8
Consistent performance	18	8	3	7	7
	Weighted Sum	**691.5**	**555.5**	**731**	**773**

From the table, we can conclude that the angular position sensor is selected as the sensor to monitor the movement of releasing bearing. There are still the same four possible sensors can be used at this position. For resistance-type displacement sensor, it is good at monitoring the performance and can last for a long time; however, a lot of modification is needed in order to assemble it on the release bearing, so it is not the top choice. The advantage of the photoelectric sensor is that it can monitor the movement well and the size is suitable; the disadvantage is that it is too expensive and the budget needs to take into consideration. The gyroscope sensor and the angular sensor are competitive when monitoring the movement of the releasing bearing, they are both not expensive, have reasonable size and need fewer modification. However, when comparing the ability to monitor the movement of releasing bearing, angular sensor is superior than the gyroscope sensor due to it can detect the information of the angle more quickly. It is important when monitoring the instant movement of the release bearing of the clutch.

5.5 Selection of Testbench

The last sub-function is the testbench design, it will provide the location for performance test and evaluation. The durability and safety should be emphasized. Three different designs are shown in the following figure, which are: rectangular single level; rectangular double level; and triangular double-level. The purpose of a double level testbench is that the controlling part can be organized underneath so that the size of the whole system would be smaller.

(a) (b) (c)

Figure 5.6 Sensor assembled at the gear lever. (a) Rectangular single level; (b) Rectangular double level(c) Triangular double level

Table 5.4 Scoring matrix of different type of driving mechanism

Criteria	Weight (%)	Rectangular Single level	Rectangular Double level	Triangular Double level
Durable testbench	18	7	7	7
Ease of manufacturing	24	8	6	3
Low cost	18	8	6	3
Reasonable size	16	5	8	8
Safety	24	8	5	5
	Weighted Sum	**734**	**626**	**500**

The weighting metrics are given below. Although the size of double level design is smaller, it would be much more difficult to manufacture and assemble. The size is not the top criteria need to consider in this sub-function. The manufacturing process for the triangular testbench would be also complicated and may cost a lot. After comparing each design based on the criteria, the rectangular single level testbench is selected to support the whole system.

5.6 Final Concept

To conclude this section, the best design for each sub-function is organized in the Figure 5.7, the angular position sensor will be used on both gear lever and release bearing; the gear transmission will be used as the mechanism to drive the hydraulic cylinder; a single-level rectangular testbench will be used to support the whole system.

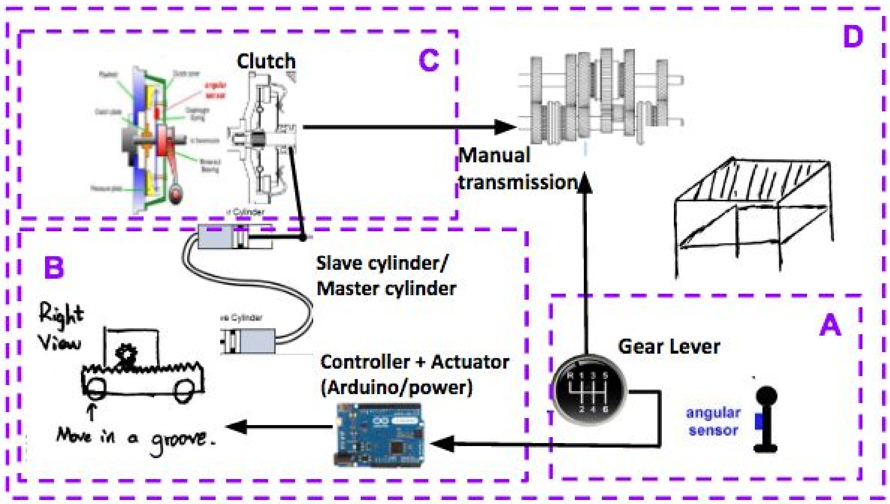


Figure 5.7 Final concept for the whole system with different sub-functions

6. Selected Concept Description

6.1 Overview

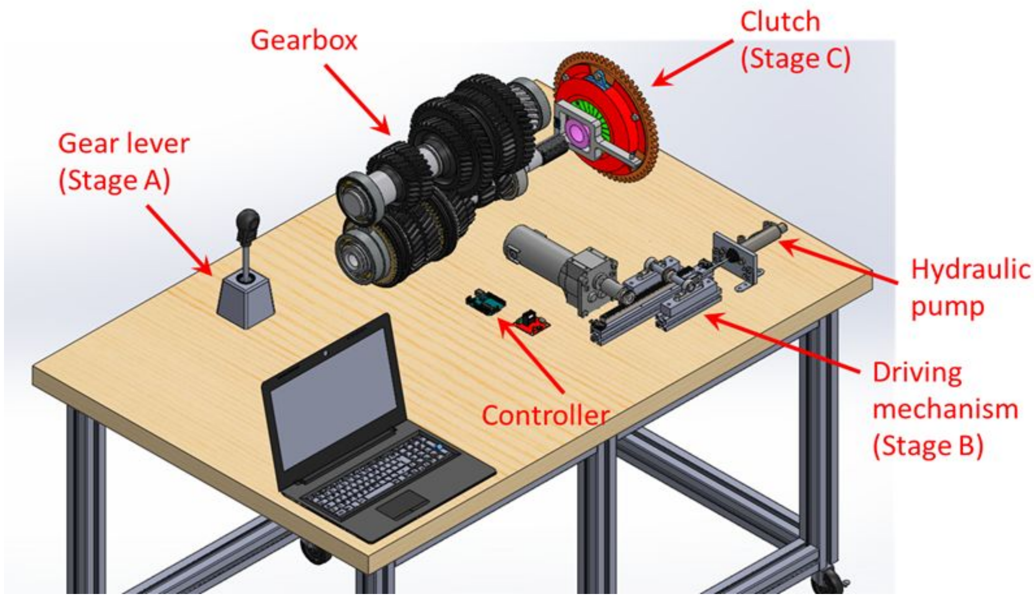


Figure 6.1 Overview of selected concept

As shown in Figure 6.1, a sensor will be attached to the gear lever, and the position information collected by the sensor will be sent to the controller and used to predict driver's intention. In a real driving scenario, the clutch has to disengage before the gear lever can be moved to change the gear ratio in the gearbox. In this way, after the data collected from the gear lever being processed in the controller, signals will be transmitted to the motor of the driving mechanism. The driving mechanism is an actuator that drives the hydraulic cylinder to engage and disengage the clutch. In order to guarantee a smooth gear changing, the driving mechanism must react quickly and accurately. The other sensor will be attached to the clutch fork. The sensor will measure the movement of the release bearing. Ultimately by comparing the data collected from two sensors, the functionality of the e-Clutch system can be proved. The countertop and structure of the testbench provides space to install all sub-systems and support of all the loads.

6.2 Engineering Design Analysis

6.2.1 Specification Analysis and Engineering Fundamental Discussion

The engineering analysis is performed before actually build the prototype. The parameter and the flowchart need to analyze is based on the engineering specification. As long as the target value is determined, the calculation should be performed in advance to test whether these goals are possible to achieve. For example, in this project, the prototype should satisfies several parameters, including: lifespan greater than 2 year; minimum load larger than 50 Kg; the response time should be limited within 0.5 seconds; and the precision and the range of the sensor are specified. The following analysis are the theoretical calculation or discussion on whether these parameters can be achieved.

6.2.2 Material Selection

Material selection is one of the major issue to consider. For this project, there are several parts need to design the structure and select the proper material. The following table includes material properties and mechanical properties for different material.

Table 6.1 Material and mechanical properties of potential material [11,12]

Material	**Elastic Modulus** (GPa)	**Yield Stress** (MPa)	**Ultimate Stress** (MPa)
Aluminum Alloy	70-79	35-500	100-550
Steel	190-210	380-1600	340-1900
Wood	11-12	40-60	50-100
Acrylic	3.2	95	70

Material selection was both dependent on the financial constraints of the project and on the required material properties for a safe design. For the prototype, aluminum alloy is chosen for the structure of the testbench. There are several reasons, including: aluminum alloy is easily accessible in Chinese market, and it is easy to manufacture to meet the size requirement of the system. The price of the aluminum alloys can range between 20-120 RMB per kilogram, giving a lot of freedom when choosing which price meets the needs. Aluminum alloy has extraordinary material and mechanical properties, it is quite strong with an ultimate stress up to 550 MPa; the average elastic modulus and yield stress give its flexibility. Aluminum alloy is also corrosion resistance, important when the system is exposed to water and can last for a longer lifetime. Compared with the acrylic board, the advantage of aluminum alloy is that it has a larger elastic modulus, so it is not that easy to bend, which is important when use this material for driving system and supporting system. In addition, the ultimate stress of aluminum alloy is much stronger than acrylic, so it is much stronger and preferred to use in many sub-system in this project.

Wood is selected for the testbench countertop. Wood has an average elastic properties and ultimate stress. The reason the team choose wood as the testbench countertop is its low density. Hence, the modulus can be compensated by the total thickness of the wood sheet, which still owns the low weight but can stand even greater force.

Steel gear and rack are chosen instead of plastic ones. From the table, steel has very outstanding elastic modulus and ultimate stress. The gear is used to transmit the torque from motor to the hydraulic cylinder, hence the deformation of the gear should be avoided. In addition, the torque from the motor is large, so the gear should withstand the force and last for a long time before breaking. This requires strong material such as steel.

6.2.3 Motor Power Analysis

As part of the customer requirements and engineering specification, the response time is also very critical and need to take into consideration. The goal of response time is less than 0.5s, and the stroke of the piston of the hydraulic cylinder is 3 cm. Estimate the whole procedure under constant speed, the linear velocity of 0.06 m/s is required. The pitch diameter of the gear is 30mm, which can convert the linear speed to the angular speed. Hence, the angular speed for the motor should be 4 rad/s. The power analysis is used to determine the whether this speed can be achieved under the constraint of the motor condition and power supply.

For the torque analysis, generally the force needed to disengage the clutch is around 250 to 370 lbf [13]. Therefore, the maximum force of 370 lbf is assumed to be the force needed on the release bearing, which is 1645 N. In addition, since the maximum displacement of the master cylinder is 3 mm, and the maximum displacement for the releasing bearing on the clutch is 1.5 mm, the ratio of force on the clutch to force need for pushing master cylinder should be 3:1.5, which is 2:1. Therefore, the force needed to push the master cylinder is 1645 N ÷ 2 = 823 N. Also, with the arm of force, which is 15 mm, the torque needed is 823 N × 15 mm = 12.3 N*m.

The motor chosen is 12V with maximum power of 120 W, which is a typical motor for driving the hydraulic system. From the torque analysis in the previous part, the minimum torque would be 12.3 N*m. Considering the fact that the torque provided by the motor should be larger than minimum torque, and the speed should be larger than 4 rad/s; the torque is chosen to be 14.5 N*m, which corresponding the 60 RPM output angular speed. After converting RPM to rad/s, the estimated speed would be 6.28 rad/s. Comparing with the target speed 3.75 rad/s, it is nearly double the value. It comes to the conclusion that the response time can be achieved within 0.5 second, and there will be no drag during driving operation.

The maximum power under the constant angular speed model can be calculated as following:

$$P_{max} = T_m \cdot \omega_{max} = 9N * m \cdot 6.28\ rad/s = 56.52W$$

Notice that the maximum power is much less than the power motor can provide, hence there will be no problem for motor to provide enough power during the whole driving procedure.

6.2.4 Failure Analysis

Testbench design

In order to determine the suitable thickness of the countertop and the size of the aluminum extrusion forming the supporting stands of the testbench, failure analysis is applied here. The goal is to determine the size of the testbench countertop; the thickness of the countertop; the the size of the aluminum extrusion. After obtaining these values, and combine with the safety factor and other aging factor designed for this project, these parameter can be determined.

Size of the testbench. Considering the size of the manual transmission gearbox, and the controlling system should be organized on the same level of the testbench, the size are designed to be 100*150 cm to leave enough space to conduct the demonstration and experiments.

Thickness of the testbench countertop. In order to provide a durable testbench, the thickness of the countertop should be considered.

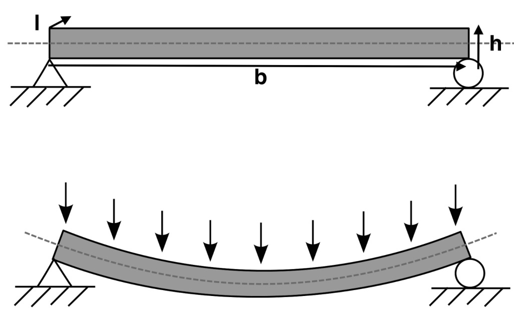


Figure 6.2 Flexural strength model: uniformly distributed stress, both ends fixed.

As shown in the Figure 6.2, the h=thickness; b=length; l=width. The expression to calculate the stress is:

$$\sigma = \frac{(FL)\cdot\frac{h}{2}}{I} \qquad I = \frac{bh^3}{12}$$

From the structure design, b = 0.6 m, L = 1 m piece of wood is used to build the testbench countertop. The total force applied on the countertop along with its own weight is estimated to be 1000 N and the common failure stress of wood is 40 MPa. The analysis focus one-half of the whole countertop, hence the force would be 500 N. The expression give us a theoretical minimum thickness = 0.01 m, which means that any value larger than 1 cm will theoretically not cause the failure of the countertop. However, considering the safety factor and different wood properties, thickness of 5 cm is selected, this would be sufficient to resist the force applied on the testbench countertop.

Supporting stands reinforcement. The rectangular structure design of the supporting stands is strong to support whole countertop and the system, however, reinforcement for the stands are needed to make the structure more stable and durable. From literature research, experimental results and continuous analytical investigation have been done to prove that the strength and deformation of biaxially loaded short and tied columns with L-shaped cross section are much better than the single I-shape structure [14]. Hence, in the testbench design, additional extrusions along length and width of the testbench are used to form L-shape reinforcements.

<u>Roller selection</u>

The failure analysis also is conducted on the roller for the testbench. The possible stress failure happens at the shaft of the roller, and the stress distribution on one roller shaft is shown in the following figure:

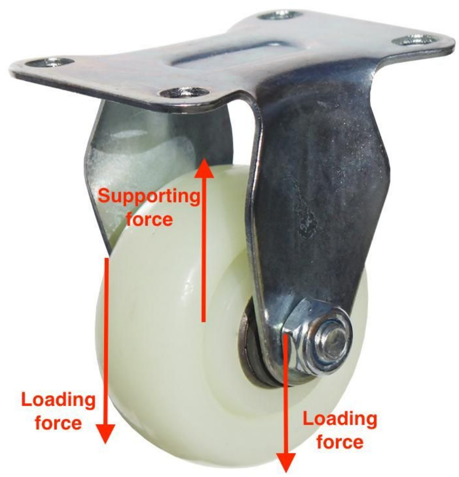


Figure 6.3 Schematic representation of force analysis for the shaft of roller

In order to simplify the model, the failure analysis use the three point bending test model, the stress distribution is shown below:

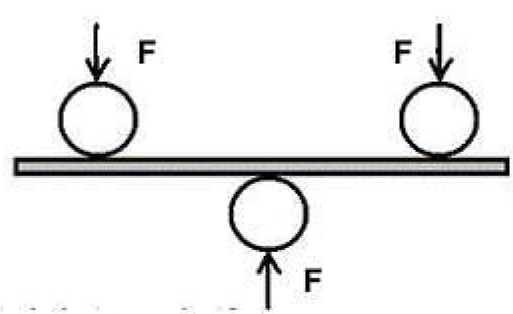


Figure 6.4 Three-point bending model

Notice that in bending test, the equation for circular cross section is

$$\sigma_f = \frac{FL}{\pi R^3}$$

Where F is the loading force, L is the length, R is the radius of the load. SInce there are six roller assembled beneath the testbench, the loading force would be one-sixth of the total weight, which is around 1000/6=155N. L for the roller is 0.08 m and the radius R is 0.01 m. The rod is made of the steel. From the equation, the flexural stress is about 3.95 MPa. From the material property table, the fracture stress for steel is 841 MPa, which is much larger than the stress applied on the rod. Considering the safety factor and possible error during the estimation, there will be still safe and durable to use these six roller to support the whole testbench structure.

6.2.5 Sensor Resolution

The outputs of the accelerometers are three relative voltage values proportional to the accelerations in xyz axes. The ratio is measured to be 160 mV/g. The resolution of the output voltage is 1mV. We need to calculate the resolution in terms of angles (°).

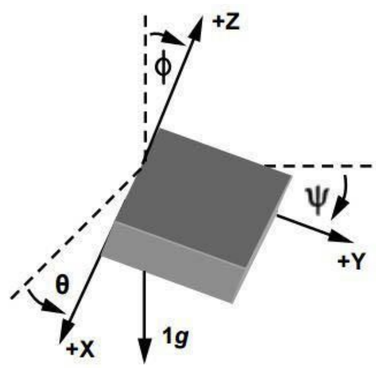


Figure 6.5 Calculation of resolution [15]

As the figure shown, angles θ and φ are needed to decide the position of the gear lever. The formula of θ and φ in terms of the three-axis accelerations A_x , A_y and A_z are

$$\theta = tan^{-1} \frac{A_x}{\sqrt{A_y^2+A_z^2}}$$

$$\varphi = tan^{-1} \frac{A_y}{\sqrt{A_x^2+A_z^2}}$$

The resolution in terms of angles (°) is

$$resolution = max \left\{\frac{d\theta}{dV}\cdot 1,\ \frac{d\varphi}{dV}\cdot 1\right\} = max\left\{\frac{d\theta}{dA_x}\cdot\frac{dA_x}{dV}, \frac{d\theta}{dA_y}\cdot\frac{dA_y}{dV}, \frac{d\theta}{dA_z}\cdot\frac{dA_z}{dV}, \frac{d\varphi}{dA_x}\cdot\frac{dA_x}{dV}, \frac{d\varphi}{dA_y}\cdot\frac{dA_y}{dV}, \frac{d\varphi}{dA_z}\cdot\frac{dA_z}{dV}\right\}$$

Since x and y axis are symmetric, we only need to calculate

$$resolution = max\left\{\frac{d\theta}{dA_x}\cdot\frac{dA_x}{dV}, \frac{d\theta}{dA_y}\cdot\frac{dA_y}{dV}, \frac{d\theta}{dA_z}\cdot\frac{dA_z}{dV}\right\}$$

In our case, the range of accelerations are

$$A_x, A_y \in [0, \tfrac{\sqrt{2}}{2}g]$$

$$A_z \in [\tfrac{\sqrt{2}}{2}g, g]$$

Case 1:

$$\frac{d\theta}{dA_x} \cdot \frac{dA_x}{dV} = \frac{1}{\sqrt{A_y{}^2 + A_z{}^2 + \frac{A_x{}^2}{\sqrt{A_y{}^2 + A_z{}^2}}}} \cdot \frac{g}{160} \cdot \frac{180}{\pi}$$

When $A_x = 0, A_y = 0, A_z = \frac{\sqrt{2}}{2}g$, it takes maximum of 0.50.

Case 2:

$$\frac{d\theta}{dA_y} \cdot \frac{dA_y}{dV} = \frac{A_x A_y}{(A_y{}^2 + A_z{}^2 + A_x{}^2)\sqrt{A_y{}^2 + A_z{}^2}} \cdot \frac{g}{160} \cdot \frac{180}{\pi}$$

When $A_x = \frac{\sqrt{2}}{2}g, A_y = 6.25, A_z = \frac{\sqrt{2}}{2}g$, it takes maximum of 0.12.

Case 3:

$$\frac{d\theta}{dA_z} \cdot \frac{dA_z}{dV} = \frac{A_x A_z}{(A_y{}^2 + A_z{}^2 + A_x{}^2)\sqrt{A_y{}^2 + A_z{}^2}} \cdot \frac{g}{160} \cdot \frac{180}{\pi}$$

When $A_x = \frac{\sqrt{2}}{2}g, \ , A_y = 0, A_z = \frac{\sqrt{2}}{2}g$, it takes maximum of 0.25.

Hence

$$resolution = 0.5°$$

The resolution satisfied our engineering specifications. Thus, the accelerometer can fit our needs well.

6.2.6 Safety Consideration

Switches are used to change operation status. Limit switch is used to tell that the hydraulic cylinder has been pushed to one end and need to change the moving direction; toggle switch is used to turn on or turn off the motor.

Limit Switch

The limit switch is a digital sensor that sends either a 0 or 1 to the Arduino depending on whether the switch is open or closed. The limitation of the limit switch is that it can only sense whether the switch is open or closed. It cannot tell how close the object is before contact or how fast the object is approaching. There is no noise in the readings for the limit switch, the switch is either opened or closed. The sensitivity of the sensor is limited by how long the the lever on the switch is. The longer the lever, the more sensitive it is.

Toggle Switch

The toggle switch is a two-terminal ON/OFF switch. It is used to control the whole circuit, when the toggle switch pole to ON position, the circuit will be connected. In this project, the toggle switch is used to turn on or turn off the power supply of the motor.

6.3 Design Description

6.3.1 Gear Lever

As shown in the section view in Figure 6.x, according to the concept selection procedure, the sensor is chosen to be a 3-axes accelerometer. The data collected by the accelerometer, after some manipulation, can tell the angular position of the gear lever. Using angular position and the change of the angular position, the controller can determine the current gear and predict the driver's intention. For aesthetic reasons, the accelerometer is temporarily determined to be attached in the middle section of the rod underneath the cover. Due to the limited space within the cover, the accelerometer is barely fitted in without interfering with the wall of the cover. However, the location to attach the sensor is not fixed, Figure 6.6 only shows one possible location to attach the accelerometer. According to the available space in different types of cars and the size of different types of 3-axes accelerometer, the sensor can also be attached to the mechanism that mechanically connect the gear lever and the gearbox.

Figure 6.6 3D model of the gear lever and the sensor

6.3.2 Driving Mechanism

A detailed 3D model of the driving mechanism is shown in Figure 6.7. The motor is controlled by the signals from the controller. The shaft of the motor is coupled with another shaft and a gear with module 1, 30mm pitch diameter, and 15mm bore diameter. A rack with same module matches with the gear, and it will convert rotational motion into linear motion to push the master cylinder. The piston of the master cylinder has a stroke around 3cm. In order to limit the range of motion of the rack, two limit switches are installed at both ends. As a results, the motor will not over extend or compress the piston, which could possibly damage the shaft, gear, rack, and the supporting structure of the master cylinder. The other gear and shaft supported by two mounted bearings is designed to constrain the possible upward motion of the rack. Finally, to reduce the friction between the rack and base countertop, a series of 2mm-thick rollers are placed in between.

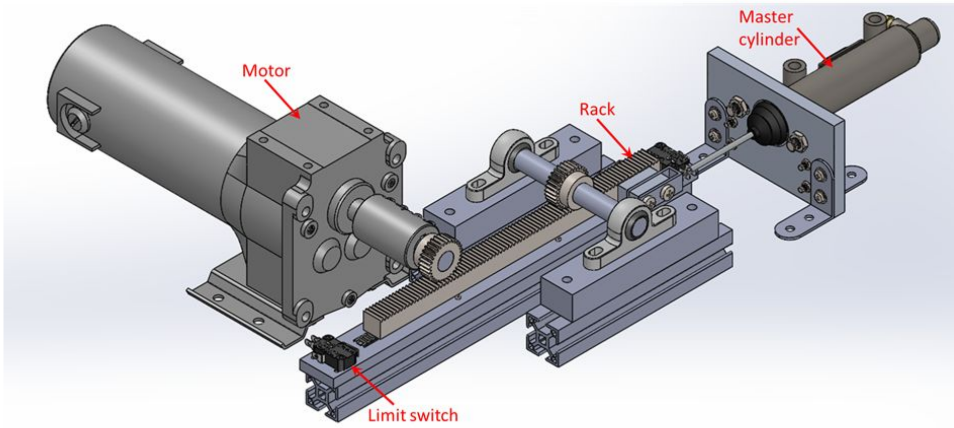


Figure 6.7 3D model of the driving mechanism

6.3.3 Clutch

The clutch fork shown in Figure 6.8 is driven by the slave cylinder in the hydraulic system. A 3-axes accelerometer is attached to the end of the clutch fork. The accelerometer can function as a angular position sensor, and from the angular position of the clutch fork the displacement of the release bearing can be monitored. By comparing the time between the detection of the driver’s intention of changing gear and the finish of the forward movement of the release bearing, the functionality of the e-clutch can be demonstrated.

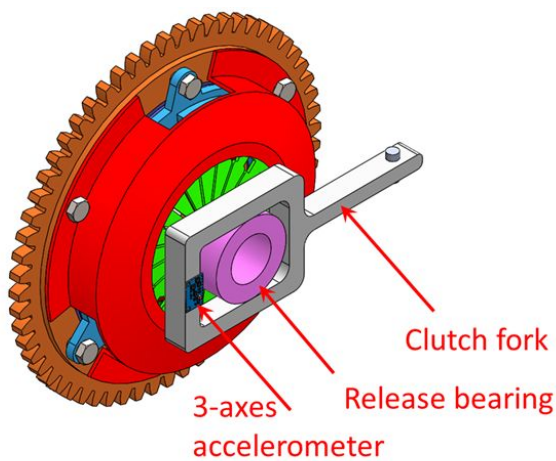


Figure 6.8 3D model of the clutch and the sensor

6.3.4 Testbench

The testbench will provide space to install other sub-systems and support the loads. The countertop is made of a wood plate with length of 1.5m and width of 1m. The aluminum extrusions have cross sectional area of 6cm* 6cm. Six legs are 70cm long, and wheels are installed at the end of each legs. Five extrusions supporting the width are 60cm long. Eight extrusions supporting the length are 80cm long

Figure 6.9 3D model of the testbench (appearance of the wood countertop set to be transparent)

7. Manufacturing Plan

7.1 Mechanical Machining

The main part need to machine is for the driving mechanism. Noticing that the tolerance for thickness of the spacer are all important, should be within 0.1 mm; and the tolerance for relative distance of the drilling hole are also important and should be within 0.1 mm. However, the tolerance for the width and length of the spacers are not important.

7.1.1 Spacer for Bearing

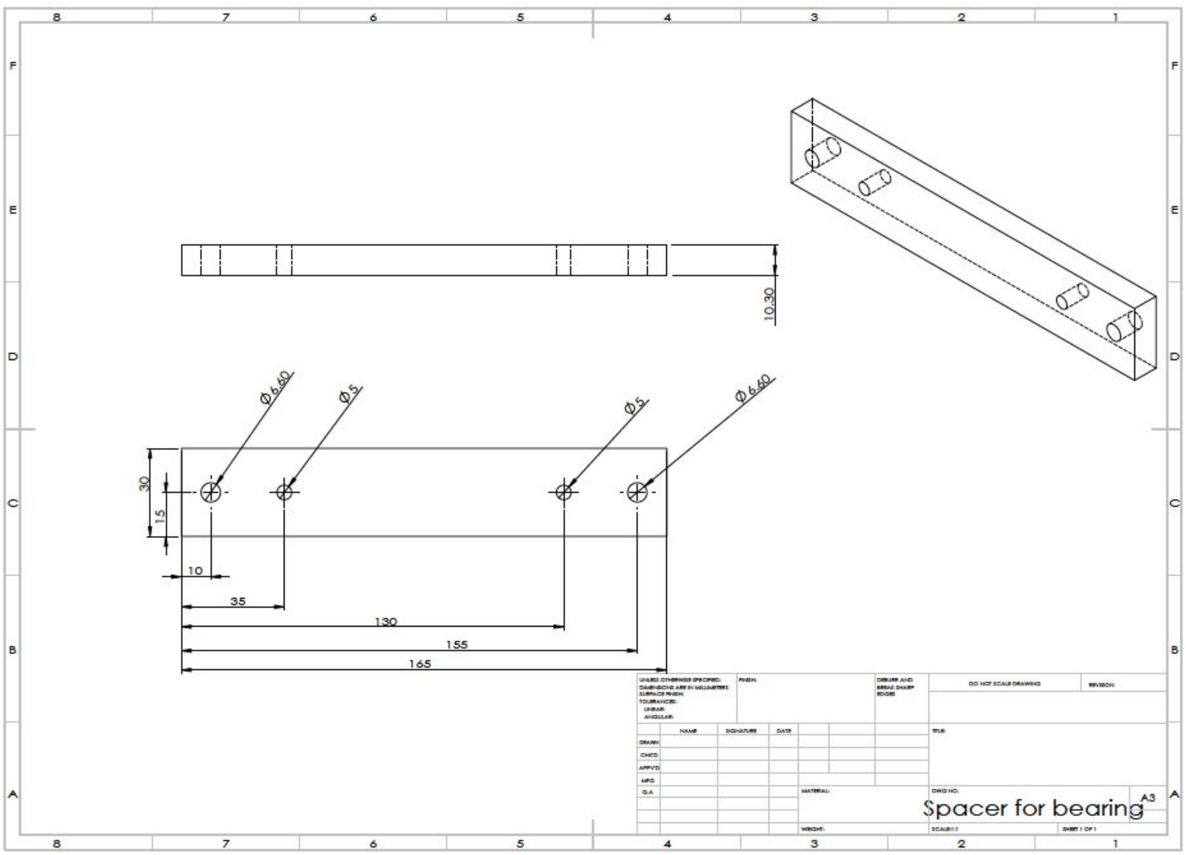


Figure 7.1 Engineering drawing: spacer for bearing

Manufacturing Plan

Part Number: VM450-001
Part Name: Spacer for bearing
Team Name: Team 8
Date: 2016/7/10

Stock:10mm aluminum plate

Step #	Process Description	Machine	Fixtures	Tools	Speed (RPM)
1	Find datum lines for X and Y	mill	vise	edge finder, drill chuck	900
2	Mill to desired thickness	mill	vise		
3	Center drill and drill hole 1	mill	vise	drill chuck, 6.5mm drill, center drill	1000
4	ream hole 1	mill	vise	drill chuck, 6.6mm reamer	100
5	center drill and drill hole 2	mill	vise	drill chuck, 5mm drill, center drill	1000
6	ream hole 2	mill	vise	drill chuck, 5mm reamer	100
7	break all burrs by hand			file	

7.1.2 Spacer for Hydraulic Cylinder Pushing

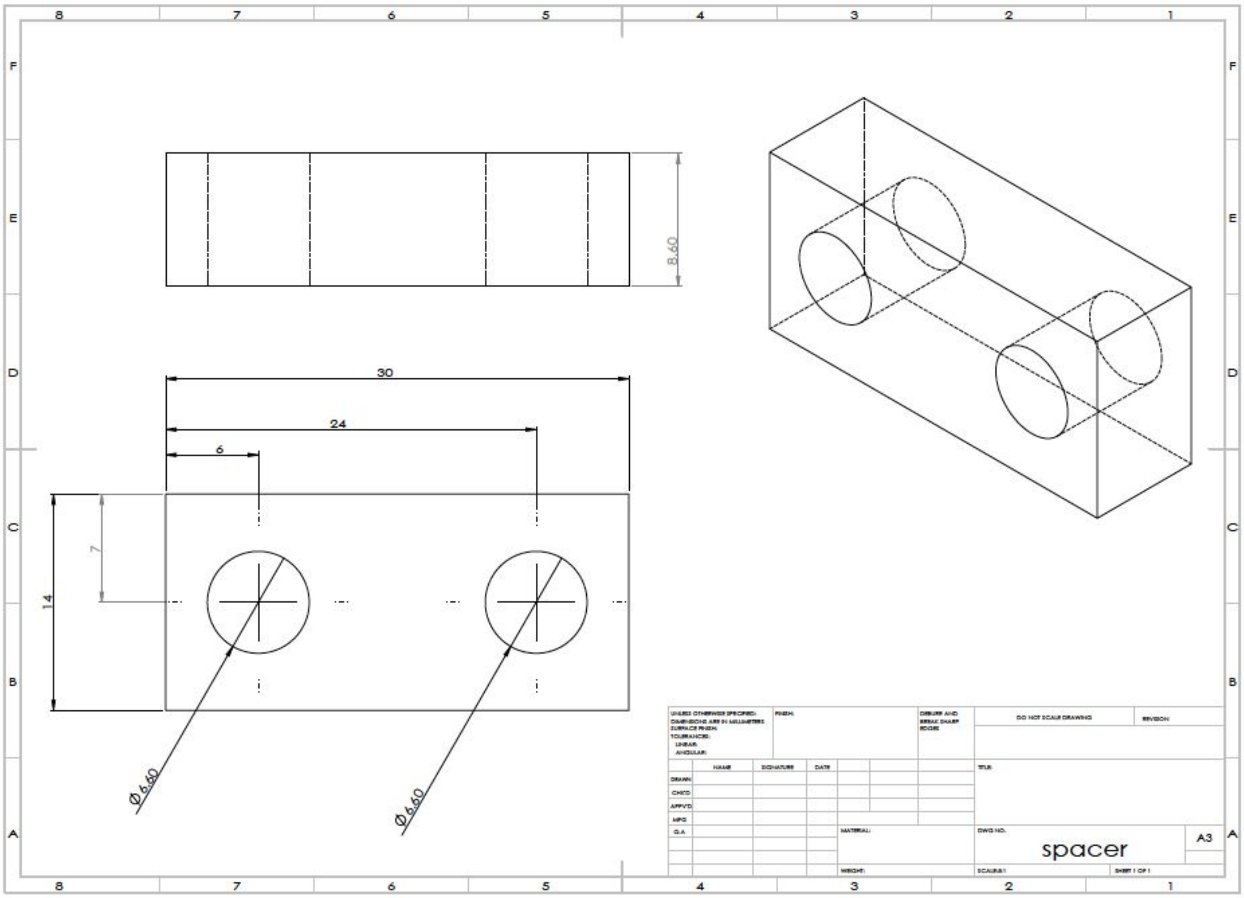


Figure 7.2 Engineering drawing: spacer for hydraulic pushing

Manufacturing Plan

Part Number: VM450-002
Part Name: Spacer for hydraulic cylinder pushing
Team Name: Team 8
Date: 2016/7/10

Stock:10mm aluminum plate

Step #	Process Description	Machine	Fixtures	Tools	Speed (RPM)
1	Find datum lines for X and Y	mill	vise	edge finder, drill chuck	900
2	Mill to desired thickness (8.6mm)	mill	vise		
3	Center drill and drill hole 1	mill	vise	drill chuck, 6.5mm drill, center drill	1000
4	ream hole 1	mill	vise	drill chuck, 6.6mm reamer	100
5	break all burrs by hand			file	

7.1.3 Spacer for Rack

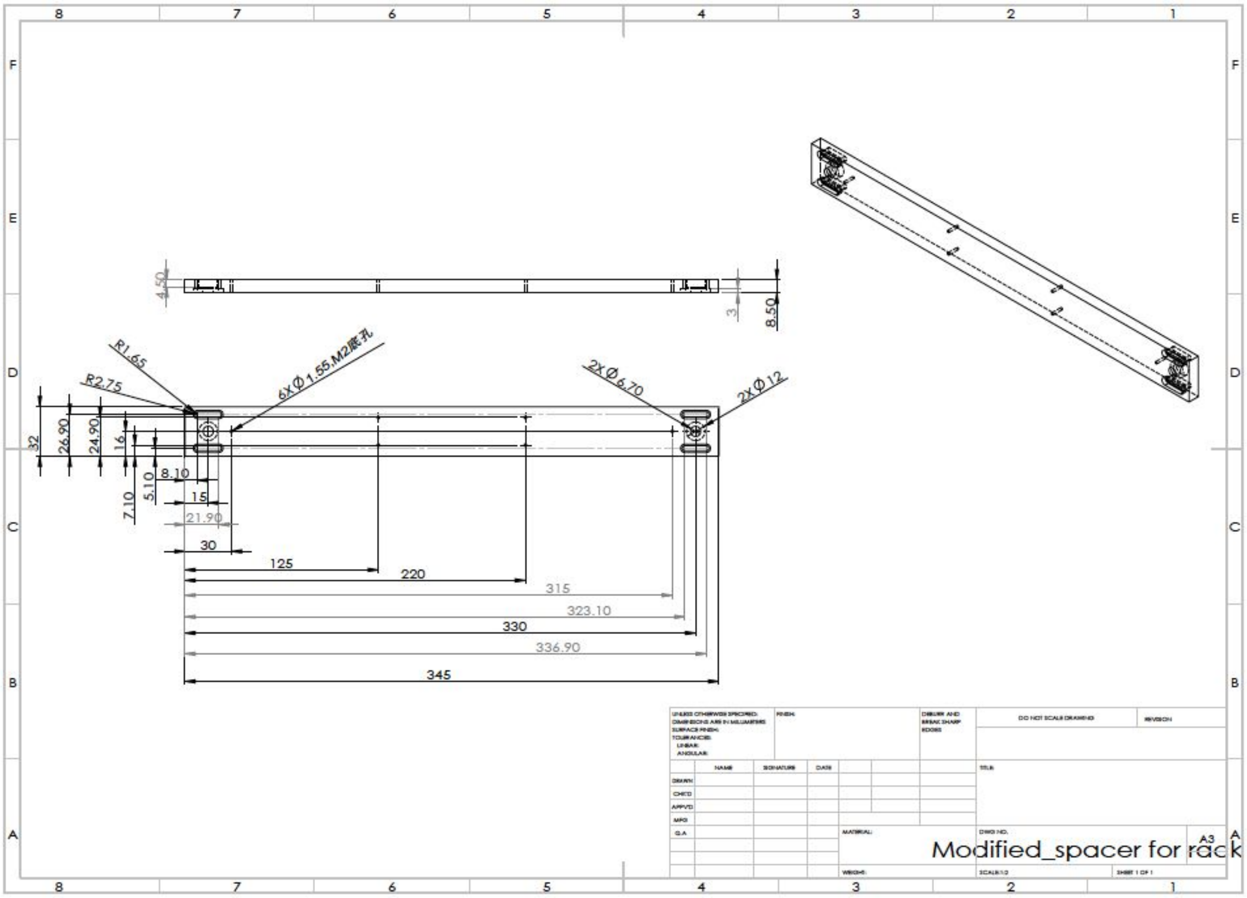


Figure 7.3 Engineering drawing: spacer for rack

Manufacturing Plan

Part Number: VM450-003
Part Name: Spacer for rack
Team Name: Team 8
Date: 2016/7/10

Stock: Polymer powder

Step #	Process Description	Machine	Fixtures	Tools	Speed (RPM)
1	3D printing	3D printer			
2	break all burrs by hand			file	

7.1.4 Support for Master Hydraulic Cylinder

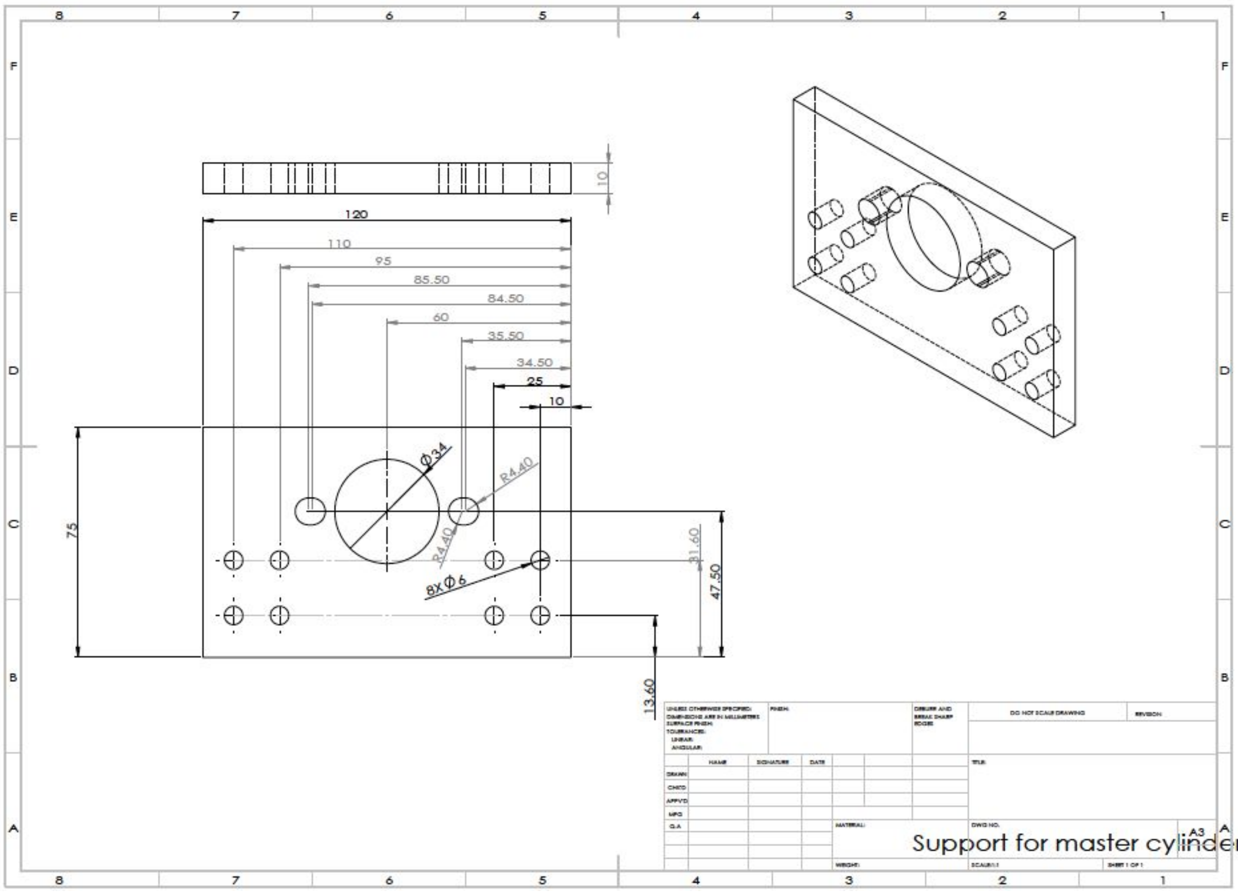


Figure 7.4 Engineering drawing: support for master cylinder

Manufacturing Plan

Part Number: VM450-004
Part Name: Supporting for master hydraulic cylinder
Team Name: Team 8
Date: 2016/7/10

Stock:10mm aluminum plate

Step #	Process Description	Machine	Fixtures	Tools	Speed (RPM)
1	Find datum lines for X and Y	mill	vise	edge finder, drill chuck	900
2	Mill hole 1	mill	vise	Digit controlled mill machine to diameter 35mm	1000
3	Center drill and drill hole 2	mill	vise	drill chuck, 6.mm drill, center drill	1000
4	break all burrs by hand			file	

7.2 Flow Charts of Programing and Simulation

7.2.1 Gear Level Detection

The following flowchart illustrates our control logic.

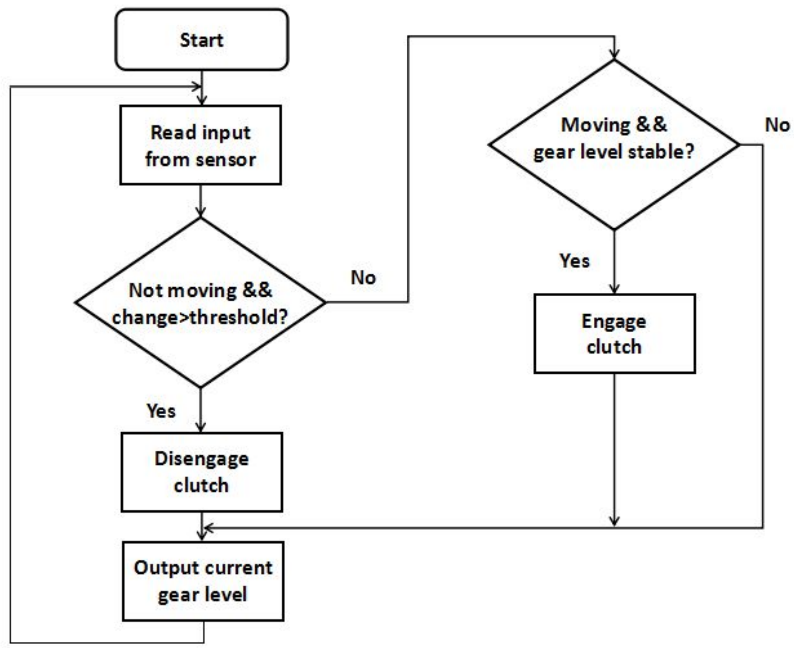


Figure 7.5 Programming logic of control system

To detect the gear lever, a 3-axes accelerometer is attached to the gear lever. The outputs of the accelerometer are three relative voltage values, which are proportional to the accelerations in x,y,z-axes. In different gear positions, the output voltage values are different. Therefore, before the test begins, a reference voltage value group is set for gear 1, 2, 3, 4, 5, R and N. During the test, if the current three relative voltage values are within a certain range of a reference voltage value group for a certain gear X (X is 1, 2, 3, 4, 5, R or N), the current gear X can be determined.

Once the test begins, the Arduino board will read the 3 voltage values from the accelerometer. Based on the changing rate of the voltage values, it can be determined whether the gear lever is moving right now. If the gear lever was in stationary (not moving) in previous loop and the change of voltage values is beyond a certain preset threshold, it can be determined that the driver wants to change the gear. Then the Arduino program will output corresponding signals to control the motor to disengage the clutch. Otherwise, if the gear lever is not moving and stable for a certain period of time, it can be determined that the driver’s behavior of changing gear is finished. Then the Arduino program will output corresponding signals to control the motor to engage the clutch. Otherwise, if the gear lever is not moving, it can determined that the driver does not want to change gear right now. After all these steps, the accelerometer will output the updated gear. The Arduino board will then read the 3 voltage values and repeat the process loop again.

7.2.2 Clutch Position Detection

In order to test the clutch position, an accelerometer is used as well, which is installed on the clutch fork. At different positions, the accelerations in x, y, z-axis are different, which will result in the different voltage value outputs of the accelerometer. Based on these relative voltage values, it can be determined the current position.

The engagement percentage is used to represent the standardized clutch position. If the engagement percentage is 100%, it means the clutch is totally engaged. If the engagement percentage is 0%, the clutch is totally disengaged.

7.2.3 Graphical User Interface

In order to monitor the current gear and clutch position, a Graphical User Interface (GUI) is used, which is shown in the following figure.

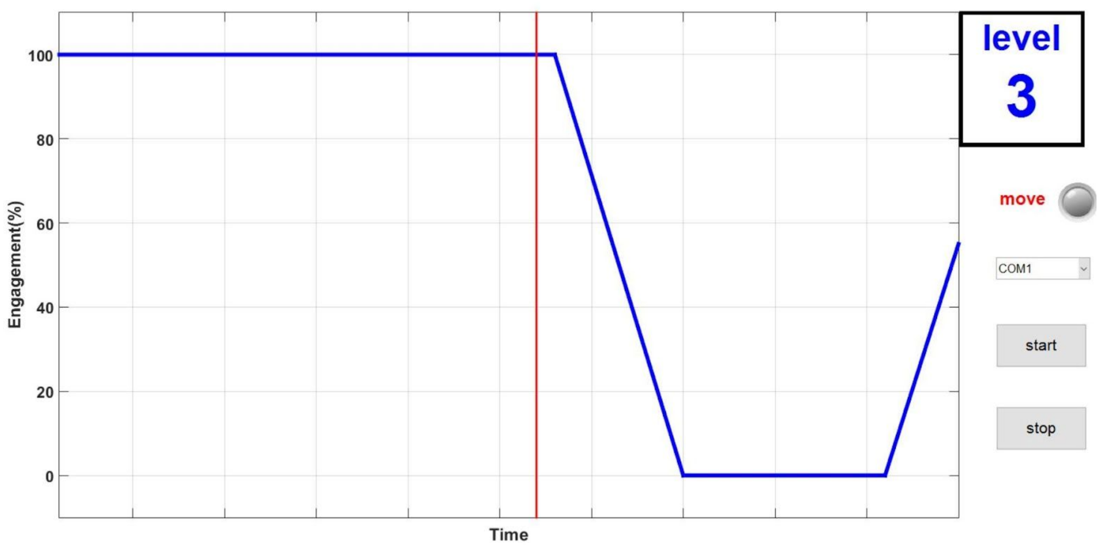


Figure 7.6 Graphical user interface

Click the “start” and “stop” buttons to start and stop the measurements. Select the computer port on this interface. The main plot shows the current engagement percentage of the clutch versus the actual time. The top right corner shows the current gear. The red light will be turned on if the gear lever is moving.

7.3 Assembly Plan

In subsystem A and C, sensors can easily be attached to desired places using tape and glue. Sub-system B are simply the aluminum extrusions reinforced by angle brackets at the connections and countertop fastened by bolts on top of the frame of extrusions. Subsystems A, B, and C are fastened on the testbench by bolts and nuts at proper positions. The positions depend on the actual dimensions of the gear lever, clutch, and hydraulic system since different types have different sizes. Therefore, only the exploded view of subsystem B is shown in this section (Figure 7.7) in order to give a closer view of the layout of different parts. Motor, bolts, and nuts are hidden in the exploded view for clearness. Spacers are designed to have proper thickness to ensure the pitch of the gear and rack at the same height.

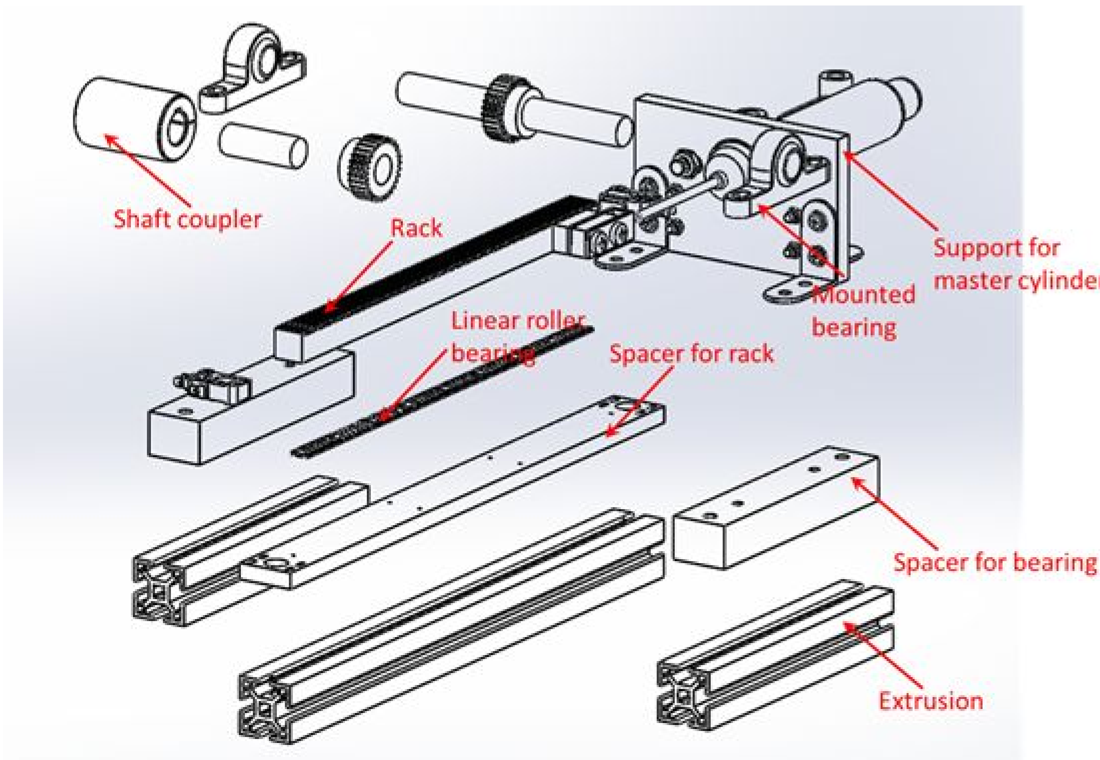


Figure 7.7 Exploded view of the driving mechanism

8. Validation Plan

8.1 Validation Plan and Experiment Description

8.1.1 Motor Power Analysis

i) Power and RPM relationship
ii) Power and torque relationship
iii) Torque and RPM relationship

The relationship between the torque and RPM should be emphasized because the motor should provide enough force to drive the hydraulic cylinder and the time to push the cylinder should be limited. Since the torque is negatively related to the RPM, the final relationship should be figured out in order to make sure the motor can provide proper force and time to fulfill the function.

The theoretical power output is the product of torque and angular speed. After the team determine the force and the speed that needed to drive the hydraulic system, the power output can be calculated. Compared with the theoretical nominal power the motor can provide, the validation of motor function can be proved.

Validation Approaches
Literature research online and find useful information about how much force needed to engage the clutch. After determine the torque needed to engage the clutch, use the motor to test whether the value is correct. From the specification of the motor, choose the suitable torque and the speed. After conduct several tests, conclude whether the selected torque value is reasonable or not.

8.1.2 Failure Load Analysis

i) Structure rigidity test and parameter includes:
Joints of testbench supporting stands; bolts; shear stress, axial loading at different position.

The failure analysis is one of the most important part during the structure design. As mentioned before in the design review, the safety factor was decided to be 2 to 5. As the result, the validation of the failure load would be important.

By completing the above analysis, proper reinforcement will be designed to improve the mechanical performance of each part and joints. For example, the bolts and nuts connection may fracture when experiencing large shear load. Different methods, including, but not limiting to, waterproof glue, bolts, and angle brackets, can distribute the stress and load. Therefore, a high safety factor can be achieved to ensure each component, along with the whole assembled structure, will not break during the test.

Validation Approaches

The structure rigidity parameter includes: ultimate tensile strength, ultimate shear load, torsion load and bending load.

1. In the Innovation lab, the MTS Insight 10 Mechanical Tester (1 and 10kN) with TestWorks will be used to measure the maximum tensile load and shear load that the joints can withstand without causing any failure. Measure the proper size of two components and use the same joint methods to connect these two. Load the experimental object in the machine and start the process. Record this strength and compared with the theoretical maximum load that it can withstand. This method to test the ultimate tensile strength can be also used at the supporting stands of the testbench. Scale down the size very carefully so that the objects will fits the machine. Record these strengths to check whether the actual strength of our material is the same as the theoretical value, which is used in the engineering calculation.

2. The MTS servo hydraulic compression torsion mechanical test frame (100K lbf. and 50k in. lb torque) can be used for testing structural panels under combined compression shear loads. Cut the blade in the proper size and load the blade on the machine. Start the experiment and record the data. This machine can be also used to examine the connection between axle; axle of the testbench roller; and the gears in the mechanism. Load both sides to two ends of the machine and start the test. Record and compare the actual failure torsion with the material properties and engineering calculation results. If the torsion between the connection is much less than the required, the connection is then safe and can withstand a long period of time.

8.1.3 Mean Cycles to Failure Analysis

The design life cycle cannot be accurately determined at this moment, as significantly large amount of time and cost are required to conclude the accurate mean cycles to failure analysis. To rough estimate the number, two options are available:

i) Preliminary research and calculation: S-N diagram
The number of life cycle is limited by the component and/joint with the lowest number of cycles.
ii) Simplified prototype testing

Validation Approaches

For calculating the mean cycles to failure, due to the cost and time, the team has to perform a theoretical calculation approaches. To determine the life cycles, the following steps will be taken:

1. For the joints, including screws and bolts, the team will search for the product description sheet to determine the product life cycle. Normally, the product description sheet contains the product life cycle information.

2. For each component, S-N diagram will be used first. S stands for stress and N for mean cycles to failure. It can be extrapolated to determine the life cycles before the part fails.

3. To calculate the life cycles based on the S- diagram, amplitude of the stress on different components should be known in advance. It can be calculated based on the force analysis. For example, when the system is not under testing, the load would be its own weight; however, during the test, there will be additional operation force applied on the system. Based on this information, amplitude of the stress can be determined as well as cycles to failure.

4. If the S-N diagram is not available, as long as the constants for fatigue calculations are available online we can calculate the life cycle. The constants include stress range, stress amplitude, load ratio, several material constants and shape factor. Following different equations, for example, Basquin and CoffinManson (Equation 1) for crack initiation:

$$\frac{\Delta \epsilon}{2} = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \epsilon'_f \left(2N_f\right)^c \qquad (1)$$

and Paris Law (Equation 2) for crack propagation:

$$\int_{a_0}^{a_f} \frac{da}{a^{m/2}} = CY^m \left(\Delta\sigma\right)^m \pi^{m/2} \int_0^{N_f} dN \qquad (2)$$

Thus, we can gain a rough estimation about the life cycle by identifying the limiting component or joint in our design.

In addition, if time and cost permits, a small prototype of the testbench will be assembled to validate the durability. Two supporting stands will be connected and simulate the same scaled force amplitude to test the life cycle. Different size of the stands then will be used to test the life cycle and the plot diagram will be plot to see the trend beneath the size of the stand and the life cycle

8.1.4 Proof of Concepts

The project is build based on the customer requirements. Hence, during the process of validation, the concepts should be examined whether they are satisfied.

In summary, the team would like to test the concepts through the manufacturing process so that If there are any problems, they can be quickly isolated, identified and solved. Therefore, by the end of manufacturing process, the team should be able to fully prove the design concepts.

<u>i) Testbench can support the whole e-Clutch system</u>

Testbench is one of the main components in this project. It is the place for demonstration, improvements and possible future development. From the customer requirements, it should be durable, and the minimum load the testbench can withstand should be at least 50 Kg.

Validation Approaches

The life cycle test will be conducted during the mean cycle failure analysis, by using the S-N diagram. The results can be compared with the engineering target value to prove whether the durability of the testbench meets the requirements. For the minimum load, different size of the load will be put on the testbench. The team will observe the flexibility of the testbench countertop. After putting a specific load on the center of the testbench countertop, a square angle tester will be located near the edge of the countertop to exam deflection of the countertop. The load that is greater than 50 kg will also be used during the validation.

ii) Limited customized machining components

The ease of manufacture is also specified by customers. The manufacture and assembly process of the system can not be too complex, or it will directly affect the popularity and promotion of this product, even the cost will rise as well. Hence, from the customer requirements, both the customized machined part and the parts added to the original part should be limited.

Validation Approaches

From the budget list, the total number of the purchased part can be counted. Then, the number of parts that added to the original manual transmission part can be summarized. In addition, the budget list of the machined part is also included in the report. Compared with the main component in the project, the percent of the customized machine part can also be achieved. These two results will then be compared with the engineering target value to see whether meet the requirements.

iii) Sensor can detect the movement precisely

The resolution of the sensor should be specified because it will affect the precision of the detection results. As mentioned in the customer requirements, both the sensor at the gear lever and clutch will be tested the resolution.

Validation Approaches

Fix the sensor at the desired position and connect the sensor to the controller. The angular position sensor can detect the voltage signal, and the precision can also be detected. After get the voltage signal, the data can be interpreting into the angle change signal, as mentioned in the engineering analysis. Hence, the precision of the sensor to detect the angle change can also be determined

iv) Sensor can detect the whole travel range

The range of the sensor is important when the customer wants to detect a relative large range of one area. Hence, the range of the sensor is considered at the engineering analysis, but also need to validate after it is assembled at the desired place

Validation Approaches

Fix the sensor at the desired position and connect the sensor to the controller. Change the position and read the signal from the sensor. The computer can collect the whole range of the movement can tell the maximum value to the minimum value. Then the range of the sensor can be determined

v) Motor can successfully drive the hydraulic system

The last step to prove the concept is to test whether the motor can actually drive the hydraulic system. The motor is included in the main function and is the key to all electronic controlling system. In this part, the motor is tested whether it can provide enough torque to drive the hydraulic system within short time.

Validation Approaches

The motor is connected to the power, and the actuator will drive the motor to rotate. The motor is also connected to the gear system, and the rack will push the hydraulic cylinder. During the experiment, the team will record several results including: whether the motor can drive the gear system; whether the rack can push the hydraulic cylinder smoothly.

8.1.5 Functionality Analysis

Three validation plans are listed in the functionality test because these are the main function of this project. To fulfill the customer requirements, the electronic controlling system will automatically push the hydraulic cylinder to engage/disengage the the clutch. Hence, the driving mechanism is the key to replace the traditional pedal, and its functionality need to validate.

Validation Approaches

For the time needed to disengage the clutch, a timer will be used in the experiment. As soon as the diver change the gear ratio, the timer will start. The driving mechanism will disengage the clutch, and the engagement (%) will be recorded in the computer. When the clutch is fully disengaged, the timer will stop, and the time needed to finish the whole process will be determined. For the time needed to drive the hydraulic system, the same process is applied. The time recorded is from the motor starts rotating to it stop. The rate of success will be evaluated by conducting certain amount of experiments. Recording the times it succeeds, as well as it fails; then the percent of success can be determined.

8.1.6 Budget

Budget is one of the customer requirements, from the target value, the total amount of money can spend should be constrained within 15,000 RMB. The cost of the project is important when it need to commercialized.

Validation Approaches

The total budget list is included in the design description and manufacturing plan. Summarize all the money spent and compared with the target value.

8.1.7 Safety Test

i) Voltage limitation

The power supply will provide power source for the motor. Due to the safety concern, the maximum DC voltage should be limited to 12V.

Validation Approaches

The rechargeable battery will be charge to its full power first, then the voltmeter will be used to detect the voltage of the battery, if the voltage is less than 12V, the power is safe to use in this project.

ii) Travel range limitation

In order to prevent the damage of the driving mechanism, two limit switch is placed at both ends of the rack. In this validation plan, the main focus will be to prove the functionality of the switch.

Validation Approaches

The limit switch is assembled at the end of the spacer. When the rack hit the limit switch, the team will observe whether the motor stop rotating. In addition, the deformation of the limit switch and the deformation of the spacer will also be observed.

8.2 Validation Results

8.2.1 Motor Power Analysis

During the engineering analysis, the torque needed to engage the clutch is demonstrated. According to the desired torque and speed, a motor (14.5N*m at 60RPM) is selected. After validation test, it can be proved that the torque is sufficient. When the motor rotates, it can freely transmit the power to the gear system and push the rack forward. The rack can smoothly push the hydraulic cylinder. In addition, the speed of motor is large enough to finish the driving procedure within desired time. During the test, the voltage of the motor was measured by the voltmeter, and the value is 8V, which indicates that the motor can even provide larger torque or speed. Hence, the motor (12V, 120W) the team choose is proved to be sufficient to provide large enough power to the hydraulic system

8.2.2 Mean Cycles to Failure Analysis

From online resources, it can be determined that with a local stress below 70 MPa, the number of cycles to failure is above 10^6. Normally, the stress is much lower than 70 MPa, since the weight of the whole structure is low and the reinforcements can distribute the stress. Therefore, for the bolts and screws, the life cycle is larger than 10^6.

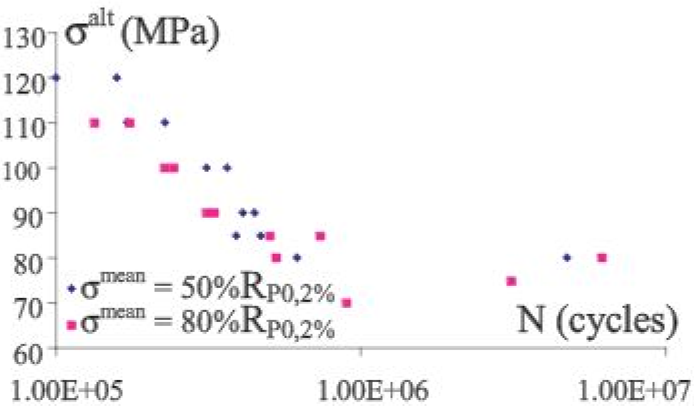


Figure 8.1. S-N curve for bolts. [16]

For other components, aluminum alloy usually reaches endurance limit when the life cycle approaches 10^6. The maximum stress corresponding to that life cycle is about 600-900 MPa. However, based on our calculation, the stress applied on the aluminum alloy is smaller than 10 MPa. Therefore, the axle has larger than 10^6 life cycles.

The life cycles for normal wood is also shown in the diagram below. With desired life cycle, the maximum stress is around 25 MPa. Therefore, the blade can reach the desired life cycle.

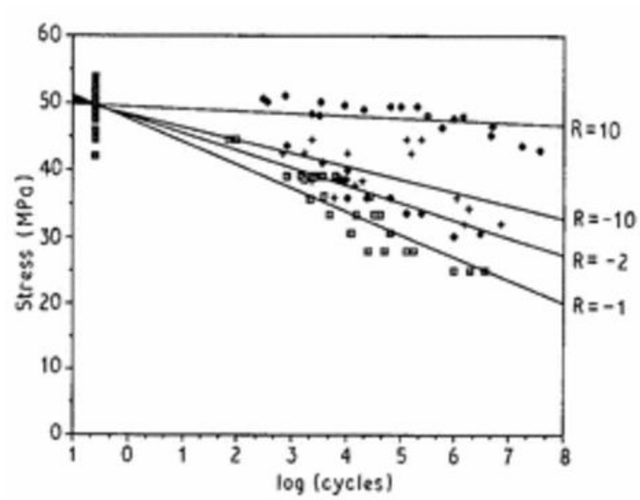


Figure 8.2 S-N diagram for normal wood. [17]

8.2.3 Proof of Concepts

i) Testbench can support the whole e-Clutch system

After doing the loading test, the team add a 100 Kg load on the testbench countertop and find out that there is no obvious deflection happens at the center of testbench countertop. After purchasing all the components, the whole system is estimated to be around 100 Kg. Hence, the testbench is proved to be strong enough to support the whole system and is an ideal location for demonstration and future development.

ii) Limited customized machining components

As shown in the budget list, the number of the main components is around fifty. In addition, from the manufacturing budget list, the number of part need to machine is five. The detailed information is listed in the following table. Hence, the percent of customized machined part is constrained within 10%.

iii) Sensor can detect the movement precisely

After connecting the sensor to the controller, the computer can read the voltage signal, with the precision of 1V. As mentioned in the engineering calculation, the precision of the angle can be determined by using the mathematical transformation, and the precision of the sensor that can detect the angle is 0.5°, which satisfy the engineering target value.

iv) Sensor can detect the whole travel range

The same procedure is used in the previous subsection, the computer will collect the data at different position. During the experiment, the maximum angle and the minimum angle the sensor can detect is -90° and 90°, hence the largest range of the sensor is x,y:[-90°, 90°], which is the same of the target value.

v) Mechanism can successfully drive the hydraulic system

When the motor is connected to the power and the controller initiate the rotation, the motor successfully transmit the power to the gear system and the rack, and the rack succeeds in pushing the rack to drive the hydraulic cylinder. In addition, the team also observe that the release bearing of the clutch engage/disengage, which indicates that the motor are proved to be able to replace the traditional pedal.

8.2.4 Budget

The total amount of money spent is less than 8,000 RMB, which is much less than the budget the customer required. Hence, budget satisfies the needs, and is validated.

8.2.5 Safety Test

i) Voltage limitation

After test the voltage of the battery when it is fully charged, the maximum voltage measured is 12.3V. Although the target value is 12V, the 12.3V is still much smaller than the voltage that will cause danger to people. Hence, the power source voltage is safe.

ii) Travel range limitation

After the validation test, the range of the rack is effectively limited within the desired range. When the rack hit the limit switch, the motor stop rotating immediately. In addition, there is no obvious deflection of the limit switch or the spacer is found after test. This indicates that the position of the limit switch is properly chosen and the way to fix the switch is ideal.

8.3 Target Value vs. Test Results

After finishing the validation experiment and engineering analysis, the target value from the engineering specification can be examined whether it meets the requirements. This table summarize whether the prototype results satisfy the engineering target value.

Table 8.1 Target value vs. test results

Engineering Specifications (Target value)		Prototype (Test results)
Life span comparable with production development time	1-2 yr.	Theoretically proved
Minimum load	>50 kg	100 kg
% of custom machined parts	<10%	10%

# of parts added to original MT system	<60	50
Money spend	<15k RMB	7,800 RMB
Volume of the testbench	2m*2m*1.5m	1m*1.5m*0.9m
Range of displacement sensor	x,y:[-45°,45°]	x,y:[-90°,90°]
Resolution	0.5°	0.5°
Response time	0.5s	0.5 s
Stability	>95%	95%
Maximum voltage for the control system	<= 12 Volts	12.3 V

First category of the needs is the physical properties. This includes life span, minimum load, cost, and safety. The life cycle is theoretically proved to be sufficiently long for the research cycle, which is greater than 2 years. The tested value for the minimum load is larger than 100 Kg, which is much larger than the target load. The actual budget is 7800 RMB, which is less than the budget sponsor gave us. The voltage of the source is close to target value, which will not cause any danger to the users. Hence, all the customer requirements for the project properties are satisfied.

Second category of the needs is the manufacturing. This includes the percent of the custom machined part, and the number of part added to the original MT system, and the volume of the testbench. The percent of the machined part is proved to meet the target, and the total number of part added is reasonable. In additional, the volume of the testbench is much smaller than the initial target value. Hence, the needs for the manufacturing are all satisfied.

Third category of the needs is the main usage, which includes the range of the sensor, resolution, response time and repeated success rate. After the validation experiments, the range of the sensor and the precision of the sensor is the same as the target value. The response time and the repeated success rate are proved to meet the requirements. Hence, all the target value are satisfied.

9. Engineering Changes Notice (ECN)

9.1 Application of New Sensor

The application test of New sensor
Was: Accelerometer
Is: Hall effect sensor
Notes: Needed to replace the accelerometer at gear lever to 2 hall effect sensors. Needed to replace the accelerometer at clutch to hall effect sensor. Magnets are added with hall effect sensors to work as a system. The hall effect sensors have more stable data. Also they won't be affected by the movement of cars.
Changed on 8/5/2016 by Yuxiang Mu and Shiwei Song.
Authorized on 7/27/2016 by Jiaxi Liu and Yang Xiao.

9.2 Change of Sensor Position

After the test process, two Hall effect displacement sensors are used to detect the position of gear lever. Each Hall effect displacement sensor is mainly responsible for the detection of three gear levels, according to the change of magnetic field. In order to achieve a precise detection, the positions of both magnet and sensors should be fixed stably, which means they cannot be fixed on the gear lever. Therefore, the magnet is fixed on the connection point of gearbox. The two sensors are fixed on the upper surface of testbench. In this way, the gear level detection is more accurate and stable.

In order to achieve a more precise detection of clutch position during the process of shifting gears, another Hall effect displacement sensor is used in the clutch system. The sensor is fixed on the inner wall of gearbox and the magnet is fixed on the clutch release bearing. In this way, the clutch position detection is more precise.

9.3 Addition of Acrylic Board

In the previous design, in order to replace the function of clutch disk, we use a spring to push the clutch fork and release bearing back. And then we use a coupler to fix the spring. However in this situation, if the screws on the coupler are failed, the coupler will be shot out by the spring, which is extremely dangerous. Therefore, to prevent the potential accident, we decide to add a acrylic board out of the gear box. This board is very close to the coupler and if the coupler is failed, the acrylic board and replace the function of coupler and hold both coupler and spring. In this way, even if the coupler is failed, it will not be a problem anymore.

10. Discussion

From the demonstration and validation results of the prototype, it indicates that the e-Clutch system and the testbench build for it can successfully meet the customer requirements and fulfill different function. The controller and actuator manage to receive the signal and drive motor; the mechanism is able to transport the power to pushing the hydraulic cylinder; the response time is improved within 0.5s; and the testbench is strong enough for conducting future demonstration.

The strengths of the project include: driving mechanism, cost, and design efficiency. The design for driving the hydraulic system to engage/disengage the clutch is using a gear and rack system. It is much user-friendly and straightforward design available now. It does not need complex structure like four-bar linkage; it either does not need to use belt and transport structure to transmit the power. The gear system simply uses the gear to effectively transport the power to the rack; and the rack is used to push the hydraulic cylinder. This design can improve the power efficiency, and directly push the hydraulic cylinder; as a result, it will use less power and need less response time. The cost is also low for the whole project. Instead of ordering one-united testbench, it is build by pieces of extrusions. The structure rigidity is also taken into consideration during the design, hence, the testbench is not only affordable, but also strong to support the whole system. Before actually manufacture and assemble the whole system, the 3D CAD model is built in advance to exam the connections and locations are properly organized, which will largely improve the project assembly efficiency. For example, polymer block is put beneath the gearbox to increase the friction and prevent damaging the testbench countertop. However, the height of the block must need to specified in order to make the connection between gear lever and gearbox in the same level. The detailed systematic designs make the manufacturing and assembly process more efficiently.

There are some weaknesses in the final prototype. First thing is the height of the components in the mechanism. In order to match the motor, the bearing and the rack are leveled up. However, extrusions are used to put beneath the components, this may lower the efficiency during the assembly process, as well as cause some error. The best way to do in the future is make one-united component which have the specified height. Another thing needing to be mentioned is that during the assembly process, the holes are drilled manually, and the location is confirmed by testing the mechanism. For the future prototype manufacture, these locations for the holes can be confirmed in advance based on the components design. In addition, one shortcoming is that the DC motor and relay are used for the controlling. The signal transport speed is slower compared with using H-bridge. This will increase the response time. However, the H-bridge type has to match the type of motor. In the future prototype, the type should be specified and matched in advance.

11. Recommendations

First, as mentioned in the discussion part, when the e-Clutch system is manufactured by company, one-united part can be made. These components can improve the efficiency during the assembly process. In addition, after the system components are determined, the location and the size are settled, then the holes and screws used to fix these components can be determined before the manufacturing. As a result, the holes can be drilled in advance, this will improve the accuracy of the whole system. Another recommendation is that using the H-bridge as the controller to drive the motor rotate clockwise or counterclockwise, this will effectively improve the response time.

Notice that the location of the sensor is important during the signal detection. In the prototype, the sensor to detect the driving intention is put near the connection to the gearbox. In this location, the angular sensor succeeds in detecting driving intention and the gear lever position. However, it is still recommended that the sensor should be placed inside the gear lever box. In the future manufacture, the box can be made larger, hence, the sensor will not hit the wall and not influence the test results.

After the validation process, a new type of sensor, Hall effect displacement sensor is used to detect the change of gear lever; movement of rack in the driving mechanism; and the change of clutch release bearing. The advantage of the Hall effect sensor is that it is more stable and the acceleration of the car will not affect the signal receiving. During the sensor test, Hall effect sensor is found that it can fulfill the same function, and might be a good replacement for the angular sensor.

Since this testbench and e-Clutch system are still used for testing the controlling algorithm and function of engaging the clutch, the actual clutch disk is not assembled on the gearbox; and the gearbox is not connected to the engine. Right now, a spring and an acrylic board are assembled at the end of the gearbox to replace the function of the clutch disk. For the future test, the clutch disk is recommended to placed on the gearbox to get the test results which will be closer to the real situation.

12. Conclusions

E-Clutch system proposed by UAES is a brand new idea and will provide great convenience for MT vehicle users. The main features and benefit of e-Clutch are pedal free shifting, stall prevention, coasting, and stop & go assist. MT vehicle has several advantages such as low cost and energy efficiency. The promotion of the e-Clutch system will increase the sale of MT vehicle. In this project, two major tasks will be focused on: building a simplified workable e-Clutch prototype with controlling algorithm and setting it onto a testbench.

During the design process, the morphological analysis is used to determine the sub-functions of the whole system, and the weighted matrices are used to select best solution for each sub-function. From the design description, the 3-axes accelerometer are attached to the gear lever and clutch to detect the driving intention and monitor the performance of the clutch, respectively. The controller and the gear transmission mechanism successfully drive the hydraulic cylinder to engage or disengage the clutch.

Engineering analysis is also performed before building the prototype, different aspects are calculated to prove the feasibility of the design. For material selection, aluminum alloy is used to build supporting structure, steel is used to make gear system; and wood is used for Testbench surface. During the failure analysis, 6 cm square supporting stands 5 cm thick wood surface is found to be strong enough for the Testbench. 12V, 120W motor is proved to provide sufficient torque and speed in the driving mechanism. In addition, for controlling part, the algorithm is built and tested, the results indicate the algorithm can identify different intention and give correct response. The wiring diagram is created for user instruction and future problem shooting.

After the validation, the test results of the prototype show that the engineering target value are satisfied. The main functionality is tested and prove that the mechanism can drive the hydraulic cylinder to engage the clutch within desired time. The testbench rigidity and lifespan are all tested and will meet the requirements. The whole system is easy to reproduce and the cost is affordable. Basically, every partial function is validated, including the sensor signal detection; driving mechanism; and clutch engagements. Future improvement for this project will focus on the application of the e-Clutch system to the engine controlling. Different sensor, like Hall effect sensor may be eventually used in this project, and the position of all sensors will be finalized in the future demonstration. In conclusion, this e-Clutch system and its Testbench successfully fulfill all different goals, it is able to demonstrate the controlling algorithm and mechanism driving.

13. Acknowledgement

Special thanks to the company sponsor: System & Function Development (ESF), UAES; and company mentor: Wengang Qin, Jiaxi Liu, Dr. Xiao Yang, UAES.

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Also thanks to the machine shop staff, who give the team a lot of help during the manufacturing process.

14. Information Source and Reference List

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Appendix

A.1 Project plan

Before starting the whole project, priority and milestones were determined in the plan, as shown in the following figure and description:

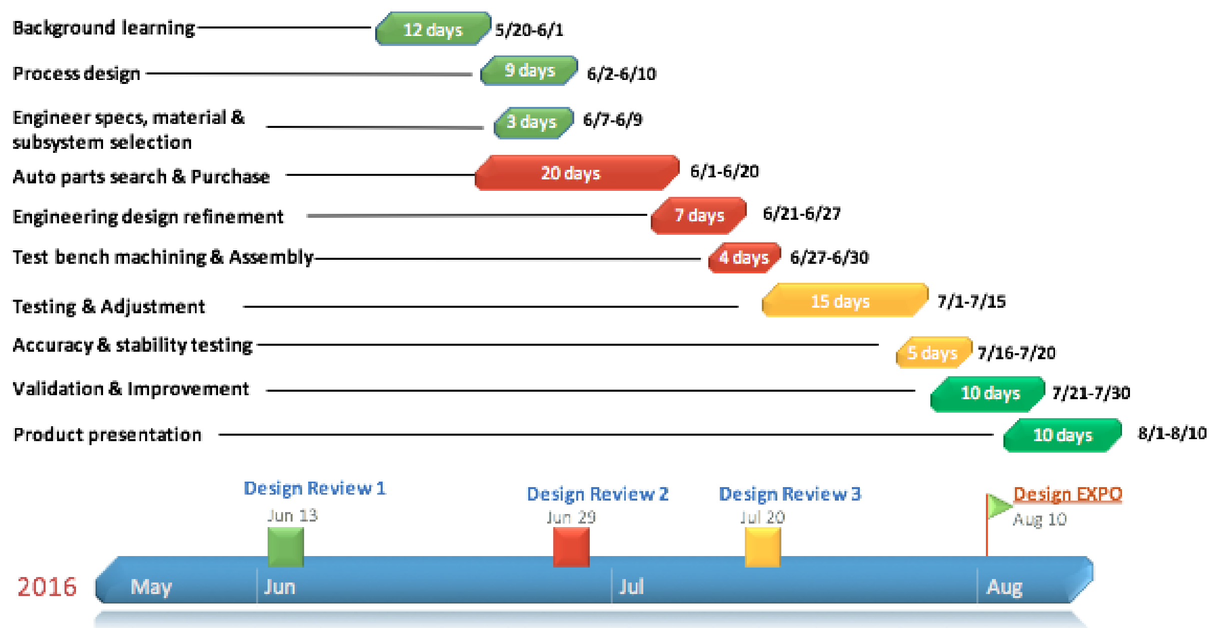


Figure A.1 Project plan and milestone

Priority from 1-5 with 5 means the most critical part need to accomplish, were assigned to the tasks. The detailed plans are described and explained in order of time.

1. Learn background information for this project, this includes: a) Study about the transmission system, powertrain, clutch from literatures, books and the internet **(5/20-6/1, priority 1)**; b) Design the process for this project **(6/2-6/10, priority 2)**: (1) customer needs and corresponding engineering specs; (2) Literature research: existing solutions, pattern, paper; (3) QFD; (4) process selection.

2. Change and confirm the engineer specs with instructor and sponsors, which is the preliminary goal to achieve in this project **(6/7-6/9, priority 2)**

3. Search different parts online or in the auto-market (comparison and determine which one to buy) **(6/1-6/20, priority 4):** a) Look for the real parts which can be used in this project: such as (1) price, (2) vendor, (3) series, (4) size, (5) weight. b). Parts need to purchase are: (1)

transmission system (with the manual handle); (2) clutch and hydraulic transmission for the clutch; (3) Controller (actuator and executor); (4) position sensor; (5) Arduino and wires for the connection; (6) power for these sensor.

4. Base on the parts selected and bought, finish the engineering design, including: connection method among different parts, estimate the weight of the whole system and the size of the testbench **(6/21-6/27, priority 3)**

5. a) After the design process, finish the engineering drawing for the testbench countertop (choose the location to secure each part); b) Assemble different parts on the testbench (machining) **(6/27-6/30 priority 4)**

6. Testing and Adjustment **(7/1-7/15, priority 5)**, including: a) Whether the sensors can tell the movement of the manual handle; b) Whether the controller can collect and transfer the information correctly (many conditions to justify and need to consider); c) Whether the motor can drive the cylinder; d) Whether the clutch can function; e) does the whole transmission system work properly? Stable? f) Is there any additional properties that can be added or shown?

7. Change parts if necessary, test again, focusing on the accuracy and stability. **(7/16-7/20, priority 4)**

8. Validation and improve **(7/21-7/30, priority 3)**, including: a) Whether our testing results meet the customer requirement? If not, can these results be improved? Or need to change the engineer specs? b) Does the engineering design meet the specs? c) Do all the parameter meet the goal?

9 Product refinement and Product presentation **(8/1-8/10, priority 3)**

A.2 Code

Arduino Code

```
#define S1_IN 0         //port for sensor1 x input
#define S2_IN 1         //port for sensor1 y input
#define S3_IN 2         //port for sensor2 x input
#define POWER_PIN 10     //port for power control
#define MOTOR_PIN_1 6   //port 1 for motor control
#define MOTOR_PIN_2 7   //port 2 for motor control
#define STOP_PIN_1 0    //port for signal to stop motor
#define STOP_PIN_2 1    //port for signal to stop motor
#define DELAY 50        //delay
#define MOVE 40         //threshold for changing gear level attempt detection
#define RANGE 18        //error range for accepting gear level
#define MAX_COUNT 5    //maximum count

int clutch[6] = {0, 0, 0, 0, 0, 0};

int s1, s2, s3;
int ps1, ps2;
int cs3;
int gear_level, pgear_level;
volatile int count = 0;
int stop1, stop2;
volatile boolean changing = false;
volatile boolean moving = false;
int  c, m;
int sum;
double engage, disengage;

//initialization
void setup()
{
  pinMode(POWER_PIN, OUTPUT);
  pinMode(MOTOR_PIN_1, OUTPUT);
  pinMode(MOTOR_PIN_2, OUTPUT);
  Serial.begin(9600);            //set bit rate to 9600 bps

  digitalWrite(POWER_PIN, LOW);

  attachInterrupt(STOP_PIN_1, stop_func1, RISING);
```

```
  attachInterrupt(STOP_PIN_2, stop_func2, RISING);

  count = 0;
  pgear_level = 0;
  changing = false;
  moving = false;
  delay(2000);
  digitalWrite(MOTOR_PIN_1, HIGH);

  cs3 = 0;
  for (int i = 0; i < 10; i ++){
    analogRead(S3_IN);
    delay(100);
  }
  for (int i = 0; i < 10; i ++){
    cs3 += analogRead(S3_IN);
    delay(200);
  }
  engage = cs3 / 10;
  disengage = engage - 180;

  ps1 = analogRead(S1_IN);
  ps2 = analogRead(S2_IN);
  c = 0;
}

//loop
void loop()
{
  s3 = analogRead(S3_IN);
  //Serial.println(s3);
  sum = 5 - (int)((sqrt(engage/s3)-1) / (sqrt(engage/disengage)-1) / 0.17) ;
  if (sum < 0) sum = 0;
  if (sum > 5) sum = 5;
  clutch[sum] ++;
  if (c == 6){
    c = 0;
    s1 = analogRead(S1_IN);
    s2 = analogRead(S2_IN);

    //changing gear level attempt detection
    m = 0;
    if (abs(ps1 - s1) + abs(ps2 - s2) > MOVE && changing == false && moving == false){
```

```
  m = 10;
  digitalWrite(MOTOR_PIN_1, LOW);
  digitalWrite(MOTOR_PIN_2, HIGH);
  digitalWrite(POWER_PIN, HIGH);
  moving = true;
}

//gear level position detection
gear_level = 0;
if (abs(s1 - 580) < 50 && abs(s2 - 394) < 20){
  gear_level = 2;
}
else if (abs(s1 - 830) < 50 && abs(s2 - 360) < 20){
  gear_level = 4;
}
else if (abs(s1 - 960) < 50 && abs(s2 - 395) < 20){
  gear_level = 6;
}
else if (abs(s2 - 820) < 50 && abs(s1 - 430) < 20){
  gear_level = 1;
}
else if (abs(s2 - 880) < 50 && abs(s1 - 395) < 20){
  gear_level = 3;
}
else if (abs(s2 - 660) < 50 && abs(s1 - 395) < 20){
  gear_level = 5;
}
gear_level += m;
if (changing == true){
  if (pgear_level == gear_level)
    count = count + 1;
  else
    count = 0;
}
if (count == MAX_COUNT && moving == false){
  digitalWrite(MOTOR_PIN_1, HIGH);
  digitalWrite(MOTOR_PIN_2, LOW);
  digitalWrite(POWER_PIN, HIGH);
  moving = true;
}
pgear_level = gear_level;
ps1 = s1;
ps2 = s2;
```

```
    int max_clutch = 0;
    int ind = -1;
    for (int i = 0; i < 6; i ++){
      if (clutch[i] > max_clutch){
        max_clutch = clutch[i];
        ind = i;
      }
    }
    Serial.write(ind * 20 + gear_level);
    for (int i = 0; i < 6; i ++) clutch[i] = 0;
  }
  c = c + 1;

  delay(DELAY);
}

void stop_func1(){
  digitalWrite(POWER_PIN, LOW);
  changing = true;
  moving = false;
  count = 0;
}

void stop_func2(){
  digitalWrite(POWER_PIN, LOW);
  changing = false;
  moving = false;
  count = 0;
}
```

MATLAB Code

```
function varargout = gui(varargin)
% GUI MATLAB code for gui.fig
%      GUI, by itself, creates a new GUI or raises the existing
%      singleton*.
%
%      H = GUI returns the handle to a new GUI or the handle to
%      the existing singleton*.
%
%      GUI('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in GUI.M with the given input arguments.
%
```

```
%      GUI('Property','Value',...) creates a new GUI or raises the
%      existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before gui_OpeningFcn gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to gui_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help gui

% Last Modified by GUIDE v2.5 19-Jul-2016 23:29:33

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @gui_OpeningFcn, ...
                   'gui_OutputFcn',  @gui_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before gui is made visible.
function gui_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to gui (see VARARGIN)
```

```
% Choose default command line output for gui
handles.output = hObject;

axes(handles.axes2);
img = imread('light_off.jpg');
imshow(img);
axes(handles.axes1);
axis([1 50 -10 110]);
xlabel('Time');
ylabel('Engagement(%)');
set(gca, 'FontSize', 16, 'FontWeight', 'bold');
set(gca, 'xticklabel',[]);
grid on;

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes gui wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command line.
function varargout = gui_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;

% --- Executes on selection change in popupmenu1.
function popupmenu1_Callback(hObject, eventdata, handles)
% hObject    handle to popupmenu1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
global COM;
COM = 1;
val = get(hObject, 'value');
switch val
   case 1
      COM = 1;
   case 2
```

```
        COM = 2;
    case 3
        COM = 3;
    case 4
        COM = 4;
    case 5
        COM = 5;
end
% Hints: contents = cellstr(get(hObject,'String')) returns popupmenu1 contents as cell array
%        contents{get(hObject,'Value')} returns selected item from popupmenu1

% --- Executes during object creation, after setting all properties.
function popupmenu1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to popupmenu1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: popupmenu controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes on button press in pushbutton1.
function pushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
global s;
global stop;
global COM;
stop = 0;
switch COM
    case 1
        s = serial('COM1');
    case 2
        s = serial('COM2');
    case 3
        s = serial('COM3');
    case 4
        s = serial('COM4');
    case 5
        s = serial('COM5');
```

```
end
set(s, 'BaudRate', 9600);
fopen(s);
size = 50;
t = linspace(1, size, size);
move = zeros(1, 10);
mp = 1;
data = [];
sdata = [];
tflag = 0;
i = 1;
si = 1;
lf = 0;
while (stop == 0)
    if (s.BytesAvailable == 1)
        x = fread(s, 1);
    else
        continue;
    end
    gear = mod(x, 20);
    x = x - mod(x, 20);
    if lf == 1
        lf = 0;
        axes(handles.axes2);
        img = imread('light_off.jpg');
        imshow(img);
    end
    if gear >= 10 && gear <= 16
        axes(handles.axes2);
        img = imread('light_on.jpg');
        imshow(img);
        lf = 1;
        move(mp) = t(length(data));
        mp = mp + 1;
        if mp == 11
            mp = 1;
        end
        gear = gear - 10;
    end
    if gear >= 0 && gear <= 5
        a = num2str(gear);
        set(handles.text2, 'String', a);
    elseif gear == 6
```

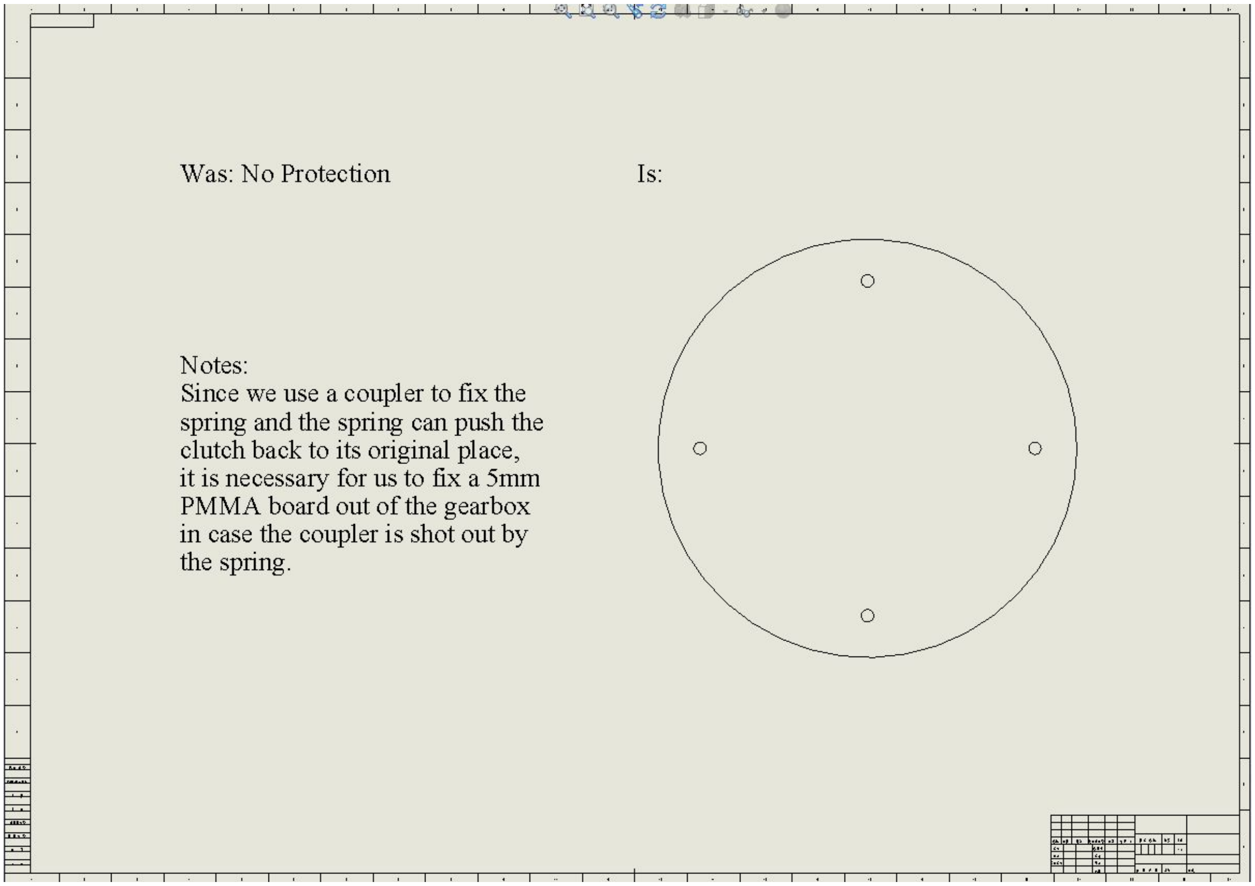
```
        set(handles.text2, 'String', 'R');
    end
    if tflag == 0
        data(i) = x;
        i = i + 1;
    else
        data = [data(2:size), x];
        t = t + 1;
    end
    if i == size + 1
        tflag = 1;
    end
    axes(handles.axes1);
    hold on;
    plot(t(1:length(data)), data, 'b', 'LineWidth', 4);
    for j = 1:1:length(move)
        if move(j) < t(1)
            move(j) = 0;
        end
    end
    for j = 1:1:length(move)
        plot([move(j) move(j)], [-10 110], 'r', 'LineWidth', 2);
    end
    axis([t(1) t(size) -10 110]);
    xlabel('Time');
    ylabel('Engagement(%)');
    set(gca, 'FontSize', 16, 'FontWeight', 'bold');
    set(gca, 'xticklabel',[]);
    grid on;
    guidata(hObject, handles);
    if (s.BytesAvailable > 0)
        fread(s, s.BytesAvailable);
    end
    pause(0.01);
end
fclose(s);
delete(s);

% --- Executes on button press in pushbutton2.
function pushbutton2_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
```

```
global stop;
stop = 1;
```

A.3 ECN

ECN for Section 9.3



A.4 Bill of material

Quantity	Part Description	Purchased From	Part Number	Price (each)
1	Passat B5 Manual Transmission System	Shanghai Sheng Hui Auto Parts co., LTD		¥3326
2	Angular Sensor	risym*	MMA7361	¥18.55
1	Arduino Board	Qi Xing Chong*	UNO R3	¥199
1	12V 120W 60rpm Motor	Cheng Peng*	5PC120SU-12	¥500
1	W90mm Motor Holder	Cheng Peng*		¥32
1	12V 25A Motor Controller	Cheng Peng*		¥90
2	L40 D35 d15-15 Coupler	Cheng Peng*		¥35
2	1M 30T D32 d15 Gear	Guang Fa Bearing Transmission Co., LTD*		¥6.4
1	1M 30T W16 H16 L1000 Rack	Guang Fa Bearing Transmission Co., LTD*		¥21
2	d15 Bearing Seat	Guang Fa Bearing Transmission Co., LTD*		¥9.5
1	12V Rechargeable Battery	Fu Lan Ka Market*		¥62
1	L20 Battery Wires	Fu Lan Ka Market*		¥3.2
1	D20 L50 Aluminum Shaft	Kunshan Ao De Wang mold co., LTD *		¥15
1	Motor Driven Board	telesky *	BTS7960	¥61.04
1	W1000 L1500 H40 Wood Board	Hong Fu Lai Furniture *		¥580
8	L600 Aluminum Extrusion	Lu Hu Aluminum Extrusion*	6060W	¥53.69
6	L700 Aluminum Extrusion	Lu Hu Aluminum Extrusion*	6060W	¥63.64
5	L800 Aluminum Extrusion	Lu Hu Aluminum Extrusion*	6060W	¥71.59
2	L500 Aluminum Extrusion	Lu Hu Aluminum Extrusion*	3030	¥10.82

6	Universal Wheel	Lu Hu Aluminum Extrusion*	75CD	¥20
34	Angle Bracket	Lu Hu Aluminum Extrusion*	4545	¥3.5
68	Aluminum Extrusion Screws and Bolts	Lu Hu Aluminum Extrusion*	M8*25-45	¥0.75
1	Brake Oil	Shanghai Sheng Hui Auto Parts co., LTD	Dot3	¥25
1	Passat B5 Brake Oil Container	Shanghai Sheng Hui Auto Parts co., LTD		¥25
4	40*40*18 Angle iron	Shi Shang Furniture*		¥1.3
8	100*100*20 Angle iron	Shi Shang Furniture*		¥3.6
20	M4*20 Tapping Screw	Shi Shang Furniture*		¥0.15
20	M4*20 Tapping Screw	Shi Shang Furniture*		¥0.18
2	Limit Switch	Changzhou Tai Ming Electronic Devices*	V-151-1C25	¥1.2
1	Relay	Shenzhen Ge Lan Rui Technology *	SLA-05VDC-SL-C	¥23
1	Relay	Bai Sheng Electronic*	SRD-05VDC-SL-C	¥15.5
1	L1000 W500 H50 EVA Board	Pao Mo Wang Guo*		¥120
3	L300 W200 H60 EVA board	Pao Mo Wang Guo*		¥18
2	L1800 Belt	Xin Yun Outdoor Stores*		¥9.8
4	M2*18 Bolt	Hua Ren Store*		¥0.05
4	M2*6 Bolt	Hua Ren Store*		¥0.04
4	M3*20 Bolt	Hua Ren Store*		¥0.08
10	M6*25 Bolt	Hua Ren Store*		¥0.31
4	M6*50 Bolt	Hua Ren Store*		¥0.52
6	M6*100 Bolt	Hua Ren Store*		¥1.18
10	M12*120 Bolt	Hua Ren Store*		¥3.94
4	M2 Nut	Hua Ren Store*		¥0.06
4	M3 Nut	Hua Ren Store*		¥0.08
20	M6 Nut	Hua Ren Store*		¥0.1
4	M12 Nut	Hua Ren Store*		¥0.15

4	M2 Spacer	Hua Ren Store*		¥0.03
4	M3 Spacer	Hua Ren Store*		¥0.04
20	M6 Spacer	Hua Ren Store*		¥0.05
14	M12 Spacer	Hua Ren Store*		¥1.42
1	M20 Spacer	Hua Ren Store*		¥3.92
80	L300 Dupont Wire	Tian Shi Kai Digital*		¥0.35
9	Needle Bearing	Guo Xin Bearing*	FF2010	¥2.7
2	L1000 Wires	Yang Guang Model*	14AWG	¥3.35
3	D9-16 Hose Clamp	tjbh*		¥0.73
1	H150 D130 Tripod	Nanchang Shan Shan Experimental Equipment*		¥7
1	L600 W150 H50 Wood Block	Import Wooden Board Market*		¥60
1	L400 W150 H22 Wood Block	Import Wooden Board Market*		¥100
1	D45 d39 L300 Spring	Jian Li Spring*		¥35
1	Gear Lever	Ai Che Zu Auto Parts*	Square Base	¥22
1	3D Printing	Cui Wei Xuan*		¥260
1	Aluminum Board Manufacturing	Hao Cheng*		¥180
			Total =	¥7639.96

L=length (mm), W=width (mm), H=height (mm), D=outer diameter (mm), d=inner diameter (mm)
*=www.taobao.com