MECHATRONIC DESIGN OF A COMPLETELY MECHANICAL QUICK CHANGEABLE JOINT FOR MULTI-PURPOSE EXPLOSIVE ORDNANCE DISPOSAL ROBOTS

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ABSTRACT

MECHATRONIC DESIGN OF A COMPLETELY MECHANICAL QUICK CHANGEABLE JOINT FOR MULTI-PURPOSE EXPLOSIVE ORDNANCE DISPOSAL ROBOTS

The EOD robot is a mobile robot used in replace of a human in explosive ordnance disposal operations of searching, detecting and handling of explosive materials. Nowadays the EOD robot's tool capabilities and overall performances are at lower levels because they are only able to use one kind of tool (gripper) for the whole bomb disposing process. The aim of this study is to design a completely mechanical quick changeable joint which will be used in the EOD robot to automatically change the tools.

By changing the grippers automatically, the robot firstly does not require to be called back for tool change and secondly can achieve different operations on the explosive material. In the locking mechanism of quick changeable joint, hydraulic and pneumatic systems are not preferred because of their weight and volume on a mobile robot. Electromagnetic locking systems are also not considered because of possible electromagnetic interaction between the arm and explosive ordnance. The reason of designing a completely mechanical joint is to eliminate the use of another actuator for controlling the locking mechanism.

An EOD robot with a quick changeable joint will be able to use different tools and accomplish complex tasks by using these different tools. Usage of this quick changeable joint in different robotic applications such as tool holding in CNC machines, lifting and pulling applications will also make an increment in the robot's processing capacity and efficiency.

This project consists of designing a completely mechanical quick changeable joint. In order to understand the best design, four different joints are designed, the critical parts are analyzed for strength and prototypes of the joints are manufactured. To test the life cycles of the joints a pneumatic test machine is designed and manufactured. After the tests, the joints are evaluated for design parameters are the best design for different purposes are determined.

ÖZET

ÇOK AMAÇLI BOMBA İMHA ROBOTLARI İÇİN TAMAMEN MEKANİK ÇABUK DEĞİŞEBİLİR EKLEMİN MEKATRONİK TASARIMI

EOD robotu, bomba imha operasyonlarında patlayıcı mühimmatı arama, bulma ve yerinden kaldırma işlemlerinde insan yerine kullanılan, mobil bir robottur. Günümüzde bu robotların kollarına sadece bir çeşit tutacak takılmakta ve sonuçta bu tutacağın yapabileceği işlemler sınırlı olmasından dolayı robotun toplam performansı da düşük olmaktadır. Bu çalışmanın amacı mekatronik tasarımı yapılan "tamamen mekanik çabuk değişebilir eklem" ile bomba imha robotunun farklı tutacakları kendisinin alıp kullanabilmesini sağlamaktır. Bu sayede robot tutacak değişimi için geri dönmek zorunda kalmaz ve patlayıcı maddeyi yalnız taşımakla kalmayıp farklı müdahalelerde bulunabilir.

Çabuk değişebilir eklemin kilitleme mekanizması için düşünülen pnömatik ve hidrolik sistemler mobil robot üzerinde ağırlık ve hacim artışına neden olmalarından dolayı tercih edilmezler. Müdahale edilecek olan patlayıcı madde ile robotun kolu arasında oluşabilecek manyetik etkileşim ihtimali göz önünde tutularak elektromanyetik kilit mekanizmalarının da kullanılması düşünülmemiştir. Eklemin tamamen mekanik yapılmasındaki başlıca etken eklemin kilitleme mekanizması için ekstra bir sürücü sistem ihtiyacını ortadan kaldırmaktır.

Mekatronik tasarımı yapılacak çabuk değişebilir ekleme sahip bomba imha robotları farklı tutacaklarını kullanabilecek ve bu tutacaklar ile daha karmaşık işleri yapabilecekler. Bu çalışma ile tasarlanacak olan eklemin CNC makinalarında çakı değişiminde, yük çekme ve kaldırma gibi diğer robotik uygulamalarında kullanılmasıyla da robotun işlem kapasitesi ve verimliliği arttırılacaktır.

Bu proje tamamen mekanik yapıda çabuk değişebilir eklem tasarımını içermektedir. En iyi tasarımın belirlenmesi için dört farklı eklem tasarlandı, kritik parçaları için dayanım hesapları yapıldı ve prototipleri üretildi. Eklemlerin ömür testi için pnömatik test makinası tasarlanıp üretildi. Testlerin sonucunda eklemler çeşitli tasarım parametrelerine göre değerlendirilerek değişik amaçlara yönelik en iyi eklemler seçildi.

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CHAPTER 1

INTRODUCTION

This research intends to design completely mechanical quick changeable joint for multipurpose Explosive Ordnance Disposal (EOD) robots. Quick changeable joint serves these robots to change their end effectors (grippers) automatically. This will increase the robot's capacity in handling various shaped objects and completing different tasks by changing the tools in a short period of time without being called back to the control station.

This project consists of designing, analyzing, manufacturing, testing and evaluating of the 4 different joints. In the design chapter some possible solutions for the joint are studied according to predefined design considerations. Four quick changeable joints with completely different working principles are designed. A test machine is build to test the life cycles of the joints. The critical parts of the joints and test machine are analyzed. These calculations are performed both in theory and in simulation programs.

After the theoretical design stage, quick changeable joints and test machine are manufactured. The material selection procedure and the manufacturing of the joints and the test machine are explained in the Chapter 6.

In the last part, testing process done with real joints in the test machine to find their life cycles. Additionally some other evaluating criteria's such as weight, factor of safety, connection speed, number of components, connection simplicity and reliability are going to be considered to choose the best joint design.

Finally conclusion of the test results will be interpreted and the best joint design will be determined as completely mechanical quick changeable joint for multipurpose EOD robots. And the future works will be given as an answer of what else is going to be done in addition to this project in order to increase the joint's performance and usability.

1.1. The Quick Changeable Joint

The quick changeable joint is a device that when attached to the wrist of a robotic arm, it increases the robot's ability to automatically change the end effectors when necessary. Figure 1.1 shows where the quick changeable joint is attached on an EOD robot. This will increase the robots capacity in handling various shaped objects and improve the adaptability to different EOD tasks.

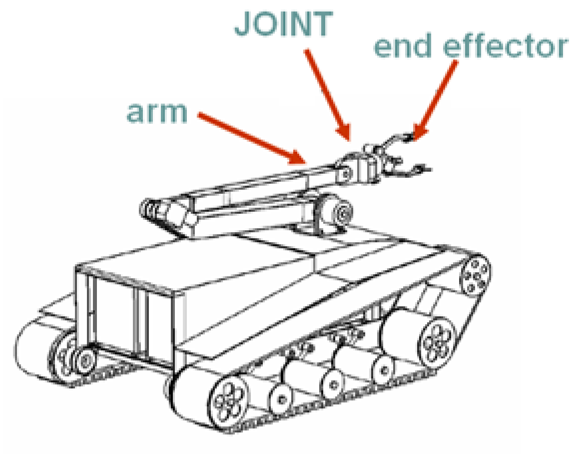


Figure 1.1. The place of Quick Changeable Joint in the EOD Robot

Quick changeability of tools in commercial explosive ordnance disposal (EOD) robots is an engineering research subject. EOD robots either carry the explosive ordnance into a containment vessel to be disposed or when the explosive material cannot be moved it's triggering mechanism is disfunctioned to stop the explosion. With an EOD robot the disarming of the explosive ordnance can be achieved remotely.

The EOD robots are apart from handling of explosive ordnance, used in areas such as disposal of landmines or handling radioactive materials. Current EOD robots only have a standard gripper. This gripper is not sufficient enough for disposal of explosives, it can only carry the explosive objects. In order to neutralize an explosive object, robot needs some special manipulators such as cutting, screwing, precise gripping, internal clamping or drilling tools. Figure 1.2 shows the different purpose EOD tools.

In a disarming operation, it is dangerous for an operator to go near the robot and change the end effector by hand. To avoid such risk, a self tool changing mechanism is needed to change the onboard tools. The mechanism requires an autonomous system, otherwise the robot would need to return to the base and wait for the operator to change its end effector. Returning to the base would consume too much time which will cause the explosion of time based bombs, or simply will decrease the mission time.

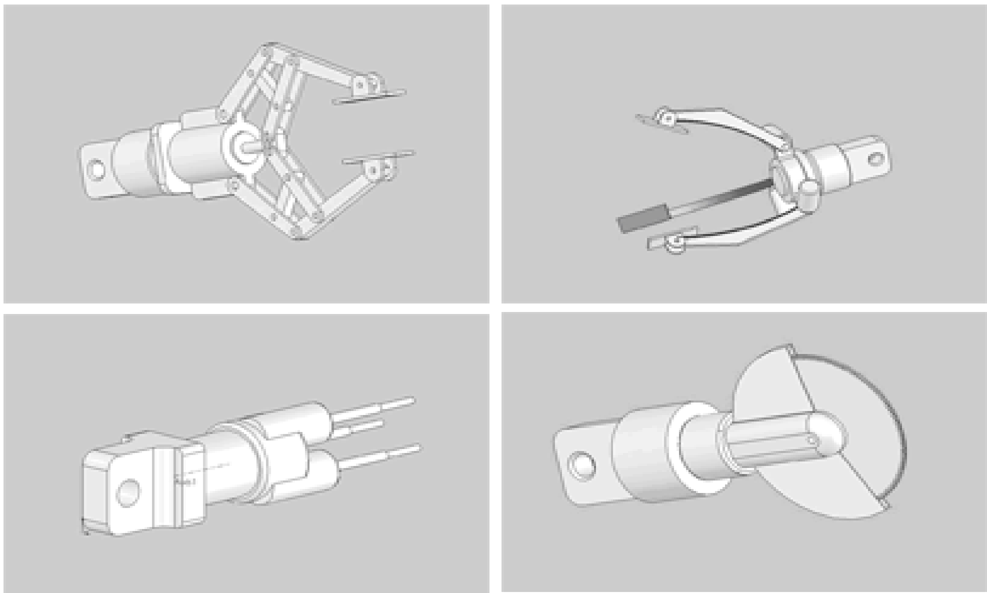


Figure 1.2. Different purpose tools of EOD Robot

The functional grippers will be used in defusing the triggering mechanism of explosive ordnance. For the different gripers to be carried on board and to be changed automatically a quick changeable joint is designed. This joint will increase the capacity of the robot.

1.2. Commercial EOD Robots and Their Grippers

In this section, four different commercially available EOD robots are introduced and then the end effector types and their changeability are investigated if exists.

1.2.1. tEODor™, by "Telerob Fernhantierungstechnik mbH"

The tEODor 2 chain-tracked vehicle is equipped with 6-axle power manipulator with telescopic lower arm and a gripper (Figure 1.3). The tEODor has only one type of gripper fixed to the arm. The only functions of tEODor are gripping and carrying an explosive object. The design of this robot does not let the gripper change (WEB_1 2005).

Figure 1.3. tEODor™
(Source: Telerob mbH, 2005)

1.2.2. Vanguard™ MK2 ROV by Allen -Vanguard Co.

The Vanguard MK2 features an articulated arm which has one type of gripper only (Figure 1.4). The manipulator arm has 3 degrees of freedom excluding 2 jaw parallel gripper having 3 degrees of freedom. In the manipulator system there is no tool changing property (WEB_2 2005).

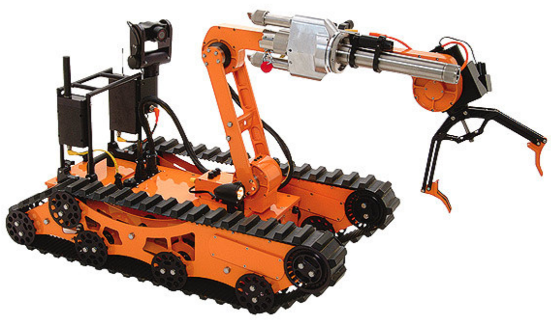


Figure 1.4. Vanguard™ MK-2
(Source: Allen Vanguard Co., 2005)

1.2.3. MK-5 EOD Robot by ESIT

MK-5 is a heavy duty EOD robot has two end effectors for different tasks. One is used for ordinary operations while the other is used for high precision and dexterous operations (Figure 1.5). Two different grippers are presented but an autonomous tool changing system for grippers is not available, so the robot needs to return the control base to change the gripper when the other one is necessary (WEB_3 2005).

Figure 1.5. ESIT MK-5
(Source: ESIT Website, 2005)

1.2.4. Wheelbarrow Super-M by Remotec Inc.

In design principle, Wheelbarrow Robot is very similar to tEODor and MK-5 robots except its unique articulated track mechanism (Figure 1.6). Depending on the end effector type, the manipulator arm has 5-7 degrees of freedom and actuated by both linear and rotational motors. A pneumatic system is used in tool connection between grippers and robot arm. Despite a pneumatic system an operator is needed to change the gripper (WEB_4 2005).

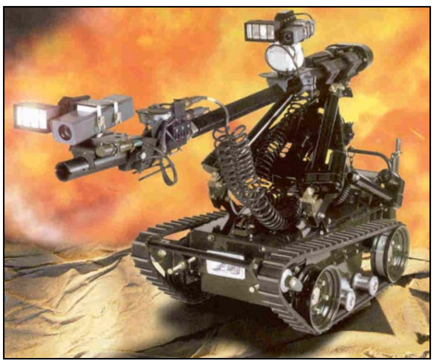


Figure 1.6. Wheelbarrow Super M
(Source: Remotec Inc., 2005)

1.3. Common Problems of Current EOD Robots

The systems are presented to the market with different arm and gripper designs having 6-7 degrees of freedom. Considering the range of tasks to be accomplished during operation, one type of end effector design is insufficient, so two or more alternative end effectors are presented by the manufacturer. However, in order to change the end effector, the robot must be called back to the base and this causes time lost. Therefore they need to have automatic quick changing joint. Currently used possible quick changing joint mechanism powered by pneumatic, hydraulic or magnetic systems. The advantages and disadvantages of these systems are summarized below.

1- Pneumatic system requires some extras component such as air compressor or tank with compressed air, solenoid control valves, vacuum generators, filters, regulators and pneumatic cylinders. When such a system is used on a robot, it will increase the weight of the robot and consume too much energy of the battery of the robot.

2- Hydraulic system also requires specific components such as hydraulics pumps, valves, oil tank and filters. This will increase the weight and cause extra energy loss.

3- If the magnetic field generating systems are used such as electromagnetic components in tool changing process, the magnetic field produced by an electromagnet may affect the triggering mechanism of special type explosive ordnance during bomb disposal process. This may be resulted with explosion of ordnance which cannot be accepted.

1.4. Alternative solutions

An alternative way of gripper changing process is equipping the robot arm with different types of grippers so they are placed on the robot arm all together like a tool magazine of a CNC machine. The operator selects the right tool and sends a signal to activate that tool. In this way, robot does not need to make extra work in order to change the tool. However all these tools would make the robot arm heavier so it would need more powerful actuators and battery to make the motion of arm. This design would be too bulky and more difficult to control.

1.5. New Approach

Different types of grippers can be placed on a magazine on the EOD robot's body. In order to use the desired tool the arm leaves the current tool and picks up the desired one. Thus robot arm needs a special mechanism in order to change its tools automatically. With this mechanism the connection process becomes feasible in both fastest and easiest way without bringing any weight or space disadvantages to the robot. The name of the new approach is called "quick changeable joint". With this mechanism a robot will be able to change its gripper quickly by doing simple motions of arm. The function of this joint is only to provide tool changing process hence it is not responsible for increasing the degrees of freedom like the other conventional joints of the robot.

With the designed joint, the robot does not require an extra actuator to perform tool changing process. Thus the magnetic field production on the arm remains constant at low levels. Consequently the new approach comes with various benefits which would increase neutralizing capacity of EOD robots. The list of the main advantages of a quick changeable joint can be listed as;

- Minimizing the magnetic field production on the gripper.
- Not requiring use of pump, tank, and valves of fluid systems.
- Not making the robot bigger and heavier.
- Providing easy and fast changing of tools.
- Eliminating the risk of using high pressure systems on the robot.
- Making the robot ready for automatic tool changing.
- Wiring for the tools become simpler.

1.6. The Scope of the Project

In the scope of this project, four different quick changeable joints are designed and produced and they are tested by the test machine which is also designed and produced. The best joint design is determined according to the test results in such criteria; lifespan, strength, weight, number of components and connection speed. The stages of the whole project are listed below;

1. **Designing of four different joints:** Quick changeable joints with four different working principles are designed in the 3D CAD software.
2. **Designing of the testing machine:** The pneumatic powered test machine is designed by considering the working requirements of all joints.
3. **Manufacturing of the joints:** All the parts of each joint are produced with the material of Aluminum-T3 alloy by the conventional lathe and milling machine.
4. **Manufacturing of the test machine:** The frame of test machine and the vertical lifting mechanism are manufactured and assembled with the pneumatic components.
5. **Testing of four different quick changeable joints:** Each joint is tested with the test machine to find its life cycle.
6. **Evaluation of the test results:** All joints are evaluated according to the design parameters to find the best suitable design for the EOD robot.
7. **Evaluation of the joint in other applications:** Each joint and its suitable application area are investigated by the results of the evaluating criteria.

CHAPTER 2

MECHANICAL DESIGN OF JOINTS

In this chapter, the design constraints are determined and four different quick changeable joints are designed according to these design constraints. Joints designs are accomplished with Solid Works© 2004. The parts of joint designs are described, the working principles and the connection and disconnection process of each joint are explained.

2.1. Design Constraints

In order to make a joint quick-changeable and automatic, some design constraints have to be defined. These constraints are listed below;

1. The robot arm is expected to carry 10 kg load maximum. The connection must withstand the bending moment caused by a 10 kg load.

2. It is aimed that the arm must pull and push a 100 kg load without lifting the load. Variable friction coefficients must be considered and joint must withstand the tensile stress caused by the friction of 100 kg load.

3. The joint design must be able to provide completely automatic tool changing process.

4. No extra actuator for the connection mechanism is allowed.

5. Only the motion of arm is allowed for the activation and deactivation of connection mechanism between the arm and the gripper.

6. Joint must allow the transmission of load, torque, control signals and electricity from the arm to grippers.

7. The joint should be at optimum weight which is less than 2 kg where it has enough mechanical strength required in constraints 1 and 2.

2.2. Existing Similar Solutions

The commercial mechanisms for tool holding are investigated. Lathe chuck and drill chucks are typical examples of such a system. In the Figure 2.1, a commercial drill chuck is shown. As the rotary part is turned, claws gets closer to each other and the drilling bit is clamped. Same principle can be used in a quick changeable joint design project. However, this mechanism requires a continuous rotary motion through the manipulator. This means an extra actuator will be needed for this task which is a conflict with the design constrains.

Figure 2.1. Typical drill chuck
(Source: ATC Machining Co., 2006)

Another mechanism is the tool holder (magazine) of CNC machines. A conical shaped tool end is clamped to the rotary head with conical grove. As the tool draws closer to the head a pneumatic system produces vacuum force to hold the tool on the rotary part. Since the pneumatic system is used in this technique it can not be used in the mechanical quick changeable joint design because of requiring a compressor and pressure tank.

Figure 2.2. Typical CNC tool magazine
(Source: ATC Machining Co., 2006)

2.3. First Joint Design

Basically, the first design is based on a simple slider mechanism. This design requires an arm motion with 2 degrees of freedom. In other words, in order to lock and unlock this joint, robot arm must move in two different axes.

This joint design is direction dependent design which means that there is only one way of locking of male and female part. The male part can enter the female part only at two symmetric positions.

2.3.1. Components of First Joint

The internal design and components of the joint are illustrated in Figure 2.3. There are two main parts called male and female part. Female part forms of two pieces and contains two horizontal and two vertical slider pins and springs. Pins are grooved in an upper side of the female part and they can move inside this groove.

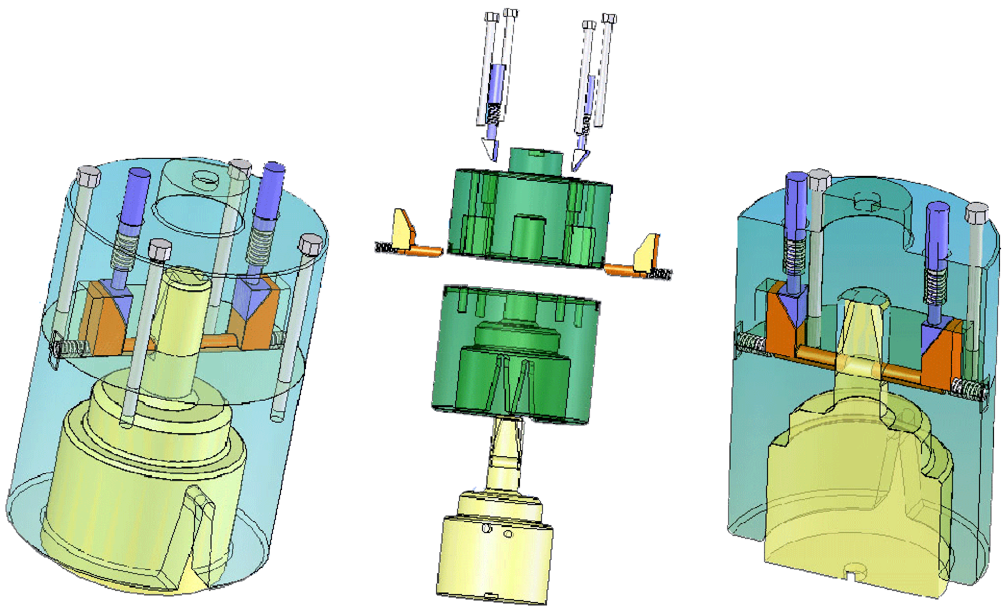


Figure 2.3. An internal, exploded and section views of first joint

2.3.2. Working Principle of First Joint

A working principle is illustrated in Figure 2.4 by showing two discrete positions. Figure on the right side shows locked position and right figure shows unlocked position of the joint. In the figure with locked position, when the vertical forces applied on top of the pins, vertical sliders start sliding down and makes the horizontal sliders moving left and right directions. Horizontal pins come out of the locking hole of male part, causing the male part separating from the female part. Locking pins are carried back by springs.

The lateral triangular shaped slots in bottom female part of the design let the male part enters to the female part at the right position and angle with 20° of tolerances.

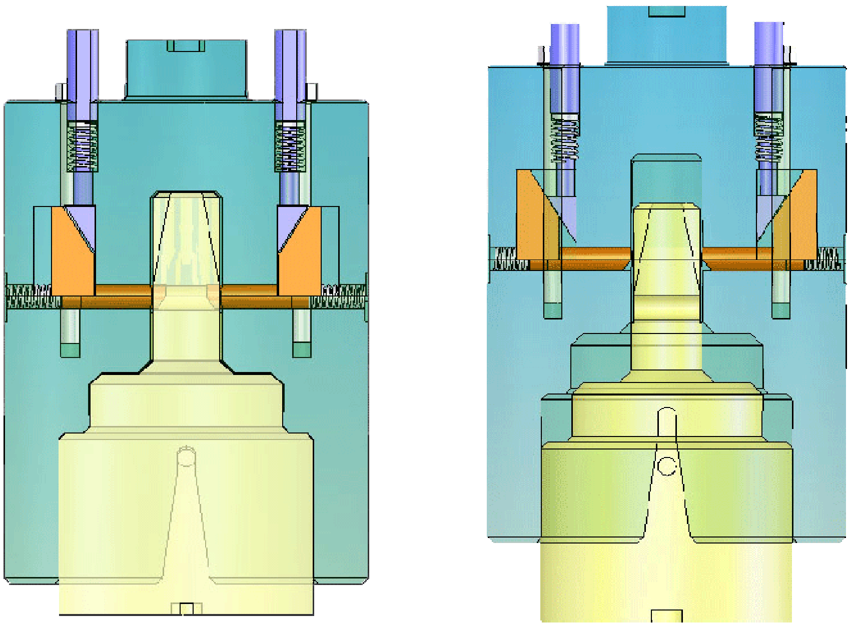


Figure 2.4. Locked and unlocked position of first joint

2.3.3. Connection and Disconnection Procedure of First Joint

Figure 2.5 shows the connection and disconnection processes of the joint design. In order to hold the gripper, the arm comes on top of the gripper. And starts going down to the gripper, after male part is completely taken into the female part, the locking mechanism is activated and it is locked.

To release the gripper, the arm pulls the female part against to the holder. By this way, vertical pins are pushed and horizontal pins will are released the male part equipped with gripper.

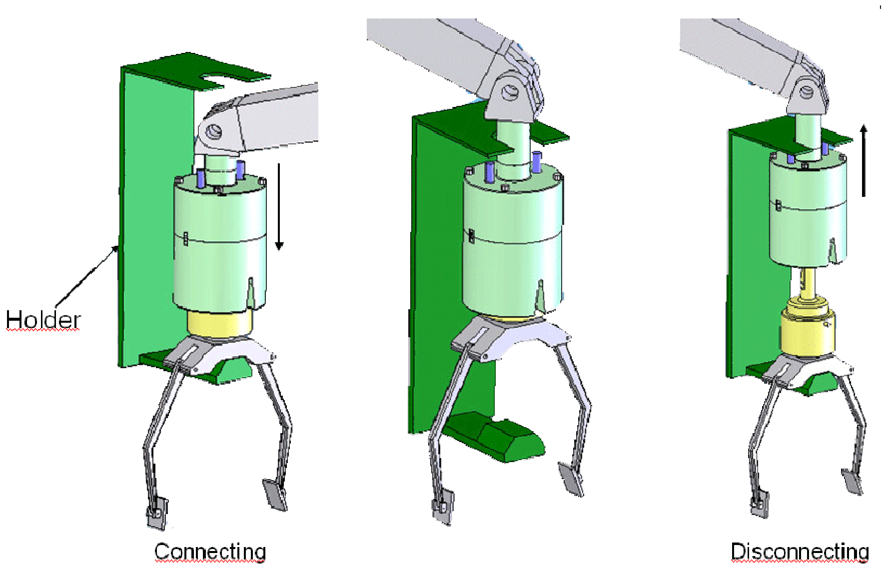


Figure 2.5. Connection steps of first joint

2.4. Second Joint Design

The theory behind this joint design is basically based on disk brake mechanism of automobiles. It requires 2 degrees of freedom motion in order to lock and unlock itself. Only vertical motion is enough for locking where both horizontal and vertical motions are required for unlocking.

The connection of second joint is achieved with direction independently which means male part has no certain entrance angle and position because of its 360˚ symmetric design.

2.4.1. Components of Second Joint

As shown in Figure 2.6 female part consists of two pieces which are called top and bottom pieces. The bottom piece has special grooves for the elements of locking mechanism. These elements are; one horizontal C-shaped segment, one activation button, two pins and spring.

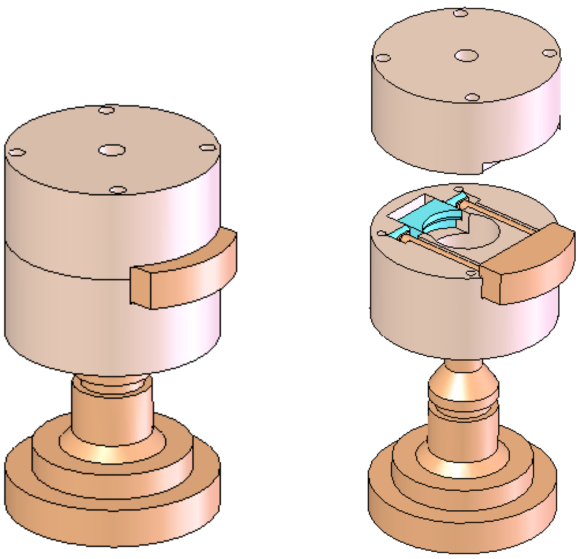


Figure 2.6. General and exploded view of second joint

2.4.2. Working Principle of Second Joint

The working principle of second joint is mainly same as the first joint. The C-shaped segment in the female part is penetrated to the male part which provides locking of male and female parts.

As it is seen in Figure 2.7, the unlocking process requires pushing the lateral button along to the center of the joint. By this way the locking segment comes out from the slot of the male part and causes the joint to unlock.

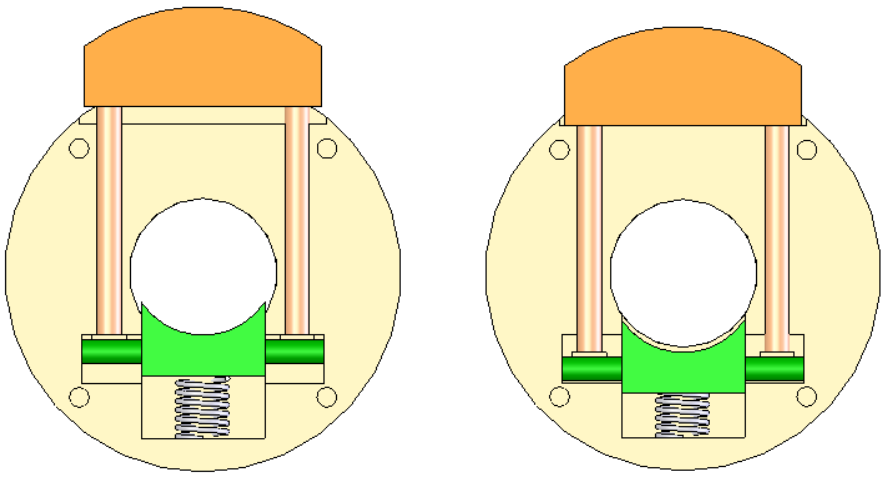


Figure 2.7. Locked and unlocked position of second joint

2.4.3. Connection and Disconnection Procedure of Second Joint

Connection process is very simple for this design, the arm equipped with female part comes on top of the male part which is attached to the gripper and by moving downward the joint gets locked.

When the robot needs to change its gripper, it should make horizontal motion in order to push the button against to the wall of tool holder on the robot's body causing the male part with the gripper to detach. The disconnection procedure is illustrated in the Figure 2.8.

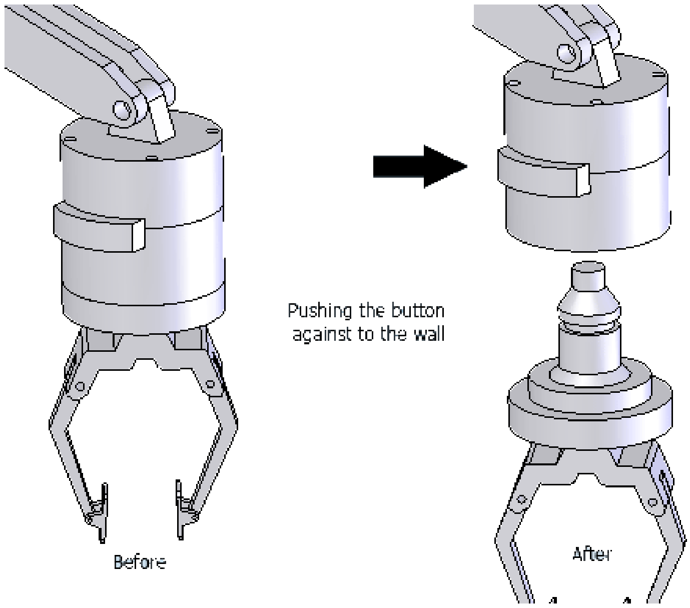


Figure 2.8. Disconnection procedure of second joint

2.5. Third Joint Design

The working principle behind this joint design comes from a locking mechanism of a door. As it is same with the door locks, female part of the joint must be able to turn with 90° angle in order to provide connection. A vertical and a rotational motion are required for this joint.

2.5.1. Components of Third Joint

This joint forms of a few basic parts which is easy to manufacture and assemble. Figure 2.9 shows the components of the joint. In the male part there is one T shaped locker element, and there is a ring around the T shaped part which is supported by the spring.

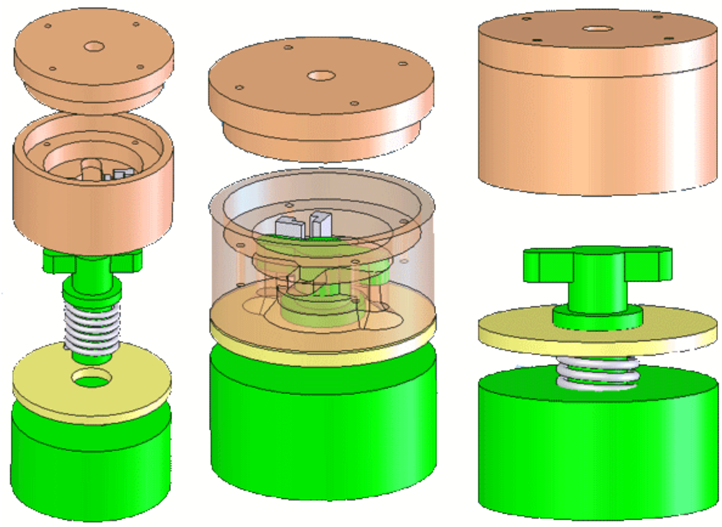


Figure 2.9. Exploded, internal and general views of third joint

2.5.2. Working Principle of Third Joint

The T-shaped locker part enters to the hole of the female part and female part turns 90 degrees with the help of the robot arm. When the turning process is completed the joint is locked itself automatically as shown in Figure 2.10. In the locked position of joint, it is not possible to turn the male part in the female part.

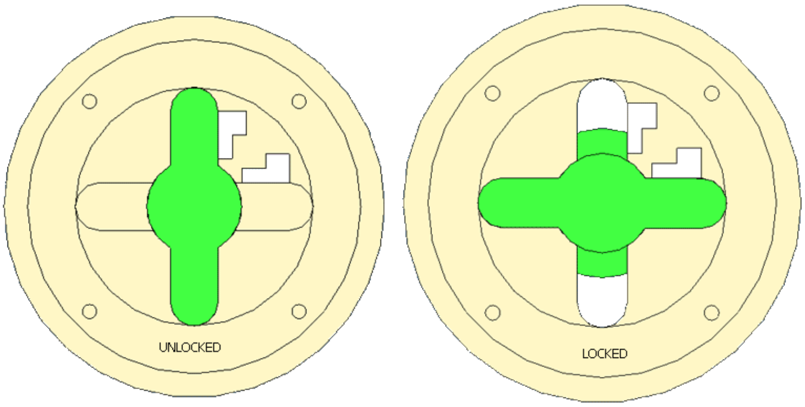


Figure 2.10. Locked and unlocked positions of third joint

2.5.3. Connection and Disconnection Procedure of Third Joint

The arm comes on top of the griper, and by moving down the male part enters through the female part. The arm applies vertical force to compress the spring in the joint, until the top part of male part hits to the inner surface of the female part. To activate the locking mechanism female part must turn 90 degrees clockwise with the compressive force. In order to unlock the joint, the female part should be rotated counterclockwise. Figure 2.11 shows the disconnection procedure.

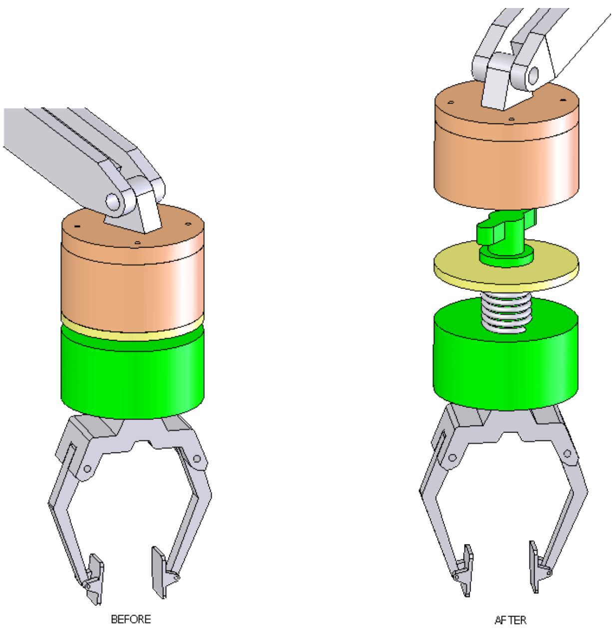


Figure 2.11. Disconnection procedure of third joint

2.6. Fourth Joint Design

The idea behind this joint is similar with the switch mechanism of pens. There are two positions on its cam mechanism. One position of the cam is used for unlocking the joint while the other position is used for locking the joint. Therefore one motion is used for both locking and unlocking of the joint which means it requires only one degree of freedom motion of the robot arm.

2.6.1. Components of Fourth Joint

As it is seen in the Figure 2.12, this design has more parts than the others. As similar with the other female parts, it consists of two portions and some groves for the latching elements. Male part has much simplest design in contrast to the female part. In the upper portion of female part there are three groves located with 120° angle symmetrically. And there are one gear, one unidirectional bearing, one ball and one cam in each grove. And to activate gear mechanisms there are three identical worm geared pins and springs and a support wristlet for pins.

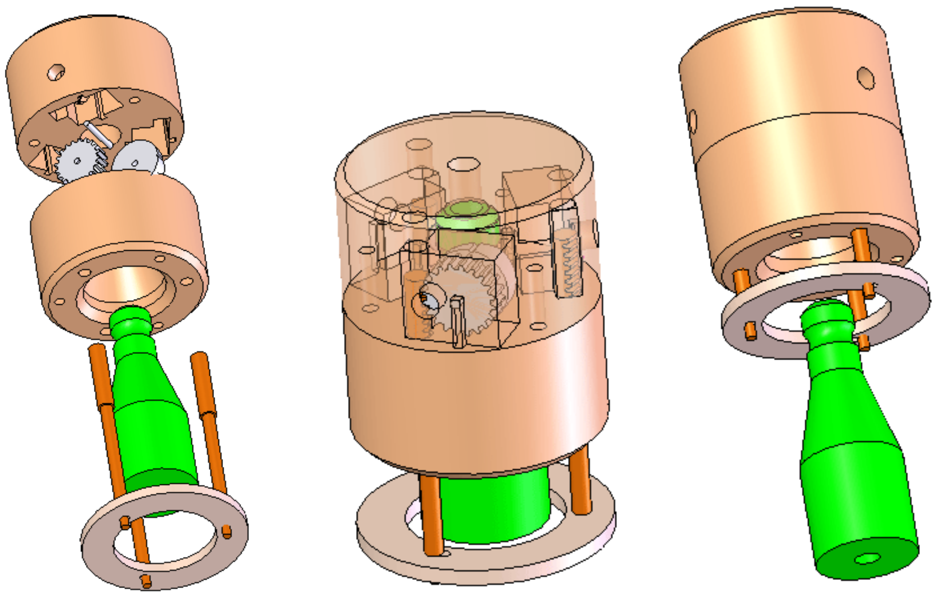


Figure 2.12. Exploded, internal and general views of fourth joint

2.6.2. Working Principle of Fourth Joint

When the geared pin is pushed, pin forces the gear to turn around a half cycle (Figure 2.14). The bearing located at the center of the gear is locked and rotates both the shaft and the cam attached to the shaft. The cam is turned from the lower position to the upper position causes the ball to come out its hole (Figure 2.13). This causes the male part to be locked in the female part. So the force exerted by the robot to the pins can be stopped. When the geared pin is pushed back with help of spring, the gear turns in reverse direction while the cam does not rotate. To unlock the joint the same operation must be done.

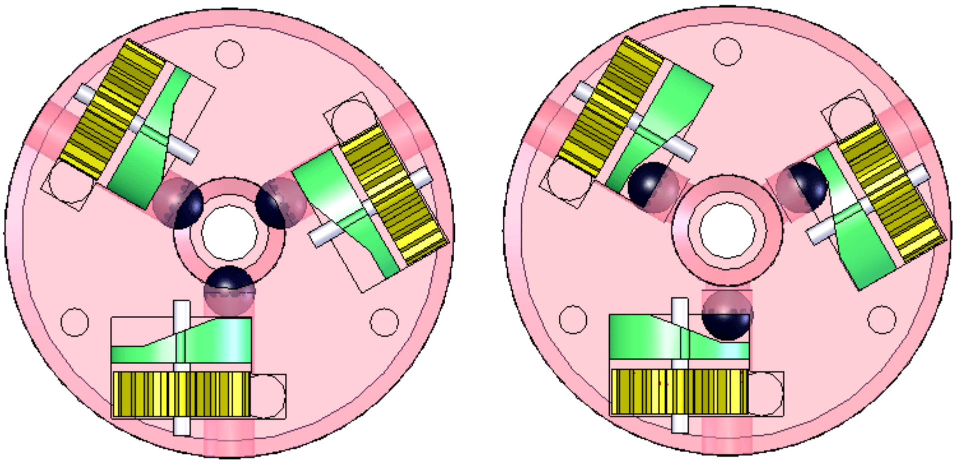


Figure 2.13. Locked and unlocked positions of fourth joint

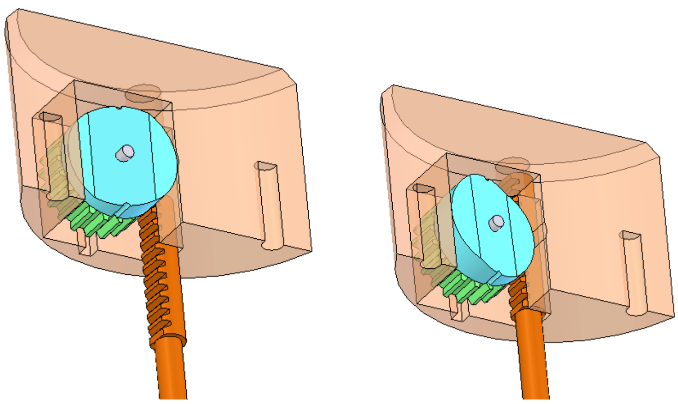


Figure 2.14. Rocker pin and cam before and after pushing

2.6.3. Connection and Disconnection Procedure of Fourth Joint

The robot arm comes on top of the gripper located in the magazine of the robot body and get closer to the gripper till the bracket contacts to the magazine (Figure 2.15). Then pushes the female part of joint against to the magazine since the pins of the bracket is completely come into the female part, so the male part is locked. In order to release the gripper, the robot needs to do the same procedure for locking the gripper. This joint is different than all the other joints by only requiring 1 vertical motion to lock and unlock the gripper to the arm.

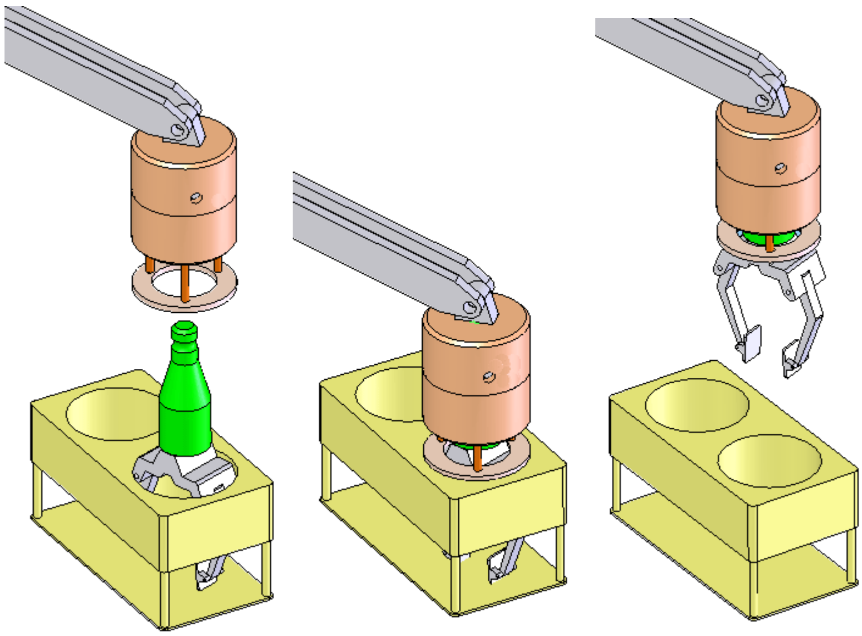


Figure 2.15. Connection procedure of fourth joint

2.7. Control and Power Signal Transmission in Quick Changeable Joints

Quick changeable joints should allow the power and control signals to the gripper to be passed. In order to achieve the power and control signal transfer, electrically conductive plates on both inside the female part and tip of the male part are placed. These transmission plates are inside of each others and are in ring shapes. The Figure 2.16 shows the power and control signals connection for the second joint design.

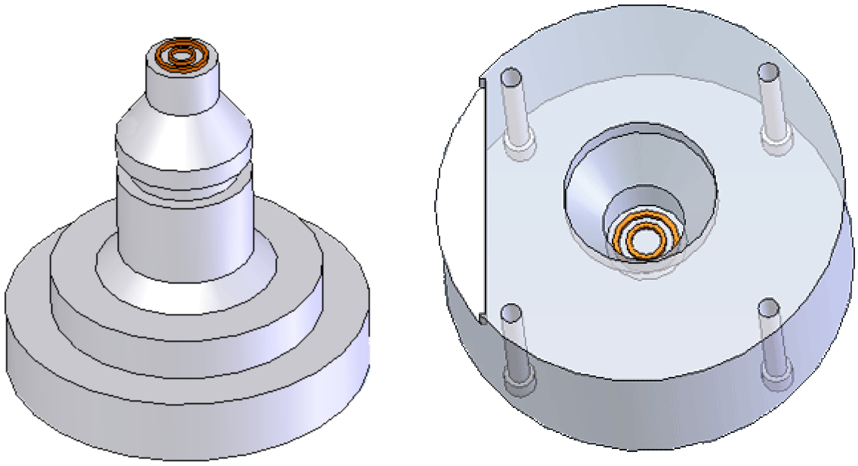


Figure 2.16. Transmission plates on second joint

CHAPTER 3

TEST MACHINE DESIGN

The test machine is required for finding quick changeable joints life spans and reliabilities. The test arm on the machine can move upward and downward with pneumatic actuators. This machine achieves the motions of EOD robot arm which is necessary for locking and unlocking the quick changeable joints. While moving up and down, the test machine has some additional pneumatic actuators to do auxiliary motions turning of quarter revolution and horizontal displacement which is required for the joint disconnection.

In this chapter the mechanical design of the test machine including working principle, machine parts and testing procedure is examined. Electronic control system and its components are also explained.

3.1. Mechanical System Design

The mechanical parts of the test machine are designed in order to meet the requirements of quick changeable joints. All joints need to be lifted in vertical direction where Joint 2 and 3 need an extra motion to activate their unlocking mechanisms. Figure 3.1 shows the test machine made of iron with a vertical lifting mechanism and one horizontal triggering mechanism. This lifting mechanism moves along the vertical path and provides joint connection with lifting the female part where the male part is attached to the vertical pin located at the bottom of the table. Horizontal arm located on the side of the table is used to attach a cylinder to make a horizontal pusher for second joint design. The simple design of the test machine provides ease of manufacture.

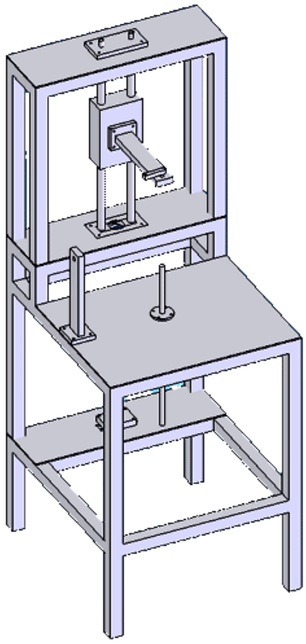


Figure 3.1. 3D design view of test machine

3.2. Pneumatic System Design

As an actuation system pneumatics is preferred in the testing machine because of its high speed and easy usage. Test machine has one testing arm which the female part of quick changeable joint is attached. The male part of the joint is stayed on the bottom surface of the testing machine. Two cylinders are used in vertical motion of arm to create three positioned motion. There is also another short stroke cylinder for horizontal motion to push the button of second joint or to turn the female part at 90° angle of third joint to unlock. Figure 3.2 illustrates the basic circuit of pneumatic system. The pneumatic components and the working principle of the components are explained in the next section.

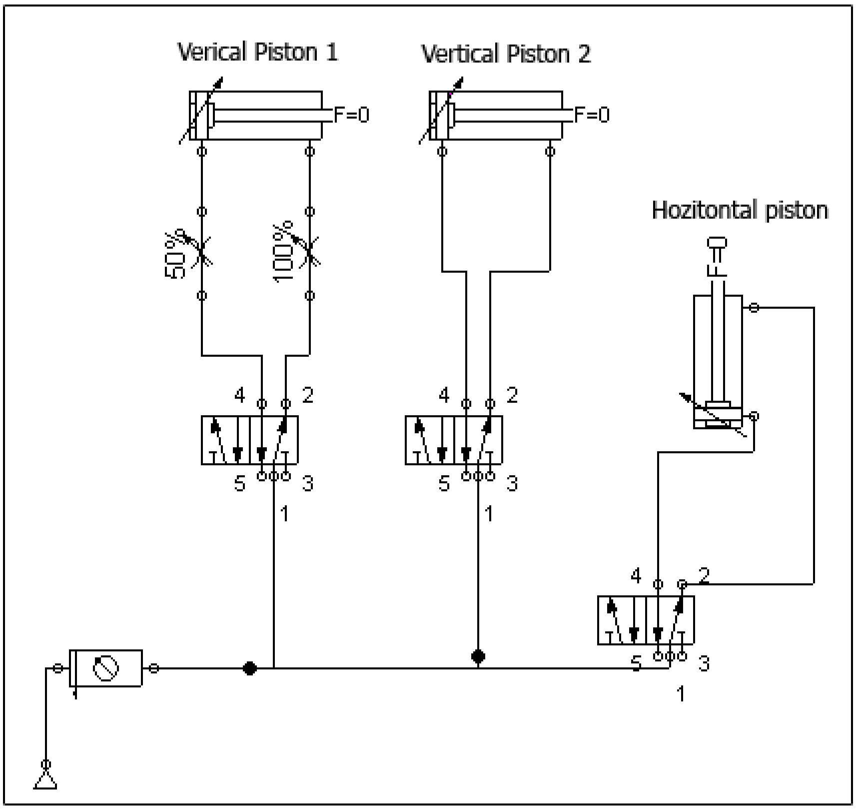


Figure 3.2. Pneumatic system circuit of the test machine

3.2.1. Pneumatic Components of the Test Machine

The main linear actuators of the pneumatic systems are cylinders. There are many kinds of cylinders due to the diameters and the stroke lengths. Diameter determines the force exerted by cylinder where the stroke determines the distance between two positions of the cylinder shaft. In this project there are three cylinders with different strokes; 25, 100 and 200 mm with equal 25 mm diameter.

Pneumatic cylinders are controlled by special type valves. These valves drive the cylinders by canalizing the compressed air through the gates of the cylinders. Generally valves have one air inlet, two cylinder outlets and two for the air exhaust. The gates connected to the cylinders named A and B ports. The exhausting ports are R and S outlets. And the P port is compressed air inlet. When the valve is activated, it connects both compressed air inlet P to the outlet B and the air exhaust R to the outlet A, so the shaft of cylinder changes its position. The activation of pneumatic valves is achieved with electricity.

Air source treatment unit includes filter, regulator, filter regulator, and lubricator, or their combined dyad or triplet. It is in standard modular design and can freely separate and combine. It can meet all requirements of pneumatic system. Regulator valve adopts balanced inlet structure with the advantages of stable pressure, high precision, and quick reaction. Lubricator is an element which can provide good lubrication for pneumatic system, with easy adjustment of oil drip.

3.3. Electronic System Design

The main goal of an electronic circuit is to control the pneumatic valves and provide motion of the test arm in order to make connection and disconnection of the joints. While the joint is testing, a trial number is counted by a micro-switch controlled by the electronic circuit.

A special control circuit is required for the test machine to control the pneumatic valves. For the four different joint designs there are four different connection processes. For example first joint design only requires upward and downward motion while the second joint design requires both vertical and horizontal motion. Because of this fact, an electronic controller is needed to control different valves in different sequences for each joint design.

Because of its simplicity and reliability the PIC16F877 is used in the control circuit. This microcontroller runs at wide speed range up to 20 MHz. It has 33 I/O pins which are grouped under 4 main ports called Port A, B, C and D. These ports and pins can be able to configure as an input or output individually.

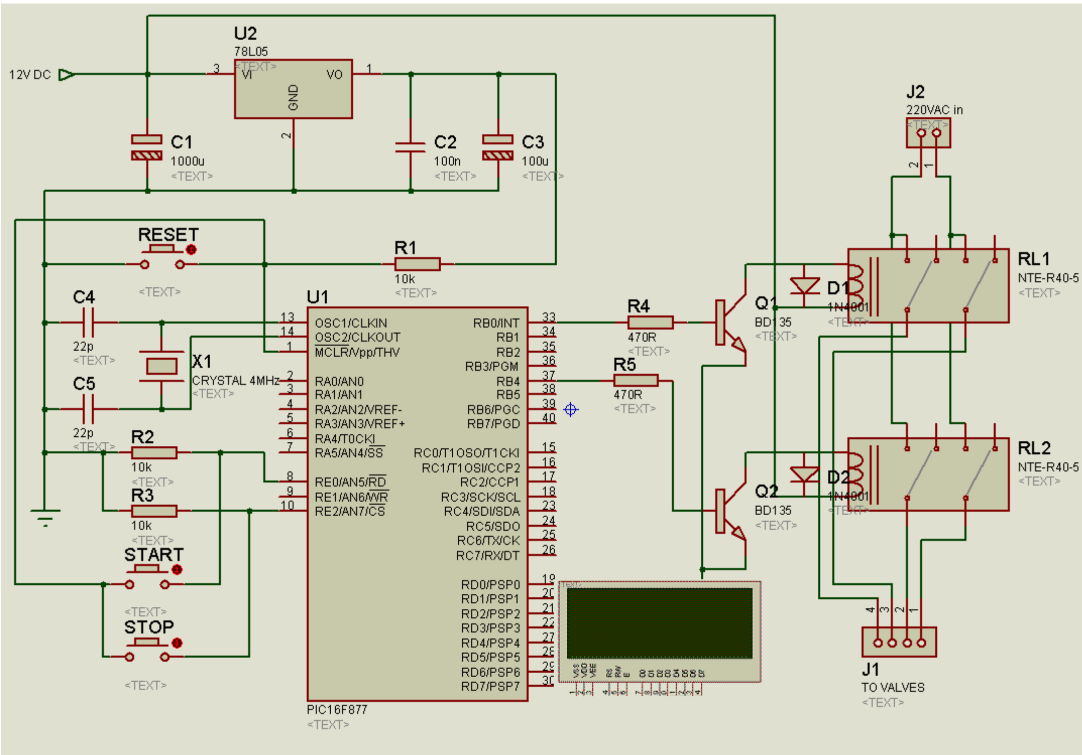
3.3.1. Electronic Components of the Control Circuit

The electronic components in circuit work under the voltage of 5V, so 12V DC voltage supplied by battery is reduced to the 5V DC with 7805 voltage regulator and it is filtered by the high-pass and low-pass capacitors C2 and C3 (Figure 3.3 and 3.4).

PIC16F877 runs at 5V DC and at the speed of 4 MHz which is determined by the oscillator crystal. The parallel 22 pF capacitors are used for eliminating the noises to affect the oscillator in the circuit. Two double contact relays of 12V nominal voltage are triggered by BD135 transistors and protected by 1N4001 diodes. These relays switch the pneumatic valves connected to terminal J1 and J2 with the input voltage of 220VAC.

A four line Hitachi compatible character LCD is used in the circuit for showing the number of connection for the joints. The LCD uses parallel communication via Port D of PIC16F877.

Three push buttons were used in order to collect input parameters such as joint type, start or stop command for the test process and resetting the system. And a micro-switch located under the male part of the joint is connected to the input port of the PIC to make an input signal during the connection of the joint.



Pneumatic test machine controller circuit scheme

Figure 3.3. Circuit scheme of the test machine controller

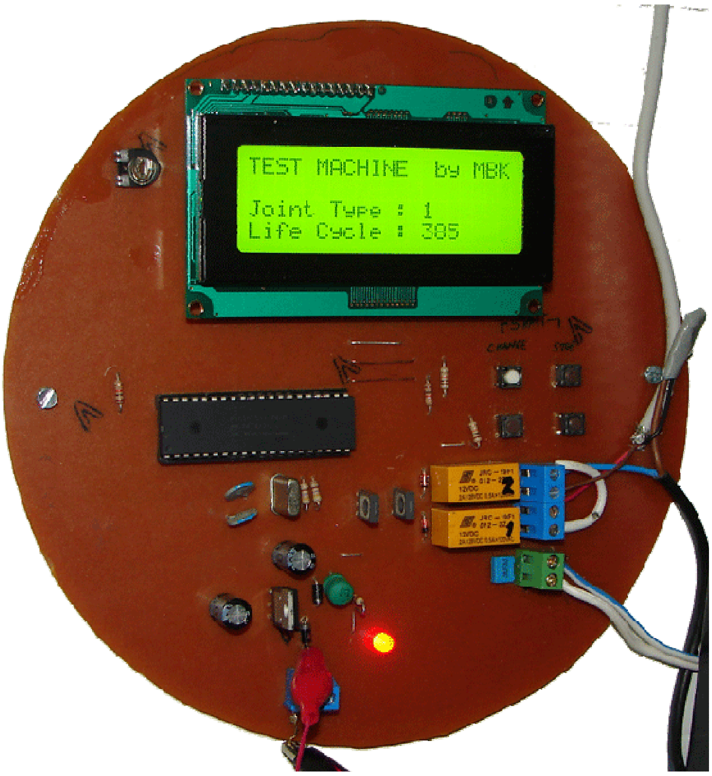


Figure 3.4. Finished view of the test machine controller circuit

3.3.2. Program code for Microprocessor

A program code for PIC 16F877 is written in PIC BASIC which is much easier to learn and use than the other programming languages such as PIC C, PIC Java or PIC Assembly. The whole PIC Basic code is given in Appendix A.

CHAPTER 4

MATERIAL SELECTION

4.1. Commonly Used Engineering Materials

Some metals and their alloys can be considered as engineering materials to be used in this application. These are iron, aluminum and steel. Cast iron is a ductile and formable metal since it has enough yield strength for some certain applications. Shaping of this metal is much easier than the others.

Aluminum is the most preferable one because of its high machinability and low density. The weakest point of this metal is the mechanical strength which is less than cast iron. Therefore some high strength aluminum alloys are produced by the improving technology. One of these alloys is aluminum 2024-T3 which is used in many applications from car to aircraft industry where the high mechanical strength and the low weight is important.

Steel can be considerable when high mechanical strength is required while the weight is not important. In small machine elements such as gears and rocks steel is most preferred.

4.2. Selection Procedure

In order to select the optimum material for quick changeable joints, mechanical and physical properties of materials are considered. These properties are especially tensile strength, yield strength, shear strength, density and magnetic property. Table 4.1 shows the properties of the common metals and alloys.

Table 4.1. Mechanical and physical properties of some metals
(Source: Shigley, J.E., 1989)

Metals / Alloys	Yield Strength (MPa)	Tensile Strength (MPa)	Density (kg/m^3)	Shear Strength (MPa)
Gray Cast Iron	135	170	7830	45
Aluminum 1100	105	110	2710	28
Alumin. 2024-T3	345	483	2768	30
Steel AISI 302	520	860	7850	186

The point on the stress-strain curve where there is a sudden increase in strain, but no increase in stress is called yield strength. It is at this point that a metal is about to permanently deform. The metal with higher yield strength is more durable than the other materials. As it is seen in Table 4.1 steel has largest strength but aluminum-T3 has enough strength when the constraints are considered.

Ultimate tensile strength is a material's ability to resist forces that attempt to pull it apart or stretch it. This is another important factor desired for joint parts. The more ductile material has the less tensile strength. Thus, it is recommended for materials to have high tensile strength. Steel and aluminum-T3 have the greatest tensile strength values.

Density is a measure of mass per unit of volume. The higher a material's density, the higher it's mass per volume. Steel has the largest density value while aluminum has the lowest density value. This means aluminum is much lighter than the steel since both lighter and stronger materials are most preferred in robotic applications. Aluminum 1100 alloy is light and weak but aluminum-T3 alloy is both lighter and stronger.

Shear stress, or just shear, is similar to stress, except that the force is applied such that the material is sheared or twisted. Aluminum alloys have the lowest shear strength according to the other metals in Table 4.1.

Magnetic property is an ability of materials to attract or repulse each others. Most metals can be easily induced and behave like a magnet or attracted by a magnet. However; only aluminum has non-magnetic property.

Because of its unique properties of aluminum-T3 alloy; it will be used in manufacturing of four different quick changeable joints and the test machine. Moreover the machining of aluminum-T3 is much easier than the other metals and alloys, and density is much lower than other metals, which means the weight of joints will be as low as possible. However; in some small parts like horizontal slider pins of first design or the horizontal buffer of second design are manufactured from steel 302 because of the required high shear strength. Since these are very small parts, they only cause a negligible 2% amount of weight increase.

CHAPTER 5

MATERIAL STRENGTH ANALYSIS

For the designed quick changeable joint mechanisms tension and shear situations are studied. For the tension case, pulling the 100 kg load (is given in Design Constraints at Chapter 2 Section 1) on a surface with average friction coefficient 0,9 creates a tensile stress on axial cylindrical section of the male part. The tensile stress is calculated as,

$$\sigma = \frac{F}{A} = \frac{4mg\mu}{\pi \cdot D^2} \tag{5.1}$$

Where, σ is tensile stress in MPa, F is for the force perpendicular to cross-sectional area in N, A is cross-sectional area under load in m^2, μ is coefficient of Friction and m for mass of load in kg.

In shear strength calculation, the force needed to pull 100 kg load causes a shear loading on locking elements of female parts. The shear stress is calculated with force acting parallel to the cross-sectional area of the part as,

$$\tau = \frac{F}{A} = \frac{4mg\mu}{\pi \cdot D^2} \tag{5.2}$$

Where, τ is the shear stress in MPa and F is for the force parallel to cross-sectional area in N

Strength analyses are completed by using CosmosXpress plug-in of SolidWorks© and the results are explained.

5.1. Tensile Stress and Factor of Safety Calculations

For tension case, the force F equals to the statically friction force of the 100 kg load between the average surfaces with the friction coefficient of 0,9 and this force is transmitted from the end-effector to the arm of the robot via the male and female part of the quick changeable joint. While doing this calculation, the weakest cross-section of the male part should be able to carry this force. This means the tensile stress on this cross-section must be in the allowable range of ultimate stress. The test region is illustrated in dark in Figure 5.1. By using Equation 5.1 the stress of the weakest section of first joint is found as 2,81MPa.

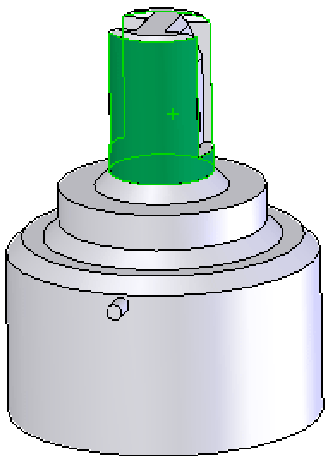


Figure 5.1. The weakest cross-section of the first joint

In order to find reliability of the component used in the joint, the factor of safety (*FS*) must be calculated (Equation 5.3). This measures how many times the stress capacity of joint component is greater than its nominal working stress. This provides an extra guarantee for the system. By using Equation 5.3 the factor of safety for first joint is found as 123.

$$FS = \frac{\text{Strength of Component}}{\text{Load of Component}} = \frac{\sigma_{yield}}{\sigma_{all}} \tag{5.3}$$

The yield strength for the material Aluminum-T3 alloy that is used to manufacture the joints is 345MPa. The section of male part with smallest diameter can carry up to 123 times greater tensile stress which is enough for this design where generally the factor of safety is taken as 10 in many engineering applications.

The same calculations are repeated for the other three joint designs. The Figure 5.2 shows the male part of the second joint. The smallest cross-sectional area is shown in darker color has the diameter of 24 mm where the other variables are the same with the previous design. The stress of the given section is 1,98 MPa under the pulling of 100 kg load and the factor of safety is found as 174.

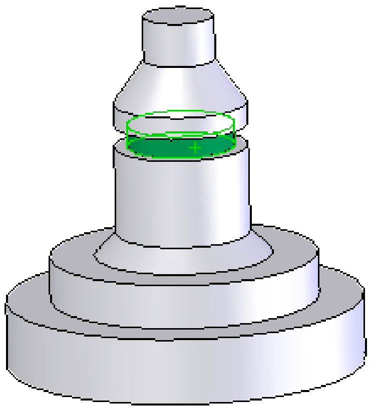


Figure 5.2. The weakest cross-section of second joint

In the male part of third and fourth joint designs, the minimal diameter *D* is 20 mm where the other parameters are same as the first joint design. Figure 5.3 and Figure 5.4 show the critical cross-section of the male parts. So the results are exactly same since their materials are both Aluminum T3 alloy.

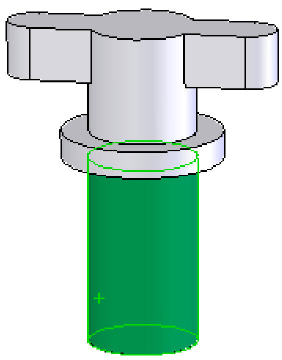


Figure 5.3. The weakest cross-section of the third joint

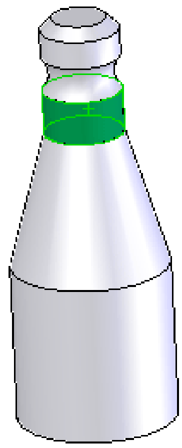


Figure 5.4. The weakest cross-section of fourth joint

5.2. The Shear Stress and the Factor of Safety Calculations

In shear stress case, the critical elements of the joints are horizontal sliders which are used for locking the male part. For the first design, as it is seen in the Figure 5.5, the shear stress at the tip of the horizontal pin is calculated. The force F equals to half of the pulling load of 100 kg because of two identical horizontal pins are used to lock the male part and carry the load. The mass m is going to be taken as 50 kg. The distance between the parallel force and fixed section is in d length and the diameter of the pin is in D length. The shear stress is parallel to the force applied and the cross-sectional area of the pin with 6 mm diameter. For the first joint, by using the Equation 5.2 the shear stress is found as 15.6 MPa. And by using the Equation 5.4 the factor of safety is found as 1,9.

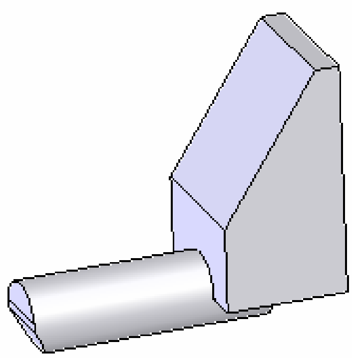


Figure 5.5. The weakest cross-section of first joint

The factor of safety for shear stress is calculated;

$$FS = \frac{\text{Strength of Component}}{\text{Load of Component}} = \frac{\tau_{yield}}{\tau_{all}} \qquad (5.4)$$

When the horizontal pin is manufactured with Aluminum T3 alloy which has the shear strength of 30 MPa, the factor of safety is found as 1,9 which is not acceptable. When Steel AISI 302 is used for this part, the shear strength becomes 186 MPa and the factor of safety is calculated as 11,9 which is much reliable and safe.

The critical part of the second joint design is horizontal buffer part which carries the load of whole system (Figure 5.6). The cross-sectional area A is 125 mm^2 with 25 mm length and 5 mm height, and the shear stress is calculated as 7,1 MPa and the factor of safety as 4,2. When Steel 302 is used for the buffer part then the FS is found as 26,2

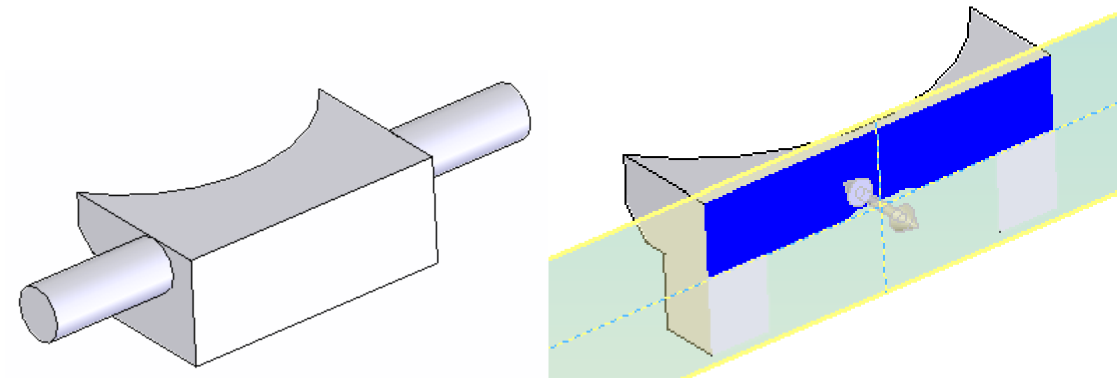


Figure 5.6. The weakest cross-section of second joint

In the third joint design since the T shaped part has symmetrical sections, the force exerted on each section will be half and the area of the cross-section is 100 mm^2. The T-shaped part and its cross-section are shown in Figure 5.7. The shear stress is found as 4.4 MPa and the factor of safety as 6,8 By changing the material to steel 302 the factor of safety is found as 42,2

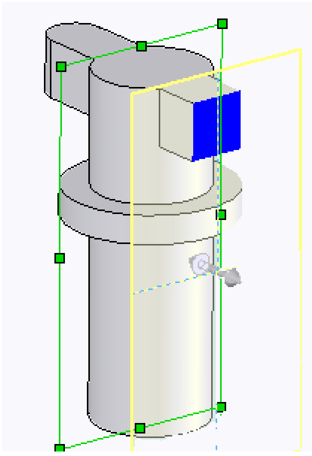


Figure 5.7. The weakest cross-section of third joint

For the fourth joint design the tip of the male part is subjected to the shear stress where the inner diameter of the fillet is 8 mm and the outer diameter is 10 mm. The cross-sectional area is shown in Figure 5.8. The shear stress is found as 31 MPa and the factor of safety as 1. By using steel 302 for the tip of the male part, the factor safety is found as 6.

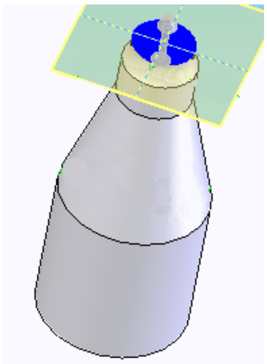


Figure 5.8. The weakest cross-section of fourth joint

In conclusion, the tensile stress, the shear stress and the factor of safety values are given for each joint in Table 5.1, 5.2 and 5.3.

Table 5.1. Tensile and shear stress comparison of joints for Aluminum-T3

Stress	Joint 1	Joint 2	Joint 3	Joint 4
Tensile Stress (Mpa)	2,81	1,98	2,81	2,81
Shear Stress (Mpa)	15,6	7,1	4,4	31

Table 5.2. Factor of Safety comparison of tensile and shear cases for Aluminum-T3

FS	Joint 1	Joint 2	Joint 3	Joint 4
FS for Tensile	123	174	123	123
FS for Shear	1,9	4,2	6,8	1

Table 5.3. Factor of Safety comparison of shear cases for Steel 302

FS	Joint 1	Joint 2	Joint 3	Joint 4
FS for Shear	12	26	42	6

5.3. Strength Analysis of Joint Parts with Computer Simulations

The static analysis and strength calculations are also computed by COSMOSXpress plug-in tool of SolidWorks©. The components of quick changeable joint designs are analyzed and modified if required. The software also determines the weak points of the structure and shows the deformed shape of critical joint parts with the material of aluminum-T3 under the excessive load which is 10 times bigger than the design load. Figure 5.9 shows the first joint bends from its junction point where the second joint deforms from its C-shaped side, the third joint bends from its horizontal arms and the fourth joint elongates by the length of its neck.

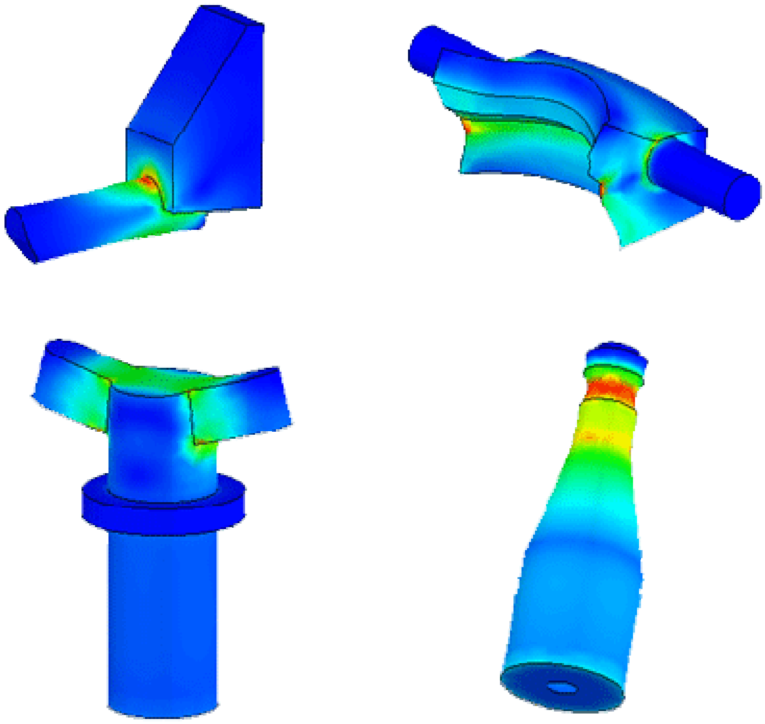


Figure 5.9. The stress distributions and deformations of joints under excessive load

5.4. Strength Analysis of Test Machine

The critical element of test machine is the arm part shown in Figure 5.10. During the testing process, the arm needs to push and pull the joint to lock and unlock it, causing bending stress. A vertical force applied by the arm is 50N which is enough for the locking mechanism. The cross-sectional area is 600mm^2 and distance between the force and the fixed point is 185mm.

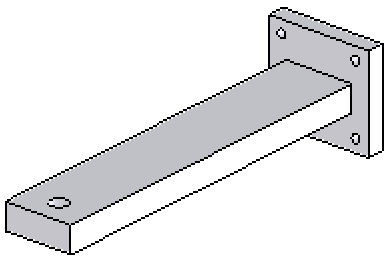


Figure 5.10. The weakest part of test machine

For the deflection Δy the equations of the strain and shear modulus must be given.

Shear modulus is: $S = \frac{ShearStress}{ShearStrain} = \frac{\tau}{\varepsilon}$ (5.5)

Where the Strain is: $\varepsilon = \frac{\Delta y}{d}$ (5.6)

The deflection Δy is calculated as $0{,}548 \times 10^{-6}$ m for the arm part which is negligible where the shear modulus of Aluminum T3 alloy is 28GPa.

By the result from the factor of safety and deflection calculations it is understood that there is no problem in strength of material on the critical part of the test machine.

CHAPTER 6

MANUFACTURING OF JOINT PARTS

In this chapter, the manufacturing processes are investigated on the first joint design as an example for every joints and the test machine.

6.1. Manufacturing of Joints

Generally lathe and milling machines are used in manufacturing the joint parts. Since the main parts are in cylindrical shape, they are all shaped by a lathe. All rectangular shapes are produced by a milling machine. The material of all joint parts is Aluminum T3 alloy which has high machinability and durability.

Figure 6.1 shows the components of the manufactured first joint. Figure 6.2 shows the components and the internal design of the manufactured fourth joint. Figure 6.3 demonstrates the male and female parts of the Joint 1, 2 and 3. Figure 6.4 shows the male and female parts of the fourth joint.

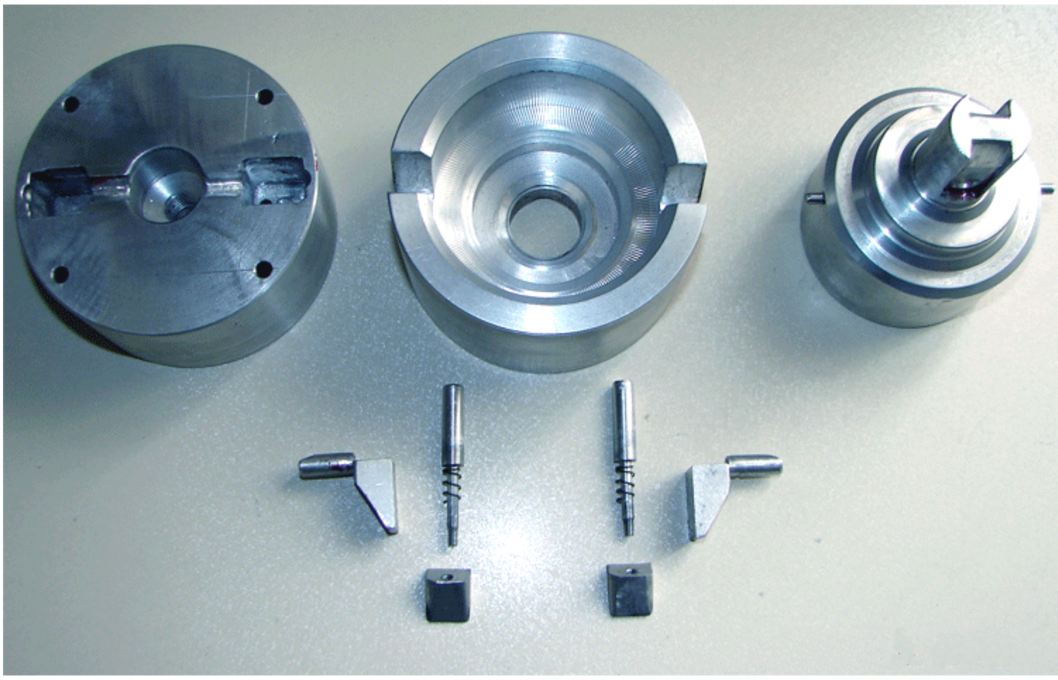


Figure 6.1. The components of first quick changeable joint

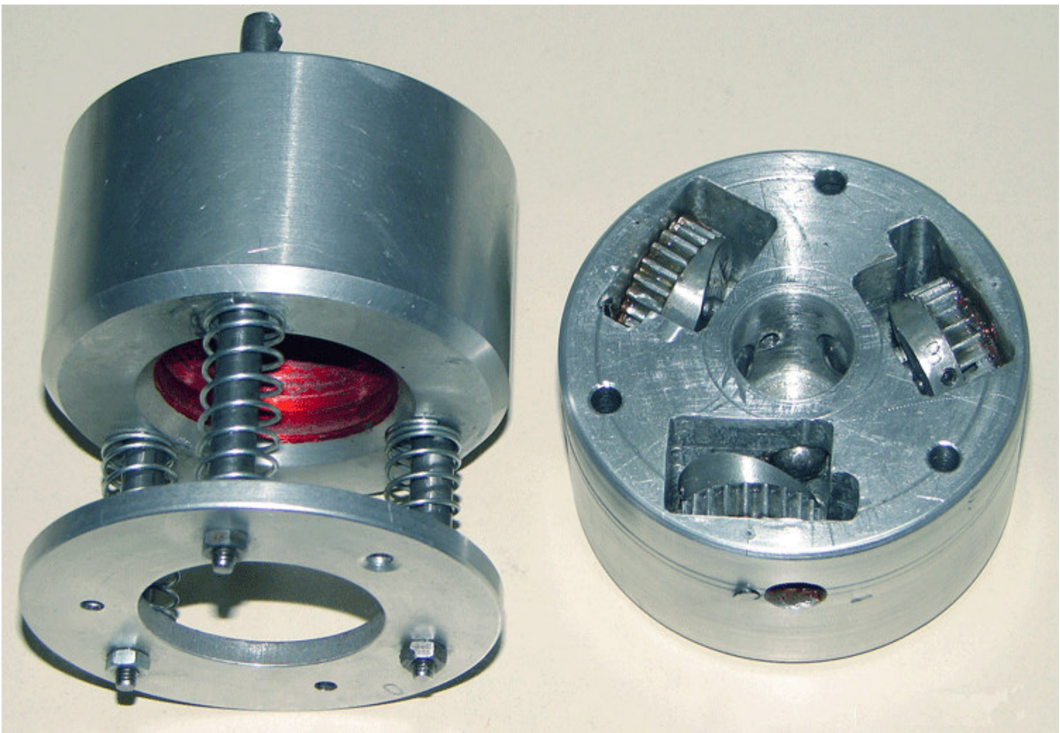


Figure 6.2. The components of fourth quick changeable joint

Figure 6.3. The male and female parts of quick changeable joints

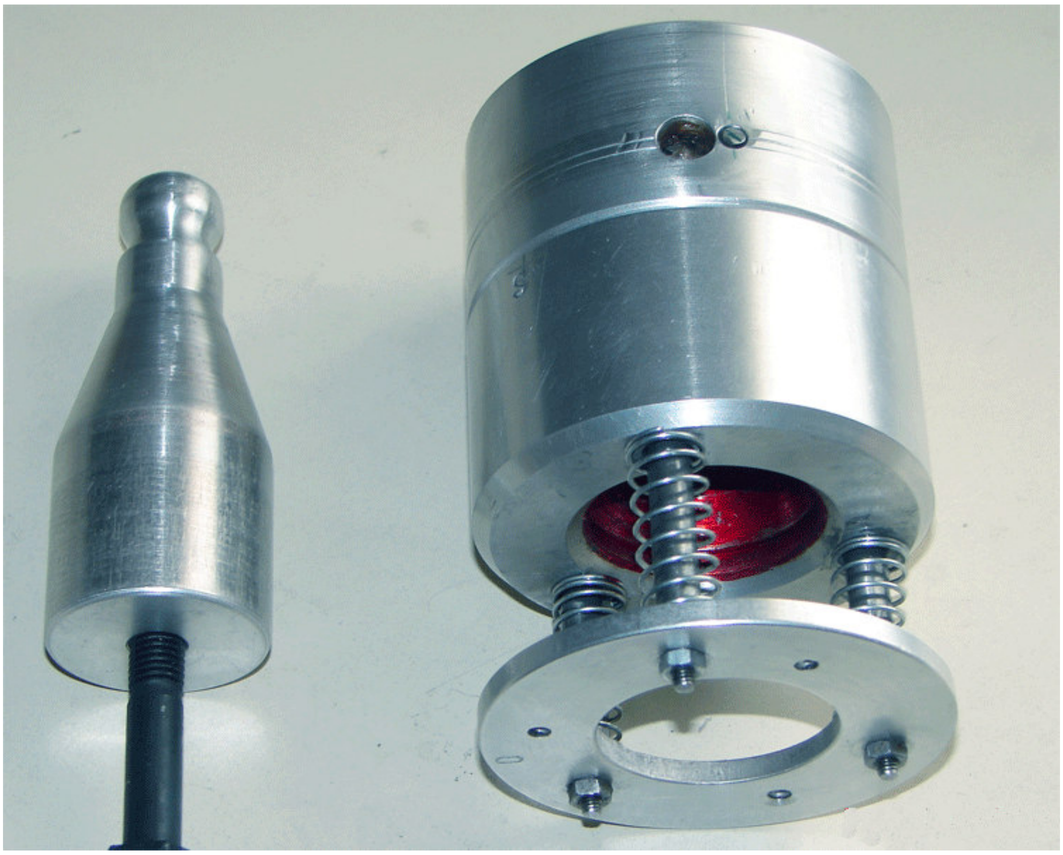


Figure 6.4. The male and female parts of fourth quick changeable joint

6.2. Manufacturing of Test Machine

Manufacturing of the test machine is explained in two stages. First stage is manufacturing of vertical lifting mechanism and the second stage is manufacturing of the iron test table.

In the first stage, a test arm and its vertical slider mechanism are produced from aluminum-T3. The test arm is milled from one piece. When it is considered that this part will be used for lifting and pushing the joints, bending and shear forces will occur because of this fact the test arm is produced as one piece. Figure 6.5 shows the manufactured vertical slider mechanism.

In the second stage, the test table is constructed by combining iron bars. Figure 6.6 illustrates the complete test machine.

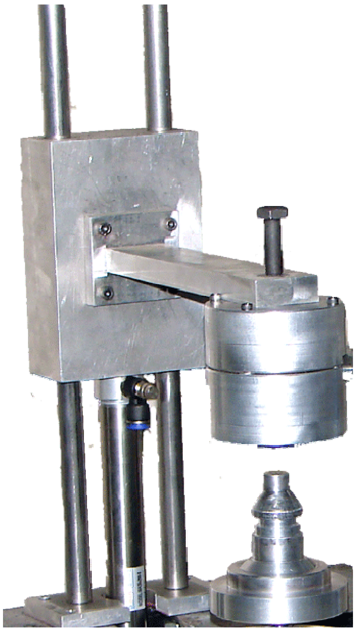


Figure 6.5. Vertical slider mechanism of the test machine

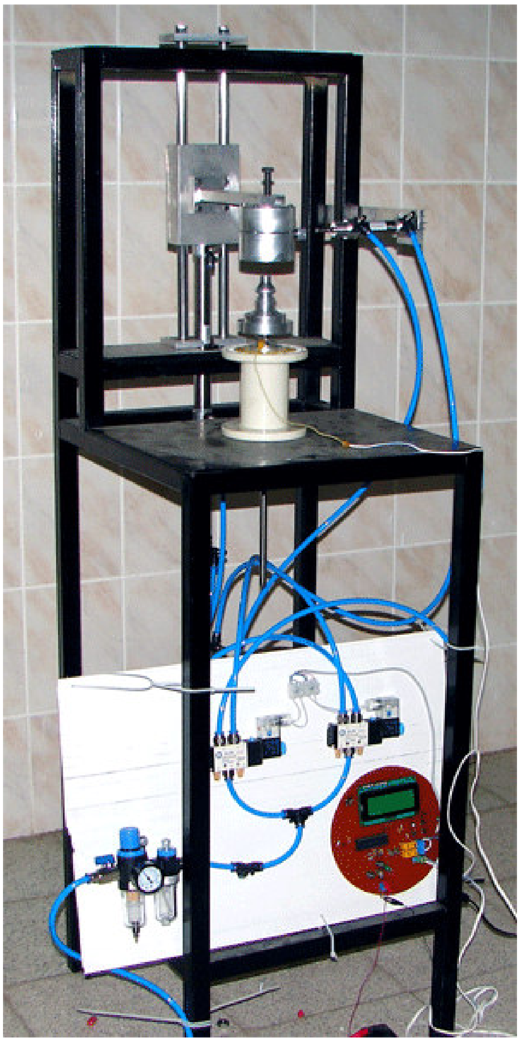


Figure 6.6. Life cycle test machine

CHAPTER 7

TESTING OF JOINTS

All joints are tested by test machine and it is understood that life spans of the joints are more than 1000 cycles. This reliability is considered satisfactory for joints which are going to be used in multipurpose EOD robots. In order to evaluate the performance of the joints other parameters are also considered. Table 7.1 shows the parameters and the joint values.

Table 7.1. A performance comparison of manufactured quick changeable joints

PARAMETER	JOINT 1	JOINT 2	JOINT 3	JOINT 4
Life Span (cycle)	>1000	>1000	>1000	>1000
Factor of Safety for Shear	2	4	7	1
Factor of Safety for Tensile	123	174	123	123
Weight (gr.)	1325	1300	1240	1430
Connection time (sec.)	2	3	4	4
Number of components	13	9	8	24
Usage simplicity	High	High	Normal	High
Reliability	Normal	High	High	Low
Required DOF of Arm	2	2	2	1

- **Pulling capacity:** Factor of safety is very important in transportation or some other human related facilities. If quick changeable joint is going to be used in connection of vehicles for pulling each others the factor of safety must be much enough. So in this type of applications Joint 3 can be useable. Because in 100 kg loading it has FS=7 for shear stress and FS=123 for tensile stress of critical part in the joint. It means this joint is capable of pulling 700 kg load without any shear in the critical part with the material of Aluminum T3. If only the material of critical part is changed with Steel 302 this increases pulling capacity up to 4300 kg in the same diameter of joint. In the EOD robot applications all joints can be used since they are all capable of pulling 100 kg load which is one of the design constraints of this project.

- **Weight:** Weight of the joint is very important when it is used in small machines. All joints are nearly at the same weights, so in EOD robot applications this parameter is not important in selecting the joint.
- **Connection time:** The connection time of quick changeable joint is vitally important in EOD robot applications which are mentioned in the first chapter. Thus for this project the joint with less connection time namely Joint 1 is preferred.
- **Number of components:** This property defines the reliability and manufacturing difficulties of joints. Manufacturing difficulties are not considered since this property does not affect the user. However, reliability is also very important for EOD robot applications. The joint with more components have increased possibility of joint failure. For an EOD robot Joint 3 has the minimum number of components and the higher reliability.
- **Simplicity:** Usage simplicity shows how easy is to lock and unlock the joint. The performance of joint for this property determines the complexity of arm motions of the robot. The joint 1 and 2 with most simple usability can be used in EOD robots.
- **DOF:** Required DOF of the arm shows how many different motion the arm should achieve to lock and unlock the joint. the Joint 4 has lowest DOF requirement.

By looking at all of these properties and their effects on the performance of the joints, Joint 2 is better in most of the parameters.

CHAPTER 8

CONCLUSION AND FUTURE WORKS

In the conclusion of this project, where more than one job is being performed by EOD robot and all of the necessary tools can not be assembled together, it may be necessary to use a tool changer. A completely mechanical quick changeable joint can do tool changing process while requiring basic motions of robot arm.

In this study, four unique quick changeable joints are designed and produced. Reliability and life cycle tests are done with these joints by using manufactured test machine. In the evaluation part it is proven that each joint has some properties better than the others. For example, by the properties of 360˚ symmetric design and non-rotating male part design, Joint 1 is much suitable for being tool holder for CNC machines where Joint 3 is suitable for the practical connection of vehicle pulling and load lifting applications with the property of high factor of safety. The Joint 4 is better if there is a limitation on degrees of freedom of the robot arm. However; when all of the parameters are considered, the joint which satisfies all parameters together must be chosen as the best quick changeable joint for EOD robot, which is Joint 2.

In future work, some modifications on joints can be done to abate their imperfections. By this way the usage area of quick changeable joint can be extended into many different areas such as many types of lifting and pulling applications and different tool changing applications. In the critical parts of the joints different steel alloys can be used instead of aluminum alloy and this will provide increment in lifting capacity of the joint. And the sizes of joints can be changed due to the requirements of new tasks.

In this thesis, the goal was to develop a quick changeable joint mechanism for multi-purpose EOD robots in order to improve their usability and efficiency which is achieved successfully. This joint will dramatically reduce the tool changing time of multipurpose EOD robots which can be very important in especially disposing time-based bombs.

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APPENDIX A

SOURCE CODE FOR CONTROL CARD

The program code for PIC16F877 is written for the control of pneumatic valves of the joint test machine. It is written in the language of PicBasic Proton.

```
‘ This program is written for controlling the pneumatic valves of joint test machine.
‘ Written by M.Bahattin KOR  in 10.05.2006
Device 16f877
Define OSC  4
DECLARE LCD_TYPE 0
DECLARE LCD_DTPIN PORTD.4
DECLARE LCD_ENPIN PORTE.1
DECLARE LCD_RWPIN  PORTE.2
DECLARE LCD_RSPIN PORTE.0
DECLARE LCD_INTERFACE 4
DECLARE LCD_LINES 4
Dim BPF as Byte SYSTEM ' Bring the system variable into BASIC
TRISA = %11111111
ADCON1 = %10000100
sayac var word
joint var byte
test var byte
role1 var portc.1 : role2 var portc.2
sayici var portd.1 : sol var portc.5 :sag var portc.4
output role1 : output role2
input sayici : input sol : input sag
joint=1 : sayac=0 : test=0
main:
lcdout $fe,2,  "TEST MACHINE  by MBK"
lcdout $fe,$C0,""
```

```
lcdout $fe,$94,"Joint Type : ",dec joint
lcdout $fe,$D4,"Life Cycle : ",dec3 sayac
if sol=0 and sag=0 then
  test=1 :    pause 100
  endif
if sol=0 and sag=1 then
  joint=joint+1 :    if joint>4 then joint=1 :    pause 100
  endif
if sag=0 and sol=1 then
  test=0 :  low role1 :  low role2 :  pause 100
  endif
if test=1 and (joint=1 or joint=4) then
  high role1 :  pause 1000 : gosub control : low role1 : pause 1000
  endif
 if test=1 and joint=2 then
  high role1 :  pause 1000 :  gosub control :  low role1 :  pause 600
  high role2 :  pause 1000 :  low role2
  endif
pause 300
goto main
kontrol:
if sayici=0 then
  pause 100
  if sayici=0 then
          sayac=sayac+1
          pause 200
          endif
  endif
return
‘ The end of the program code.
```

APPENDIX B

STRENGTH ANALYSIS WITH SIMULATION SOFTWARE

The static analysis and strength calculations are computed by CosmoXpress plug-in tool of SolidWorks®. The critical components of quick changeable joints are analyzed and modified when required. The software also determined the weak points of the parts and showed shows the deformed shape under excessive load.

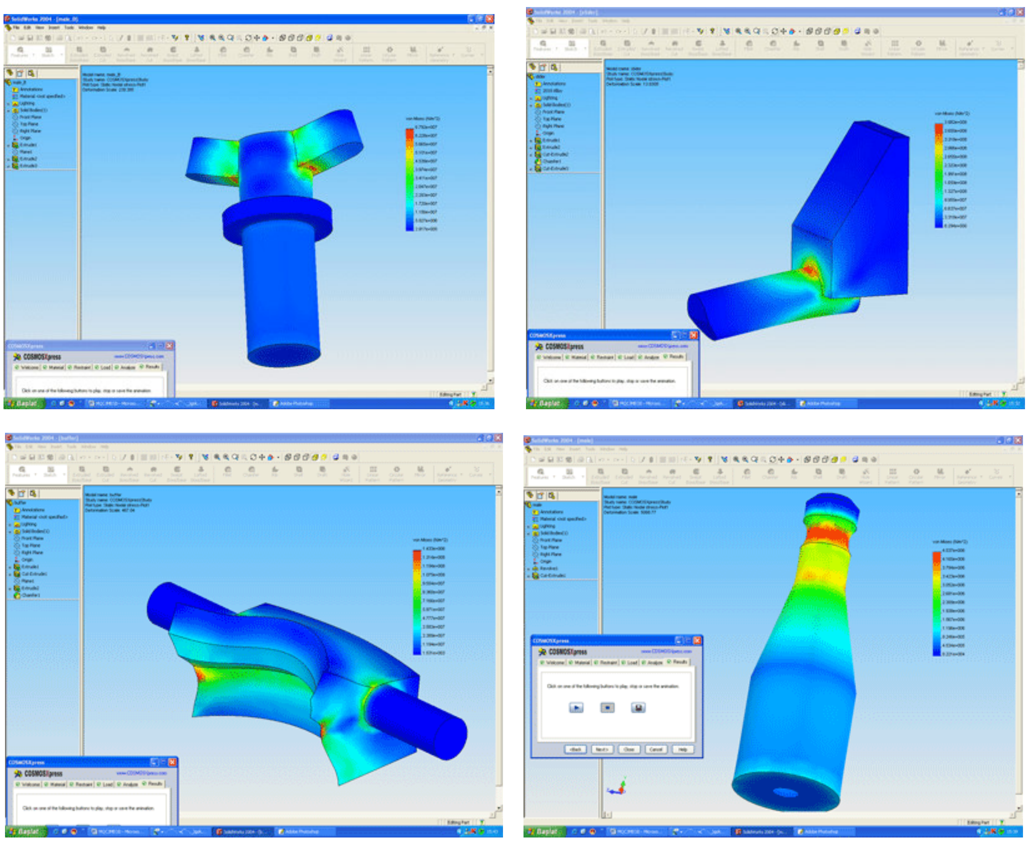

Figure B.1. Deformed shapes of the critical parts