



Umwelt-Campus Birkenfeld

FACHHOCHSCHULE TRIER

Course of studies: Mechanical Engineering

Internship report

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Main Project:

“Design and Prototype of a Robotic Testing Fixture
for Artificial Knee Joints”



Mentoring CUICAR: Laine Mears, Ph.D., P.E.

Mentoring FH Trier: Prof. Dr. Peter Gutheil

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1 Preface

As part of the bachelor program at Trier University of applied science, location Birkenfeld each student has to complete a twelve week internship in a qualified company or institution.

The acquired competencies during the study period should be deepened by subject-specific development of projects in the practice.

Therefore the students have to operate as independently and responsibly as possible taking into account the conditions and requirements in the respective company.

The supervising tutor of my first technical project Stefan Hirsch told me in a project meeting that there is possibly an opportunity to do the twelve week internship at CU-ICAR.

To find out more about that opportunity I contacted Prof. Dr. Peter Gutheil who was visiting faculty at CU-ICAR at that time.

He offered me a couple of projects but all within the scope of 6 months including the bachelor thesis. But I only wanted to do the twelve weeks internship.

He was so nice to search for a project which could be done in twelve weeks.

Laine Mears had a robot which did not work properly and searched somebody who was willing to find and solve the problems.

I felt able to repair the robot and took this unique opportunity.

1.1 The CU-ICAR

The Clemson University International Center for Automotive Research (CU-ICAR) is an advanced-technology automotive and motorsports research campus where university, industry and government organizations engage in synergistic collaboration.

CU-ICAR is strategically located in the rapidly growing Southeastern automotive and motorsports region. The 250-acre campus in Greenville, South Carolina is midway between Charlotte, North Carolina, and Atlanta, Georgia, on the Interstate 85 corridor.

It offers master's and doctoral automotive engineering programs and the nation's only Ph.D. in automotive engineering.



Figure 1: Campbell Graduate Engineering Center

The Campbell Graduate Engineering Center (**Figure 1**) building houses the automotive engineering graduate program and is the center for systems integration research activities as well as faculty, student, staff offices and conference facilities.

2 Work with the Robot

2.1 About the Robot

The robot at CU-ICAR (**Figure 2**) is a KUKA KR3 an articulated robot with six rotary joints.



Figure 2: KUKA KR3 at CUICAR

The 3 in its name (KR3) stands for the payload which is 3 Kg. His maximum height is 885 mm. The maximum range is 635 mm. (**Figure 3**) The weight (excl.controller) is approximately 53 Kg.

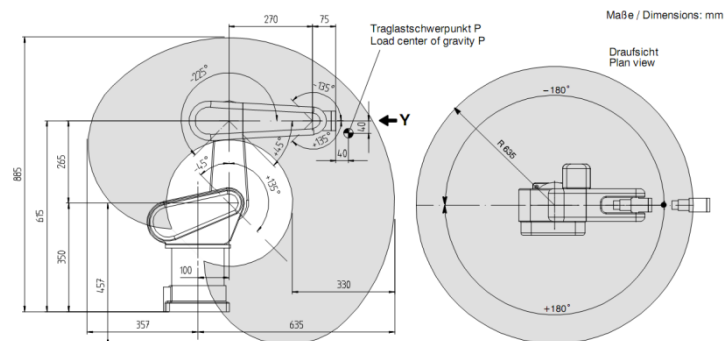


Figure 3: Work envelope

It is a comparative small robot because it is designed for teaching purposes.

The robot is controlled by the KR C3 controller. (Figure 4)

Operator control elements on the “KR C3” control cabinet

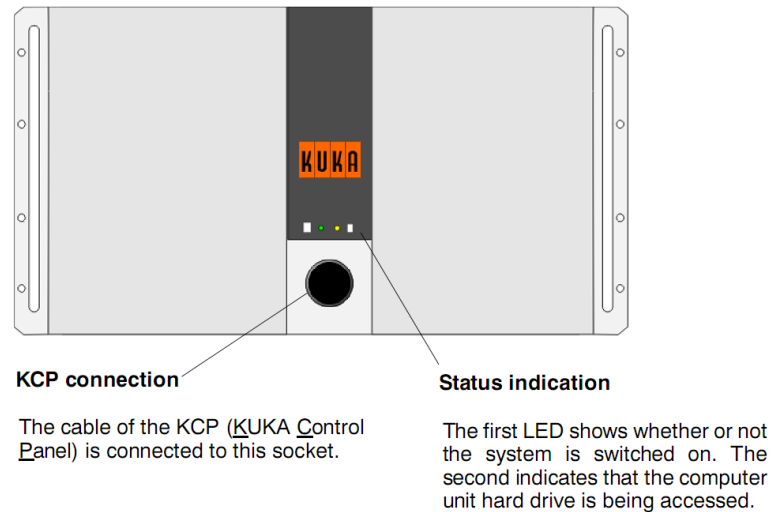


Figure 4: KR CR3 controller

The main human interface device is the KUKAControlPanel(KCP) (Figure 5)

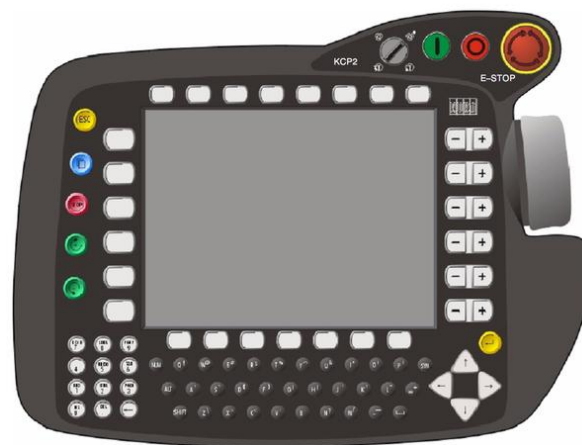


Figure 5: KUKAControlPanel (KCP)

A PS2-Keyboard and a computer monitor can be connected, too.

There is also the opportunity connect multiple robots to let them work together or let them be controlled by a central controller.

2.2 Recommissioning the Robot

My first exercise was to recommission the Kuka KR3 which didn't function probably until that time. Therefore I first read the English operation manual and I acquaint myself with the basic program steps. After that I put the robot into operation and let him drive simple procedures.

But I only received error messages. The Robot already reported the error message:

"...Software end switch reached" although the axle was still far from the end position.

I reasoned that the mastering of the incremental encoders was wrong. I studied the printed and extensive English version of the operating manual again.

I found out that when the robot is not used for a prolonged period of time and is not connected with the power supply system, the lead batteries which are internal in the controller will become empty.

This controller saves the positions of the incremental encoder and when the lead batteries become empty these positions will get lost.

Therefore the robot did not know the real position of his arms and presumed a threaten collision.

After that I performed the procedure of new mastering the axles.

Therefore the axles need to be driven manually to the exact zero position.

In contrast to industrial robots there is no precise equipment to find the zero position.

Most industrial robots are equipped with dial gauge cartridges. **(Figure 6)**

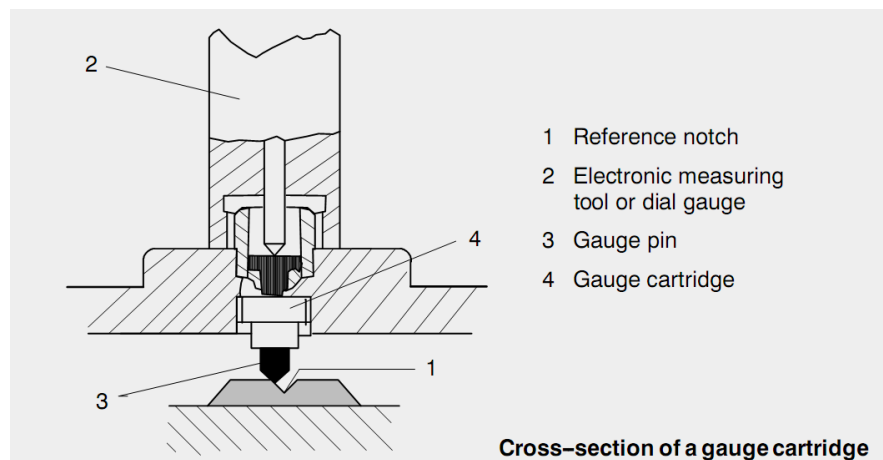


Figure 6: Cross-section of a gauge cartridge

This robot has only coarse verniers which must be aligned by visual judgment. (**Figure 7**)

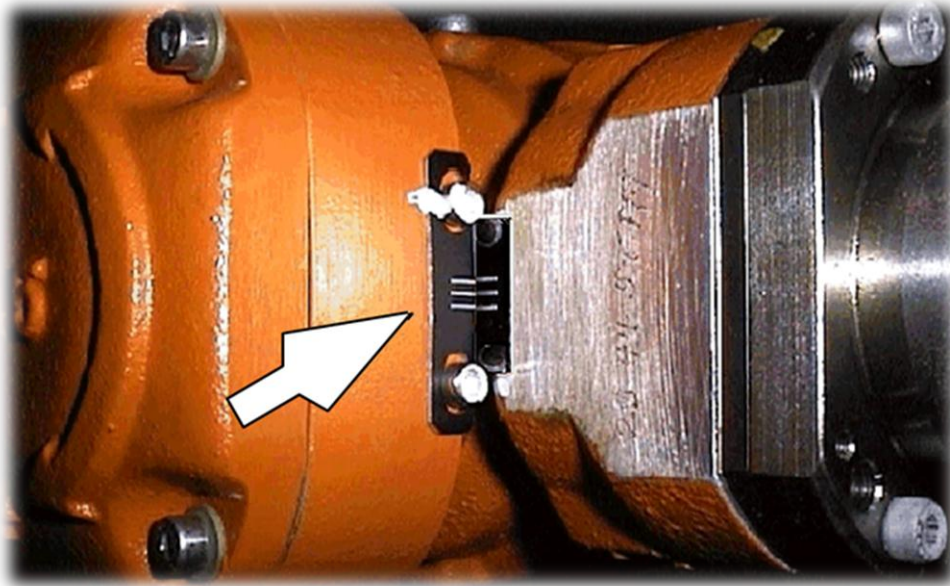


Figure 7: Vernier

I brought the axes in the supposed zero position and mastered them new.

First it seemed like that the Robot executed all motions correctly. But then I noticed that I didn't align the verniers precise enough. As I taught the table as a new coordinate system I realized that when the arm is full stretched there is a difference from the tooltip to the table of about 3 cm between the right and left end of the work envelope.

I repeated the mastering and adjusted the markings as well as possible with the eye.

I noticed that a hardly visible modification of the rotation angle already resulted in a change at the end of the robot arm about several mm.

After the next try to teach the table as coordinate system the difference was still 1 cm.

This deviation was not close to be acceptable to me and I repeated the mastering again and again until the robot was able to find every point on the table accurate to +/- 1 or 2 mm.

After the new mastering I attended myself to the manual to learn all necessary programming commands of the robot. For this purpose I wrote several little test programs until I proficient the programming commands.

2.3 Pneumatic Gripper

Now I tried to put the pneumatic gripper (**Figure 8**) which was already fixed on the robot into operation.

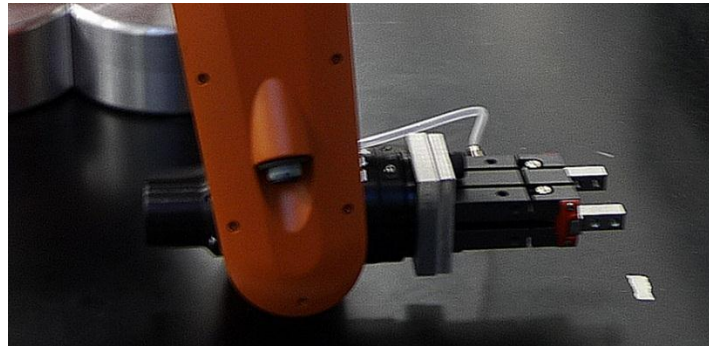


Figure 8: Pneumatic gripper

After a long search in the manual I found a hint that there is a solenoid valve integrated in the robot. But on that page was not written how to activate the solenoid and I searched through the manual again. On this point the printed English manual was no help to me. It took too long to understand what I had to do and I was told that the operating instructions are in several languages on the installation CD.

Now with a German manual I found and understood the article about the solenoid valve.

I had to reconfigure the output ports to make the solenoid work.

Unfortunately the pressurized air supply is on the opposed corner of the room.

Frank provided me a portable compressor and I could “play” with the gripper.

The command to close the gripper is: “Pulse (\$out[1],true,1)”

The command to open the gripper is: “Pulse (\$out[2],true,1)”

Later I found out that you can use the menu key “GripperTech” (**Figure 9**) to open or close the gripper.



Figure 9: GripperTech

2.4 KRC Editor

I wrote some test programs to become familiar with the gripper but programming with the KUKAControlPanel was laborious so I searched for a possibility to create and to edit the program on a PC. I found a lot of commercial programs with costs and after a long search I found an open source KUKA editor named “KRC Editor”.

It’s available on: <http://www.krcreditor.de/blog/?lang=en> and you can switch between German and English.

This program provides a similar surface (Figure 10) like the KUKAControlPanel but has a lot of advantages e.g.: write a program offline, Syntax completion, tag & drop, search & replace etc.

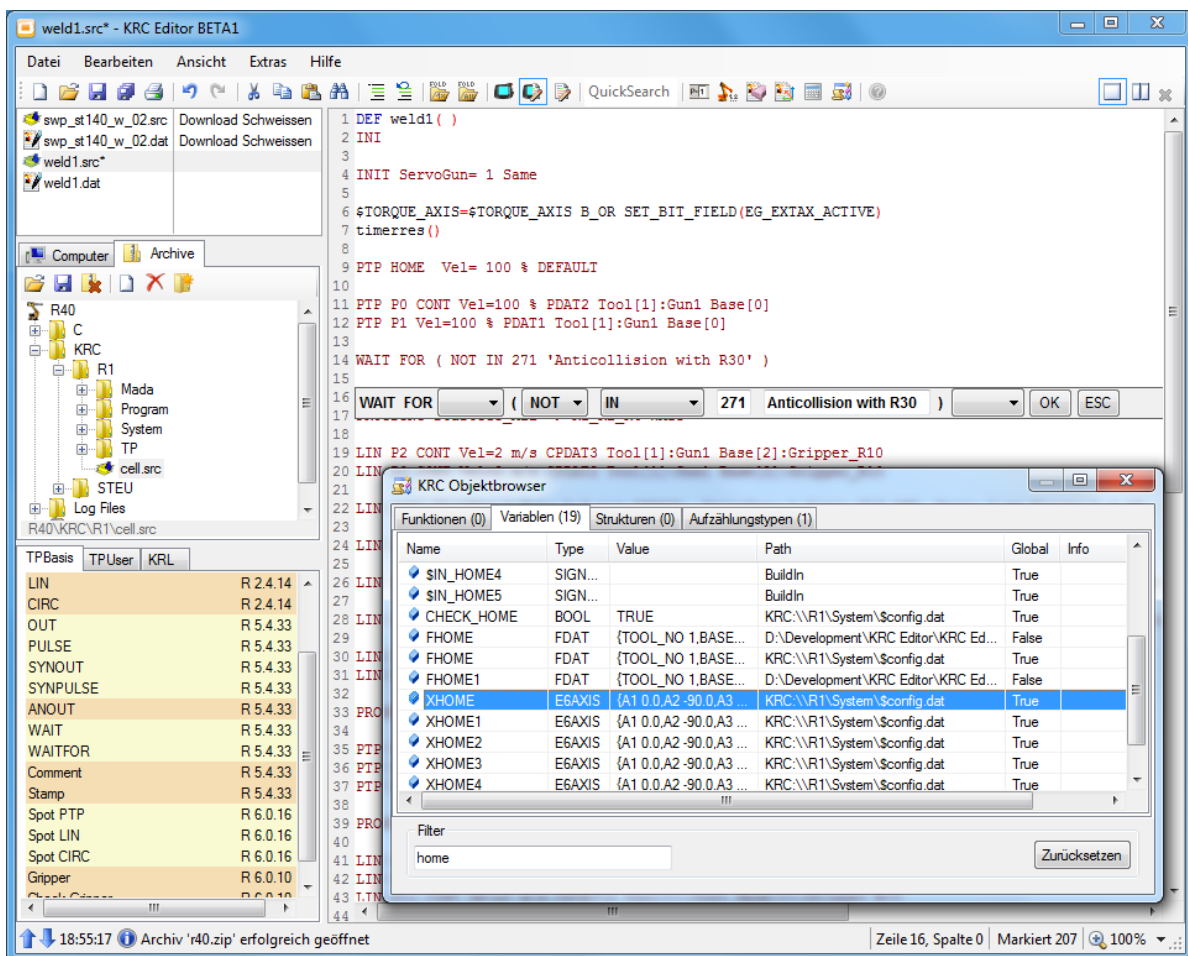


Figure 10: Surface of the KRC Editor

2.5 Enable the USB-Port

The KRC Editor was quickly installed on my notebook but it required several files from the KUKA controller. For data exchange a Floppy drive is built in the controller but my notebook has none.

Although the KUKA controller has an USB port but it was without function and in the index of the manual was no indication of an USB-Port.

I skimmed over the manual but couldn't find any information.

After that I read all the possible chapters line by line but couldn't find anything.

Also internet researches in German and English didn't help me to find a satisfactory result.

I only found the hint that the USB-Port was deactivated by default in the BIOS.

To get to the BIOS a reboot is required but by turning off the robot the computer always entered sleep mode. To reboot the computer I needed access to the Windows surface.

So I searched in the manual how to change the Windows surface. By default the controller does a warm start which skips the Windows surface. A reboot can only be done after a cold start.

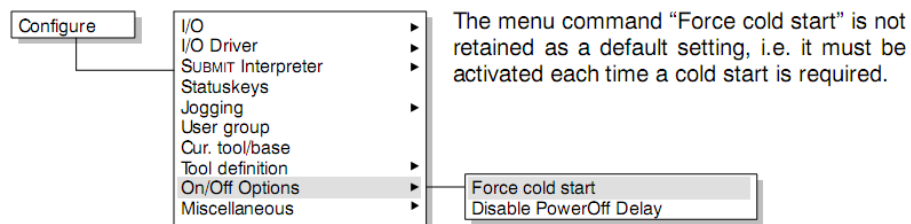


Figure 11: Force cold start

During the reboot the KUKAControlPanel didn't work but without keyboard there is no access to the BIOS.

So I searched a keyboard. First I wanted to ask the computer service technician but he wasn't there.

So I asked everyone who crossed my ways for their keyboard and explained my problem.

But their keyboards all had a USB-Port but I needed a PS/2 port.

Finally I found Kurt the computer service technician near the copier where he attended a repair.

He gave me a suitable keyboard and the respective configuration settings were quickly done.

After the reboot of the control it was in the user mode which was circumscribed in its functionality.

For a change in the expert mode a password was required which I didn't know.

I looked in the manual if someone noted the password there but I had no luck. By trying some simple words and numbers I found it out.

Now I could search the files for the editor program and copied them on the USB stick.

After I copied the required files to the prescribed destination I wrote a test program with the KRC Editor but it did not run right away on the control.

I found the suitable setting after several attempts.

I increased my knowledge in programming with the KRC Editor for some time.

3 Demonstration program

I had to write a demonstration program which should make the robot do something interesting.

I let the robot grab a whiteboard marker with the pneumatic gripper to let it draw some straight lines on a piece of paper which was positioned upon the table. I draw squares, triangles and simple words.

The words made with straight lines which were programmed by hand weren't spectacular enough - I wanted more.

I remembered that a NC-Compiler is integrated in one of the CAD-Programs I have on my Notebook.

After I found out how the NC-Compiler works I tried different possibilities of the NC code output until I received a reasonable compatible NC code.

These commands were not direct compatible for the KUKA Controller so I had to modify them.

Using the windows integrated text editor and the function search and replace I got the NC program in the adequate form. Then I added the other necessary commands with the KRC editor.

The robot drew the circle which I had created with the CAD program.

Well a circle is still not spectacular enough for a demonstration.

I created an A4 sheet filling "HELLO". (Figure 12)

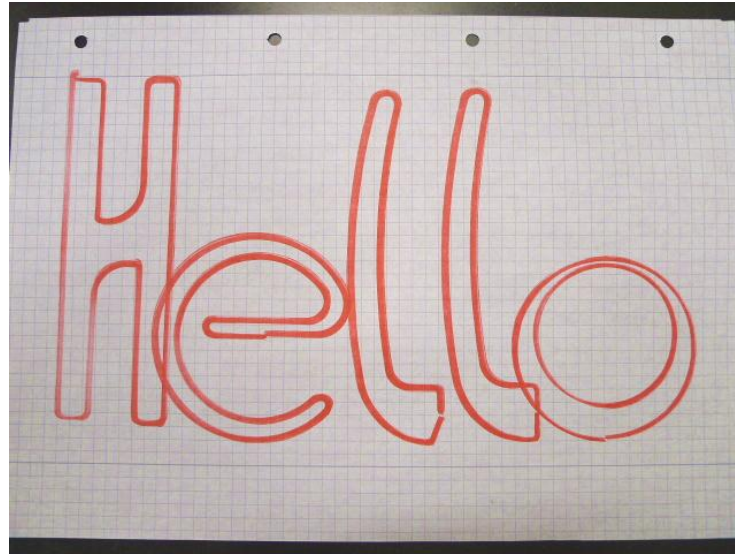


Figure 12: "Hello" drawn by the robot

It was a respectable result but the robot needed about 7 minutes to execute the 616 lines. (Figure 13)

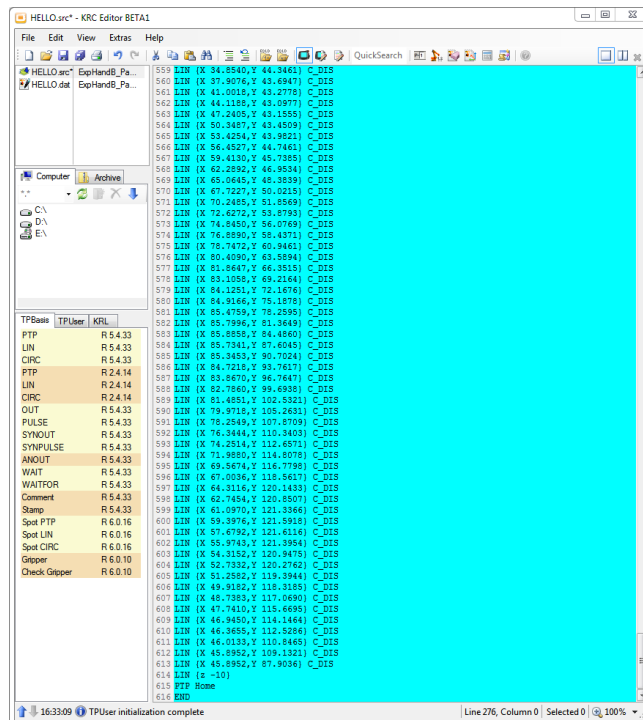


Figure 13: 616 program lines

This was way too slow. Probably every spectator would fall asleep.

And I had to press two awkward confirmation buttons in the teaching mode all the time.
 I had to choose something better.

A well curved heart was the best compromise between program runtime and complexity of the geometry. (**Figure 14**)

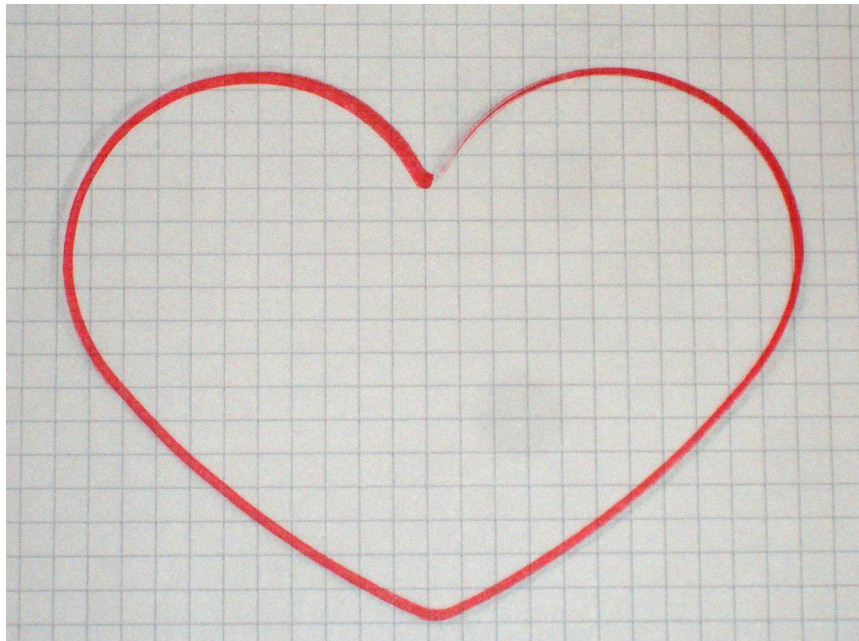


Figure 14: Robot drawn heart

The execution of the therefore necessary 131 programming lines takes about one minute.
 This should be a suitable program for a demonstration.

4 Middle school students

During my internship middle school students from the Gateway to Technology program would be visiting the Clemson research center to explore research hands-on.

Each of Laine's students should prepare and implement an attempt with the students.

I should show the school students what I was doing with the robot and let them do some basic programming of the robot.

4.1 Pen holder

Until then I used a whiteboard-marker for writing which was held with the pneumatic gripper.

This was very wobbly and pardons no mistake also the whiteboard-marker did not draw clean lines.

I searched for a different way to attach a pen or marker.

Laine gave me a permanent marker and I decided to design a holder for that marker which only guides the marker and allows up and down in "Z". Gravity should push the marker onto the paper.

In a Hardware Store nearby I found a short PVC pipe with threads on both ends and the permanent marker did fit pretty good inside.

Furthermore I found a fitting end cap in which I later drilled a hole barely big enough for the black part of the permanent marker. (**Figure 15**)



Figure 15: Permanent marker

The grey part is a little bit thicker than the hole in the pipe cap and holds the marker inside.

The own weight of the marker did not suffice to draw a clean line so I added a lead weight.

The bore in the end cap fits almost free from play to the black part of the marker.

This allows an up and down movement of the marker of about 15mm.

That will make it a lot easier for the kids to touch the paper with the tip and will compensate little meanderings during the drawing.

To attach it on the robot I used the other thread on the pipe.

I quickly drew a sketch of a little plate with an inside tread matching to the pipe and two holes matching to the adaptor plate on the robot.

Gary from the machine shop was so kind to make the plate out of a piece of wood lying around.

I assembled the parts and mounted the holder on the robot. Therefore I only had to unscrew the two bolts which hold the gripper and use the same screws to mount the marker holder.

I tested the marker and the result was very satisfying.

Then I defined the holder as a new tool and changed the programs "Hello" and "Heart" to use the new marker.

I planned to let the students do as much as possible with the robot.

Ideally every student should move the robot once.

To explain the different coordinate systems and the difference between Point-To-Point-movement and Linear-movement seemed important to me.

Then they should teach the sheet of paper on the table as new coordinate system by using the different coordinate systems.

To draw squares of different sizes on that paper should be the last task.

4.2 The visiting day

The middle school students arrived and after a tour through the building they've been divided into groups. Four groups of seven to eight students became assigned to me.

I had about a half hour for every group to show and teach them as much as possible.

First I showed every group the artificial knee joint and let the robot draw the heart.

Group number one was only girls and almost each one of them wanted to take a robot drawn heart with so I let the robot draw some more.

The second group found that squares were too easy and wanted a more challenging exercise.

They wanted to write CUICAR and programmed both "C" and the "U".

Group number three programmed the "A" and something close to an "R".

The last group was not able to program a single line so the "I" was missing.

Except the last group all kids have been astonishingly attentive and learned quickly so it was a pleasure to show them how the robot is functioning.



Figure 16: Visiting day participants

5 Testing Fixture for Artificial Knee Joints

John Desjardins an Assistant Professor at Clemson University wanted to use the robot to make measurements on artificial knee joints.

John, Laine and I met in the ICAR in order to show John which opportunities the robot provided.

John found the robot for suitable and Laine did not want that the robot would be unused after I left and until he will be used again in fall semester.

So I had to design and manufacture a testing fixture consisting of a holder which should connect the femur part of the knee joint with the arm of the robot and a second one which should connect the tibia part with a six-axis-load-cell. (**Figure 17**)



Figure 17: Six-axis-load-cell

It should allow a displacement of about 10 mm into Z and measure this displacement but all other degrees of freedom should be locked and it should use a spring to create a force into Z.

I do not like springs and after evaluating all the options I decided to take a pneumatic cylinder for the production of the force which has the advantage to adjust the force.

Based on that requirements I begun the design.

5.1 Femur part holder

First I thought about how to mount the femur part of the knee joint on the arm of the robot.

I had to look after possible collisions and tried different options.

There was only one expedient possibility which allowed the robot bending the knee through 90° without causing a collision. (**Figure 18**)

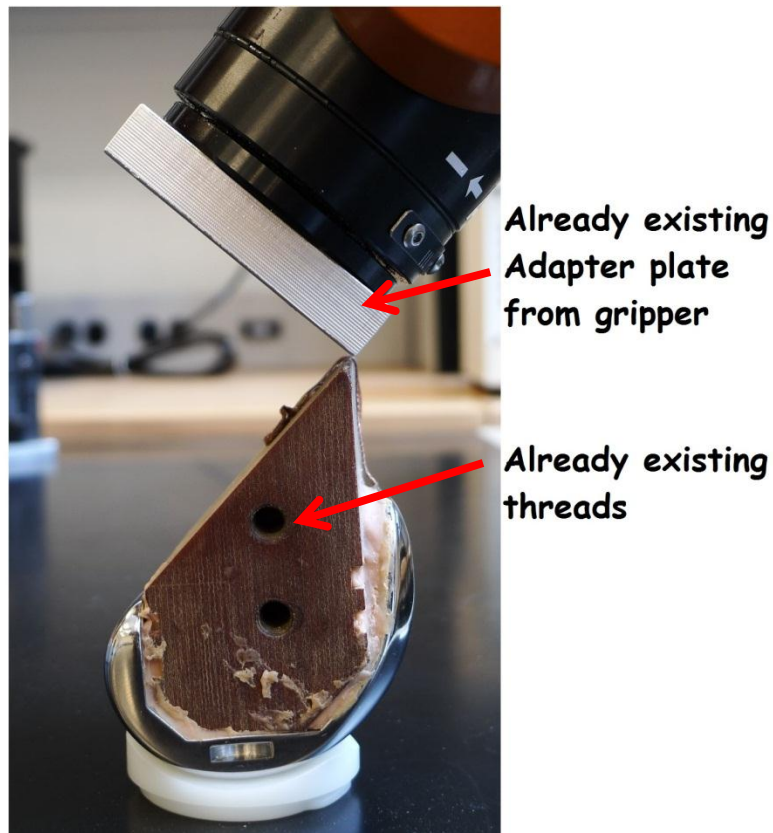


Figure 18: Sole expedient possibility

I searched for options to mount the femur part of the knee joint on the robot.

Garry had to manufacture it because I was not allowed to operate the machines due to insurances reasons.

After a conversation with Garry I decided that the holder had to be designed as simple as possible.

With a complicated part I would need to write a work order and Garry had to compliance the working order so that I had to accept a long waiting time but an easy part he was poised to bring forward.

It wanted to use the already existing adapter plate of the gripper and the existing threads of the upper part of the knee. **(Figure 18)**

My first idea was to bend the holder out of sheet metal. **(Figure 19)**

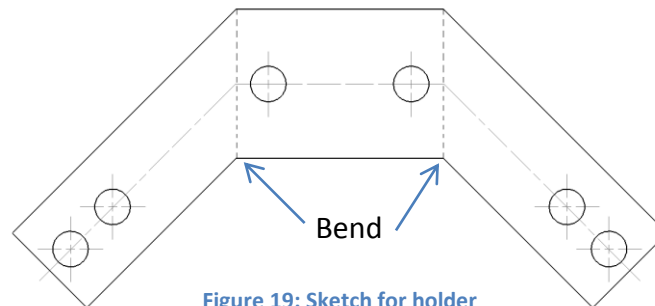


Figure 19: Sketch for holder

Garry and I searched for suitable scrap metal in order to avoid ordering new material.

But we couldn't find suitable sheet metal which would ensure enough stability.

Garry made the proposal to manufacture the holder out of 3 steel strips and weld the parts together.

I adapted my design to this new material and Gary made it on the next morning.

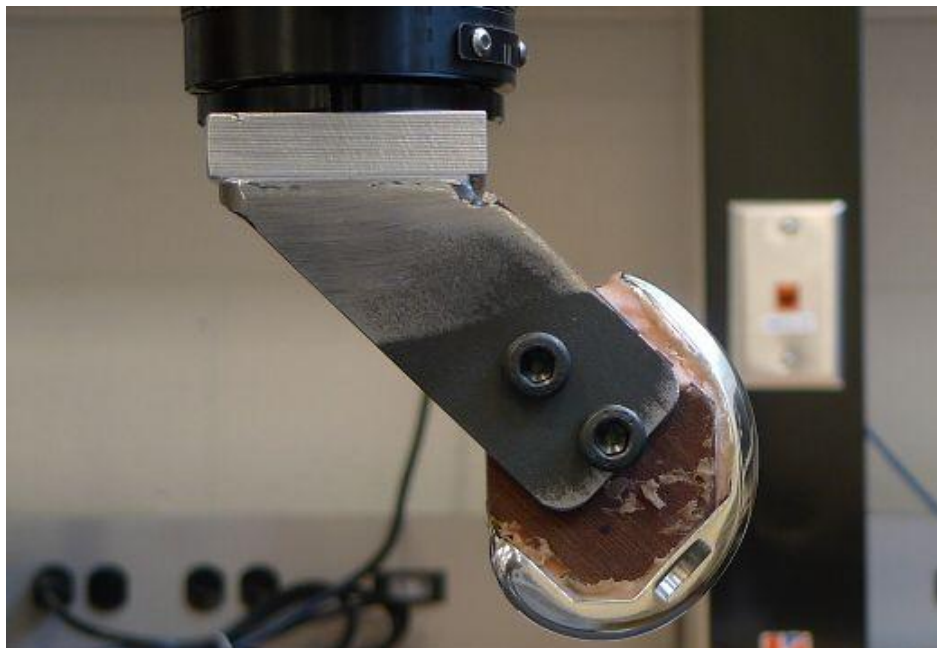


Figure 20: Femur part mounted on robot

The generated holder **(Figure 20)** holds the femur part of the knee joint free from play in the desired position.

5.2 Determine maximum compressive force

After completing the femur part mount I thought about the tibia part.

In a meeting John mentioned that he had a pneumatic cylinder in his laboratory in Clemson which would possibly be suitable.

According to the requirements from John the lower fixture should allow a displacement of 10 mm in Z.

The considered pneumatic cylinder must have 10 mm stroke at least.

After that I had to think about the bore diameter which needs to match with the forces the test will be realized.

John wanted ideally to realize the test with forces near body weight. But from the start it was clear to both of us that it was not possible for the little robot to handle such forces.

The payload of the KR3 is 3 Kg, but this value is for lifting not for pushing.

The manual said nothing about how much the robot can push down.

I could extract from the manual that the maximal force is limited by the current limiting of the servo motors.

That means if the current becomes too high the current control will switch the robot off.

To determine how much the robot can push I used a bathroom scale.

Therefore the robot and the already completed femur part of the knee pushed against the scale from different angles until the current limiting switched the robot off.

Most of the time axle 5 was the limiting factor.

By outstretched and fully bended knee position the axle 5 was either $+45^\circ$ or -45° to Z so that there was a relative big lever. In these positions the current limiting switched axle 5 off by 75 to 80 pounds.

By half flexed knee, when axle 5 was collinear to Z and it was no lever for axle 5 and so no torque was produced axle 2 or axle 3 (depending on the position) was the limiting factor and the force was higher.

In that positions the current limiting switched off at 120 pounds.

No axle was switched off at a lower value than 75 pounds equal which angle.

So I fixed 60 pounds as a save value.

5.3 Pneumatic cylinder

Now I had the value to determine whether the available piston was suitable or not.

After a some emails with John's assistant and after he send me the specifications it was clear that their pneumatic cylinder (**Figure 21**) was suitable.



Figure 21: Pneumatic piston

With a bore of 32 mm and a rod diameter of 15 mm the effective area is 627.3 square millimeters or .97 square inch. Almost every psi creates one pound of force.

To create the 60 pound force only 62 psi are required.

The cylinder hadn't been used for a long time so I had to check the functionality first.

I had no appropriate hoses or fittings and also the guys in the machine shop didn't have the matching parts.

They send me to Barker Air & Hydraulics and I bought the necessary fittings.

When I checked the functionality of the cylinder a lot of air got lost.

After tightening all screws on the cylinder and sealing the fittings the cylinder was airtight and I could continue the design.

5.4 The guiding

The guiding should be simple and easy to manufacture to not stick in the work order process.

Because of that I should use parts from McMaster-Charr where possible.

Out of their assortment I choose linear motion shafts and the fitting bushings.

I should order the material for the plates there, too.

Six inch wide and $\frac{3}{4}$ inch thick aluminum round blanks seemed to be a good choice because my original design was with three shafts in a 120° arrangement.

I made a CAD draft (**Figure 22**) and sent it to John Desjardins to get his agreement.

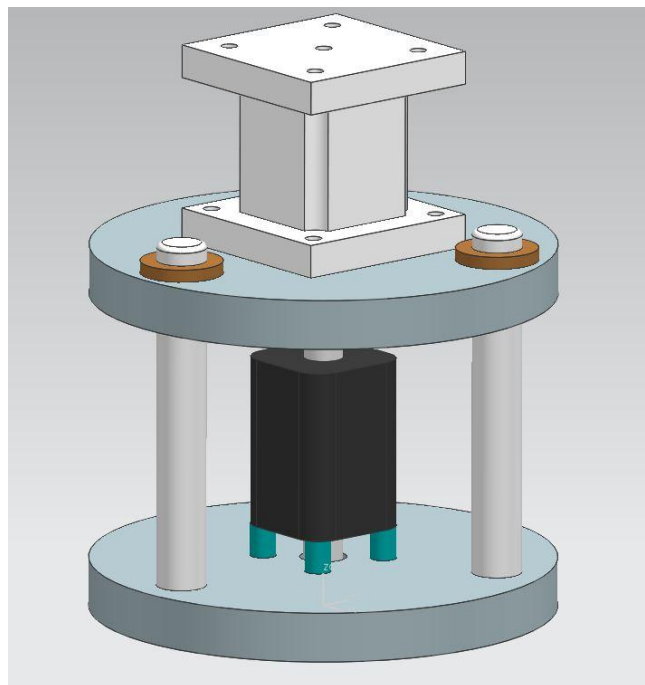


Figure 22: First design

He didn't like the design and we discussed per email but we didn't reach an agreement and decided to meet personally.

During the personal conversation we could clear up some misunderstandings and he insisted on a square design and four shafts.

In his opinion the disks had been way too thick and clumsy but they need to be thick because the rods will be held by press fit.

Whether round or square was equal for me but I had my doubts about the four rods.

First there is a one-third more friction and it is also static over determined and the risk to tilt is higher.

After the agreement upon the final design (**Figure 23**) John's assistant Roy and I ordered all the necessary parts at McMaster-Charr.

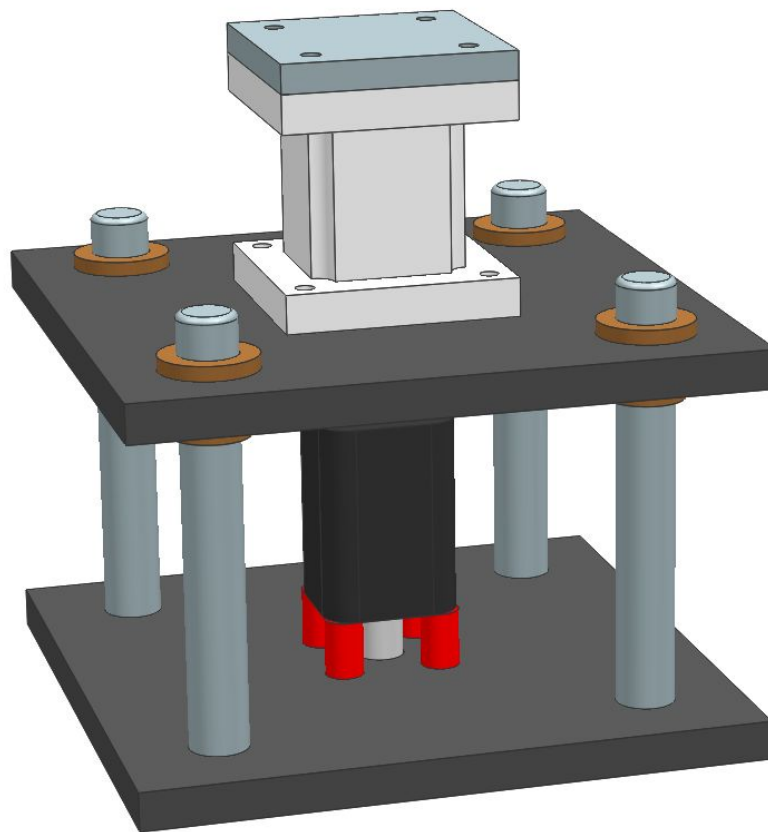


Figure 23: Final Design

The final design was very simple and fast to build.

The raw material we ordered already had the right dimensions and the machine shop only had to drill some holes and to cut some threads.

In the lower aluminum plate (**Figure 24**) four countersink holes and one through hole for the attachment of the pneumatic cylinder and four precise holes for the press fit insertion of the shafts needed to be drilled.

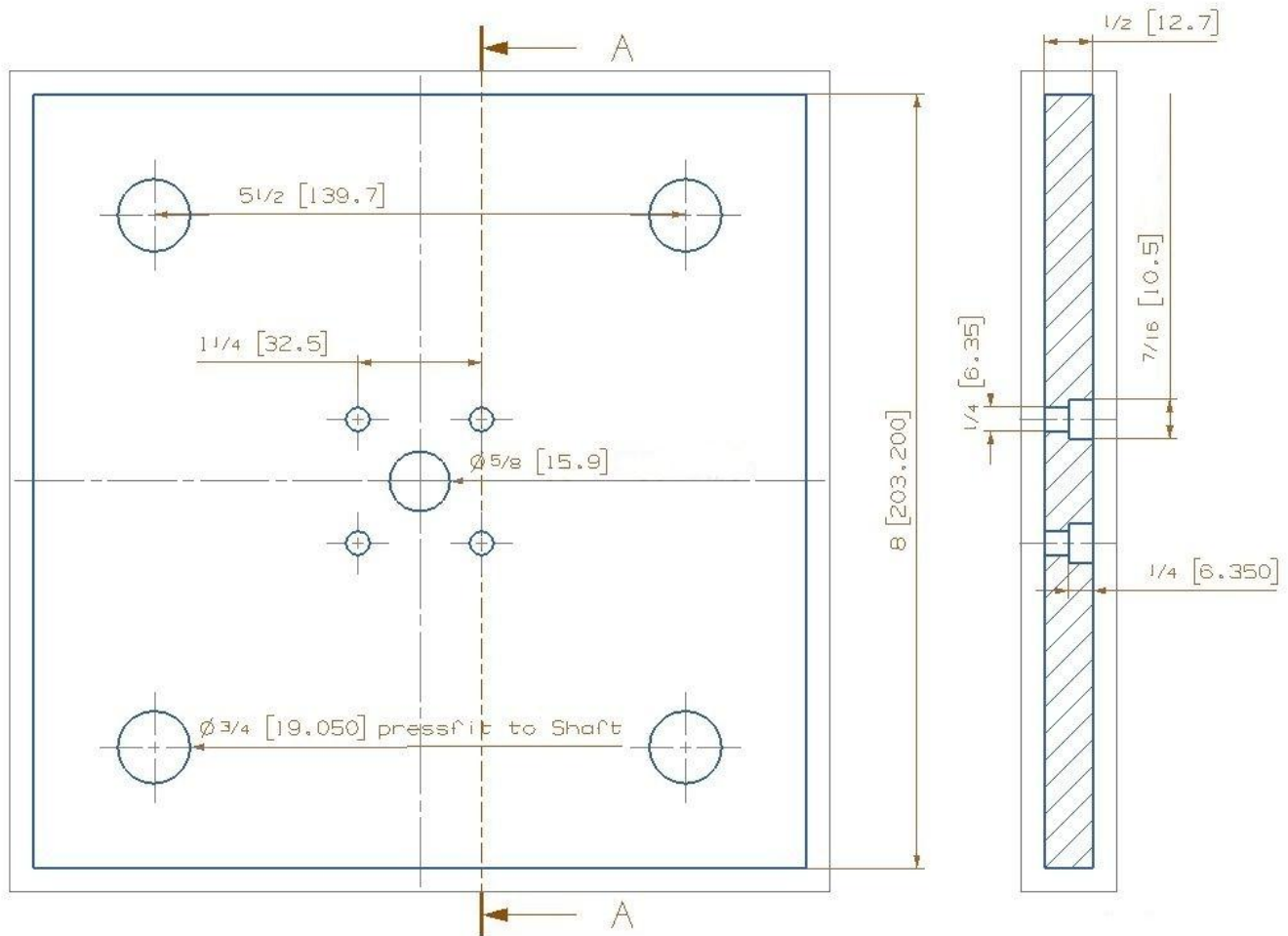


Figure 24: Lower plate

In the upper plate (**Figure 25**) the machine shop only had to cut threads for the screwing on the load cell and drill four holes to press in the bushings.

These two pieces were sneaked in the other order Roy had running at the Clemson machine shop. The spacer was forgotten on the order but I found some in the nearby hardware store and was able to screw everything together.

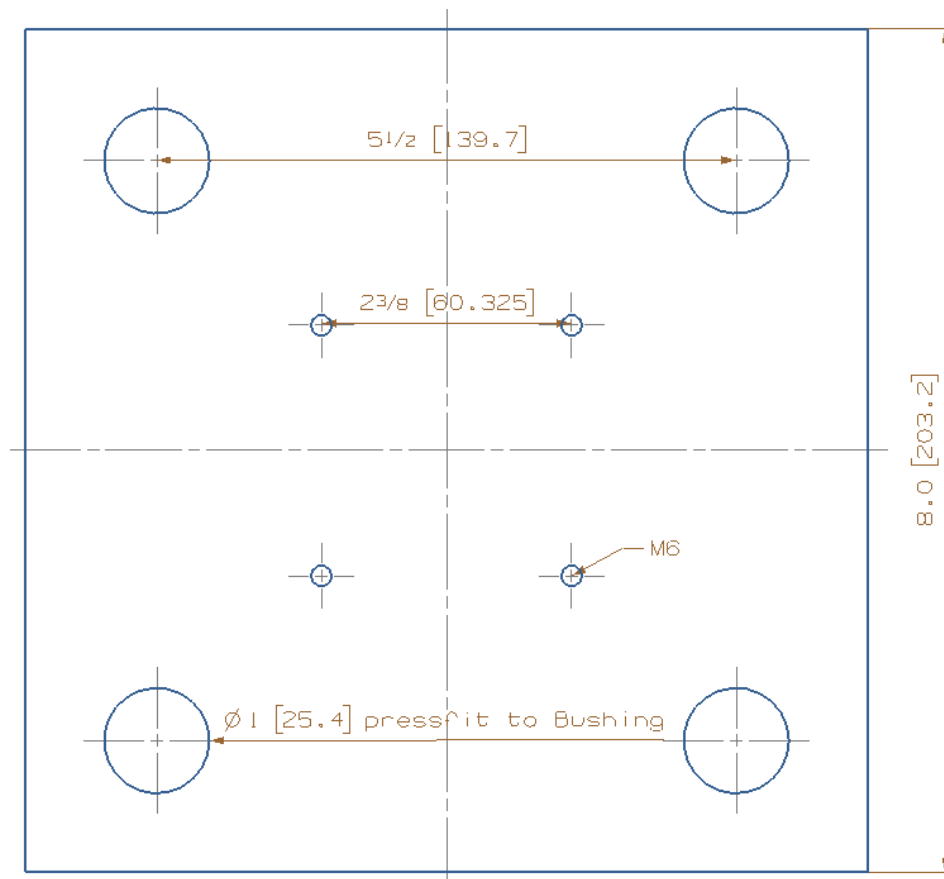


Figure 25: Upper plate

5.5 Lubrication

The Clemson machine shop had lubricated the bushings with white sticky grease.

At the beginning it was very good but after two days it was dry and so sticky that it was locked.

It was really hard to get rid of it and for the cleaning I had to disassemble it.

Then Garry gave me some very low viscosity oil.

First the oil lubricated excellent but it was too thin and did not stay at the points which needed the lubrication. I tried another too thin oil.

The viscose oil I found was gear oil.

This worked for a certain amount of time but after a few days it had run away.

It should work with not out drying grease or with very high viscose oil.

5.6 Tibia part

The tibia part was cast in bone cement to make it fit for a different fixture.

I had to free the tibia part from the bone cement and to saw the titanium to get a flat undersurface.

To free it from the bone cement with hammer and chisel was a mess - the chips flew across the room.

Now the titanium needed to be cut but nobody wanted to saw or mill the titanium.

They said the only way to cut the titanium would be the EDM machine.

I had to wait a while until one of the few students who are able to operate the EDM was free.

Then it was not possible to fix the tibia part in the EDM. We had to build an adaptor.

After two wire breaks and refilling the water tank the EDM machine aborted on the last of the four pins.

There still was a little layer of bone cement insulating it from the wire.

I wanted to saw the pin with the hand saw and they just smiled about me because everybody thought that titanium is difficult to machine. After six cutting movements the pin was sawed off.

To connect the tibia part with the load cell another plate was needed.

I drew a sketch and Mathew offered me to machine it on the mill by the time the mill would be free.

It took some days until the mill was free and after Gary modified the screws I assembled it. (**Figure 26**)

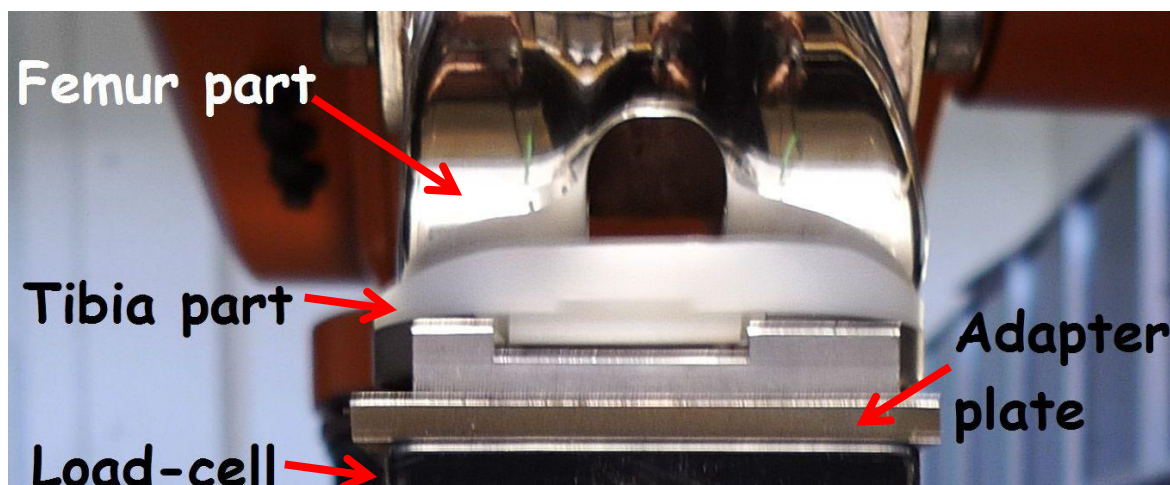


Figure 26: Assembled knee

5.7 Displacement sensor

The last thing to do was to choose and mount a displacement sensor to measure the Z displacement.

Originally John wanted therefor a LVDT (Linear variable differential transformer).

I searched a long time for a suitable LVDT but they all had been too expensive.

I talked with Laine about the price and he recommended asking Mike Messman who knows more about measuring systems.

Mike recommended using a linear potentiometer instead which is cheaper and just as well.

I asked John and he was consent with the linear potentiometer.

Then I searched for a linear potentiometer. While I was searching Mike came to me.

He had one linear potentiometer left produced by Novotechnik. (**Figure 27**)

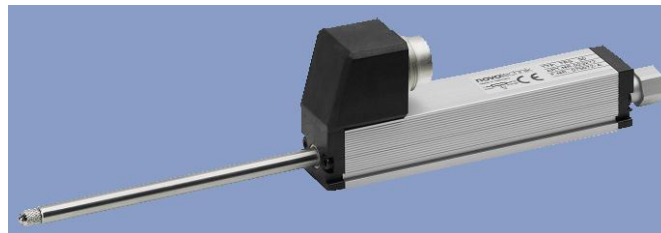


Figure 27: Linear potentiometer

The linear potentiometer he had left was perfect for the task.

I began to search for an option to mount the linear potentiometer on the fixture but it did not fit between the two plates.

To mount the linear potentiometer a hole needed to be made into the upper plate.

This was my last week. Monday I only did organizational things. Tuesday nobody who was able to make the hole was there. On Wednesday Thomas was so nice to make the hole with the EDM.

Roy the assistant of John came up to the CU-ICAR on the next day to get a robot introduction.

He will execute the measurements with the artificial Knee Joints and I showed him how to operate the robot and all necessary commands.

I showed Roy how I planned to mount the linear potentiometer on the fixture. (**Figure 28**)

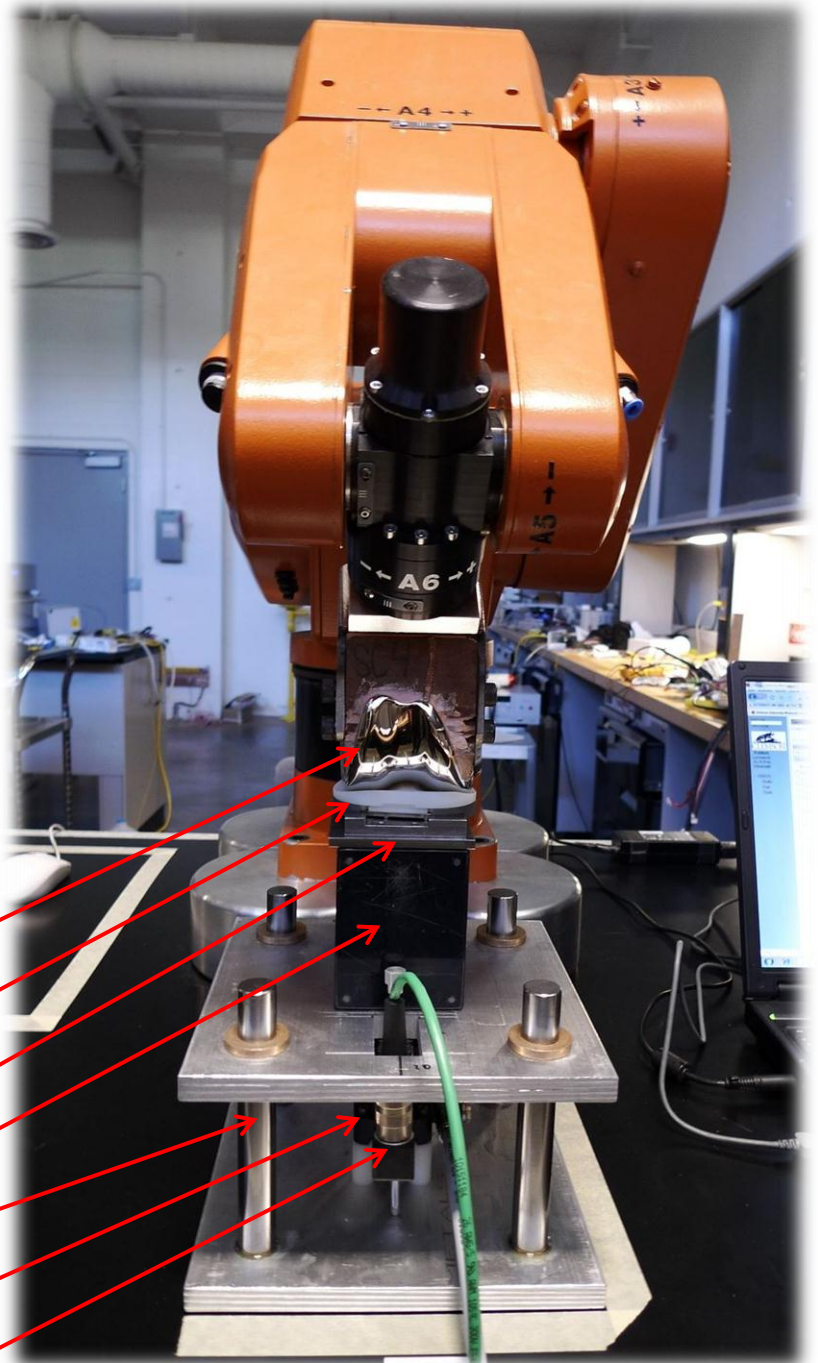


Figure 28: Linear pot. in desired position

5.8 Test setup

The test setup is almost complete.

On this picture a lead battery took the place of the load cell which still was in Clemson for calibration and the linear potentiometer which is shown on its final place needs to be mounted.



Femur part mounted on robot

Tibia part

Plate connecting tibia part and load cell

Will be the replaced by the load cell

The guiding

Pneumatic cylinder

Linear potentiometer

Figure 29: Test setup

6 Conclusion

The last day at CUICAR has come and the artificial knee joint measurement device was ready so far, except the little holder for the linear displacement sensor.

That day there was nobody to machine the holder for me.

A day ago I showed Roy how I planned to mount the linear potentiometer on the device.

I called Roy and told him that the device is ready so far and he agreed to take care about to mount the linear potentiometer. In the meantime he mounted the sensor.

He will also bring the six axis load cell and the data collecting system to complete the device.

In my time at CUICAR I put the KUKA KR3 back into correct operation.

I also reactivated the build in valves for the pneumatic supply what made the gripper usable again.

To draw with the robot for educational purposes I designed and build an excellent working error friendly pen holder with about 15mm play in Z direction.

During the work on the robot I expanded my programming knowledge eminent.

Between I introduced interested students in to the operation of the KUKA KR3 and showed them basic programming tasks.

For visiting middle school students I prepared exercises with the robot and supervised the procedure.

The most time I spend with the design and prototype of a robotic testing device for artificial knee joints.

To manufacture the necessary parts I had to work together with Clemson's and CUICAR's machine shop because I was not allowed to use the available machines due insurance reasons.

The testing device is now ready for the final assembly with the real specimens.

I want to thank the CUICAR for the good collaboration and for the great opportunity to absolve my internship in their outstanding institute.

For my fellow students I wish that they also have a great time there and that the cooperation of our universities will last long.

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