Alexander Hjelm

Utveckling av rotationshuvud till CNC-testbänk

Degree thesis of 22.5 credit points
Mechanical Engineer

Date/Term: 2010-12-02
Supervisor: Lars Jacobson
Examiner: Nils Hallbäck
Serial Number: X-XX XX XX
Sammanfattning:


Uppgiften går ut på att antingen köpa en färdig lösning eller att designa tillverka och installera ett rotationshuvud på testbänken vars funktion är att simulera vatten jet, laser och plasma skärmaskiner. Testbänken är speciellt konstruerad för att användas av ProCom och av dem används den för att testa nyutvecklade algoritmer till CNC styrningen men också för att testa nyutvecklad maskinvara före introduktion till marknaden.

Testbänken har sina axlar drivna av elektriska motorer och så kommer också dom två nya axlarna bli styrdla. Testbänken arbetar utan några som helst processkrafter vilket betyder att endast dess egen vikt behöver tas hänsyn till.

Bakgrunden till detta krav på två extra axlar är att deras kunder som är maskintillverkare har fått allt högre och högre krav på sina maskiner, av denna anledning måste ProCom ha möjligheten att testa och verifiera sin utveckling i så likvärdig miljö som möjligt för att verifiera utvecklingen av ny programvara.

Examensarbetet är mestadels gjort med konstruktionskaraktäristik och berör ifrån allra första början med förstudier och förklaring av maskinen till slutet med ett färdigt rotationshuvud monterat.

Ifrån dem föreslagna konstruktionslösningarna som togs fram under förstudierna blev två av rotationshuvudena valda att gå vidare med till produktion och senare installation. Tack vare en modul design genom hela konstruktionen blev det möjligt att integrera två typer av rotations huvuden i en konstruktion. Att byta läge mellan dom två olika typerna av huvuden kunde göras mycket enkelt med bibehållen pression.
Summary:

The thesis was written during an internship at ProCom GmbH in Aachen, Germany. It is a project with the goal to upgrade their already existing three linear axis test bench with two additional rotary axes. The task is to either find an already existing solution or to design, manufacture and install a rotary head on the test bench. The test bench is used to simulate water jet, laser and plasma cutting machines and is designed for internal use by ProCom. It is used to test new developed algorithms of their CNC software but also to test newly developed hardware before it is introduced to the market.

The test bench has its axis driven by electrical motors and the additional two rotary axes would also be controlled the same way.

The test bench is operated without any process force which means that only its own weight will have to be taken into consideration.

The background to this requirement of an extra two axis is that customers are starting to demand a five axis control system for their machines and therefore it must be possible to test and verify the software in a realistic environment.

This degree thesis is mostly done with design characteristics and concern from the very start with pre studies, explanation of the machine to the very end of the project with a mounted rotary head. Among the proposed rotary heads from the pre-studies, two rotary heads were chosen to go further with to be developed, manufactured and installed.

With a modular design, to change between the two heads is possible with only minor effort.
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**APPENDIX**

1. PLANNING
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1. INTRODUCTION

The degree thesis is an obligatory course at the end of the Bachelor studies at Karlstad University and Faculty of technology and science. The course is normally read at half speed during the spring. For this thesis, the choice was to do it during autumn of 2010 at full speed since it then could be done abroad, in Germany.

The course extent is 22.5 credit points which can be compared with 640 hours or 4 months of full time work. The company where the thesis was written at is ProCom GmbH in Aachen, Germany. The supervisor at the company has been Dr Andreas Kahmen and from Karlstad University Lars Jacobson.

The project and report has been done from studying the test bench and doing research about plasma, water jet and laser cutter rotary heads that is on the market today. From that point several solutions where presented, which could be adapted to the already existing machine. Two of the rotary heads were then chosen to proceed with. The heads were developed in CAD with a modular design, manufactured and installed on the machine.

Drawings and photos are to be found in the appendix which is at the end of this report.

Thanks to:
Assigner: ProCom GmbH.
Supervisors: Dr Andreas Kahmen, Lars Jacobson.
Examiner: Hans Johansson.
And to all other people that have helped me.
1.1 BACKGROUND

At ProCom GmbH in Aachen, CNC control systems are developed for use in water jet, plasma and laser machines. The market is growing quickly for their costumers and the demand on high precision machining therefore increases. For high precision it is usual to tilt the nozzle to reduce the taper. This is often found when cutting in thicker parts with water jet see figure 1. To remove taper, the head has to be capable of tilting the nozzle more than (+/-)10°. However it is not only needed to remove taper but also to be able to cut bevels which is a large step towards 3D machining. For that reason a minimum of (+/-) 45° tilt is a requirement. This is what costumers achieve with their machines, so the test bench has this as an absolute minimum.

![Figure 1: w/ (2) and w/o (1) taper reduction from www.flowwaterjet.net](image)

1.2 PROBLEM FORMULATION

The Bahr Modultechnik test bench should be updated from having three linear axes with two additional rotary axes so that the bench can simulate a five axis movement.

Furthermore, the two addition axes should have the kinematics that are used on the state of art head on the market and at the same time not be too advanced from a manufacturing perspective.
1.3 PURPOSE

The purpose of this project is finding a solution that fits the test bench from Bahr Modultechnik without any major reconstruction of the machine. Together with that the movement of the additional two axes in the rotary head should match the state of the art rotary head in the market. One other purpose is also to have documents about which one is the most used type of rotary head on the market. So that the developers can put their effort in to the solution that will have the highest demand in the coming years.

![Figure 2: Test bench](image1)

![Figure 3: Test bench Z-axle](image2)

1.4 GOAL

- To analyze and group the requirements for a rotary head.
- To find an already existing rotary head that can be adapted to the test bench or to design a rotary head completely from scratch.
- On a cost-efficient way find a solution that fulfills all the requirements. That includes a rotary head design with as little material as possible in order to reduce the price and save the environment.
- To find a solution that is safe for the people standing next to it while testing since the axis movements can be very fast.
- Have fully tested the machine in the end November before the project is over.
1.5 DELIMITATIONS

The delimitations for this project are that it is restricted to this specific machine that is the Bahr Modultechnik test bench. The restriction is even inside the machine; the Z-axis where the rotary head is supposed to be fitted should not need any modifications to achieve the goal, so it will be left the way it was delivered as a standard machine.

The rest of the machine is dimensioned for the mass that will be added according to Bahr Modultechnik. Therefore does not any additional work have to be done on the rest of the machine. Even though it is intended to add two axes, the project will not include working with the programming or the electrical installation to the amplifiers that control the electrical motors. The programming of the CNC unit will be done when the head is attached to the machine.

1.6 PLANNING

The project started by identifying different working phases so it would be possible to set up sub targets to reach in a defined period of time see Appendix 1.

The phases where:

1. Classification of rotary head design concepts used in water jet, plasma and laser cutters.
2. Definition of a suitable design concept for the test bench.
3. Research on components available on the market.
4. Design of the rotary head.
5. Preparations during production of the rotary head.
6. Build up of the rotary head.
7. Integration and test of the rotary head in the test bench.

The planning that was approximated in the beginning was later adjusted to the real time of each phase as seen in the end of Appendix 1.
2. REQUIREMENT ANALYSIS

The head should have the same kinematics as the head which is used by the majority of machine builders since the machines purpose is to test software that later will be updated to the already existing CNC software. At the same time it cannot be a head with a design that is too advanced since aspects like time and cost have to be taken in to consideration.

The parts will be assembled “in house” in a workshop for electronic assembly without machines like for example hydraulic press or similar. Therefore should the parts be easy to assemble.

The precision of the rotary head has to be at such a level that software changes can easily be seen with the eye and not just behaving in a certain way because of imprecision. As described in the introduction is the absolute minimum (+/-) 45° for bevel cutting, however for future development it is necessary to be able of (+/-) 60° so the B-axis will not be the limitation when the machine builders is coming closer to full 3D machining.

The head must be able of cutting out simple contours from a plate, e.g. a square or circle. If this should be realized it has to be able of turning at least one revolution. But since it not always the same contour that will be used it not possible to know where the “Lead in” to the contour will be. In the extreme case this means it could be 359°+360°.

SUMMARY OF REQUIREMENTS

1. Commonly used by machine builders.
2. Possible to integrate to the test bench.
3. Easy to assemble.
4. Precise enough to see changes in software
5. Simple inspection of the axes movements.
6. Minimum Nozzle tilt angle of 60 degrees.
7. Total weight less than 3kg\(^1\). 
8. Minimum 360° clockwise and counter clockwise movement of the C-axis.
9. Minimum requirement of acceleration around C and B axes: 50 rad/s\(^2\) \(^2\).

\(^1\) Based on the maximum mass put on the carrier to the Z-axis, specified from Bahr Modultechnik of 8kg. An approximation of the already existing Z-axle mass to 5kg leaves an additional mass of 3kg.
\(^2\) Minimum requirement is based on the maximum acceleration in the CNC software.
3. CONCEPT

3.1 RESEARCH ON KINEMATICS IN THE MARKET

The state of the art rotary heads were identified in a web research about mostly water jet machines that is documented in Appendix 2. They were listed in a table with some factors that would be important for this specific task.

- Simplicity,
- Price,
- High precision,
- Fit the test bench,
- Speed (based on axis corrections needed),
- Maximum cutting angle.

The important qualities of the different rotary heads were sorted with help of a point system Appendix 3. Each property was given a factor of its importance. Then each head was given a grade which was multiplied with the importance of that property.

Table 1: Score summary from Appendix 3

<table>
<thead>
<tr>
<th>Type of head</th>
<th>1. OMAX-AB</th>
<th>2. OMAX-BC</th>
<th>3. Perndorfer</th>
<th>4. Differential</th>
<th>5. Tilted C-axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total score (Max 100)</td>
<td>22</td>
<td>61</td>
<td>81</td>
<td>61</td>
<td>44</td>
</tr>
</tbody>
</table>

OMAX-AB is a head that has its B-axis tilted. It has a good clearance to the work piece and has an easy design.

The OMAX-BC was found out to only be able of 7° tilt. This was not enough as listed in the requirements.

The Perndorfer head has a very basic design and is developed by one of ProCom costumers. It has infinite rotation but needs much compensation. It can easily be understood by the machine operator since it has its axes horizontal and vertical.

The Differential head is actually a head that is used on a milling machine with a very robust design. However it is a little bit tricky to get the hoses down to the nozzle in this design since the design is encapsulated. And the kinematic is the exact same as the Perndorfer head, but this one got the double support for the nozzle (double bearings).

The Tilted C-axis head is a bit complex but gives similar kinematics as the New OMAX. The head needs a tilted C-axle which is difficult to implement in a machine design without major redevelopment of an already existing vertical C-axle.
A list with the most important properties was created and the research was started by visiting the machine builder’s web pages. Facts where listed and summarized in Appendix 4 that later should be summarized to identify the different groups that where on the market today Appendix 5.

It is possible to see four specific groups of rotary heads Figure 4-7, the names are made up for this report:

**Basic Head**

![Basic Head](www.perndorfer.at)

**Fork Head**

![Fork Head](www.watercut-nw.de)

**Tilted Head**

![Tilted Head](www.ymax.com)

**Special Head**

![Special Head](www.igems.se)

In these four groups can the specific heads from the previous page also be categorized.

<table>
<thead>
<tr>
<th>OMAX-BC</th>
<th>Tilted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perndorfer</td>
<td>Basic</td>
</tr>
<tr>
<td>Differential</td>
<td>Fork</td>
</tr>
<tr>
<td>Tilted C-axis</td>
<td>Special</td>
</tr>
</tbody>
</table>
By analyzing the differences between the groups/kinematics and having in mind that the rotary head should be integrated in the machine with the aim to imitate the state of art machine on the market. The idea to use an unusual solution like in the “Special Head” category and for example the IGEMS AB head would not be appropriate to reach the goals.

3.2 RESEARCH ON AVAILABLE HEADS IN THE MARKET

The company that had delivered the test bench was contacted, but they did not have any idea at all how to integrate a solution that would reach the requirements.

There was some alternative rotation tables proposed from Festo but the weight was far above the limit of 3kg and the cost was higher than it would be to design “in house” and manufacture it. Companies that were contacted: Bosch Rexroth, Festo, Bahr Modultechnik but none of them had heard of such a thing to buy as a finished solution. Festo proposed that they could design and manufacture the head if it would be needed.

3.3 CONCEPT ALTERNATIVES

Even if the IGEMS solution is good and it would reduce the amount of X, Y correction while cutting as for example a coned surface, the complexity of the solution did not match the goal and requirement. Two groups could now be identified that were by far the most used rotary head solutions that seemed to match the requirements.

The heads had the following qualities as described in Appendix 5:

**Basic**¹ head, advantages/disadvantages:

+ Simple design
+ Easy to maintain
+ High possible cut angle > 90°
+ Good modular construction to fit 3-axis machine
+ Easy to wire hoses on to the head
+ Very common on the market
+ Easily understood for CNC operator
+ Easily visually inspected
- More moving axis when 3D machining
- Can come quite close to work piece with rotary head when 3D machining
Tilted\(^{(2)}\) head, advantages/ disadvantages:

+ No compensation movements of linear axis!
+ Relatively simple design
+ Easy to maintain
+ Good modular construction to fit 3-axis machine
+ Very common on the market
+ Good clearance to work piece when 3D machining
- Quite difficult to wire hoses
- Small possible cut angle <60°
- Difficult to understand as a CNC operator

[1] Basic head 10 of 28*
[2] Tilted head 8 of 28*

* 28 is the total amount of identified rotary heads that could be placed in a specific group that explains the design/kinematics of it.

3.4 DECISION ON SUITABLE CONCEPT

The two types of kinematics which are the most common, easy to integrate without any redevelopment on the machine and have a simple design were decided to go further with.

The basic head has the advantage that it is already used by one of the customers that would in the future look for a system that supports the basic head kinematic. But the kinematics of the head was not optimal for all kind of manufacturing. So for the future there should most probably be a bigger demand on the Tilted head.

The decision was to continue with two heads and see how the heads would look when they were integrated in the Bahr Modultechnik test bench in the CAD environment.
4. DESIGN

4.1 DETAILING OF THE CONCEPT

4.1.1 COMPARISON OF BASIC AND TILTED HEAD

In this section a detailed comparison of the Basic and tilted head is done.

When any rotation head is used they will always at some stage need a compensation movement. A compensation movement is something that has to be done as a side-effect of a wanted movement. The compensation movement has often to be done by the linear axles which have the biggest masses to move around. So if a head has a kinematic that needs big compensation movement, big masses have to be moved around. This means that the machine will be slow. On the other hand is it impossible to operate a machine without compensations at some stage, but the goal is to have as small compensations as possible and rather have the compensations on the axes with smaller masses as for example B- and C-axes then on the linear axes.

To describe the heads kinematics, the axes which are used have to be introduced. The linear axes are X, Y and Z and the rotation axes is A, B and C. See Figure 8. For the Basic and Tilted head an A-axis will not be used since the machine will only be using 5 axes. The differences between the Basic and Tilted is the angle between B–axis and C-axis. The C-axis is used to rotate the head around the Z-axis. For the basic head, the B-axis changes the tool angle by rotating around the Y-axis.

The heads have a bit different kinematics and need compensation in different cases. The Basic head has some disadvantages when doing taper reduction operations or bevel cutting which means the head is operating with different angles on the tool/B-axis.

Basic: When the B-axis is turned it needs compensations movements in X or Y and Z so that the tool center point stays at the same place. The reason is that the tool center point of the tool is not in the point where the B and C axis cross each other. It could also be described as the tip of the tool has a lever to its rotation axis.

Tilted: The B-axis on the tilted head has a 45° angle. When the B-axis is turned the tip of the tool will stay in the same point, it can need a slightly compensation with the C-axle but it depends on the shape of the contour.
When reading the following explanation it could be helpful to use a pencil as a tool. In the center of Figure 11 is the volume of a cone that will be machined in the following comparison between the heads.

**Basic head:** The basic head has a distance between the tool center point and the point where the B-axis and C-axis cross each other as seen in Figure 9. In this description a pencil should be held on the middle. Now it should be imagined that there is a virtual axle between the fingers, which is the B-axis. Draw a cross on a paper and keep the pencil vertical pointing against the point where the lines cross each other.

If the tip of the pencil (tool center point) would be locked at the cross on a surface where the machine should cut a cone, first it turns the B-axis and at the same time it has to correct with the Z- and X- or Y-axis so that the tool center point stays in the same position.

This can be seen with the pencil since the tip will not point at the point where the lines cross each other anymore, if the pencil is turned around the virtual axis between your fingers. So the whole head (hand) has to be moved to be pointing at the center of the cross again. When the angle of the cone-wall has been adjusted and the machine should start to circle around the tool center point to do the walls, it has to make corrections in all axes except from Z-axis.

**Tilted head:** Now hold the pencil in the tip and imagine an axis between the fingers again. If the head is design with the axis lined up in the same point as the tool center point, as is described in Figure 10 it is called “Tilted Head”.

With the tilted head no correction will be needed when the tool is turned around the B-axis to stay in the same point with the tip of the tool. When this is made and the machine should start doing the walls of a cone, only the C-axis has to be turned to do the walls of the whole revolution around the cone.

This is also possible to see with the pencil, since the tip of it is still pointing to the center of the cross even though it has been turned around the B-axis/virtual-axis between the fingers.

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**Figure 9:** Basic heads kinematic.

**Figure 10:** Tilted heads kinematic.

**Figure 11:** Cone.
4.1.2 REALIZATION
The heads was built up with a modular design on a Fischertechnik model to easily see the kinematics of the different heads. This was very helpful for further understanding.

Figure 12: Tilted head
Figure 13: Tilted head
Figure 14: Basic head
Figure 15: Basic head
To realize what so far was only an idea and a model, a first version was developed in Pro Engineer CAD environment. In Figure 16 and 17 is the first version of the rotary head. Here the Motor plate is one piece. It was not designed with so much of manufacturing technique in mind, but just to show how it could look. To find the right scale and clearance between the new parts the whole Z-axis was inserted together with motors for both Z- and C-axes as seen in Figure 8 and 9.

To be able to see the result of software development, the idea to fit something that could draw on the surface at the bottom of the machine in under the C-axle arose. The result is the pencil fitted to the B-axis.

The motor that is used in this version of the rotary head is from Jenaer\textsuperscript{1} which was the smallest engine they could deliver. It had the specifications to fit the amplifier and only had the weight of 0.3 Kg, together with a torque of 0.31 Nm.

The construction to fit the “Pencil holder” is made so that it is bolted in the engine axle and locked against the inner-ring of a bearing in the “Motor plate”.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure16.png}
\caption{Basic head}
\label{fig:basic_head}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure17.png}
\caption{Basic head and Z-axis}
\label{fig:basic_head_z_axis}
\end{figure}

\textsuperscript{1} Model: 17H13-0230-101K1-52(30) from Jenaer
4.1.3 MODULAR DESIGN

Since both of the heads had their advantages in different aspects, the best would be if they could be combined in one modular design so that both types of heads could be used in the same construction. This would mean that it would no longer be needed to choose between the rotary heads. If that would be possible, simulations with the two most used heads for bevel cutting could be operated in the same test bench.

The heads are not supposed to be used simultaneous however to easily see the differences between them, they have both been placed on the module plate in *Figure 18*.

![Figure 18: Basic and Tilted in modular design.](image)

In this construction the motor is fitted to the motor plate in the exact same way, the only thing needed is to unplug the screws and turn the C-axis 180° to refit the motor plate with another angle. The C-axis is turned because the cables “zero” point should be at the same place.

The tilted solution required a design of the part which holds the pencil/tool that has to be corrected between the two types of heads. The same angular difference as the motor plate does from the C-axis, has the “Pencil holder” had to be corrected so that it is parallel with the C-axis again.

The module idea was taken further to the “B-axis holder” on the motor axle where two screws should be switched to change the different angles between the B-axis and the pencil.
One requirement was that the pencil “nozzle” should at least be able to reach an angle of 60 degrees. From the design’s point of view that would mean that it had to be made with less than 90 degrees angle on the B-axis so that the construction would not weaken or that other parts than the pencil’s tip would reach the surface first.

Tests with 37° on the motor plate were made in Pro Engineer CAD to see which angle offsets would be possible for the tool, this resulted in:

<table>
<thead>
<tr>
<th>B-axis (Motor)</th>
<th>Pencil (nozzle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>-&gt; 32</td>
</tr>
<tr>
<td>55</td>
<td>-&gt; 36</td>
</tr>
<tr>
<td>90</td>
<td>-&gt; 47</td>
</tr>
</tbody>
</table>

From this simulation could the conclusion be made that the engine plate had to have a steeper angle which also meant that the B-axis would be given another angle compared to the C-axis. This would result in that the ratio\(^1\) between the B-axis and the offset between C and the pencil’s axels would be more the same. So the angle on the plate was changed from 37° to 45° which result in an angle of 60° on the tool when the B-axis was turned 90°.

\(^1\) At 90 degrees angle on the engine plate the ratio will be 1:1 between the motors movement of the B-axis and the angle between the pencils (nozzles) center axis and C-axis. At 45 degrees the ratio will be 3:2.

### 4.1.4 CORRECTED OFFSET TO THE C-AXIS

The first version of the Tilted head in the modular way had a design error that was found from easy simulation of the movement by holding a pencil and turning it around a tool center point as described in Chapter 4.1.1.

So there had to be a correction to align the center of the pencil’s center axis with the center axis of the C-axis. The position that the tip was in had to be corrected as well, to be in the point where B and C-axis cross each other as is explained in Figure 20.

![Figure 20: First version with modular design](image1)

![Figure 20: Corrected to remove c-axis offset](image2)
4.2. DIMENSIONING OF MAIN COMPONENTS

In this section the main components will be described more in detail for further understanding why they look the way they do and what advantages against other alternatives they had. For further understanding which parts are described see Figure 1 in Appendix 8.

The meaning of for example (REF108) is that it refers to Reference 108 in Appendix 7 where the drawings are.

4.2.1 JOINT BETWEEN HEAD AND C-AXLE

The two most used ways of transferring a torque between two parts is either by using splines or a woodruff key. Since the axle was not prepared for the two most common methods it meant that the Z-axle would have had to be torn apart and removed from the test bench to be machined. Since the C-axle only can be dissembled by removing it downward it meant that a lot of parts would have to be torn apart.

Trying to attach the rotary head in a simple way without tearing the test bench apart the Clampex, which is a part produced by KTR was found to be interesting. The Clampex is specified to handle a torque of 40Nm for this type of construction. The KTR 105/250 products decreases in inner-diameter and increases in outer-diameter when it is assembled.

There were two alternatives from KTR. One was model 250 and the other 105. Both have self-centering construction. The difference is how you attach the additional part to the axle. For this application the KTR 250 could not be used since the screws that would have to be dissembled when changing the type of head would have come to close to the Z-axle, so that they would be impossible to unscrew.

If that would not have been the case, the KTR 250 is a bit bigger but it locks the construction axially in a bit more safe way, because the head could then get support from the neck seen in Figure 21.

Figure 21: KTR 250
Figure 22: KTR 105
Figure 23: KTR 105 mounted inside the head
4.2.2 COMPONENTS BETWEEN B-AXLE MOTOR AND TOOL

Pencil:
The idea was to find a plotter pencil, however they were mostly quite expensive and had a diameter of ½” which was too large. Instead, parts from a usual pencil are used. The inner part of a pencil that the ink is stored is in most cases made of plastic. It is not a stable construction on its own without housing so the idea was to use the front part from a standard pencil and attach it in one end of a housing made of aluminum.

The parts are:
1. Housing made of aluminum (REF109 and 111).
2. The tip of a standard pencil.
3. The cap taken from a standard pencil.
4. Grease to make the ink stay in the housing.
5. Ink.

Cap:
The cap (REF 105) in the design has three purposes. One is to secure the screws in the Clampex. The second is to lock the construction axially to the axle since the cap is bolted with an M8 inside the C-axis. The third is to calibrate the whole head to the C-axis.

Pencil holder:
The pencil holder (REF 106/107) was first designed with screws holding the pencil/tool from one side. However if a pencil/tool with an smaller diameter than 10mm was fitted it would have moved the pencil out on the center axis which has to be align with the rest of the construction to work. So the holder was design with a gap that could be reduced from both sides by tightening the M4 screw.

To make the construction even more flexible, a cylinder (REF108) which also has a gap was design that could be inserted inside the above described construction. The cylinder has an inner diameter of 8mm and an outer diameter of 10mm.

This makes it possible to insert a tool in the construction that has a diameter of 7-11mm or even less if a new cylinder would be manufactured.
4.2.3 FEM CALCULATION OF MECHANICAL STRUCTURE

The goal with the FEM calculations is to verify the design will be able to withstand external forces that can occur. The torque simulation is to test rapid acceleration around the C-Axis where the most powerful motor is positioned. There could have been a simulation of the motor torque from the B-Axis, however it is negligible in its size of maximum 0,7Nm.

The rotary head (REF102 and 103) was FEM-analyzed with the center of the module-plate locked in all directions, just as it will be when it is stuck to the CLAMPEX 105 that is the part inside the head that decreases in inner diameter and increases in outer diameter to hold the parts together. There were two different simulations made which are described below. In total were there four simulations made (two of each).

1. Simulation of motors weight together with the extreme case when the “nozzle” hit the ground. The Motor plate and the Module plate were mounted together. In the bottom of the motor plate was a force of 200N applied. The force was in the direction of the Normal to the surface where the motor will be installed.

2. Simulation of a torque on the motor plate, to verify that it can stand rapid acceleration around the C-axis where the most powerful motor was positioned. The torque was applied around the center were the motor axle will have its hole thru the motor plate. The applied torque was 4,5Nm.

The maximum tension was in all cases found in the threads.

Material data:
AL6061-T6
Yield strength = 276\(^{(1)}\)MPa
Ultimate tensile strength= 290\(^{(1)}\)MPa

<table>
<thead>
<tr>
<th>Result for basic:</th>
<th>Safety factor</th>
<th>Appendix/Page</th>
</tr>
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<td>2. Model max 40MPa</td>
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<table>
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<th>Safety factor</th>
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</tr>
<tr>
<td>2. Model max 37Mpa</td>
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<td>6/2</td>
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</table>

4.2.4 DIMENSIONING OF ELECTRICAL MOTOR

The goal was to find a motor for the B-axis. The motor should be a small servo motor because of the precision in a servomotor. It should stand a force of 3N at the tip of the tool which meant that the motor has to be capable of approximately 0.2Nm.

- Weight of no more than 0.4kg,
- Compatible with an amplifier that could use a Sercos and EtherCat interface.

There were three alternatives on motors that where possible to use. The motors were brushless rotary servo motors with the same torque and maximum speed.

1. AKM1 from Kollmorgen
   + Supports Sercos interface and EtherCat
   + Connectors positioned in a good way
   - Expensive

2. 17H13 from Jenaer
   + Cheap
   - Does only support EtherCat

3. MSM019A from Bosch Rexroth
   + Supports Sercos interface and EtherCat
   - Connectors positioned in a bad way, see figure 24
   - Expensive
   - Motor axle without woodruff key

For development reasons, the opportunity to have several interfaces in the amplifier together with the good position of the connectors, made the AKM1 the most appropriate alternative.

Figure 24: To show how bad positioned the cables were on the Bosch motor.
For future development of the test bench the data for the motor can be useful, and also to understand what the motor is capable of.

**Model:**

AKM11B-AKCNR00

AKM= The series of Brushless servomotors
1= Motor frame size
1=Rotor stack length
B=Winding type
A=International standard mount
K=Open keyway
C=IP65 connectors
N=No brake
R=Resolver
00=Standard motor without shaft seal

**Basic facts:**

- Rated torque [Nm] 0,17
- Peak torque [Nm] 0,71
- Rated power [kW] 0,14
- Voltage [V] 230
- Rotor moment of inertia [kgcm²] 0,017
- Weight [kg] 0,35

**Drawings:** Appendix 8

- Amplifier model: Servostar 303
- Cable length: 15m
- Amount of cables: 14
To verify the choice of motor some calculations were done. This was to be sure that the motor would be capable of moving the B-Axle holder with tool at the maximum speed of the CNC software. The average densities and inertia was calculated in Pro Engineer.

**B-AXIS MOTOR**
Minimum requirement of acceleration$^{(1)}$: 50 rad/s$^2$

Analysis of [REF 104,106,108 and 109] gave the following information:
Volume = 2.13e-05 M$^3$
Surface area = 1.13e-02 M$^2$
Average density = 5.26e03 KG / M$^3$
Mass = 1.10e-01 KG = 110 GRAM

Principal moment of inertia:
5.45e-02 TONNE * MM$^2$ < = > 5.45e-05 KG*M$^2$

**Technical Data AKM1$^{(1)}$:**
Rated torque (Standstill): 0.17 NM
Rotor moment of inertia: 1.7e-06 KG*M$^2$

Rotor inertia + Parts inertia = 5.62e-05 KG*M$^2$

\[
\frac{\text{Torque}}{\text{Moment of inertia}} = \text{Acceleration} \Rightarrow \frac{0.17NM}{5.62e-05 \text{ KG*M}^2} = 3026 \text{ rad/s}^2
\]

**C-AXIS MOTOR**
Minimum requirement of acceleration$^{(1)}$: 50 rad/s$^2$

**Technical Data MSK040B$^{(2)}$:**
Rated torque (standstill): 1.7NM
Rated torque (Maximum): 5.1NM
Rotor moment of inertia: 0.0001KG*M$^2$

[1] Minimum requirement is based on the maximum acceleration in the CNC software from ProCom GmbH
[2] MSK040B is delivered by www.boschrexroth.com
[3] AKM1 is delivered by www.kollmorgen.com
4.2.5 TOLERANCES

The goal with the tolerances was to meet the requirement of an easy assembly and to achieve high precision. Since there was no way of ordering a motor that had a thread inside the axle, the axle holder had to be locked axially by a tight tolerance. To calculate the needed temperature difference between the motor axle and the “B-axis holder” (REF104) a formula was used that was found in *Maskinelement Karl Olof Olsson, first version, page 132*.

\[ \Delta r = R_i \cdot \alpha \cdot \Delta T \]

Where:
- \( \Delta r \) = Inner diameter of the hub (–) outer diameter of the axle.
- \( R_i \) = Inner diameter of the hub.
- \( \alpha = 0.000012^{(1)} \)
- \( \Delta T \) = Temperature difference (to be calculated)

\[ \Delta T = \frac{\Delta r}{\alpha + R_i} \Rightarrow \frac{(8.0 - 7.97)}{8.0 + 0.000012} \Rightarrow 312^\circ \text{ Celsius} \]

If the motor axle had been stored with a temperature of 20° Celsius it would have meant that the “B-axis holder” should have a temperature of 332° Celsius. This was calculated as a test to see how high temperature would be needed.

Since the exact same diameter would not be possible to calculate, an example was made to calculate if the h7/H7 would not be perfectly machined and the tolerance would fall out by 0.005mm from its standard.

That would result in the following temperature needed.

\[ \Delta T = \frac{\Delta r}{\alpha + R_i} \Rightarrow \frac{(8.0 - 7.995)}{8.0 + 0.000012} \Rightarrow 52^\circ \text{ Celsius} \]

This would mean that the axis holder (REF 104) would have to be heated to a temperature of 52°+20° = 72° Celsius. This would be reasonable for this application. However the goal is to be able of sliding it on without any need of heating the axle holder (REF104). Except from the pins through the B-axis holder which needed a bit more force, this was because they were missing an axial locking except from the friction between the parts.

[1] Value found in Maskinelement, table 4.1-1
To verify that there would be a solution if the given tolerance would not be as tight as expected, a glue company was contacted for some expert advice.

According to Loctite technical expert in the field of machine design and gluing we were given the following advice after Krister Essvik had been showed pictures and drawings of the head.

**Krister Essvik, Application Engineer, 2010-09-07:**

"Use an easy grip tolerance, diametrically tolerance of maximally 0,1mm. Use Loctite 603, it will give you about 20 Nm for every mm² in shear load – This should be enough without any Woodruff key for your application"

The main focus was that it should be easy to assemble as specified in the requirement. Therefore a clearance/middle fit was taken rather than a grip fitting in the rest of the design. In a meeting with the manufacturer the surface roughness was discussed and decided based on in which application the parts would be used and on their expertise in the field.

4.2.6 STEEL THREAD

In this design the Modular plate is made of aluminum. The Motor plate is fixed to the Modular plate with steel screws that has to be dissembled/assembled every time the mode of the head is changed. This means that it is in the long term a critical part because it will be exposed for many different users with different amount of knowledge how to use a torque wrench. One way of increasing the reliability of the construction was to fit an insert thread made of steel. This will reduce the tension on the first thread up to 50%\(^1\).

4.3. ADDITIONAL COMPONENTS

In this chapter the additional components will be presented. The goal is to describe why these parts have to be used.

4.3.1 WIRING AND CABLE HOUSING

The rotary head has to have a minimum rotation of 360° clockwise and counterclockwise on the C-axis as described in Chapter 2. That means that the cables to the B-axis motor have to be wired in a way so that it can handle the rotation without getting stuck or to find a solution that is wireless.

The first alternative was the slip ring that could provide the rotary head with electricity during endless rotation (Figure 25) for up to 15 cables. This would also have the advantage against cables in the way that it would not be needed to have a hardware stop, or extra internal software stop to prevent that the cables would be ripped off if an error would occur in the CNC software.

The problem with a slip ring is however the disturbance and the limit of data that can be transferred since the surfaces are not all the time in contact with each other.

There were several alternatives on the market for transferring the electricity to the head as for example Figure 26 that is possible of 3,000° of rotation. In a market analyze from a known automation magazine¹ a suitable solution was found for the cables as seen in Figure 27. The solution did not need so much space as the solution for 3000° which was not even necessary for this application.

¹In SPS Magazine (Zeitenschrift für Automatisierungstechnik) Ausgabe 9 Jahrgang 23 Page 104-106.
If a plastic protection would be used it had to be attached to the Z-axle and to the motor. It would have been best if the protection could have been attached to the head but since it had the modular design and the motor would not be attached in the same place all the time made it impossible to do it that way. The requirement was that it should stand the external forces and protect the cables from abrasion when the C-axis is turned.

It was decided to use cables together with a flexible housing which then meant that a safe way for the maximum angles had to be found. It also means that every time the mode of the head would be changed, the modular plate has to be turned 180° to keep the “zero point” for the cables.

The other axles (X,Y,Z) on the machine have their axis limited by both software and hardware stops. The hardware stop is magnetic sensors located in all end of the guide ways. And the software limits are in the CNC program.

If the B-axis would be limited by a magnetic sensor, more cables would have to be wired down and on to the rotary head. This is not positive since the more cables going to the head; the harder it would be to have all cables together and still be flexible enough for the rotation.

Since the module plate now would be turned 180° when changing between the different types of heads because of the cables and that it also has to be able of doing (+/-) 360° made it not look like a good idea to attach a magnetic sensor to the rotary head as a limit.

The Bosch Rexroth motor that is attached to the C-axle has a multiple absolute measuring system; this means it can have inputs in the control interface to have limits. For example independent limits on the motor that will not be in direct contact with the CNC if some error would occur.

The same aspect would also have to be solved for the B-axis. Not because of cables but so that the Pencil “Nozzle” should not hit any of the other parts on the head.

In the decision which motor to use a requirement of a single absolute measurement system or a multiple was necessary. This means it could have programmed limits within one revolution for single, and limits for several revolutions for multiple. Since the motor would be used for an application where the tool as a maximum would be moved (+/-) 135°, a single system would work perfectly.

Notice: “Multiple absolute measuring systems” was not an alternative for so small engines.
4.3.2 CALIBRATION UTILITY

Since the position of the tool in the tilted head was very important as described in Chapter 4.1.4 a calibration tool was developed. The tool was given a modular design; it can calibrate the center of the pencil to the C-axis. And it can calibrate the distance that the pencil or other equipment that can be used sticks out from the pencil holder, to make sure that the tip of it is in the point where B- and C-axis crosses each other.

![Figure 28: Calibration of pencil length](image)
![Figure 29: Calibration alignment](image)
![Figure 30: Calibration alignment](image)

4.3.3 MOUNTING SUPPORT PLATE

To simplify the installation and keep the precision of the construction, a mounting plate was developed. The mounting plate is to be used when the B-axis holder is pressed on the motor axle. The reason why it was necessary is because the distance between the motor plate and the holder must be 1mm to keep the pencil “nozzle” align with the C-axle.

![Figure 31: Mounting plate](image)
4.3.4 FLEXIBLE TABLE

Since we now added a pencil to the construction, there was one thing that would have to be taken in consideration. What would happen to the head if the machine would do a jump on the Z-axis. The most natural way of removing the problem if an error would occur and the contact pressure on the tool would be too high is to have the pencil/tool spring-loaded. However that would mean that the tool center point would fall out of the spot where the axis is crossing each other if the Tilted head would be used.

So instead of solving it the way as all plotters have it, the idea was to use a soft material that would be put in under the board. This was to make the height of the surface a bit more flexible if the pencil pressure would reach a certain limit that was decided from testing.
## 5. TEST AND EVALUATION

### 5.1 FUNCTIONALITY

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<th>Maximum angle around C-axis:</th>
<th>(+/-) 370°</th>
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<tr>
<td>Motor:</td>
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<td>Weight of the rotary head (w/o motor):</td>
<td>0,65kg</td>
</tr>
<tr>
<td>Weight of the rotary head (w/ motor):</td>
<td>0,95kg</td>
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<tr>
<td>Material:</td>
<td>AlMg4,5Mn and Fe36013FN</td>
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<td>Cable protection:</td>
<td>Triflex R from IGUS</td>
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<tr>
<td>Other equipment:</td>
<td>Mounting plate and Calibration tool</td>
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<td>Amount of parts:</td>
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<td>Clamp:</td>
<td>Clampex 105, 14/26. Inner diameter of 14 and outer diameter 26mm.</td>
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<td>Precision:</td>
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<td>Pencil (nozzle)</td>
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<td>135°</td>
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<th>Maximum angle with Tilted head:</th>
<th>(+/-) 60°</th>
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<td>Pencil (nozzle)</td>
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<td>45°</td>
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<td>39°</td>
</tr>
<tr>
<td>90°</td>
<td>60°</td>
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5.2 ACCURACY

In this chapter is some of the test listed that where performed. These tests were made to verify that the head could manage the requirements listed in *Chapter 2*.

**Test 1**
Purpose: See if the plastic protection and cables can turn around the C-axis without getting stuck to anything.
How: The C-axis should be turned to the maximum and minimum angles ten times. This should be done with both the Basic and the Tilted head.

**Test 2**
Purpose: See if there is any offset between the tool and the C-axis.
How: The Z-axis will be lowered against the surface in under the tool with 0° angle on the B-axis. When the tool is in contact with the surface the C-axis should be turned one revolution to see if it will only be a dot or a circle drawn on the paper.

**Test 3**
Purpose: See if the tool center point stays in the same point even do the angle on the tool has been changed.
How: This test is only for the Tilted head. The Z-axis will be lowered against the surface in under the tool. When the tool is in contact with the surface the B-axis should be turned to plus 45°. Then should the C-axis be rotated one revolution and the surface checked. Then turn the B-axis minus 45° and do it all over again.

![Figure 32: Result of test 3](image)

**Test 4**
Purpose: See if there is any geometrical errors in the head or if the surface in under is uneven.
How: This is for the basic head. Turn the B-axis to 45° and lower the tool to the surface. Then turn the C-axis one revolution in each direction to see if the circle is perfectly round.

5.3 USABILITY

From the tests in *Chapter 5.2* could the head be verified to manage the requirements listed in *Chapter 2*. The cables can stand high speeds on the C-axis with up to 720° rotation and the precision was as good as it can be with a 0,7 mm pencil attached to the head. When the tilted head was tested in test two and three the dot on the surface had a diameter of less than 1mm. Test four with the basic head made an perfect circle which was controlled measured with an compasses.
6. CONCLUSION

The first phase was to do a research to gather information about the machines on the market. This was done by collecting information from over 150 companies and listing which type of kinematic was mostly used by the machine builders for their 5-axis cutting heads. This research was the base for the rest of the project since the two kinematics which was the most used ones were decided to go on to the next phase with. The first thing to look for was if there were any products on the market that had these kinematics and satisfied the requirements (see chapter 2). Several companies that were selling products to similar machines as the test bench were contacted, but none of them could deliver a solution that had this kinematic and was as lightweight as required.

One of the heads has the B-axis on 90° angle from the C-axis and the other head a 45° angle from the C-axis. The head with 90° angle was called Basic head and the 45° head Tilted. For a detailed explanation about the geometry please read (Chapter 4.1.1.).

To get a deeper understanding of the differences between the two heads, a model was built. This was to simulate movement and to get inspiration to the coming design phase. From the very beginning the plan was to only have one head to go in to the design phase with, but now there were reasons which made both heads highly interesting to proceed with (see Chapter 3).

If there could be a solution to integrate the two kinematics in one head the test bench’s importance for the future development would be dramatically increased. This was realized with a modular design on a plate where the motor could be attached on one side for one kinematic and on the other side for the other kinematic. The modular plate was developed with two important aspects in mind. One was to keep the precision of the head even if it would not be assembled in one fixed position and the other was to make it easy for the user to switch between these two different modes.

The software development in the machine is verified by logging and visual inspections were the visual inspection is much faster than to analyze the data in the log. To see the B-axis movement easier a tool was integrated in the design of the head. The tool-holder had a modular design and had to be switched when the mode of the head was changed. To make it possible to use several different tools with different diameters an additional cylinder was developed. This made it possible to attach tools as for example pencil, laser pointer or a knife to the tool holder.

Figure 33: The basic head
The already existing C-axle was missing a woodruff key which would have been the simple solution to transfer the torque to the head. But as a result of a research done in automation magazines and on internet, a product was found that could clamp two parts together and transfer a torque of 20 times bigger than necessary, but still being a compact light-weight solution. The head was changed in the CAD to fit this new solution and FEM analyzed to verify the construction was strong enough.

When the dimensioning of the main components was finished, the research for a suitably B-axis motor together with an amplifier could begin. And when the B-axis motor was selected, the weight that the C-axis motor had to handle was known. On the C-axis there already was an existing motor, so some calculations had to be done to see if the motor was powerful enough or if an additional gear would have to be installed. From the calculation was the motor verified to be strong enough, so nothing had to be done.

The head did now consist of 7 components which had to be assembled manually. To keep the precision that had been specified for the manufacturing another two tools was developed. One tool was developed to only be used the first time the whole head was assembled and the other tool for calibration of four things.

1. The tool length for the tilted head which was essential for the kinematic of that head.
2. That the tool holder for the tilted head was aligned with the C-axis.
3. That the tool holder for the basic head was aligned with the C-axis.
4. To set the zero position for the B-axis the first time it would be configured in the amplifier.

Now that it was decided that a tool would be attached to the head there was one situation that could happen which would be good to think about. This was if the Z-axis would “jump” and the contact pressure for the tool would increase dramatically. For plotter machines this is avoided by having the tool spring-loaded, this could also be done in this test bench if it would not have been for the Tilted head which has to have its tool center point in a fixed point compared to the B and C-axis (described in chapter 4.1.1). So instead the table under the head was made flexible in its distance to the Z-axis. The table was modified to stand a contact pressure that was decided from testing different flexibilities of the foam which was put in under a board that the tool would operate on.

Thanks to the calibration tool the head could be verified to have a precision within (+/-) 0,05mm after assembly.
The precision of the machine is good enough to see the changes and has gives ProCom many alternatives for future testing and development. Things that now can be tested with the new rotary head:

- Two different kinematics,
- Taper reduction,
- Bevel cutting,
- Compensation for leaning table,
- Tests with different tools as for example a pencil or a knife,
- Tests with multiple interfaces in the amplifier to control the B-axis.

With the newly developed design only two pins and two screws have to be dissembled and reassembled in another position which could be done in less than 10 minutes.

**For future development:**

Two ideas for a future project that may be suitable for a bachelor thesis work in electrical engineering. From the research on internet and fairs it can be seen that some machine builders have the rotation for the C-axis limited from two revolutions and up. Some machines can rotate the C-axis infinite but not a majority, however in the future it will probably be a solution existing in every machine. This is because it would not be needed to rotate the C-axis back to the zero point to continuing cutting after the limitation is reached. Today the test bench can rotate 720° because of the limit from the cables to the B-axis motor. This could however for a future project be upgraded to an infinite solution in the test bench as well. One solution in particular that could be used is a slip ring which has the same kind of solution that is used in all steering wheels on cars.

Water jet machines are most often used to cut bigger sheet metal plates which can have irregular surface height. The machine compensates this buy measuring the “zero” position in Z-axis at start of the program and sometimes during cutting by stopping the machine and moving the Z-axis down with the sensor that has to touch the work piece. To optimize this maneuver the test bench could be updated with a measuring system that communicate with the CNC software and compensate for angular and height in-corrections. If three points on the work piece would be measured the software could compensate for the angle on the table and for the distance to the work piece. If the sensors would be taking measurements all the time the software could actively compensate without any interruptions in the cutting.
7. REFERENCE LIST:

**Persons:**
ProCom GmbH:
Dr Andreas Kahmen, Harald Müller, Dr Arne Lorenz, Willi Schmitz, Andreas Müller.

**Documents:**
ProCom GmbH Internal wiki, Customer list, 2010-08-05

In SPS Magazine (Zeitenschrift für Automatisierungstechnik) Ausgabe 9 Jahrgang 23 page 104-106.

**Books:**


*Formler och Tabeller för Mekanisk Konstruktion*, edition 6, Karl Björk, Karl Björks Förlag HB


**WebPages:**
Loctite Worldwide design handbook, [http://loctite.fast.de/wwdh/se/i115ch07.htm](http://loctite.fast.de/wwdh/se/i115ch07.htm), Chapter 7.1, Date 2010-09-02

AKM product manual, [www.kollmorgen.com](http://www.kollmorgen.com) / Products / Motors / Rotary servomotors / AKM Series. Chapter 41.2 and 42.1, Date 2010-08-25

Descriptive photo of Taper reduction, [www.flowwaterjet.net](http://www.flowwaterjet.net), Date 2010-10-08

**Programs:**
Pro Engineer 3.0
Rexroth IndraSize 04V16
Projektron BCS 6
## APPENDIX 1

### Planning Week

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<td>Research on components available</td>
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### Real structure

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### Hours spent in the project[^1]:

| 32 | 41 | 40 | 43 | 40 | 43 | 33 | 37 | 37 | 22 | 40 | 38 | 40 | 32 | 36 | 33 | 38 |

[^1]: Documented with help of Projektron BCS 6

Total hours 625

Alexander Hjelm
Why should you tilt the head?

1. Creating sharp edges.

2. Increasing precision by removing taper.

3. Creating beveled edges for artistic purposes or for die relief.

Figure 1: Explanation of axes
1. OMAX-AB

Advantages/ disadvantages:
+ The Tilt-A-Jet may reduce X,Y, and Z travel slightly (Taper doesn't disappear).
+ Less moving axis makes higher precision (If the software is good).
+ Can reduce production time (Depending on shape of part).
- Not easily adapted to already existing test bench.
- Big investment.
- Cannot be maneuvered manually.
- More difficult to program.

Cutting Angle (B-axis)
From 0° vertical to 7° horizontal.(corrected)

Figure 2: OMAX-AB

Movie:
http://www.youtube.com/watch?v=EYEA3MAvRKo

Products from OMAX (technical specifications):
2. OMAX-BC

Advantages/ disadvantages:
+ The Tilt-A-Jet may reduce X,Y travel slightly.
+ Can reduce production time *(Depending on shape of part).*
+ Can be fitted to our C-axis.
- Big investment.
- Difficult to maneuver manually.

Cutting Angle (B-axis)
From 0° vertical to 60° horizontal.

![OMAX-BC](image)

*Figure 3: OMAX-BC*

*Movie:*

*Tilted Head,* [http://www.wardjet.com/5-axis.html](http://www.wardjet.com/5-axis.html) 2010-05-15
3. Perndorfer

Advantages/ disadvantages:
+ One costumers have showed that this is what type of rotary head they would prefer
+ Easley fitted to already existing C-axis.
+ Low production coast.
+ Can be maneuvered manually.
+ Can work >90°
- More moving axis.

Cutting Angle (B-axis)
From 0° vertical to >90° horizontal.

Figure 4: Perndorfer head

Perndorfer head, www.perndorfer.at, 2010-08-15
4. Differential CA head attached to a VMC

Advantages/ disadvantages:
This is usually an attachment to 3-axis VMC and intended for light jobs (milling)
+ Slim design.
+ Easely fitted to already existing C-axis.
+ Can be maneuvered manually.
- Difficult to wire hoses for laser and water jet.
- Electric/ Water/ laser cables are running between the axes and therefore C-axis travel is limited.

Cutting Angle (B-axis)
From 0° vertical to ~50° horizontal.

Figure 5: Differential head

Comparison between milling heads, http://numeryx.com/cnc/5axes.htm, 2010-08-15
5. Tilted C-axis

**Advantages/ disadvantages:**

+ Fast angle movements,
+ Water house inside C-axis,
- Cannot be maneuvered manually,
- Advanced construction,
- High production cost.

**Cutting Angle**
From 0° vertical to 90° horizontal.

*Figure 6: Tilted C-Axis*

*Tilted C-axis head, [http://www.wardjet.com/5-axis.html](http://www.wardjet.com/5-axis.html) 2010-08-15*
## Which rotary head:
1. Taper reduction water jet cutting head
2. Water jet cutting head for bevel cutting
3. Costumers Prototype
4. Differential CA head attached to a VMC
5. Tilted C-Axis rotary head

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<td>5</td>
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<td>4</td>
<td>3</td>
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<td>High Precision (2)</td>
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<td>4</td>
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<td>Fit our machine (4)</td>
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<td>24%</td>
<td>68%</td>
<td>90%</td>
<td>68%</td>
<td>49%</td>
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Maximum score = 5.
(0-4) Where four is the most important factor.

0-100% where a solution with 100% would be perfect.
### APPENDIX 4

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<tr>
<th>Basic</th>
<th>Type</th>
<th>Precision</th>
<th>Size</th>
<th>Cut angel</th>
<th>Modular upgrade</th>
<th>Simplicity (hoses)</th>
<th>Spec Y/N</th>
</tr>
</thead>
<tbody>
<tr>
<td><a href="http://www.perndorfer.at">www.perndorfer.at</a></td>
<td>Water</td>
<td>x</td>
<td>Big</td>
<td>120°</td>
<td>Easy</td>
<td>Easy</td>
<td>J</td>
</tr>
<tr>
<td><a href="http://www.yildirimmakina.com">www.yildirimmakina.com</a></td>
<td>water</td>
<td>+/- 0.05 mm</td>
<td>Small</td>
<td>110°</td>
<td>x</td>
<td>Easy</td>
<td>J</td>
</tr>
<tr>
<td><a href="http://www.alex-watercut.de">www.alex-watercut.de</a></td>
<td>Plasma</td>
<td>x</td>
<td>Big</td>
<td>52°</td>
<td>x</td>
<td>Easy</td>
<td>J</td>
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<tr>
<td><a href="http://www.cumatec.eu/eng">www.cumatec.eu/eng</a></td>
<td>Laser</td>
<td>x</td>
<td>Big</td>
<td>x</td>
<td>x</td>
<td>Difficult</td>
<td>J</td>
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<tr>
<td><a href="http://www.huber-grimm.de">www.huber-grimm.de</a></td>
<td>Laser</td>
<td>x</td>
<td>Medium</td>
<td>x</td>
<td>x</td>
<td>Medium</td>
<td>x</td>
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<td><a href="http://www.ptv.cz">www.ptv.cz</a></td>
<td>Water</td>
<td>x</td>
<td>Big</td>
<td>x</td>
<td>x</td>
<td>Medium</td>
<td>J</td>
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<tr>
<td><a href="http://www.woma-products.com">www.woma-products.com</a></td>
<td>Water</td>
<td>x</td>
<td>Medium</td>
<td>45°</td>
<td>x</td>
<td>x</td>
<td>J</td>
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<td><a href="http://www.well-engineering.de">www.well-engineering.de</a></td>
<td>Laser</td>
<td>x</td>
<td>Small</td>
<td>110°</td>
<td>Medium</td>
<td>Easy</td>
<td>J</td>
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<tr>
<td><a href="http://www.cato-cuttingsystems.com">www.cato-cuttingsystems.com</a></td>
<td>Laser</td>
<td>x</td>
<td>Small</td>
<td>45°</td>
<td>x</td>
<td>Easy</td>
<td>J</td>
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<td><a href="http://www.basentechniksysteme.de">www.basentechniksysteme.de</a></td>
<td>Laser</td>
<td>x</td>
<td>Medium</td>
<td>45°</td>
<td>x</td>
<td>Easy</td>
<td>J</td>
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<th>Cut angle</th>
<th>Modular upgrade</th>
<th>Simplicity (hoses)</th>
<th>Spec Y/N</th>
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<td><a href="http://www.omax.com">www.omax.com</a></td>
<td>Water (+/- 0.09° (±6 arc minutes))</td>
<td>Medium</td>
<td>60°</td>
<td>x</td>
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<tr>
<td><a href="http://www.jetedge.com">www.jetedge.com</a></td>
<td>Water (+/- 0.2-0.5)</td>
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<td><a href="http://www.stako.nl">www.stako.nl</a></td>
<td>Water</td>
<td>0.01 mm</td>
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<td><a href="http://www.techniwaterjet.com">www.techniwaterjet.com</a></td>
<td>Water</td>
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<td><a href="http://www.waterjetcorp.com">www.waterjetcorp.com</a></td>
<td>Water (+/-0.05 mm)</td>
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<td><a href="http://www.maklaser.de">www.maklaser.de</a></td>
<td>Laser(6 axis)</td>
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<td>Plastic</td>
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<td><a href="http://www.prussiani.com">www.prussiani.com</a></td>
<td>Water (+/- 0.1 mm)</td>
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<th>Precision</th>
<th>Size</th>
<th>Cut angle</th>
<th>Modular upgrade</th>
<th>Simplicity (hoses)</th>
<th>Spec Y/N</th>
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<td><a href="http://www.haprotechnik.at">www.haprotechnik.at</a></td>
<td>0.2 micrometers</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td><a href="http://www.resato.com">www.resato.com</a></td>
<td>Water (+/-0.2 mm)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td><a href="http://www.atech-chemnitz.de">www.atech-chemnitz.de</a></td>
<td>Water (+/-0.05 mm)</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td><a href="http://www.cobalm.de">www.cobalm.de</a></td>
<td>Water (+/-0.02)</td>
<td>Small</td>
<td>5°</td>
<td>x</td>
<td>Medium</td>
<td>N</td>
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**Comment:**

Combo = Water+Plasma+Laser
x = Unknown
J = Yes
N = No

**Requirements:**

- Cut angle > 45°
- 5 axis
- Possible to wire hoses on to the head

---

**Page A4.1**
Identified rotary head groups: Basic, Tilted, Fork, and Special

**Basic head, advantages/disadvantages:**
+ Simple design
+ Easy to maintain
+ High possible cut angle > 90°
+ Good modular construction to fit 3-axis machine
+ Easy to wire hoses on to the head
+ Very common on the market
+ Easily understood for CNC operator
+ Easily visually inspected
- More moving axis when 3D machining
- Small clearance to work piece with the rotary head when 3D machining

Figure 1: Basic Head from [www.perndorfer.at](http://www.perndorfer.at)


**Tilted[^2] head, advantages/ disadvantages:**

+ No compensation movements of linear axis!
+ Relatively simple design
+ Easy to maintain
+ Good modular construction to fit 3-axis machine
+ Very common on the market
+ Good clearance to work piece when 3D machining
- Quite difficult to wire hoses
- Small possible cut angle <60°
- Difficult to understand as a CNC operator

[^2]: Figure 2: Tilted Head from [www.omax.com](http://www.omax.com)
Fork⁽³⁾ head, advantages/ disadvantages:

+ Easy to wire hoses on to the head
+ Many spare parts on the market for the robot
+ Good clearance to work piece when 3D machining
+ Small movements in all axis for 3D machining
- Difficult to understand as a CNC operator
- Very uncommon solution for Water jet, plasma and Laser machining

Figure 3: Fork Head from www.watercut-nw.de
Special\(^4\) head, advantages/ disadvantages:

- No compensation movements
- High possible cut angle
- Easy to wire hoses
- Very difficult to manufacture
- Each concept is unique on the market
- Difficult to maintain
- Difficult to understand as a CNC operator
- Not very common on the market
- Vulnerable for abrasive material

Figure 4: Special Head from [www.igems.se](http://www.igems.se)

(1) Basic 10 of 28*  (2) Tilted Head 8 of 28*  (3) Fork 1 of 28*  (4) Special 9 of 28*

28 is the total amount of identified rotary heads that could be placed in a specific group that explains the design of it.
Figure 1: Basic head simulation 1 (Scale 1:180 for the deformation)

Figure 2: Basic head simulation 2 (Scale 1:950 for the deformation)
**Figure 3:** Tilted head simulation 1 (Scale 1:260 for the deformation)

**Figure 4:** Tilted head simulation 2 (Scale 1:1300 for the deformation)
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Designed by A.Hjelm
Approved by - date
Model name: LONGPENCIL
Date: 14-Sep-10
Scale: 1.000

ProCom GmbH
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<td>Material: Steel, (± 0.1), (mm)</td>
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**Designed by:** A. Hjelm  
**Approved by - date:** 08-Sep-10  
**Model name:** HYLSA  
**Date:** 08-Sep-10  
**Scale:** 3.000

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**ProCom GmbH**

Drawing name  
**Edition:** 108  
**Sheet:** 1 (1)
Material: AlMg4.5Mn, (± 0.1), (mm)

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Designed by: A. Hjelm
Approved by - date: 08-Sep-10
Model name: LOCK
Date: 08-Sep-10
Scale: 1.000

ProCom GmbH
Material: Steel, (±0.1), (mm)

Dimensions:
- φ25
- 25
- 22
- 30
- 40
- 3.5
- 7
- 3.5
- 4
- 4 x Ø3 (H7)

Tolerance: ±0.05

ProCom GmbH

Drawing name: 104
Edition: 1 (1)
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Material: AlMg4.5Mn, (± 0.1), (mm)

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ProCom GmbH

Drawing name

102

Edition

Sheet

1 (1)
Figure 1

1. Z-Axis
2. C-Axis
3. C-Axis bearing
4. Modul plate
5. Clampex 105
6. Lock
7. Motor plate
8. Motor
9. B-Axis holder
10. Pencil holder

Figure 2
The goal of Appendix 9 is to describe how the head can be dissembled, reassembled and calibrated. This instructions start with dissembling since the head is pre-assembled on the machine.

**Warning 1:** Servomotors are precision equipment. The flange and shaft are especially vulnerable during storage and assembly — so avoid brute force!

**Warning 2:** The pins through the B-Axle holder should only be assembled from the flat side of the B-Axle holder and vice verse for disassembly.

**Tools needed:**
1. Hammer,
2. Hexagonal (5mm),
3. Hexagonal (3mm),
4. Spanner (13mm),
5. Spanner (7mm),
6. Screwdriver (ø 2,5mm).

**Taking it apart in five steps:**

1. Take a steady grip around the B-Axle holder. Align the screwdriver with the pins through the axle holder (from the round side for disassembly) and do small but distinctive punches on the screwdriver.
2. Unscrew the two M6 screws (counter clockwise for disassembly)

3. Remove the Motor plate straight out from the surface that it is mounted on and refit it on the other side of the Modular plate.
4. To change the position of the pencil

5. Positioning the angle of the cables by using the plate.
Assembling and calibration:

For assembling, follow the instructions for Taking it apart backwards except from that no screwdriver should be used.

Assembling Torque:
M8 => 8Nm
M6 => 5Nm
M4 => 2Nm

Tools needed for calibration:
1. Spanner (13mm),
2. Hexagonal (4mm),
3. Spanner (7mm),

Tool number 2 and 3 is used to un-tighten the M4 screw that clamps around the tool.

The calibration tool can calibrate two things:
Notice: When changing the mode, only the pencil length will have to be calibrated. The only time the alignment can be questioned is if the Modular plate has been removed or if brutal force has been applied to the rotary head.

1. The tool length for the tilted head which is very important.
2. The alignment between the pencil holder and the C-axis.

Unscrew the M8 in the center of the C-Axis

Remove the M8 screw and put the cylinder back

Calibration of the Basic head

Calibration of the Tilted head