Design of an End Effector for Drilling in Automated Processes

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Abstract

In an attempt to solve a problem concerning drilling, a project was started at the universities in Linköping and Lund. As a part of the project this thesis aims to help solve the drilling problem. The goal of this thesis is to design an end effector that will help avoid slipping when drilling.

The methods used were taken from David G. Ullman’s book *The Mechanical Design Process*. Members involved in the project were interviewed to get an understanding of the task. With that done the concept generation phase began, resulting in several concepts. With the use of evaluation methods, such as feasibility judgment and Go/No-Go screening, a final concept emerged. All of the parts and details of the concept were designed with respect for the customers’ requirements and demands.
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1 Introduction

Anybody who has ever drilled in metal knows that it is extremely difficult to prevent the drill from slipping and going off to the side, leaving misshaped holes. This is of course not something that is accepted in the industry. The tolerances are very high and mistakes are not allowed. Up until recently the only solution has been to use fixtures that you attach the drill to, thus stabilizing it. This is all done manually. For a few holes there is no problem, but for on for example airplanes, where thousands of tiny holes have to be drilled, it quickly becomes expensive work. In recent time, robots have begun to emerge to take over the production industry. The problem is that robots do not yet have the accuracy that the airplane industry requires.

To create a way to solve the problem, a project was started in the universities of Linköping and Lund. The original concept was to place sensors at the end of the robot so that they could measure force and torque and then minimize the slipping. A regulatory system would analyze the numbers from the sensors and move the robot so that the force and torque would be as small as possible.

1.1 Previous work

In his report En studie av en industrirobots beteende vid borning, Jonas Svernstam mentioned an unwanted phenomenon called slip-stick. When drilling with a robot, torque is created on each of the robots six joints, causing the drill to slip. This report is a follow up to Svernstam’s report. One of his conclusions was that the end effector had to be developed further and that force sensors had to be built in to it. That is exactly what this report does.

1.2 Thesis

The purpose of this work was to develop an end effector that would attach to a robot. The end effector should hold a drill and also incorporate a sensor. The drill was manual and initially meant to be held by hand. Therefore a structure had to be designed to be able to attach this drill to a robot.

1.3 Goals

The goal is to be able to design a product that will help in the project that was started in Linköping and Lund.

1.4 Structure/method

The methods used in the report are based on David G. Ullman’s book The Mechanical Design Process. There are other similar methods available but the reason this book was used was that it was being used in the courses TMMI08 Konstruktionsmetodik and TMMI11 Konstruktionsprojekt and it was recommended that this book be used in this thesis. The report is divided into the different practices that Ullman brings up in the book.
1.5 Limitations

The task did not involve choosing what sensor or robot to use or to write the code for the regulatory system. The purpose of this report was solely to design the end effector.
2 The design process

In his book *The Mechanical Design Process*, David G. Ullman mentions that the best practices for the design process are:

- Project planning
- Specification development
- Conceptual design
- Product development
- Product support

Since the purpose of this report only was to develop an end effector, the product support part was not necessary.

2.1 Project planning

The first stages of the design process are: forming the design team and creating a project plan. Since this was a one-man job the first stage was finished rather quickly. The project plan took a little more time to develop. The designated time was ten weeks. Ten weeks in which a product was to be developed. Since it is very difficult to know in the beginning of a project what is going to be done on which day, this project was divided into weeks. The major parts of what Ullman describes as the design process were distributed among the weeks. Some parts in the project planning were given a whole week whereas some parts would share weeks with other parts. In big corporations, resources like people and money have to be considered in the project plan. Since this was a less complex task resources were not considered.

2.2 Specification development

In the specification development one of the first tasks is to identify the customers and generate their requirements. This is also the part of the design process where the problem has to be examined thoroughly so that there is a full understanding for it.

2.2.1 Understanding the problem

To fully understand what the premise of the problem was, several people involved in the project were interviewed. They gave their views on the task and what they wanted the outcome to be. This helped develop an understanding for the assignment.

The task was to design an end effector. An end effector is a kind of tool holder, which is placed at the end of a robot. The end effector in this case should hold a drill as well as a sensor. The drill that would be used in this project was a Desoutter CFD 1155398, which is a manual drill, meant to be held by hand and not by a robot. Herein lies the problem. The drill had to be held by a robot in some way. Figure 1 is a CAD model of the drill that was used.
Figure 1: Model of the Desoutter drill that was used

The sensor that would be used was a JR3 160M50A-I80. The sensor is able to register forces up to 2000 N and torque up to 160 Nm. A detailed drawing of the sensor can be found in Appendix 2 and a Figure 2 is a photograph of the sensor.

Figure 2: JR3 sensor attached to robot

At the front of the end effector there is a pressure foot. It is the part of the end effector that is in contact with the material that shall be drilled. The pressure foot can be compared to the foot that holds the fabric in place in a sewing machine.

The robot that would be used was an ABB IRB 4400. It is a fast and compact robot which is used for medium to heavy handling. Its load capacity is 60 kg, which means that it will be able to carry the end effector complete with sensor and drill. It will also be able to handle the estimated force and torque that is created in the drilling application. The robot can move smooth and rapidly with high accuracy, which is extremely useful in this case where it has to make sudden changes to act on the changes in force and torque.
To understand the basics of the problem at hand simple tests were carried out in the robot lab at IKP. The equipment was a force/torque sensor ATI FT3774 with a cylinder attached to one end. The tests showed that it was virtually impossible to create a force that was solely in the z-axis, there were always small forces in the x- and y-axis. This of course also led to torque around the axis as well. If more force was applied along the z-axis, then the force in the x- and y-axis would grow as well. This would eventually make the cylinder go off to the sides. This showed what the main problem was: to create a system that made the robot move so that the x-y forces never got so big that slipping occurred. The FT-sensor should register the forces in all of the axes and when they reached a critical point in the x- and y-axis the regulatory system would give instructions to the robot to move so that it would bring the forces down. What this report brings up is the designing of the end effector that holds the drill and the sensor.

2.2.2 Customer requirements
Customers can be anyone from buyers and support personnel to end users. In this case the customers were considered to be the people involved in the project. Those closest connected to the part of the project concerning the end effector were interviewed. They were given questions about their demands and requirements on the product, what they
wanted the outcome to be and other questions that concerned the end effector. Some questions were written down before the interviews and some emerged during it. During the interview many requirements were noted and more knowledge surrounding the project was obtained. These are the requirements that were brought up:

- Stiff
- Light
- Cheap
- Easy to change drill
- Pressure foot to be small

Several other requirements that did not come directly from the customers were added as a complement:

- Easy to produce/simple construction
- Easy to mount drill
- Not interfere with the robot’s movements
- Use all of the robot’s degrees of freedom
- The drill should not be able to move sideways at the pressure foot

The requirements from the interviews had to be met in some way. This was done by developing engineering requirements. The engineering requirements were as follows:

- Stiffness can be measured by how much the construction deforms. Deformation in the z-axis is not relevant. However, if it deforms in the x- or y-axis the holes will be drilled in the wrong places. To prevent this, Deformation sideways was put as an engineering requirement.
- Light is of course measured by Weight.
- Cheap is measured by Price.
- Easy to change drill can be measured in three ways. The first is Number of tools used, the second is Time to change drill and the third is Number of actions to change drill.
- Pressure foot to be small is measured by Pressure area.

All of these requirements were used when the conceptual design phase started. They helped point towards the right goal and made it easy to single out ideas that did not meet requirements. Those concepts could then be either thrown away or reworked.

### 2.3 Conceptual design

Before a concept can be developed all of the functions have to be clearly stated. This is done by decomposing the product and then defining each individual function. After that is done the concept generation can begin.
2.3.1 Defining functions
The functions of the end effector are as follows:
- Hold the drill
- Transfer energy from robot to material
- Be attached to sensor
- Be attached to robot

2.3.2 Concept generation
In this project brainstorming was mainly used. Ideas were scribbled down on a blank piece of paper and concepts began to take form. To get better looking concept sketches the 3D CAD application CATIA was used for most of the sketching instead of using paper and pencil.

There are mainly two different ways to attach the end effector to the robot. There is a hanging and a pointing configuration. Which is the best to choose differs from case to case so in the concept generation both configurations were used.

Both of the configurations have one major pro and con that have to be considered when designing.

In the hanging configuration the major con is that when drilling, torque is created around the joint that is furthest out, joint six. This is an unwanted effect that can be reduced by minimizing the distance from the robot to the drill. Using the equation \( M = F \cdot d \), where \( M \)=torque, \( F \)=force applied on drill and \( d \)=distance, it is easy to see that if the force applied on the drill and the orthogonal distance both increase, torque will begin to grow. Even if the distance is minimized, the torque cannot be eliminated in this method. This problem never occurs in the pointing configuration because the orthogonal distance is zero. The force applied on the drill goes straight into the robot.
without creating the unwanted torque. Because of this, the robot is able to put a lot of force and support straight behind the drill.

An important point is accessibility and here the hanging configuration is the better choice. Again, joint six is in focus. When joint six turns with the hanging configuration it brings the drill around, moving it to another position. This does not happen with the pointing configuration because the axis that goes straight through the drill, the z-axis, is aligned with joint six of the robot. When joint six turns there the drill is left in exactly the same position all the time. This means that there is no actual need for joint six and it can be eliminated. But if there is access to a robot with six joints it is a shame not to use all of them.

When it comes to holding the drill there is basically just one way to do it, and that is to grip it at the at the back and in the middle. The best way would be to hold it at two places, because it would be the most stable solution. Exactly how this would be done could be solved at a later stage. For the concept generation, all that was needed was a general idea of how to handle the drill.

The result of the concept generation was nine different concepts. The next step was to choose which ones to continue working on.

2.4 Concept evaluation
Something that is important when working with many different concepts is to try to single out the good ones from the not so good. This is difficult because not much is known about the concepts. They are merely early sketches and not finished products. There are however some methods that can be used and they are presented here.

2.4.1 Feasibility judgment
The first method that was used was a process called feasibility judgment. This is based on three immediate feelings when you see the concept:

1) It is \textit{not feasible}, which means that the concept should be discarded.
2) It is \textit{conditional}, which means that the concept might work if some changes were made.
3) It is \textit{worth considering}, meaning that the concept is neither good nor bad.

The purpose of the feasibility judgment was to single out concepts that just did not seem like good ideas and leave only good concepts. This is the outcome of the feasibility judgment that was performed on the initial nine concepts.
Concept 1: It is conditional

Since the four rods from the pressure foot were not in line with the other rods, it would cause the force from the material on the structure to be led directly into the drill, which was an unwanted effect. The major part of the force should be taken up by the structure and transferred back to the robot. Also, the pressure foot is way too big. It did not have to be a square. A lot of area could be cut away and a triangle would be sufficient. If the pressure foot was a triangle there would be no need for four rods any more.

For this concept to work the following had to be done:
- The pressure foot would have to become smaller
- The force from the material should not be led directly into the robot
- It had three rods instead of four
Concept 2: It is not feasible

The pressure foot was too big and had to be reduced to a triangle. This caused the walls leading up to the pressure foot to be reconstructed as well. Using walls on the sides of the foot was not a good idea as it restricts access when changing drills. The rest of the structure was a complex assembly using many angles. This might have caused problems when producing it. If the structure was not created from a single block but instead screwed together the demands on the tolerances of the angles would have been very high. This is an expensive procedure which went against the customer requirement of the product being reasonably cheap. Also, much material was used in this product. Maybe even so much that it became heavy and a burden to handle which was in conflict with the customer demand of it being light.

For this concept to work the following had to be done:
- Reduce the area of the pressure foot
- Reduce the number of angles used in the structure
- Reduce amount of material used so as to make it lighter
- Remove walls on the sides of the pressure foot

Since so much work had to be done on this concept it was decided to discard it.
Concept 3: It is not feasible

![Figure 9: Concept 3](image)

Not much is right about this concept. Its pressure foot was ridiculously large and the structure of it was way too complex to even consider producing in this project. It incorporated many angles, which as described before sets high demands on the tolerances. The purpose of this concept was for the drill to be held tight at its handle. Since the handle was created for a human hand and not blocks of metal it would be an arduous task to create something like this.

For this concept to work the following had to be done:
- Cut material from the pressure foot, thus making it smaller and a triangle
- Reduce the number of angles used
- Develop a way to hold the drill tight by the handle

Since so much had to be done for this concept to work it was quickly thrown in the waste basket.

Concept 4: It is conditional

![Figure 10: Concept 4](image)

This concept was very clean and did not use any complicated angles or production methods of any kind. The only problem with it was that the pressure foot was too big and therefore had to be made into a triangle.

For this concept to work the following had to be done:
- The area of the pressure foot had to be reduced and made into a triangle
Concept 5: It is not feasible

This was not really a very complex structure, but the supporting beams at the top had some angles that had to be exactly right. Complex angles should be avoided as much as possible. The pressure foot was also too large and a square which had to be turned into a triangle. This concept also had walls on two sides of the pressure foot which would limit access for drill changing.

For this concept to work the following had to be done:

- The area of the pressure foot had to be reduced and made into a triangle
- The walls on the two sides of the pressure foot had to be removed and replaced by something that gave better access to the drill
- The use of non-right angles had to be kept down

These changes could not be made without designing a concept that did not create other problems, so it was decided that it was simply not feasible.

Concept 6: It is not feasible

Concept 6 was the same as concept 5 except the way they were mounted to the robot. Concept 5 was pointing and Concept 6 was hanging. Since Concept 5 was decidedly not feasible, neither was Concept 6.
Concept 7: It is not feasible

For this concept to work the pressure foot would have to be changed to a triangle and the four rods would have to be reduced to three. The other four rods that link together the two gripping places for the drill would be threaded. It would allow the two grips to be screwed together and create a firm grip of the drill.

For this concept to work the following had to be done:
- The area of the pressure foot had to be reduced and made into a triangle
- It had to have three rods instead of four leading up to the pressure foot
- More knowledge had to be gained about threaded rods

There was not a whole deal to be done on this concept but not much confidence was had in it from the designer and it was unclear if the threaded rods would work. Therefore it was decided not to work on it any further.

Concept 8: It is not feasible

This concept was hastily thrown together and not much thought was put into it. Therefore it was decided quite quickly that it should be discarded.
Concept 9: It is conditional

![Figure 15: Concept 9](image)

This concept already had a triangular pressure foot, so no work had to be done there. The gripping places however could be narrowed down to create a slimmer looking structure.

For this concept to work the following had to be done:
- The structure was slimmed down at certain places

The outcome of the feasibility judgment was that three concepts were redesigned. These were concepts 1, 4 and 9. They became concepts 1.1, 4.1 and 9.1. All of the issues that were brought up in the evaluation were solved, thus making them better solutions.

The three illustrations that follow here are the reworked concepts.

![Figure 16: Concept 1.1, which has a triangular pressure foot](image)
2.4.2 Go/No-Go screening

To further single out the good concepts from the bad ones a Go/No-Go screening was performed. In such a screening, each concept is compared with the customer requirements. If the concept meets the requirements it gets a “Go,” otherwise it gets a “No-Go.” The advantage with this method is that it eliminates concepts that should not be considered further. It also helps generate new ideas.

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Concept 1.1</th>
<th>Concept 4.1</th>
<th>Concept 9.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Stiff construction</td>
<td>Go</td>
<td>Go</td>
<td>Go</td>
</tr>
<tr>
<td>2. Cheap</td>
<td>Go</td>
<td>Go</td>
<td>Go</td>
</tr>
<tr>
<td>3. Light</td>
<td>Go</td>
<td>Go</td>
<td>Go</td>
</tr>
<tr>
<td>4. Easy to change drills</td>
<td>Go</td>
<td>Go</td>
<td>Go</td>
</tr>
<tr>
<td>5. Small pressure foot</td>
<td>Go</td>
<td>Go</td>
<td>Go</td>
</tr>
<tr>
<td>6. Not take up force from pressure foot in drill</td>
<td>Go</td>
<td>Go</td>
<td>Go</td>
</tr>
<tr>
<td>7. Use different drill diameters</td>
<td>Go</td>
<td>Go</td>
<td>Go</td>
</tr>
<tr>
<td>8. Easy to manufacture/simple construction</td>
<td>No-Go</td>
<td>Go</td>
<td>Go</td>
</tr>
<tr>
<td>9. Easy to mount drill</td>
<td>No-Go</td>
<td>Go</td>
<td>Go</td>
</tr>
<tr>
<td>10. Not interfere with robot movements</td>
<td>Go</td>
<td>Go</td>
<td>Go</td>
</tr>
<tr>
<td>11. Use all of the joints</td>
<td>No-Go</td>
<td>Go</td>
<td>Go</td>
</tr>
</tbody>
</table>
1. **Stiff construction** – Since it was impossible to know exactly how stiff the different concepts would be, they were all simply considered stiff enough for the task and got a “Go”.

2. **Cheap** – The same idea was used here as in the previous requirement, namely that it was not possible to measure the cost as this stage. Since the structures were not complicated or made of exclusive materials they were considered cheap enough and also got the “Go” sign.

3. **Light** – Once again it was not possible to compare the three and so they all were a “Go”.

4. **Easy to change drills** – Some of the earlier concepts had had some complex structures around where the drill would be. These were thrown away and in the three remaining concepts it is fairly easy to gain access to change drills without having to move parts around. All three of the concepts were “Go”.

5. **Small pressure foot** – This was a detail that was changed in the feasibility judgment. Some of the concepts using a large pressure foot did not make the cut, and some were redesigned. The three concepts in the Go/No-Go screening had all been redesigned and therefore got the “Go” sign here.

6. **Not take up force from pressure foot in drill** – One very important feature of the end effector was to take up as much force as possible, thus relieving the drill from any force or torque that could harm and disfigure it. The end effector had to be designed in a way that made it redirect the forces generated by the work away from the drill and instead into the robot. When the concepts were designed this was kept in mind, which is why the three concepts were considered to “Go”.

7. **Use different drill diameters** – This was never a problem so the three concepts easily got a “Go”.

8. **Easy to manufacture/simple construction** – Although the three concepts would be reasonably easy to manufacture, Concept 1.1 was thought to be somewhat complicated in its assembly. It therefore received a “No-Go” while the other two got a “Go”.

9. **Easy to mount drill** – This was another area where the complexity of Concept 1.1 was a disadvantage. It would be quite complicated to mount the drill, whereas in the other two concepts it could easily be done by just removing a part and sliding the drill in. Concept 1.1 got a “No-Go” and the other two got a “Go”.

10. **Not interfere with robot movements** – For this part it simply had to be assumed that none of the concepts would create any conflicts with the robot’s movements. They all got a “Go”.

11. **Use all of the joints** – As mentioned earlier, the pointing configuration does not utilize joint six at all. This can be solved by giving the pointing configuration a small offset. Doing this enables it to more places easier. This solution combines the advantages of both the hanging and pointing configurations; it gets the strength and stability of the pointing configuration but also the added accessibility of the hanging configuration.
The Go/No-Go screening showed that concepts 4.1 and 9.1 were the obvious choices to follow up on. Concept 1.1 was discarded and not worked on any more since it had received three No-Go’s.

The next step in the evaluation phase was to choose between concepts 4.1 and 9.1. A way to do this was to present them to the other people involved in the project. Before that, the two concepts were presented to Sergio Da Silva. He gave some suggestions for changes to Concept 9.1. For example, he wanted the pressure foot to be turned upside down and put supporting beams at the sides. This would give more support to the pressure foot. This was done, and with that, the name of Concept 9.1 was changed to Concept 10. These two concepts would be presented to the other members of the project.

### 2.4.3 Presentation of concepts

On may 22nd 2006 there was a meeting in Lund where most of the people involved in the project all met. Two concepts were presented at the meeting, Concepts 4.1 and 10. They were described as thoroughly as possible and then the participants were asked to write what they thought about the concepts in a so-called belief map (which can be found in Appendix 1). Not too many were satisfied by the concept. They had many questions and comments. Most of the questions concerned the lack of a sensor close to the pressure foot. The belief of some participants was that the sensor should sit between
the robot and the end effector, whereas others thought that the sensor should be in the front close to the pressure foot. Another question was the one concerning the connection to the robot. Some people wanted an end effector pointing at a 45 degree angle, a design that is in between a hanging a pointing configuration.

![Figure 21: 45-degree configuration](image)

### 2.4.4 Follow up to the presentation

New concepts were created incorporating the ideas brought up at the presentation. The question of where the sensor should be placed turned out to be a tough one to find a satisfying answer to.

The 45 degree model was considered for a short while but was abandoned for being too complex. If there had been more time this concept might have been able to go through the evaluation phase. Since this concept was brought up when almost half of the project time had gone there was simply not enough time to begin with a whole new concept.

The main purpose of the presentation of the end effector was to get some feedback for the concepts. This was done and although the criticism was not overwhelmingly positive there was still some belief that the concepts could actually work. The concept that got the best reviews was Concept 10, so it was decided to continue working on that concept. This eliminated the need for further evaluation methods.

### 2.4.5 Finite Element Method – FEM

FEM is a method for calculating stress and deformations in complex structures\(^1\). This can easily be done directly in CATIA. Using this method it was easy to see how much the concept would deform when a force was applied to it. This gave hints as to where reinforcements had to be done. It is also possible to see the stress in the structure but the most interesting thing to know was the deformation since that was one of the major customer requirements.

Since the FEM analysis only gives approximate results they should not be read religiously. In the FEM analysis in this experiment all of the parts of the assembly were

\(^1\) [http://www.asd-online.com/eng/eng_jsmindex.htm?fem-analysis.htm](http://www.asd-online.com/eng/eng_jsmindex.htm?fem-analysis.htm) (060621)
generated into a single part. This is the simplest way to do it and because of time shortage this method was chosen.

The forces used were 200 N along the z-axis and 100 N along the x-axis. These are not exact numbers but they were an educated guess based on previous tests done by IKP.

The back plate was said to be clamped, which means that it was tightly fastened to a wall or some other rigid object. It will not actually be clamped in the tests, it will be connected to the robot which is quite yielding. This adds some further uncertainty to these analyses.

![Figure 22: Illustration of the forces on the pressure foot](image-url)
Analysis 1
By this stage in the project the final concept had already been decided, so in the first FEM analysis the final concept, Concept 10, was studied. All of the parts of the concept were generated into a single part and then a FEM analysis was conducted. This was a good way to see how the concept might behave if a force was applied to it. As can be seen in Figure 23 there would be a lot of deformation in the front at the pressure foot. This was probably because it was so narrow in the front and did not have much support. In the back of the structure there was hardly any deformation at all and this was assumed to be because of the support plates. The deformation at the pressure foot was 0.329 mm. It is not possible to know if the actual deformation will be like this test, but it is in the same area. What was most important was that it showed that there might be some unwanted deformation taking place at the pressure foot. To resolve this issue several changes and more FEM analyses were made. Most of the changes were thought up quickly by brainstorming.

Figure 23: FEM analysis 1
Analysis 2
It was thought that the narrowness of the part of the structure between the pressure foot and the support plates was one of the reasons for the deformation. To resolve this, that part of the plate was simply widened (Figure 24). Instead of having two angled sides from the support plates leading up to two straight sides that went to the pressure foot, two angled sides went all the way to the pressure foot. After the redesign was made an FEM analysis was performed. The result is shown in Figure 25 and shows that there was virtually no change at all. The deformation would decrease from 0.329 mm to 0.313 mm. So the narrowness of the plate at the specified place had nothing to do with the deformation at the pressure foot.

Figure 24: Concept 10 with a wider nose

Figure 25: FEM analysis 2
**Analysis 3**
A way to make the structure more rigid is to make the plate thicker. The thickness of the plate was increased from 8 mm to 10 mm. Also other parts of the structure were increased in size to 10 mm to further help keep the deformation down. The result can be seen in Figure 27. The deformation at the pressure foot decreased but not as much as one might hope. It was 0.224 mm, which was less than in the two previous cases but more had to be done to further stabilize the structure.

![Figure 26: Concept 10 with thicker parts](image1.png)

![Figure 27: FEM analysis 3](image2.png)
Analysis 4
The next experiment was to attach a beam to the bottom of the plate so that it looked and acted like a T-beam. This was thought to make the structure many times more stable. The FEM analysis proved that this was indeed the case. The deformation at the pressure foot dropped drastically all the way down to 0.0578 mm. The beam was oversized and heavy but that was not important. The design of the beam was not something that was of interest at this point. The analysis simply showed that the use of a beam would be a very good way to stabilize the structure and bring down deformation.

Figure 28: Concept 10 with a beam attached

Figure 29: FEM analysis 4
Analysis 5
The drill itself was thought to bring some stiffness to the structure. Since a model of the drill had been created this could be analyzed with FEM. The analysis showed that the stiffness was increased. The deformation at the pressure foot was brought down to about half of what it would be without the drill attached. This was however a further approximation since it was unknown how the drill will behave when a force was applied to it. The exact materials and compositions of the drill were unknown. In Figure 30 it looks as though the drill would destroy the pressure foot by drilling into it but this is because of the skewed proportions. The drill will hopefully go perfectly through the designated hole without any problem.

Figure 30: FEM analysis 5
Conclusion of the FEM analyses
Since FEM only gives approximations it does not show exactly what will happen or the magnitude of the deformation. Therefore none of the solutions presented here were incorporated into the final concept, they were merely suggestions for making the structure more stable, should this be needed. However the best suggestion obviously seemed to be to attach a beam to the bottom of the plate, as can be seen in Table 2. If the beam was to be attached none of the other methods would be necessary. The reason for not incorporating the beam in the final concept was that it was uncertain how the end effector would behave with the drill attached. It is possible that that would be enough to make it stable enough to meet the customers’ needs. If there proved to be a need for further stabilization and stiffness it would be a simple task to add the beam to the end effector.

Table 2: FEM analysis comparison

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Deformation at pressure foot [mm]</th>
<th>Deformation decrease compared to Analysis 1</th>
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<tr>
<td>1 – Concept 10</td>
<td>0,329</td>
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<td>2 – Wider nose</td>
<td>0,313</td>
<td>5 %</td>
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<tr>
<td>3 – Thicker plate</td>
<td>0,224</td>
<td>47 %</td>
</tr>
<tr>
<td>4 – T-beam</td>
<td>0,0578</td>
<td>470 %</td>
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<tr>
<td>5 – Drill attached</td>
<td>0,185</td>
<td>78 %</td>
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3 The final concept

After the presentation of the concepts it was decided that Concept 10 would become the final concept that would be the only one that would be worked on from that point. This was done and the result is presented here in detail. Drawings of all of the parts can be found in Appendix 2.

3.1 Plate

The plate started out as just a plain rectangular plate. It was easy to see that a lot of material could be cut away to make the design more light and sleek. The thickness was initially 10 mm but after discussions with Sergio Da Silva it was reduced to 8 mm. Ulf Bengtsson at IKP confirmed this as a good thickness. He said that if it had been 2 mm it would be very floppy. 8 mm would without a doubt make it stiff enough. If the plate still proved not to be stiff enough a beam could be welded to the bottom of it, making it a sort of T-beam. This would drastically increase the stiffness and make the design more rigid. The plate was first made to be as long as the drill was, but Sergio Da Silva thought that there was no need for that. The plate was then shortened 90 mm, which made the back of the drill stand out a bit outside of the design.
3.2 Back plate

Since the sensor had a diameter of 160 mm the back plate was made slightly larger, 170 mm. Holes were put in it in a circular pattern matching the ones in the sensor.

3.3 Support plate

The plate screwed to the back plate would not be enough to hold it in place. Support plates were needed. They were designed so that they had a 45-degree angle.

3.4 Pressure foot
In most of the early designs the pressure foots were all square. This is an evolved design based on the triangular pattern. It does not actually have only three sides, it has more than that, but it incorporates the idea that the pressure from the material is transported through three points into the end effector.

### 3.5 Front supports

![Figure 36: The front support and its location](image)

In the first concept of this design the pressure foot was turned upside down. Sergio Da Silva’s immediate reaction to that was to turn it around. In order for that method to be stiff there was a need for supports. One support was put on each side of the pressure foot. Like the support plates in the back the front supports were also designed with a 45 degree angle. Henrik Kihlman later confirmed that this was necessary since they had had problems before with pressure feet being too weak.

### 3.6 Middle hold

![Figure 37: The middle hold and its location](image)

This middle hold sits in the back of the threaded part of the drill. For a while there was an idea that the middle support could have been threaded on the inside of the hole. That idea was abandoned after discussions with Ulf Bengtsson who said that it would be very difficult to produce. Instead he came with the suggestion that the track running through the threaded part of the drill could be used.

The middle hold is a single piece with a hole in it, which is fitted onto the drill. To keep it in place and prevent it from turning there is a small protrusion that runs in the track. On the threaded part of the drill there is a ring that can be screwed on. This ring is screwed on tight and pushes the middle hold into place and keeps it there.
3.7 Back hold

![Figure 38: The parts of the middle support](image)

![Figure 39: The location of the back hold](image)

The back hold consists of several parts. To hold the drill firmly two copper fittings are used. When the back hold is screwed together pressure is put on the copper. Since copper is relatively soft it will form itself after the pattern in the drill thus making a very tight grip. In order for the copper not to be able to move inside the middle hold there are two protrusions into the hold, which prevents rotation. Together with the middle hold this will make the drill sit firmly in the end effector.

3.8 The final concept with the drill attached

This is what the end effector would look like with the drill mounted.

![Figure 40: The final concept with drill attached](image)
4 Recommendations for future development and evaluation

The first thing that has to be done is of course to produce the end effector. Since the metal shop at the university was closed for rebuilding this could not be done in the time designated to the thesis work.

The next step is to start evaluating the end effector to examine if it meets the high standards. All of the customer requirements that have been brought up in this report have to be considered and hopefully all of them will be met.

Some changes may have to be done to make the end effector more stiff. The recommended action, according to the FEM analysis, is to attach a beam to the plate, making it resemble a T-beam.

If the middle support proves not to hold the drill tight enough, an alternative solution can be used. It involves using a screw, that when tightened, makes the grip on the drill much firmer. The screw would go through the whole middle support. An illustration of this idea is seen in Figure 41.
5 Conclusion

What was initially nine concepts became one final concept through multiple evaluations and redesigns. The final concept was developed with the customers’ requirements in mind and followed standard design procedures. The concept will hopefully be an important piece of the project that it is a part of. What remains to be done is to produce a prototype of the end effector and carry out tests on it to see if it meets the customers’ requirements. Some modifications may have to be done if some of the parts of the end effector are insufficient. They include implementing a beam and using an alternate middle support to hold the drill in place firmly.
6 References

6.1 Literature
Jonas Svernstam; En studie av en industrirobot beteende vid borrning. Tekniska Högskolan, Linköpings Universitet. Linköping, 2005


6.2 Internet

http://www.asd-online.com/eng/eng_jsmindex.htm?fem-analysis.htm

6.3 Personal
Ulf Bengtsson, IKP, LiU
Magnus Engström, SAAB
Jan Fåger, MEEQ AB
Mathias Haage, LTH
Henrik Kihlman, IKP, LiU
Klas Nilsson, LTH
Gilbert Ossbahr, IKP, LiU
Sergio Da Silva, IKP, LiU
Appendices

Appendix 1 – Belief maps

Name: Klas Nilsson, LTH

Table: Belief map, Concept 4.1, Klas Nilsson

| CONFIDENCE | Very high | | | | |
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| KNOWLEDGE | Very low | Low | Medium | High | Very high |

Table: Belief map, Concept 10, Klas Nilsson

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**Name:** Mathias Haage, doktorand, LTH

**Table: Belief map, Concept 4.1, Mathias Haage**

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Name: Magnus Engström, SAAB

Table: Belief map, Concept 4.1, Magnus Engström

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Table: Belief map, Concept 10, Magnus Engström

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**Name:** Gilbert Ossbahr, IKP, LiTH

**Table: Belief map, Concept 4.1, Gilbert Ossbahr**

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Name: Jan Fäger, MEEQ AB

Table: Belief map, Concept 4.1, Jan Fäger

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KNOWLEDGE
Figure: JR3 160M50A-I80
Figure: Back support, upper part
Figure: Back support, lower part
Figure: Front support
Figure: Plate

**Right view**
Scale: 1:3

**Bottom view**
Scale: 1:3

**Front view**
Scale: 1:3

**Left view**
Scale: 1:3

**Top view**
Scale: 1:3
Figure: Support plate
Figure: Pressure foot