***Master Thesis***

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**Concrete 3d printer**

*Division of Machine Design • Department of Design Science*

*Faculty of Engineering LTH • Lund University • 2015*



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Preface

This master thesis was done on the last semester of my education in mechanical engineering at Lund University. Firstly I would like to thank my colleague Borja Serra that has been working on the ABB robot and the metal frame in the project. We have had close collaboration throughout the entire project and it has been great to have someone that you can discuss ideas with. Secondly my thanks go to my supervisor Olaf Diegel that has offered guidance and given me many good advices on the way. Thirdly I have to thank the workshop technicians in the workshop at IKDC for all the help with manufacturing of the prototype. I would also like to thank August Hamelius and Mikael Backebjörk for our collaboration in the aspect of printing material, and Sibelco Nordic AB and Elkem Nordic A/S for the supply of this. Lastly I want to thank my examiner Giorgos Nikoleris that also has been a good contact throughout the project.

Lund, June 2015

Lars Henrik Anell

Abstract

In this project the aim was to design a concrete 3d printer. This report focuses on the extruder part of the printer and the printing material. The basic principle of 3d printing is that it is an additive manufacturing technique, on the contrary to the traditional subtractive manufacturing techniques. The potential benefits of concrete 3d printing compared to the techniques that are used today are that it could be a cheaper, faster and more environmentally friendly manufacturing process.

The methodology used to develop the design was taken from Ulrich & Eppinger`s *Product design & development*. A modified version of the general product development process was used for the project.

The product specification from the start was that the concrete 3d printer would be able to create a line of concrete, 30-40 mm wide and 10-20 mm high. When this had been achieved it was thought that the printer would be able to manufacture street furniture. To accomplish the product specification some key features of the extruder were considered. They were the orifice shape, side trowel design and flow creating mechanism. From evaluation matrices it was decided that the conceptual design of the extruder would have a square orifice, two rectangular side trowels and a rotating auger to create a flow of concrete.

To assess how well the design fulfilled the specification a prototype were manufactured that abled testing in reality. The first test was carried out with a sand- and water mixture due to its recyclability. In the early stages of testing it was observed that a) a more powerful motor was needed, b) that instead of a planar bottom part a cone-shaped bottom part was necessary and c) an overall need for more robust materials for the extruder was demanded. After each test improvements were made on the extruder to be followed by additional tests. When a design that worked in principal was found different printing materials were tested such as mortar, standard concrete and EPS-cement. It was found that in order for the extruder to work the material could not be too viscous and thereby block the orifice. However, it was also understood that the material would have to be viscous enough to be able to support itself and build several vertical layers. Therefore a special mixture of concrete was needed to satisfy both these requirements. A special mixture of concrete was tested and the results were very good. It was able to be extruded but also had the ability to build vertical layers. A chair made of the concrete was printed.

The conclusion of the tests was that the working mechanism of the extruder is suitable for this application. However, there is need for a specially mixed concrete like the one used in the project for it to be both extrudable and buildable.

**Keywords:**

Concrete, 3d, printer, product development

Sammanfattning

I detta projekt var syftet att utforma en betong-3d-skrivare. Denna rapport fokuserar på extruder-delen av skrivaren och material att skriva ut i. En annan student jobbade med programmering av en ABB-robot och utformade en ram som roboten skulle hänga i. Extrudern skulle fästas på robotarmen och därmed kunna förflyttas av robotrörelserna. Ramen skulle gå att förflytta så att hela systemet kunde flyttas till en plats där det kan skriva ut det som efterfrågas. Målet för vad som skulle skrivas ut var i huvudsak parkbänkar och dylikt.

Den grundläggande principen för 3d-utskrift är att det är en additiv tillverkningsteknik, tvärtom till de traditionella subtraktiva tillverkningsteknikerna. De potentiella fördelarna med betong-3d-skrivning jämfört med de tekniker som används i dag i betongsammanhang är att det kan bli billigare, snabbare och mer miljövänligt att bygga när tekniken är välutvecklad.

Metodiken som användes för att utveckla en design är hämtad från *Product design and development,* Ulrich & Eppinger. En modifierad version av den generella produktutvecklingsprocessen användes och den största delen av projektet utgörs av testning och förbättring av prototyper.

Produktspecifikationen från början var att betong-3d-skrivaren skulle kunna skriva ut en linje av betong som var 30-40 mm bred och 10-20 mm hög. För att åstadkomma detta betraktades några viktiga funktioner hos extrudern vilka var formen på öppningen av extrudern, sidoslevarnas konstruktion och flödesmekanismen. Från utvärderingsmatriser beslutades det att den konceptuella designen av extrudern skulle ha en fyrkantig öppning, två rektangulära sidoslevar och en roterande matarskruv för att skapa flödet av betong.

För att se hur väl designen uppfyllde specifikationen tillverkades en prototyp för att kunna testa den i verkligheten. Det första testet genomfördes med en sand -och vattenblandning på grund av att det är ett återvinningsbart material till skillnad från betong. I de tidiga stadierna av testning observerades det att en mer kraftfull motor behövdes. Ett antal motorer testades genom projektet för att kunna säkerställa att den slutgiltiga motorn var tillräckligt stark. Istället för en plan bottendel utvecklades en konformad bottendel i syfte att skapa en bättre flödesväg för skrivarmaterial. I början uppstod det problem med att transportera skrivarmaterial till extrudern. Detta löstes delvis med ett y-format rör med en mycket större inloppsdiameter. Vidare testning bekräftade att det plastmaterial som användes i den konformade nederdelen av extrudern var för svagt eftersom sprickor började bildas i denna. Därför designades en liknande del av stål och aluminium istället. När designen av extrudern fungerade principiellt testades olika material som murbruk, standardbetong och EPS-cement. Olika material fungerade olika bra. Till exempel fungerade murbruk och EPS-cement på liknande och tillfredställande sätt medan standardbetong fungerade mindre bra. Det konstaterades att för att extrudern skulle fungera får inte materialet vara alltför visköst och därmed orsaka stopp i röret. Men det var också observerat att materialet måste vara såpass trögflytande att det skulle kunna vara självstödjande och möjligt att bygga flera lager utav det på höjden. Därför behövdes en speciell blandning av betong för att möta båda dessa krav.

Via kontakt med betongavdelningen på Lunds universitet inleddes ett samarbete med två studenter som gjorde ett projekt om lämplig betong för 3d-skrivning. Betongen som studentera hade tagit fram bestod av nio olika ingredienser och varje ingrediens hade en noggrannhet på grammet. Testerna med denna typ av betong fungerade väldigt väl. Den kunde både tryckas ut genom extrudern och det var även möjligt att bygga flera lager på varandra utav betongen. Med hjälp av specialbetongen kunde relativt höga strukturer byggas.

På grund av svårigheter med att få roboten att rotera och hoptrasslande av sladdar valdes att avstå från sidoslevar i den slutgiltiga produkten.

Slutsatsen av testerna var att verkningsmekanismen hos extrudern fungerar och är lämplig för denna tillämpning. Men tekniken kräver en specialbetong som den som används i projektet för att den ska vara möjlig att både extrudera och bygga flera lager utav.

Antalet olika detaljer som kan skrivas ut med denna teknik är mycket stort. I detta projekt testades bara raka linjer, men kurvor hade antagligen också fungerat. ABB-roboten är egentligen inte väl anpassad för detta projekt då den har relativt liten räckvidd. Det finns robotar som skulle ha varit mer lämpliga för detta projekt.

För vidare forskning inom området kan det tänkas att det testas hur olika former på öppningen i extrudern skulle påverka extruderingen, till exempel en triangulär eller cirkulär form. Med hjälp av höj- och sänkbara sidoslevar kan de vara nedfällda vid utförandet av raka linjer för att sedan lyftas upp när roboten roterar. På detta sätt skulle sidoslevar kunna användas utan att förstöra den extruderade betonglinjen vid svängar.

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# Introduction

*In this chapter an introduction and the aim of the thesis is included.*

## Introduction

In almost every industrial sector, automation of processes has contributed to a faster and cheaper way of production. The sector of construction has not been automated in the same manner as other industrial sectors. Therefore large benefits could be obtained by further automating this process. With a more automated process the advantages compared to conventional manufacturing is that it takes less time, is less costly and more environmentally friendly [1].

3d printing, or rapid prototyping, was first introduced in 1987. Today there are many different techniques within this area but the basic principle is the same. It is an additive manufacturing technology, meaning that it adds on material layer by layer, on the contrary to most traditional manufacturing methods that are subtracting material. The 3d printer prints thin cross sectional areas of the detail, one at the time, on top of each other and creates by this way the whole detail. The main advantages with this technology are that it can manufacture complex unstandardized details rapidly [2].

Concrete is a material that is made out of aggregates of stone and cement paste (a mixture of cement and water). The cement hardens when it reacts with water and form cement paste which in turn acts as a binding agent for the aggregate of stone. Concrete is the most produced material in the world due to its strength, durability and relatively low cost. To change the characteristics of concrete, chemical admixtures can be added to the mixture. There are numerous different admixtures. To mention a few there are superplasticizers (reduce the amount of water needed by 12-30%), retarders (slows down the setting time of concrete) and accelerators (speeds up the setting time of concrete). The type of cement, water amount and mixing time are important factors that affect the admixtures’ performance [3].

## Aim

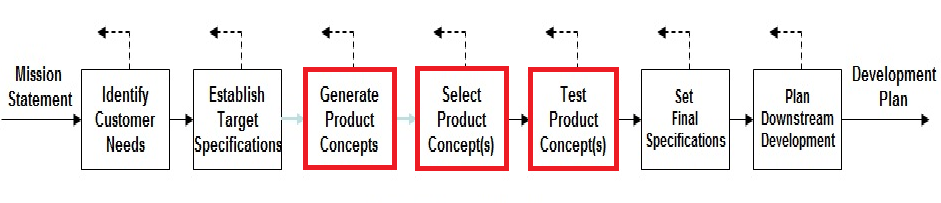
The aim of this master thesis project was to design an extruder for a concrete 3d printer. It will be attached to the end of an ABB robot arm which is hanging upside down from the ceiling of a frame made out of metal beams. The frame can be moved since it has wheels that have contact with the ground. The dimensions of the frame will be such that it allows manufacturing of the 3d detail that is to be printed. This particular 3d printer will be focused on manufacture of street furniture or demo houses made out of concrete. It will be discussed whether this manufacturing technology seems appropriate in constructing these details. Since concrete is to be used, the need of as light weight concrete as possible is preferable because of the robots limitations of loads. Therefore research will be done in the material aspects of concrete and to find as light weight concrete as possible.

# Method

In this chapter the methodology of the thesis is presented. The chapter also describes the structure of the report.

## The development process

The product development process will be based on the methodology presented in *Product development and design*, Ulrich & Eppinger [4].



**Figure 2.1** Product development process [4].

The process is somewhat modified because of the novelty of the product in the project. The steps that are performed are *Generate product concepts, Select product concept* and *Test product concept,* see figure 2.1.

## Generate product concepts

There are several steps within this section. These are

1. Clarify the problem
2. Search externally
3. Search internally
4. Explore systematically
5. Reflections of the process

By clarifying the problem it is meant that a greater understanding of the problem will be achieved if the major problem is broken down to smaller sub problems. It is also important to recognize critical parts of the problem. Search externally means that one looks for ideas to concepts by reading literature, performing benchmarking, looking for patents with similar technology and interviewing experts in the field. The meaning of internal search is that one shall think on its own, do brainstorming, wish and wonder and so on. Explore systematically means combining different concepts and classify different areas of the problem with the aim to cover all potential solutions. Lastly a reflection of the process should be done.

## Select product concept

To select a concept the method *Concept scoring* is used. The process is as follows

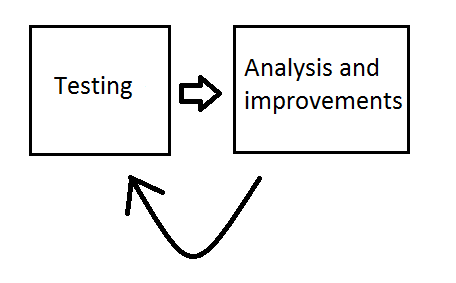
1. Prepare evaluation matrix
2. Scoring of concepts
3. Ranking of concepts
4. Combination and improvement of concepts
5. Selection of concept
6. Reflection of the process

The evaluation matrix contains the concepts and the different criteria by which the concepts will be evaluated on. If necessary the criteria can be weighted according to their relative importance. The scoring should be performed by comparing the concept to a reference and find out if the concept is worse, similar or better than the reference in the given criteria. Ranking of the concepts is done by summarizing the concepts points and finding out which concepts that got the most overall points. If necessary one could combine the best concepts and further develop these. The concept with the highest score will be selected for further development. Lastly a reflection of the process should be done.

## Test product concept

In the testing of a product concept or prototype it is important to apply “good experimental practice”. This means being as objective as possible and this will contribute to get the most out of the test. The test will mostly include identifying variables and a plan for analysis of the output data.

The major work of the thesis is made in this part. By using an iterative process the design is tested, analysis of the test and improvements of concept is made, testing is done again and so on, see figure 2.2.



**Figure 2.2** Iterative testing process.

## Structure of report

In chapter 3 it is presented how the concept generation was carried out and which concept that has been selected. In chapter 4 the conceptual design of the extruder is displayed and what components and materials that are needed. This is followed by chapter 5 wherein testing of prototypes, analyses and improvements are performed. Chapter 6 includes results of the thesis and chapter 7 a conclusion, discussions and recommendations for further research.

# Product specification, concept generation and selection

In this chapter the specifications of the product is explained. Furthermore the process of generation and selection of concept is described.

## 

## Product specification

The extruder of the concrete 3d printer shall be able to produce a line of concrete, 30-40 mm wide and 10-20 mm high.

## Concept generation

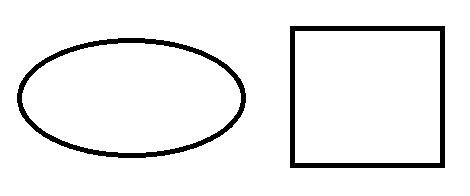
There are three main features of the extruder that are crucial for fulfillment of the product specification. These are

* The shape and size of the orifice of the extruder
* The shape, size, mechanism and number of side trowels
* The flow creating mechanism

Every feature can be designed in multiple ways which leads to many possible combinations.

### Orifice of extruder

The orifice of the extruder is critical for the shape of the extruded concrete. Some simple geometries are considered, such as an ellipse and a square, see figure 3.1. The reason why only these two geometries are taken into consideration is because they have already been evaluated in the report *Experimentation and analysis of Contour Crafting (CC) process using uncured ceramic materials* by Hongkyu Kwon.

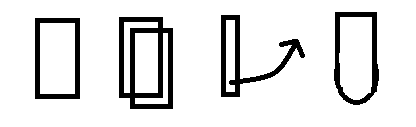


**Figure 3.1** Possibleshapes of orifice.

### 

### Side trowels

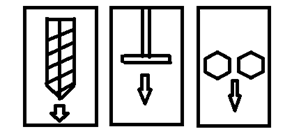
To be able to create the desired width of the concrete line side trowels are needed. They also create a nicer surface finish. Possible designs of the trowels are rectangular or more complex shape, trowel on only one side or both and adjustable angle on trowel, see figure 3.2.



**Figure 3.2** Possible designs of side trowels.

### Flow creating mechanism

To create the flow of the concrete some sort of mechanism is needed to produce this. The possibilities considered are a screw mechanism, a pump and a gear mechanism, see figure 3.3.



**Figure 3.3** Possible flow creating mechanisms.

## Evaluation and selection of concept

The three main features will be evaluated separately. For this product it will be assumed that the best option for each feature will result in the best overall solution. The options will be graded 1-3 on every criterion relative to each other, 1 being the worst and 3 being the best. The options with the highest total point will be used for further development.

### Cross section

The orifice feature is going to be evaluated on created surface finish on the concrete line and ease of manufacturing, see table 3.1.

**Table 3.1** Evaluation of shape of cross section.

|  |  |  |
| --- | --- | --- |
| **Criteria/Shape of cross section** | Ellipse | Square |
| Created surface finish | 2 | 3 |
| Ease of manufacture | 2 | 3 |
| **Total** | **4** | **6** |

In the report *Experimentation and analysis of Contour Crafting (CC) process using uncured ceramic materials* by Hongkyu Kwon it is clear that the surface finish created with a square orifice is better compared to an ellipse orifice. The ease of manufacture is greater with a square orifice than an elliptic one. [1]

### Side trowels

The side trowel feature is going to be evaluated on created surface finish on the concrete line, capability of creating the desired width and simplicity, see table 3.2.

**Table 3.2** Evaluation of side trowels.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Criteria/Side trowels** | 1 side trowel on 1 side | 2 side trowels, one on each side | 2 adjustable side trowels, one on each side | 2 side trowels with more complex shape, one on each side |
| Created surface finish | 1 | 3 | 3 | 3 |
| Capability of creating the desired width | 1 | 3 | 3 | 3 |
| Simplicity | 3 | 3 | 1 | 2 |
| **Total** | **5** | **9** | **7** | **8** |

It is obvious that only one side trowel will only create good surface finish on one side. Also the width will be difficult to control with only one side trowel. Adjustable side trowels would probably be the one option with greatest range of opportunities since they would be able to create angular sides on the concrete line. However it will be difficult to get them to function well. For this project two side trowels with rectangular shape is enough. [1]

### Flow creating mechanism

This feature will be evaluated on created flow, simplicity and ease of manufacture, see table 3.3.

**Table 3.3** Evaluation of flow creating mechanism.

|  |  |  |  |
| --- | --- | --- | --- |
| **Criteria/Flow creating mechanisms** | Screw | Pump | Gear |
| Created pressure | 3 | 3 | 3 |
| Simplicity | 2 | 1 | 1 |
| Ease of manufacture | 2 | 2 | 1 |
| **Total** | **7** | **6** | **5** |

The simplest solution to the flow mechanism will be to use some sort of screw mechanism.

### Selected concept

From the evaluation of possible solutions the selected concept is an extruder with a square orifice, two non-adjustable rectangular side trowels (one on each side) and a screw mechanism to create the flow of concrete, see figure 3.4.

## 

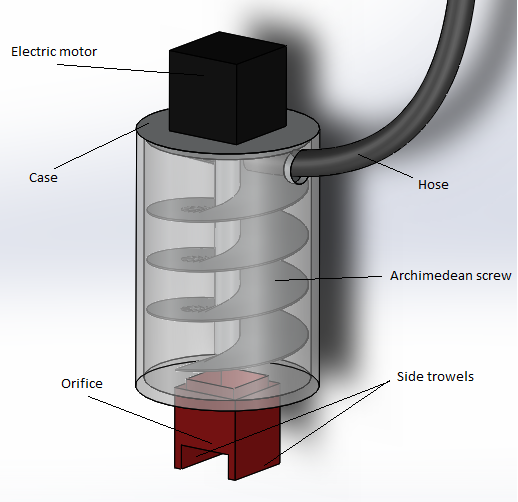
**Figure 3.4** Selected concept.

# Conceptual design

This chapter contains a brief description and figures of the conceptual design.

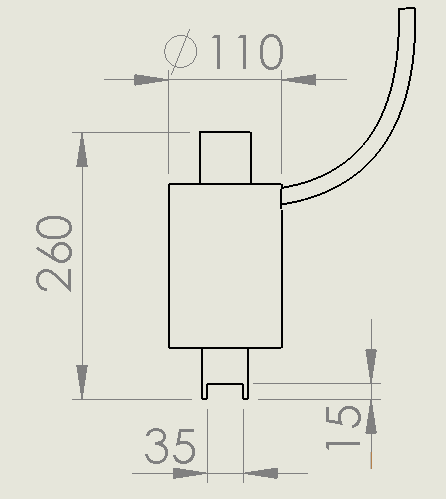
## CAD design

To make CAD models the software *SolidWorks* is used. The concrete is delivered from a container through the hose. An electric motor drives the Archimedean screw/auger which pushes the concrete down. The orifice and side trowels decide the dimension of the extruded line of concrete, see figure 4.1.



**Figure 4.1** Conceptual design of extruder on 3d printer.

Estimated measurements were also set, see figure 4.2.



**Figure 4.2** Estimated measurements of extruder (mm).

## Technical review: Components and materials

The components and its materials that are needed for the extruder are

* **Electric motor**- of the shelf component
* **Hose**- flexible material to perform bending motion
* **Auger**- metal for robustness
* **Pipe with top- and bottom lid**- hard plastic for cheapness
* **Side trowels**- hard plastic or metal for robustness
* **Coupling**- metal for robustness
* **Attachment to robot**- hard plastic or metal
* Threads, nuts, set screws and regular screws

# Testing of prototype, analyses and improvements

In this chapter it is described how the tests of the prototypes were carried out. After each test follows a section of analysis and potential improvements are discussed.

## Purpose of test

The prototype will be tested on how well if fulfills the product specification.

## First test

The first test was carried out with the first prototype of the extruder, see figure 5.1. The auger is mounted to the electric motor and is operating inside the extruder, see figure 5.2. The test was carried out using a sand and water mixture instead of concrete, see figure 5.3. This is because the sand will not harden, can be reused and its similarity in properties to concrete.



**Figure 5.1** Extruder in first test.



**Figure 5.2** Auger coupled to electric motor.



**Figure 5.3** Sand mixed with water.

In the test the electric motor was too weak and could not run with even a small amount of sand mixture in the extruder. Also the hose`s diameter was too small and the sand mixture was not able to flow through it.

### Analysis and improvements

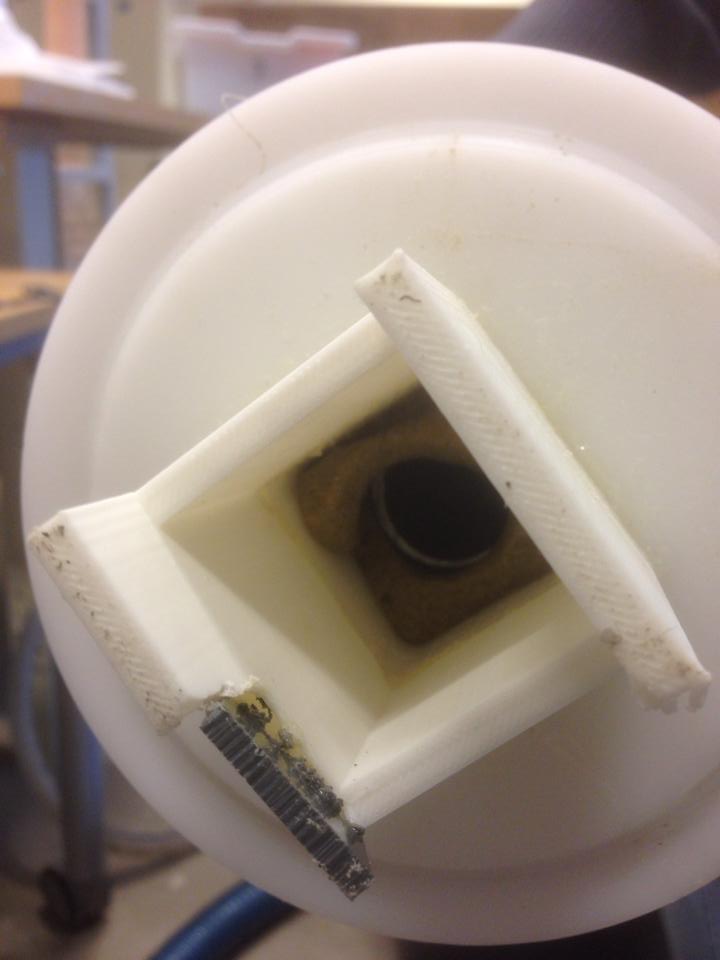
A hose with a bigger diameter is needed and the hole in the extruder for the hose therefore has to be adjusted to the new measurement. A stronger electric motor is needed. The change of motor also means change of measurements on coupling, on hole, on top lid and change of screws.

## Test with stronger motor

The new electric motor is strong enough, see figure 5.4. It has a maximum torque of about 3 Nm. However it started to turn itself with the top lid instead of turning the auger. The original fixation for the top lid with just a rubber seal is not enough. Another observation was that it seemed difficult for the sand mixture to exit the orifice, see figure 5.5.



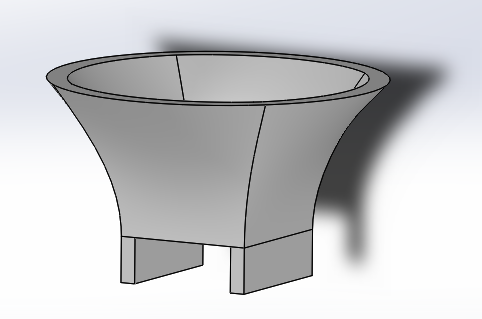
**Figure 5.4** New stronger motor mounted on extruder.



**Figure 5.5** Orifice of extruder. Difficult for the sand mixture to be extruded.

### Analysis and improvements

The top lid will be screwed together with the pipe to keep it fixated. The difficulty for the sand mixture to exit from the extruder is believed to do with the fact that the mixture is very viscous and that the bottom surface is planar. When it arrives in the bottom part of the pipe it gets stuck and compressed rather than exiting the extruder. This results in stopping of the motor because of too much resistance and very little sand mixture exiting the extruder. Therefore testing will be done with a cone-shaped bottom part so that the sand mixture more easily can exit the extruder, see figure 5.6. The cone-shaped bottom part will be 3d printed in plastic in one piece.



**Figure 5.6** New cone-shaped bottom part designed in CAD.

## Test with cone-shaped bottom part

The top lid is now fixated and is not moving as a result of it screwed together with the pipe. The new cone-shaped bottom part is glued and taped on to the pipe. The tape is just temporary to speed up the testing process, see figure 5.7.



**Figure 5.7** Extruder with new cone-shaped bottom part.

There is no compression of the sand mixture anymore, instead it gets pushed out through the orifice, see figure 5.8.



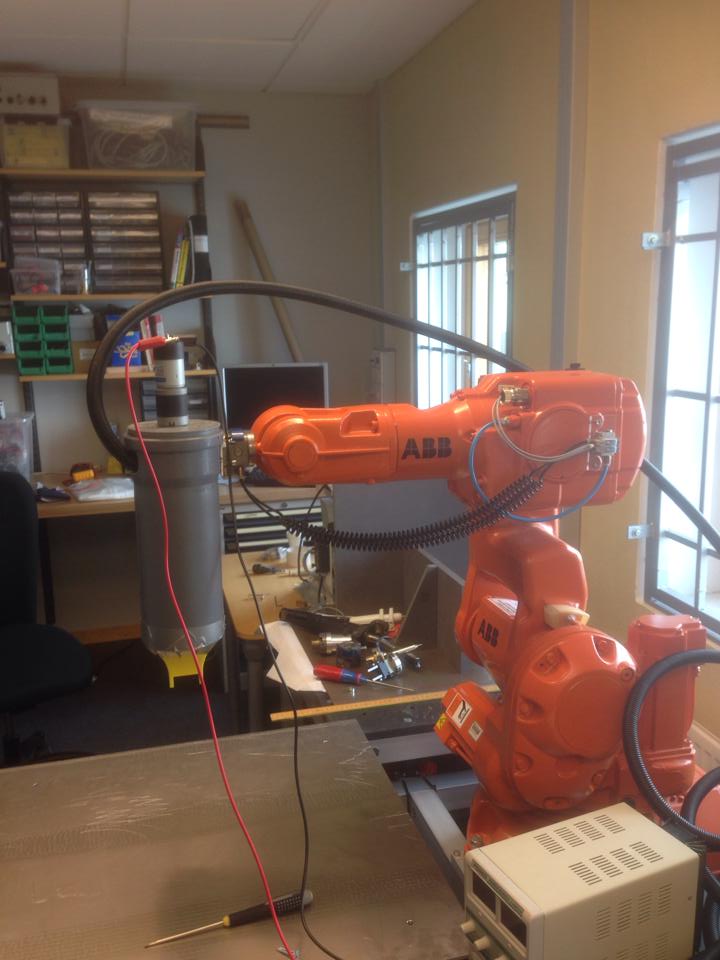
**Figure 5.8** Results of test with cone-shaped bottom part.

### Analysis and improvements

The current design results in a weight of the whole extruder without any material inside of approximately 1, 5 kg. Its volume is about 2, 5 liters. The sand mixture`s as well as typical concrete`s weight is about 2 kg per liter which leads to a total weight of the extruder filled with concrete of about 5-7 kg. The arm of the ABB robot has only capacity to carry a weight of about 6 kg and therefore the weight of the extruder has to be considered in later testing.

## Test with the extruder attached to ABB robot

The test was done with the extruder attached to the ABB robot arm, see figure 5.9. It is attached to the robot by a washer and screws on the side of the extruder.



**Figure 5.9** Test with extruder attached to ABB robot.

It created a line of sand mixture but the extrusion rate was slow, see figure 5.10. It was seen that with the attachment on the side the extruder it will limit its range of motion.



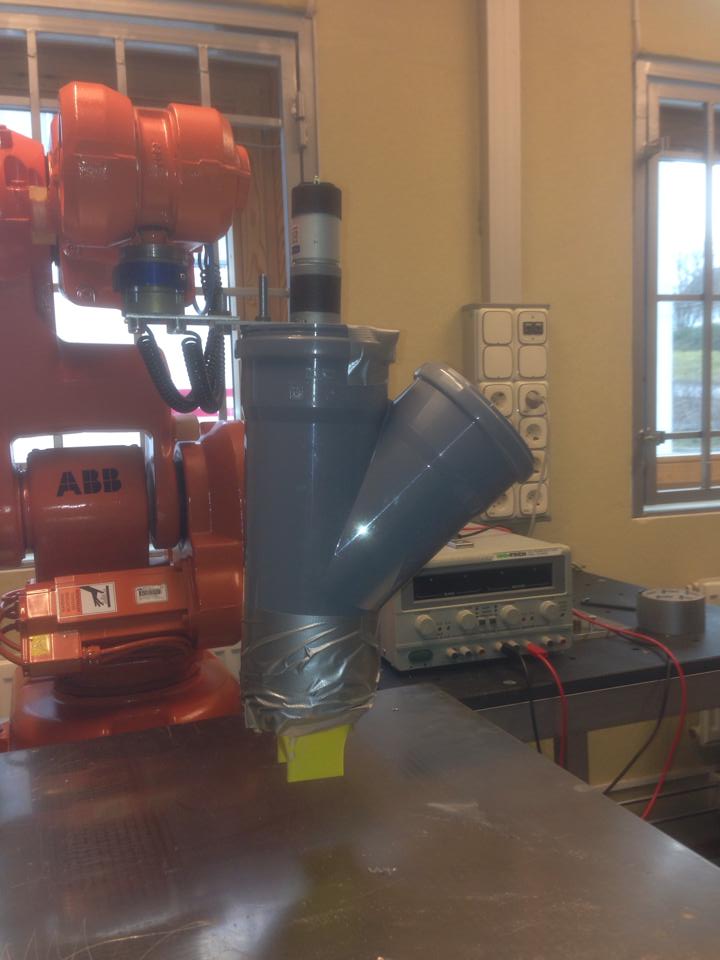
**Figure 5**.10 Extruded sand mixture.

### Analysis and improvements

To increase the rate of extrusion a motor that turns faster is needed. Therefore there will be a change of motor and some adjustments on the top lid to fasten the new motor.

## Test with y-pipe

Instead of using a regular pipe tests will be done with a y-pipe, see figure 5.11. This is because of trouble in getting the sand mixture transported to the extruder. The benefits with this design compared to the earlier are that the inlet diameter is much larger and that there is no part of the hose that is horizontal. The angle of the inlet pipe is 45º. The attachment to the robot is now screwed to the top lid instead of the side. This will allow the extruder to turn around its center axis.



**Figure 5.11** Extruder with new y-pipe.

The motor is still too weak and is stopping when the extruder is loaded with a lot of sand mixture. The bottom part (yellow part) is too fragile and is starting to break at the screws, see figure 5.12. This attachment allows the extruder to rotate around its center axis. However, when rotating it also will move in circular motion because the robot`s center axis and the extruder`s center axis are not coincident.



**Figure 5.12** Formation of cracks in the bottom part.

### Analysis and improvements

A problem with the sand mixture is that it`s not homogenous. The sand is not dissolving in the water and when it is compressed this will push out the water making the mixture dryer and more viscous. A more homogenous fluid needs to be found, a new and stronger motor will be ordered and a new bottom part of metal is going to be designed to make it more rigid. To make an attachment where the robot`s center axis and the extruder`s center axis are coincident would be a much better solution than the current one.

## Test with porridge

To test with a more homogeneous fluid this test was made with porridge instead of sand mixture, see figure 5.14. A new and stronger motor is mounted and a new motor axis has been made to fit it, see figure 5.13. The motor has a maximum torque of about 21 Nm. The bottom part is now made of steel and aluminum and will withstand much higher tensions than the one made of plastic.



**Figure 5.13** Extruder with new motor and new metal bottom part.

The test went well and the extruder created a steady flow of porridge. The motor is much stronger than the last one. The extruder seems overall more robust than before.



**Figure 5.14** Porridge used in testing.

## Test with standard concrete

This is the first time the test is carried out with concrete, see figure 5.15. The concrete used is standard fine grain concrete and the water: concrete ratio is about 1:6.

When testing, rather than exiting the extruder the concrete stays in the extruder and fluctuates in it. It behaves a lot like the sand mixture. The motor is also rotating in an uneven fashion and sometimes comes to a stop.



**Figure 5.15** Standard fine grain concrete.

### Analysis and improvements

It is believed that the observations are the result of a too viscous fluid, i.e. it creates too much friction for the extruder to push it out. Therefore the same concrete but with higher water ratio will be tested, thereby making it less viscous. The uneven rotations of the motor are probably a result of pieces of stone in the concrete getting trapped between the auger`s blade and the wall of the pipe. The final material used for printing has to have as small pieces in it to prevent this from happening.

## Test with standard concrete with added water

In this test a standard concrete mixture with more water is used, see figure 5.16. The result was a bit better than the last test with less water but the material is still not exiting the extruder easily enough.



**Figure 5**.16 Standard concrete with added water.

### Analysis and improvements

It could be that regular concrete is not suitable for 3d printing. Further tests will be made with mortar, and a type of EPS-cement.

## Test with mortar

This test will be made with mortar instead of concrete, see figure 5.17. The difference from concrete is that the stone material in concrete is replaced with sand (finer grains) in mortar [6]. The texture is similar to the sand mixture used before.

The test went well and the extruder created a steady flow of mortar. This material seems less viscous than the concrete mixes used and that is probably why it works better.



**Figure 5.17** Mortar.

## Test with EPS-cement

The test will be made with EPS-cement which is a kind of light weight concrete where the stone material is substituted to expanded polystyrene (plastic), see figure 5.18. If the ABB robot shall be able to carry the weight of the concrete in the extruder it has to be as light as possible. As a comparison EPS cement has a density of about 350 kg/m3 whereas regular concrete has a density of about 2400 kg/m3 [5].

The results were similar to the mortar test, it works well. The successful outcome is believed to be associated with the less viscosity of the material. One reflection is how much the

material`s viscosity changes with just adding a small amount of water or a small amount of dry material. This indicates that the mixing of printing material has to be very precise in the aspect of different ratios of material and water. Another reflection is that why the concrete in earlier tests did not work probably has to do with the higher viscosity of the material. The concrete will block the orifice when it reaches the narrower section and will be too hard to push out. This is why the material used in printing has to be not more viscous than that it will block the narrower section. The drawback of a less viscous material however is that it will be more likely to slump when printed, meaning that it will be harder to build vertical structures. A compromise between these two factors needs to be found.



**Figure 5.18** EPS-cement.

### Analysis and improvements

For appearance and aesthetics the extruder will receive a spray paint in silver. An attachment for the robot that will coincident the extruder`s center axis and the robot`s center axis has also been made.

## Test with special concrete mixture

In order to find a solution to the problem with viscosity a special mixture of concrete will be tested. The recipe includes nine different ingredients, which have an accuracy in grams and has been developed by August Hamelius and Mikael Backebjörk, civil engineering at Lund University. The ingredients by weight are Baskarp® sand (fine grain), base cement, Baskarp® sand (coarse grains), water, fly ash, Elkem Microsilica® silica fume, superplasticizer, retarder and fibers, see Appendix B for detailed recipe. The concrete is mixed in a machine mixer for about 5-7 min before use.

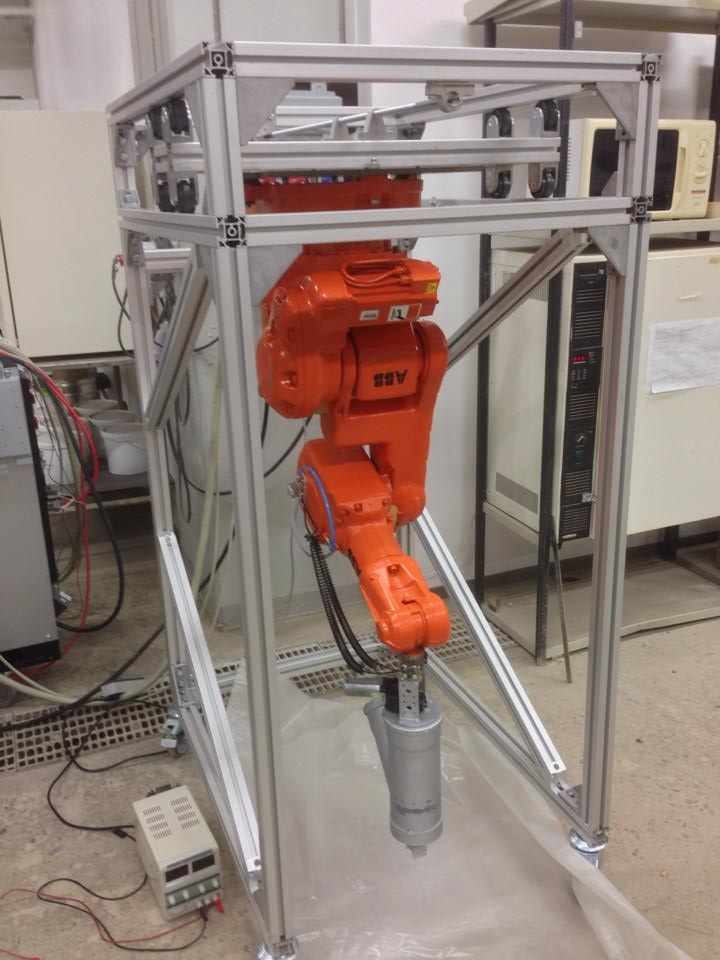
The test went very well. The extruder could handle the mixture without problem even if it had quite high viscosity and was able to build several layers of it, see figure 5.19. Somehow it manages to be extrudable, i.e. able to be extruded, but yet buildable, i.e. able to build several layers of it. The mixture seems to stiffen when not moved and get less viscous when moved. This could be the suitable mixture for this type of application. The extruder filled with the special concrete weighed less than 5 kg.



**Figure 5.19** Extruded material of the special concrete mixture.

## Test with special concrete mixture with extruder attached to robot

The robot is now mounted upside down within a metal frame, see figure 5.20. The only thing missing is a hose and a container of concrete to make it a fully automatic process. In this test concrete will be manually fed into the extruder with a spade. The robot was programmed to build a wall and then a square to test how well the system manages to build several layers and the ability to make corners.



**Figure 5.20**

The test went very well. The printer was able to build a wall structure that was about 2 cm wide and about 45 cm high, see figure 5.21, 5.22, 5.23 and 5.24. In this test it was the robots limitations that prevented it from building higher than 45 cm. The wall was very straight and not tilting to one side at all. This was accomplished by the robot`s accuracy. One good property of this concrete is that when it is still it stiffens and becomes more viscous within some minutes. The lowest layers of concrete had stiffened a bit after printing for a while and doing the top layers. It is good for building high that the lower layers stiffens and can support more weight and not slumping. At first the robots speed was 5 mm/sec but it was seen that this was too slow because of too much flow of concrete from the extruder. A slight adjustment to 10mm/sec of the robots speed resulted in a much better extrusion when the motor on the extruder ran at its maximum speed at 24 V. The whole wall took about 30 minutes to build including pauses. Pauses had to be taken because only 3 litres of concrete were used at the time. The mixing of the next batch of concrete was done while the robot was still. A problem however was that the motor of the extruder was becoming very hot when printing for this long time. When doing the square it was seen that when the robot rotates 90º at each corner the side trowels interfere with the concrete causing cracks in the extruded line, see figure 5.25. This caused one of the side trowels to break because of too much tension. Another problem with the turns is that the cables for the motor on the extruder get tangled up.



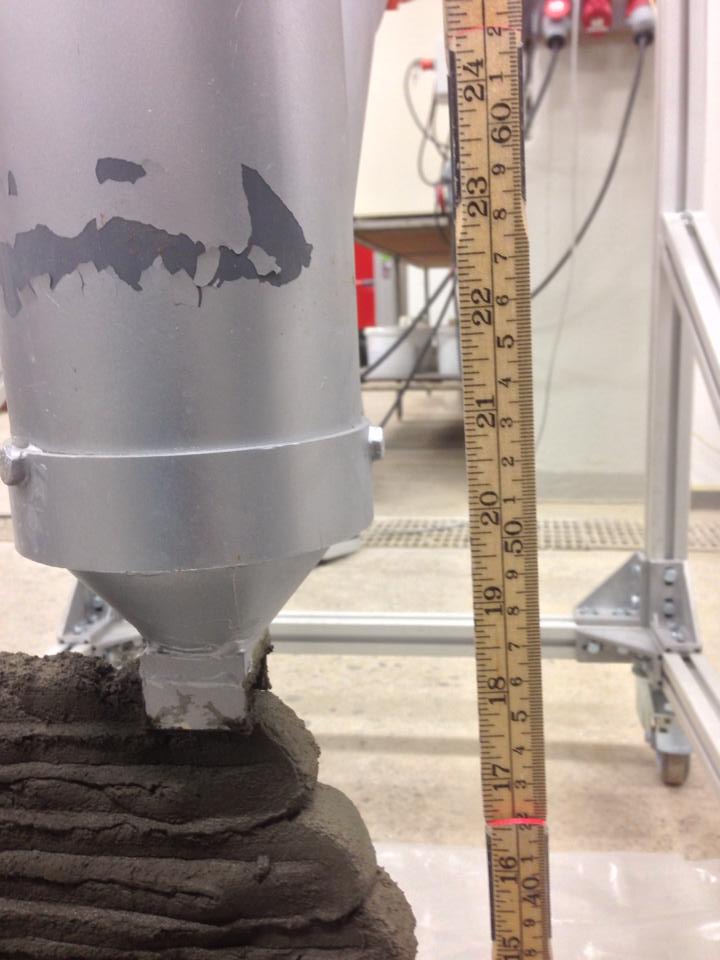
**Figure 5.21** Front view of wall.



**Figure 5.22** Side view of wall.



**Figure 5.23** Side view of wall.



**Figure 5.24** The wall was about 45 cm high.



**Figure 5.25** Square made by the printer.

### Analysis and improvements

The motor is getting too hot probably because of it is under dimensioned for this application. Because lack of time there will not be an order of a new motor but instead trying to cool it by putting heat sinks on it. If the side trowels are rejected there will be no interference in the concrete. The robot also doesn’t have to rotate because the side view of the orifice then will be the same in all four directions. The problem however is that when removing the side trowels it will be harder to control the width and height of the extruded line of concrete. Still, for this particular project, there are more benefits without side trowels than with them resulting in rejection of them and just using a square orifice.

## Test with special concrete mixture with extruder mounted on robot and hose

In this test the whole system will be tested. The bucket on top of the metal frame will be fed with concrete. The hose is attached to it with hose clamps and only resting on the extruder to be able lengthen and shorten when the robot is moving, see figure 5.26.



**Figure.5.26**

When feeding the bucket with concrete it was observed that it falls down to the extruder but stops in the section of the 45º inlet, see figure 5.27. The concrete is probably too viscous to flow all the way down just relying on gravity. Even when the extruder was manually fed the concrete sometimes needed to be pushed down to the section of the auger. The extruder without side trowels functioned well. The benefit is that the robot does not have to turn and get tangled up in cables. The drawback is that the line of concrete is now a bit wider and higher and that these measurements is now more likely to change over time due to how big the flow of concrete is.



**Figure 5.27**

### Analysis and improvements

For the transportation of concrete from the bucket to the hose to work it probably needs some sort of flow creating mechanism to create more downforce than just gravity. However, if using another auger at the top in the bucket would demand the hose to be completely filled with concrete all the time. This would put a lot of weight on the extruder and it is possible that it would not be able to handle this weight. Due to the lack of time in the project this 3d printer will be fed manually.

# Results

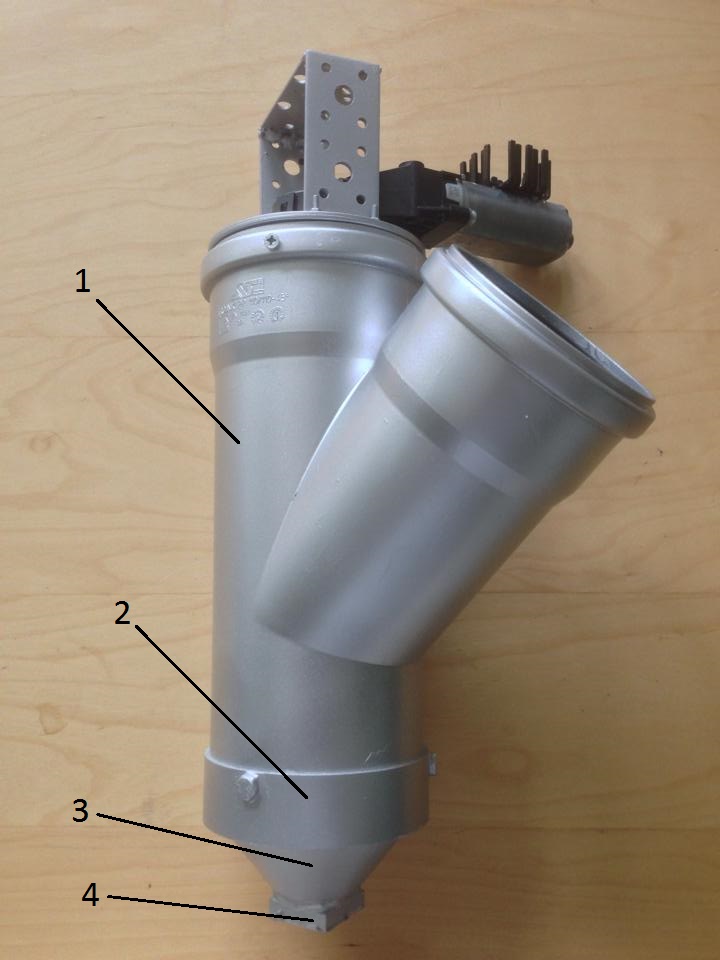
In this chapter the final product is presented.

## Final product

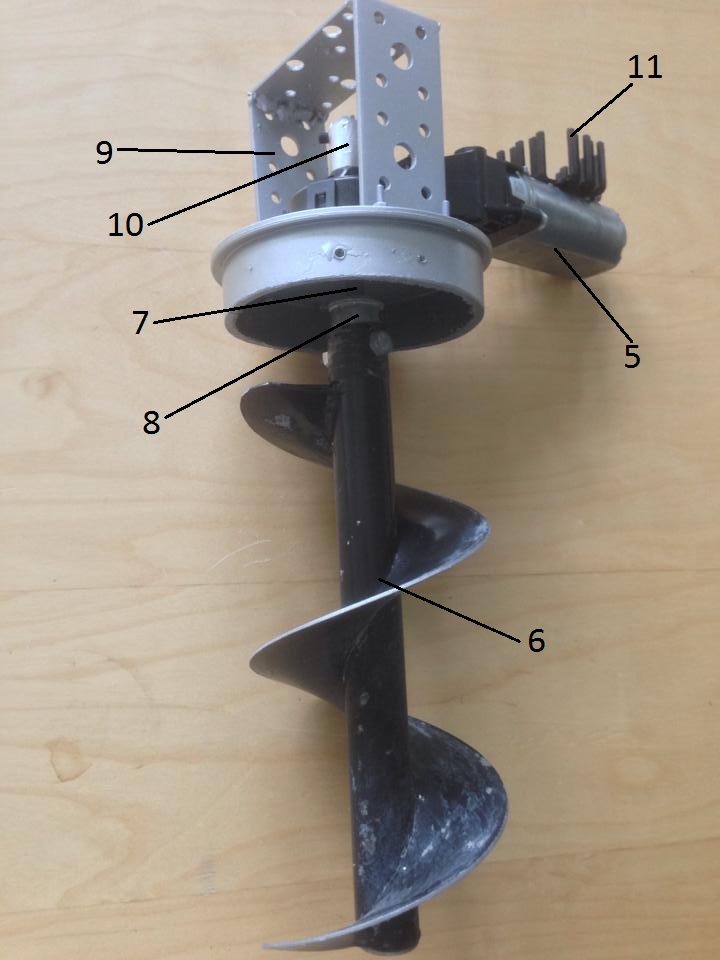


**Figure 6.1** Final design of extruder.

## Manufacture of final prototype



**Figure 6.2** Manufacture of final prototype.



**Figure 6.3** Manufacture of final prototype.

1. Y-pipe with top lid, of the shelf-product. Top lid is screwed together with the pipe, see figure 6.2.

2. Connection between pipe and cone-shaped part. Lathed to fit on the pipe. Fastened to the pipe with just a tight fitting. Epoxy-glued to the cone-shaped part, see figure 6.2.

3. Cone-shaped part. Modified steel funnel, see figure 6.2.

4. Square orifice. Cut and glued on with epoxy to the cone-shaped part, see figure 6.2.

5. Motor, see appendix C for technical specifications. Screwed together with top lid, see figure 6.3.

6. Auger, of the shelf-product. Cut, drilled hole in and grinded to fit inside the pipe, see figure 6.3.

7. Axis. Milled to get a square shaped cross section in the section at the motor, see figure 6.3.

8. Coupling. Lathed, and drilled holes in, see figure 6.3.

9. Attachment to robot. Welded together and drilled holes in to attach to robot. Screwed together with top lid, see figure 6.3.

10. Metal piece to attach the axis to the motor vertically, see figure 6.3.

11. Heat sink on motor, see figure 6.3.

## Data for final concrete

Compressive yield strength: ~105 MPa [7]

Tensile yield strength: ~13 MPa [7]

## Printed details



**Figure 6.4** Planks of wood have been placed as a seat on the chairs.

# Conclusion, discussion and recommendations

In this chapter the conclusion is presented. Also a discussion and recommendations for further research is outlined.

## Conclusion

The overall working principle of the extruder is suitable for concrete 3d printing. A major point is the need of a special mixture of concrete like the one used in the project. The concrete has to be extrudable but also buildable which was failing with standard concrete for this printer.

## Discussion and recommendations for further research

The concrete used in the project has about the same density as standard concrete. This puts a lot of tension on the attachment between the robot and extruder if a hose filled with concrete would rest on the extruder. An added clamp in the attachment could solve this problem. With manual feeding the attachment can bear the load of the extruder filled with concrete.

Regarding the weight of the used concrete it was mentioned as an aim to find as light weight concrete as possible. Since the recipe of concrete was more advanced than expected at the beginning of the project and due to the lack of time, it was difficult to do something about its weight. Adding some other material trying to make it lighter could possibly result in different properties for the concrete, a difference that was unwanted for this project. Still, one could test to add EPS-balls (plastic) or something similar for this purpose. The more light weight the concrete becomes the easier it would probably be for any printer to work with the material. As mentioned, the special mixture of concrete can be adjusted and just by changing small amounts of some ingredient could result in different properties for the mixture, so one could try a more viscous or less viscous type of the mixture to suit their needs.

Throughout the project a problem has been to transport the concrete from a container to the extruder. In this project it has been relied on gravity and for the concrete to fall down to the extruder. However, when the concrete is too viscous, like the one used in the project, gravity is not enough. The special concrete mixture used makes this even more difficult by becoming stiffer when being still for only a couple of minutes. One solution for this could be to manufacture a much bigger extruder and load it with all concrete needed for the printing session. In this way the concrete will be moved all the time and staying less viscous. It will also end the need of a transportation system to the extruder.

Due to lack of resources in the project only 3 litres of concrete could be mixed at the time. Since the printer demanded surveillance when printing, it had to be paused when mixing the next batch of concrete. When starting printing again it was observed that the last concrete from the last batch left in the extruder had stiffened a bit and was blocking the orifice. A screw driver was used to puncture the blockage and to let the new concrete flow through the extruder. It would have been good to make the section between the auger and the orifice of the extruder as short as possible to prevent blockage. The auger`s lower section could also be cone-shaped like the extruder`s walls to fit in it. By this way there will be less blockage of the orifice when paused and no wastage of concrete that is not used when ending printing.

A lot of further experimentation could be done on the orifice of the extruder. The shape could be changed for example to a circle or a triangle to see how it works compared to the square orifice used in this project. A lid to the orifice could also be tested to be able to be more precise when printing and not. Adjustable side trowels could be tested to see if one would be able to print angular walls. With the ability to adjust the angle of the side trowels they could be raised every time making a corner to prevent them from interfering with the extruded line of concrete. When the orifice has left the corner the side trowels could then be lowered again to be able to control the dimensions of the extrusion. If one changes the dimensions on the orifice this should result in change of resolution of the printer. With the robot`s accuracy it could be a good idea to make the orifice much smaller and able to print much more detailed pieces.

During the project there has been underestimation of the needed force and rigidity of the extruder to be able to function properly with concrete. It should be recognized for further research that the force needed to extrude concrete through an extruder like this demand relatively high forces. The motor used in in the final product is probably under dimensioned.

As mentioned before, when building structures on the height, the lower layers have time to stiffen a bit while the higher layers are extruded. This results in the wall increasing its ability to support its own weight over time. This is a good property for building high structures. Another technique to build these could be to clean the extruder, wait for 24 hours for the concrete to harden, and then continue building on the wall. With this technique one should be able to build even higher structures.

Use of a finite element software, for example ANSYS, could have been useful for calculating the tensions and strains in the extruder and from that knowing what material would have been suitable for the application. However, the fact that there are several different materials such as plastic and metal and that many parts are assembled by glue would probably make it difficult to do calculations. Also the fact that the printing material is concrete makes it difficult to simulate. Therefore it was decided that manufacture of a prototype and testing it in reality would be a better solution.

The number of different details that could be printed with this printer is vast. In this project only straight lines has been made but one could also do curved shapes. It is only the robot`s movement that limits this. This particular robot is less good for 3d printing because of its limitations in range. For further research one could test to integrate supports such as pieces of wood in the printing to be able to make cavities in the detail.

The concrete`s compressive yield strength is very high, about 105 MPa. For the use of street furniture this is much more than needed and shows the range of applications this concrete can be used in. The tensile yield strength is much less, about 13 MPa. In retrospect it was understood that the lower part of the back seat of the chair will be subject to high tensions and would possibly fracture when leaning ones back on it. To make it more rigid concrete steel could be placed inside the back seat and further down in the square structure while the concrete hasn’t hardened yet. Another important aspect concerning the strength of the structure is the attachment between layers. Research should be done in this area to see if this causes decrease of strength in the structure.

The whole project has involved four master thesis students. Two of them were working on finding a suitable concrete for 3d printing. In retrospect it is clear that the tasks of developing both a suitable concrete and an extruder was too much work for just one master thesis student. Without the students doing research in concrete and their resources a good solution for printing material probably would not have been found.

# References

1. Kwon, H. (2002). Experimentation and analysis of contourcrafting (CC) process using uncured ceramic materials (Electronic). Doctoral thesis. Industrial and systems engineering, University of southern California, USA. http://contourcrafting.org/wp-content/uploads/2013/04/HK-Thesis.pdf
2. (2015). What is Rapid Prototyping? (Electronic). Stratasys Ltd, Minnesota, USA.

http://www.stratasys.com/resources/rapid-prototyping

1. (2015). Cement and concrete basics (Electronic). Portland cement association, Illinois, USA.

http://www.stratasys.com/resources/rapid-prototyping

1. Ulrich, Karl T. & Eppinger, Steven D. (2012). Product Design and Development. McGraw-Hill Education New York, USA
2. (2015). CM 630 Lättmassa (Electronic). Produktdatablad, Combimix AB, Bålsta, Sweden.

http://www.combimix.se/pdf/Combimix\_CM630\_PDB\_SV.pdf

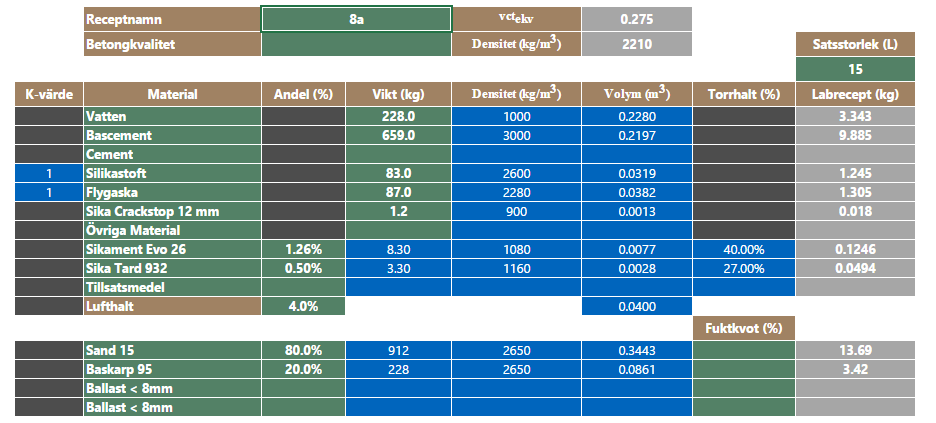
1. (2015). Murbruk M10 (Electronic). Produktdatablad, Combimix AB, Bålsta, Sweden.

http://www.combimix.se/pdf/Combimix\_MurbrukM10\_PDB\_SV.pdf

1. Backebjörk, M. & Hamelius, A. (2015). (Electronic). Concrete for 3D-printing- properties in fresh and hardened state. Master thesis, Civil engineering, Lund University, Lund, Sweden.
2. : Time plan

The project has almost always been on time. In the beginning of the project it was decided to have a prototype working roughly at the middle of the project, but it was difficult to make a detailed time plan in the beginning because of the unknown results of the experiments.

1. : Recipe for special concrete mixture



1. : Technical specifications for motor used on extruder

