LAPPEENRANTA UNIVERSITY OF TECHNOLOGY

LUT School of Energy Systems

LUT Mechanical Engineering

Pasi Piispa

A NEW APPROACH TO DESIGN AND DEVELOPMENT OF A METAL ADDITIVE MANUFACTURING MACHINE

Examiners: Professor Antti Salminen

D. Sc. (Tech.) Hamid Roozbahani

ABSTRACT

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A New Approach to Design and Development of a Metal Additive Manufacturing Machine

Master's thesis

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95 pages, 76 figures, 3 table

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Keywords: powder bed fusion, powder removal, building platform changing, additive manufacturing

This thesis is studied designing of additive manufacturing machine. Many different components and component combinations are selected to use in designed machine. In researching components was kept the focus on that the first prototype should be quite easily modifiable and tuned without large additional costs. In first stage of thesis is researched information from literature. In literature research is founded the available machines in the market and commonly used building methods.

In second stage of the study is focused to design the machine. Designed machine has integrated additional functions which give more value for the machine in the markets. Designed additional functions of the machine automatic powder removal, automatic powder circulation, integrated nitrogen generator and automatic building platform change-over mechanism. Founded components are evaluated against the requirements of the machine and additional information of the components are collected from components manufacturers and suppliers.

In third stage was created dynamic model of the designed machine three main motions and controller for dynamic model. Three main motions are recoater movement, lifting platform movement and building platform change-over arm movement. In dynamic model has evaluated a suitability of the components more precisely. With created controller was evaluated the motions, PID controller gains, positioning and work cycles of the model. Created controller also give guidelines to design the whole machine controller in future.

Some of the components are oversized on purpose to give more opportunity to modify and adjust the machine first prototype.

TIIVISTELMÄ

Lappeenranta teknillinen yliopisto
LUT School of Energy Systems
LUT Kone

Pasi Piispa

Uusi lähestymistapa suunnitella ja kehittää 3D tulostin metallimateriaalille

Diplomityö

2017

95 sivua, 76 kuvaa, 3 taulukkoa

Tarkastajat: Professori Antti Salminen
TkT Hamid Roozbahani

Hakusanat: pulveripeti, jauheen poisto, rakennusalustan vaihto, ainetta lisäävä valmistus

Diplomityössä tutkittiin ja kehitettiin suunnitelma ainetta lisäävälle valmistuskoneelle. Koneeseen on valittu useita osia/osakokonaisuuksia. Komponenttien valinnassa otettiin huomioon joustavuus, jotta ensimäistä versiota kehitetystä laitteesta olisi mahdollista muokata ja säätää ilman suuria lisäkustannuksia. Ensimmäisessä vaiheessa etsittiin kirjallisuudesta tietoa markkinoilla olevista koneista ja kappaleen rakennus menetelmistä.

Toisessa vaiheessa diplomityötä aloitettiin kehittämään konetta. Kehitettävään koneeseen haluttiin lisätoimintoja, kuten automaattinen jauheen käsittely ja poistaminen sekä automaattinen rakennus alustan vaihto. Tässä vaiheessa keskityttiin tutkimaan kirjallisuudesta ja tuotekatalogeista sekä tiedusteluilla komponentti valmistajilta ja toimittajilta komponenttien suoritus kykyjä ja ominaisuuksia. Saatujen ominaisuuksien pohjalta muodostettiin osakokonaisuudet laitteen päätoiminnoille. Komponenttien ominaisuuksia verrattiin laitteeseen haluttuihin ominaisuuksiin ja laitteessa syntyviin voimiin. Tätä kautta arvioitiin komponenttien soveltuvuutta.

Kolmannessa vaiheessa tehtiin kehitetyn koneen merkitsevimmistä liike toiminnoista dynaaminen malli, jolla arvioitiin tarkemmin osien soveltuvuutta ja osilla saavutettuja ja niihin kohdistuneita liikkeitä ja voimia. Malli tehtiin siten, että vastaavaa mallia olisi mahdollista käyttää myös tulevaisuudessa uusia koneita kehitettäessä muuttamalla ominaisuuksia ja parametreja mallissa. Dynaamiseen malliin tehtiin myös ohjaus koodi jolla saatiin simuloitua mallin toimintaa käyttäen paikoitus komentoja. Tällöin mallista nähtiin toden mukaisemmat liikeradat.

Joitakin koneen liikkeen tuottavia komponentteja on tarkoituksella hieman ylimitoitettu. Tällä tavoiteltiin joustavuutta ensimmäisen prototyypin säätämisessä ja jatkokehityksessä.

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Pasi Piispa

Pasi Piispa
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LIST OF SYMBOLS ANB ABBREVIATIONS

a	Acceleration
a_{arm}	Acceleration of change-over arm
A_{plate}	Effective area of the sealing plate
$D_{belt\ wheel}$	Diameter of belt wheel
D_{piston}	Piston diameter
D_{roller}	Diameter of the roller
f_{1V}	Frequency when input voltage is 1 V
F_{arm}	Force which effect the change-over arm
F_{belt}	Force in one belt
F_{const}	Constant force factor
$F_{cylinder}$	Cylinder dimensional force
F_{dim}	Dimensional force
f_{drive}	Motor driving frequency
F_{freeze}	Freezing force
f_{init}	Frequency when $n_{motor\ rpm}$ is true
F_{powder}	Resistive force of the powder
F_{reduce}	Reducing force
g	Gravity acceleration
h	Height position of the lifting platform
h_{max}	Lowest platform height position on printing process
i_{gear}	Gear ratio of the gear
l	Perimeter length
M	Torque
M^2	Beam quality value
$m_{capacity}$	Lifting capacity
$m_{recoater}$	Mass of the recoater
m_{comp}	Mass of the largest printed component
$m_{full\ plate}$	Mass of the fully printed building platform
M_{in}	Input torque
M_{out}	Output torque

$m_{real\ plate}$	Real mass of the empty building platform
m_{plate}	Weight of the fully printed building platform
n_{belt}	Number of belts
$n_{motor\ rpm}$	Motor revolutions per minute
$n_{motor\ rpm}$	Motor rotational velocity in revolutions per minute
p	Pressure
r_{pulley}	Radius of the belt wheel
t	Time
U_{in}	Input voltage in frequency inverter
$U_{in\ recoater}$	Recoater motion input signal in volts
$U_{in\ change}$	Change-over arm motion input signal in volts
v	Velocity
V	Volume
$v_{recoater}$	Velocity of the recoater
Δp	Pressure difference
ρ	Density
τ	Torsional stress
ω	Angular velocity

3D	Three dimensional
AC	Alternative current
BASA	Ball screw assembly
DC	Direct current
PID	Proportional Integral Derivative
PLSA	Planetary screw assembly
SLM	Selective laser melting

1 INTRODUCTION

Purpose of this thesis was design additive manufacturing machine main functions. Main functions are movement of the recoater, levelling of the lifting platform, closing the lifting chamber, powder filling in the recoater, building chamber atmosphere and gas circulation, laser processing, changing building platform, powder removal and powder journey. Additive manufacturing is strongly increasing field and new manufacturers and machines are coming in the markets.

1.1 Background

Additive manufacturing which is also called 3D (Three dimensional) printing (Frazier 2014, p. 1917) is a manufacturing process where component is created by adding material directly on component by layer by layer. Component is generated directly from 3D digital model with additive manufacturing machine. Each layer is a cross-sectional shape of the part which is added after previous layer. By additive manufacturing is possible to do complex parts like channels inside the component which are difficult or even impossible to do with traditional manufacturing methods like drilling. (Horn 2012, pp. 256-258.) Against moulding a mould price might rise quite large and small series are unpractical to manufacture. Additive manufacturing will not need a mould so even customer specific components with complex shapes are cost effective to manufacture in small series with additive manufacturing method. (Klahn & Leutenecker & Meboldt, 2014, p. 142.)

Additive manufacturing is highly growing industry and many companies around the word are investing on development of additive manufacturing technology. Year 2014 in word wide there was 49 manufacturers who produce and sell the industrial grade additive manufacturing machines. On year 2015 number of manufacturers was 62. Many of large companies are pushing themselves on the additive manufacturing markets. Several companies are developing additive manufacturing machines together. Machine development activities are focusing to add novelties in the machine. Many of the investments are focusing to develop the opportunity to build final production-quality components. Most advanced example is the larger scale machine MetalFAB1 which has automatic building platform handling, automatic powder removal and building volume is 420 x 420 x 400 mm^3. Base price of this machine is 1.1 M€. (Wohlers & Caffrey 2016, pp. 45-48.)

By the market data and reports the assumption is that the markets has room for new machines and new manufacturers. Lappeenranta University of Technology has shown the interest to research and design an industrial grade additive manufacturing machine for metal materials which is compatible in markets and it is possible to sell with reasonable profit.

1.2 Research problem

Research problem was to study the flexible and cost effective solution for the first prototype of the additive manufacturing machine main sections. First prototype of the machine should be possible to modify and adjust without large additional costs.

1.3 Aim of the research

Aim of the study was to study design for new additive manufacturing machine. The final idea is to build and launch the machine on the market after the funding is secured. Machine will include functions making it unique and competitive on the market against other manufacturer's models. Results of the study will include solution for main sections of the machine which allow to test and adjust the first prototype of the machine without significant additional costs. Designed machine will include automatic powder removal, powder circulation and automatic building platform change-over mechanism.

1.3.1 Research questions

Research question is: out of which kind of solutions and components it is possible to build a reliable metal additive manufacturing machine first prototype with ability to test and adjust the functions of the machine to real production machine without significant additional costs? Second research question is: how should all of the functions of the designed machine be integrated such that it will operate automatically and continuously without manual service during printing processes.

1.3.2 Hypothesis

Hypothesis is that most of the functions can be carried out with basic components. Dynamic model and created controller can be used in testing of different scales of machine in future with a quite small changes.

1.4 Research methods

Used research methods are literature study and personal interviews. Also the suitability of founded solution is studied with dynamic modelling. Motions of the system are studied with created controller by using more realistic positioning algorithm.

In literature study the suitable components which work properly in machine were found. Properties of the selected components were evaluated with calculations with dynamic model and conversations with components suppliers and manufacturers.

Dynamic model was created based on selected components. The suitability of the selected component were evaluate with dynamic model based on the properties of the components. Dynamic model was created for change-over arm motion, recoater motion and lifting platform motion. Dynamic model was made that way it is possible to use also with other scale machines by modifying parameters in model. With controlling software was made controlling code to control dynamic model to evaluate motions by using more realistic positioning commands.

Further details of the components were defined with personal interviews thus more information to evaluate the suitability of the component was gathered. The price range of the components was also defined with personal interviews. Interviews were made via email. Individual face to face interviews were not arranged. Information was collected via usual request for quotation conversations.

1.5 Scope of the study

This study was scoped to additive manufacturing machine for metal materials by powder bed fusion principle. Study was scoped in several machine main functions. Main functions of the machine are movement of the recoater, levelling of the lifting platform, closing the lifting chamber, powder filling in the recoater, building chamber atmosphere and gas circulation, laser processing, change-over mechanism for building platform, powder removing and powder journey. Prices of the components are classified information and therefore the prices will not be published.

Dynamic model was scoped to three main dynamic functions of the machine. These three main functions are recoater movement, lifting platform movement and building platform change-over mechanism arm movement. Dynamic model was scoped also to evaluate to study the actuators forces and components suitability of the purpose.

2 LITERATURE REVIEW

Building volume of the designed machine was 400 x 400 x 400 mm³. Literature review was focused on that scale machines. In markets there is several additive manufacturing machines which building volume is approximately 400 x 400 x 400 mm³. Quite common operating methods on machines in the market is powder bed system and dynamic powder feed or wire feed system. Larger scale additive manufacturing machines prices are quite often over million dollars.

2.1 Machines on the market

In markets there is some additive manufacturing machines which have building volume close to 400 x 400 x 400 mm³. Totally there is only a few companies produce additive manufacturing machines. Some of these manufacturers use multiple laser on their machines. Laser beam focusing optics are either f-theta lens optics which is lens system which correct the focal length changes based on laser beam position in lens or with 3D optics which is moving focal lens optics which use moving lens for correcting focal point diameter when focal length change. (FormUp™ machines; The MetalFAB1; Machines; Selective Laser Melting Machine SLM 500; EOS M 400-4; Vierke 2016a.) In next sections the machines available with large working volume area presented.

Company EOS use in their model M 400-4 four 400 W fiber lasers and f-theta lens optics. Machine has 400 x 400 x 400 mm³ building volume. Each laser has 250 x 250 mm² working field, which are 50 mm overlapped. Beam focal point diameter is 100 µm. Price range of the EOS M 400-4 machine is over one million Dollars. (EOS M 400-4; Machine search.)

Company AddUp has model named FormUp™ 350. Their machine use 3D scanner and machine is possible to purchase with one or two 500 W fiber laser. Machine has 350 x 350 x 350 mm³ maximum building volume. The machine is developed to cover full production line. With integration of specific modules it is possible to combine certain functions, like powder processing and building platform handling. Layer thickness is possible to modify and it depends on used powder. With maraging steel thinnest layer thickness is 20 µm. Beam focal point diameter was not founded. (The MetalFAB1.)

Company SLM-Solutions has selective laser melting machine SLM 500 which has 500 x 280 x 365 mm³ building volume. Machine use 3D optics and it is possible to order with two or four fiber lasers which powers of 400 W or 700 W. Beam focal point diameter on machine is 80–115 µm. Machine has variable layer thickness between 20–75 µm. SLM Solution also offer a building platform removal station where powder and component is possible to remove without skin contact by using integrated cloves. Removed powder is transported automatically to powder supply unit where it is prepared to use again. Price range of the machine is over one million dollars. (Selective Laser Melting Machine SLM 500; Machine search.)

Concept laser has new model named M LINE FACTORY. In machine has two unit. M LINE FACTORY PRD and M LINE FACTORY PCG. PRD unit is the production unit and PCG unit is the processing unit. Processing unit handle the set-up and dismantling process and powder management. It is possible to integrate several machines to work together. Building volume of the machine is 400 x 400 x 425 mm³. Machine is possible to order with four 400 W or four 1000 W fiber lasers. Machine has moving focal lens optics. Beam focal point diameter is adjustable between 50–500 µm. Machine layer thickness is adjustable between 20–100 µm. (Machines; Technical data M line factory.)

Concept laser has also quite big model which name is X LINE 2000R. Machine building volume is 800 x 400 x 500 mm³ and it use two 1000 W fiber laser. Price range of the machine is over one million Dollars. (Machines; Machine search.) Based on machine building volume this machine is not very well comparable against designed machine.

Company Additive Industries has machine named metalFAB1. Machine is possible to order with automatic building platform handling and heat treatment unit, two building chambers and automatic powder removal. Machine building volume is 420 x 420 x 400 mm³ and it use multiple lasers. Base price of the machine is approximately 1.1 million Euros. (Wohlers & Caffrey 2016, p. 48; The MetalFAB1; Machine search.)

2.2 Technologies

Additive manufacturing machines in the markets use several kind of technologies to operate. Quite common methods are powder bed -, powder feed - and wire feed systems. Energy sources can be an example laser beam, electron beam and plasma arc. (Frazier 2014, pp. 1918-1919.) This thesis concentrates on powder bed fusion with laser as heat source.

Figure 2.1 shows the principle of powder bed fusion. In SLM (selective laser melting) process, powder bed fusion method use fine powder which are melted with a laser beam.

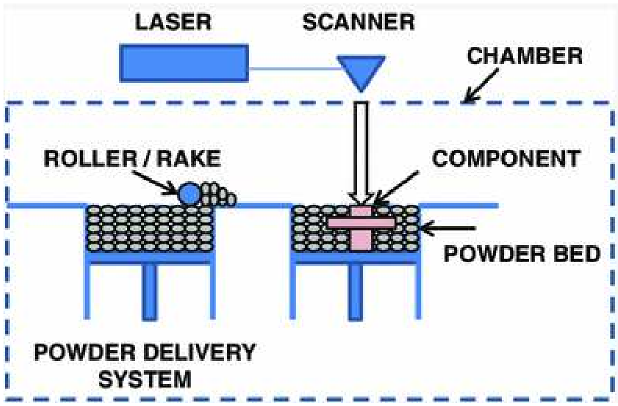


Figure 2.1. General principle of the powder bed fusion (Frazier 2014, p. 1919).

Recoater (roller/rake in figure 2.1) will spread thin layer of the powder on powder bed and laser start to melt the powder on selected areas. After laser is melted selected areas, powder bed is lowered and Recoater will spread new layer of the powder. This cycle is repeated after the component is done. (Frazier 2014, p. 1918-1919; Klahn & Leutenecker & Meboldt, 2014, p. 138.)

3 MAIN MOTIONS

Designed machine main motions are movement of the recoater, movement of the lifting platform and building platform change-over. Sections are presented below with operating principle. Each section has own criteria of the components which are based on working principle and dynamical needs to ensure that the machine can work without reliability problems. Each of the next section focuses to select suitable and cost effective solution for motions developed which fulfil the needs of machine to ensure proper performance for machine. Motors are insulated from chamber where powder is handled and selecting components were focused to select components which are sealed. Like bearings and runner blocks are including sealing's to avoid a dust in contact surfaces.

3.1 Movement of the recoater

Recoater spread a new powder layer building platform. Movement of the recoater main components are electric motor, worm gear reducer, shafts, belt components and linear motion guides. Rotating motion of the motor is converted to linear motion with belt drive. Figure 3.1 shows the principle of power transmission for recoater movement.

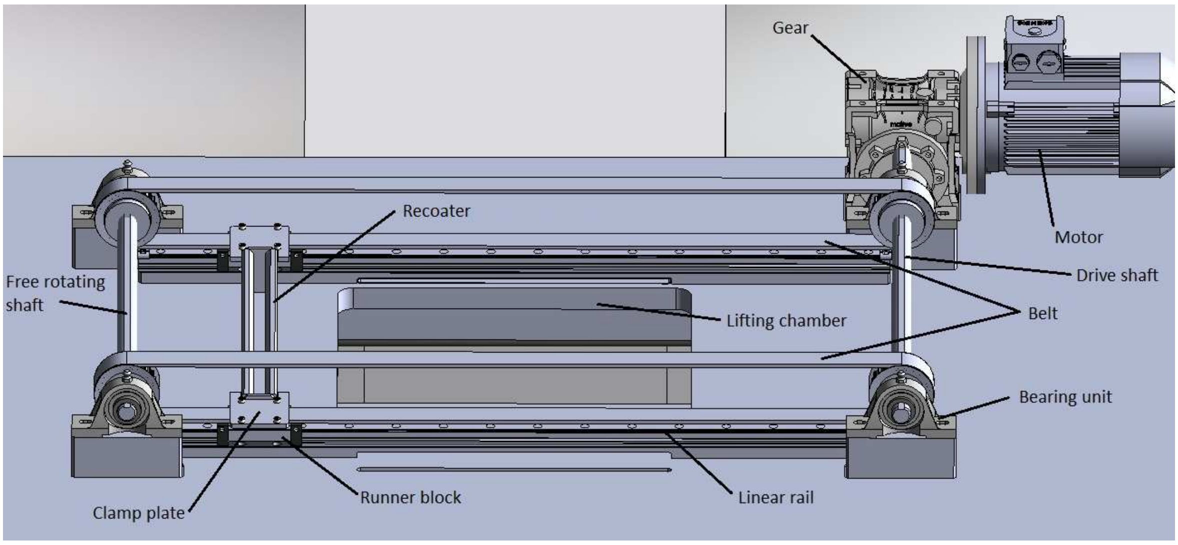


Figure 3.1. Principle of power transmission for recoater.

Motor rotate the gear which rotate the shaft. Belt wheels are mounted to shaft which rotates the tooth belts. Transmission has 2 shafts so that the belt is a closed circle which is mounted on recoater. Driving motor on both direction will create two directional movement for recoater. Motor was covered and that way insulated from main chamber where fine powder is handled. Motor cover is not shown in figure 3.1.

Recoater is driven with a belt drive on both sides. Therefore the force moving the recoater was assumed to be similar on both sides of the recoater. When shaft rotating it pull the recoater on both sides at the same velocity. Recoater was mounted on the blocks from both ends and the recoater slide on the rails when belt is pulling. If rails has tolerance error in height direction it cause deviation on recoater motion trajectory. In that case thickness of powder layer would vary in different positions of powder bed. Too large variation may cause accuracy problems for printed component.

Selected linear rails and runner blocks for recoater motion is Rexroth size 25 ball rails. Rails secure that the motion of the recoater stays linear. Linear rails also avoid the bending of the recoater. Figure 3.2 show the general image of linear rail with runner block.

Figure 3.2. Linear rail and runner block (Bosch Rexroth AG 2014, p. 50).

To reject that height deviation problem, selected rails and runner block are from tightest tolerances class which Rexroth offer. Runner block has viper sealing to protect the contact surfaces for dust. Runner block load capacity is 37 kN which is more than enough because weight of the recoater is less than 50 kg. Roller block preload class is C3 and accuracy class is UP. Largest tolerance class rails and roller blocks height deviation is given ± 100 µm, but in selected accuracy class and preload class height deviation is ± 5 µm. Linear rail maximum velocity is given 5 m/s and maximum acceleration is given 500 m/s². (Bosch Rexroth AG 2014, pp. 12, 33, 50.)

Selected belt components are quite basic components. Belt wheels are from Jens-S 24 tooth pulleys. Belt wheel is mounted on a shaft. Belt wheel convert rotational movement of the shaft to be linear movement on the tooth belt. Figure 3.3 shows the general shape of the belt wheel with keyway and stop screw thread.

Figure 3.3. Belt wheel (Hammashihnap. kiinteällä navalla).

Belt wheel is possible to order pre-machined with 25 mm diameter shaft hole, keyway and threats for stop screws in a hub (Hammashihnap. kiinteällä navalla). Belt wheel move the belt which is attached to recoater. When belt wheel rotate it convert the rotational motion to linear motion on recoater.

Selected belt is steel wired polyurethane belt AT10. Width of the belt is 32 mm. Belt maximum tensile strength is given on product catalogue to be 5120N. With maximum load belt elongation is approximately 0.4 %. Belt maximum ambient temperature is 80 °C. (Elatech 2015, pp. 10, 24-25.)

Belt is attached in recoater with AT10 clamp plate. With clamp plate is possible to create strong joint between recoater and belt. Figure 3.4 shows the principle of the clamp plate.

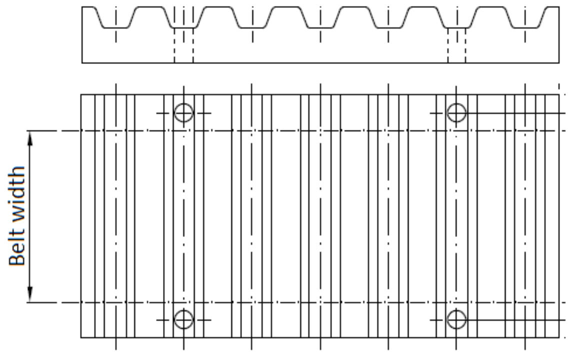


Figure 3.4. Clamp plate (Mod. Elatech 2015, p. 97).

Clamp plate shape is same as tooth belt. Belt is compressed between clamp plate and recoater with screws. Clamp plate is wider than a belt. Therefor belt will not need holes because of mounting screws. Screw holes diameter in clamp plate is 9 mm. (Elatech 2015, p. 97.)

Belt is driven with electric motor. Rotation is reduced with worm gear. Motor is attached in gear directly with a flange. Figure 3.5 shows the motor and gear combination.

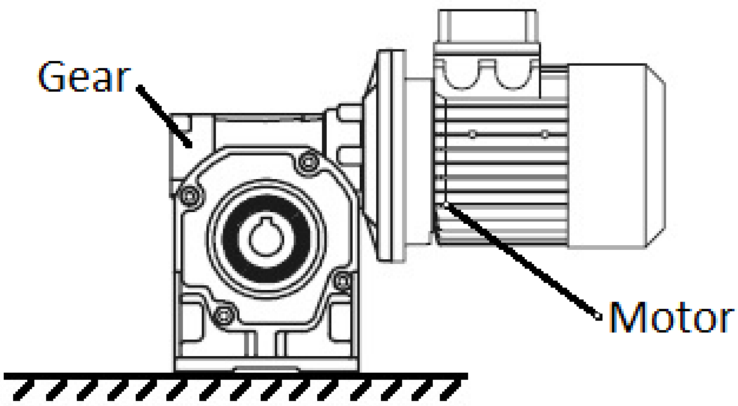


Figure 3.5. Motor and gear combination (Mod. Motovario S.p.A. 2013, p. 1).

Selected motor is asynchronous 750 W three phase 4-pole AC (Alternative current) motor with mounting flange type 80. Motor mounting position is selected to be IMB5 which means that the motor is attached directly on gear with a flange. Motor can produce 5.01 Nm torque. Selected motor asynchronous rotating speed is 1430 RPM with 50 Hz frequency. Motor is possible to add with DC (Direct current) standing brake, which make sure that the motor will not rotate freely. This brake will not need its own DC power source, because brake system include full-wave rectifier. Motor is also possible to order with integrated pulse sensor enabling the positioning of the recoater without additional positioning sensor. (Vem 2017; Honkatukia 2016.)

Selected worm gear is Motovario SW worm gear reducer. Size of the gear frame is 063 and gear ratio is 30. Gear has several options to different gear rations in same frame between 7.5 and 60. Gear mounting type of the motor is 80B5. Which means that the mounting is same as in selected motor. Gear own mounting type is B3, which means that the gear standing with own feet. Gear can handle 1.1 kW motor and maximum input torque is approximately 5.57 Nm. Gear output type is hollow shaft for 25 mm diameter shaft. Tolerance class of the shaft attachment is ISO H8. (Motovario S.p.A. 2013, pp. 11, 20, 24, 32, 33.)

Motor velocity need to be controlled. Motor velocity and positioning was decided to control with frequency inverter. Frequency inverter allow to modify driving frequency of the motor. Figure 3.6 show the Vacon 10 series frequency inverter.

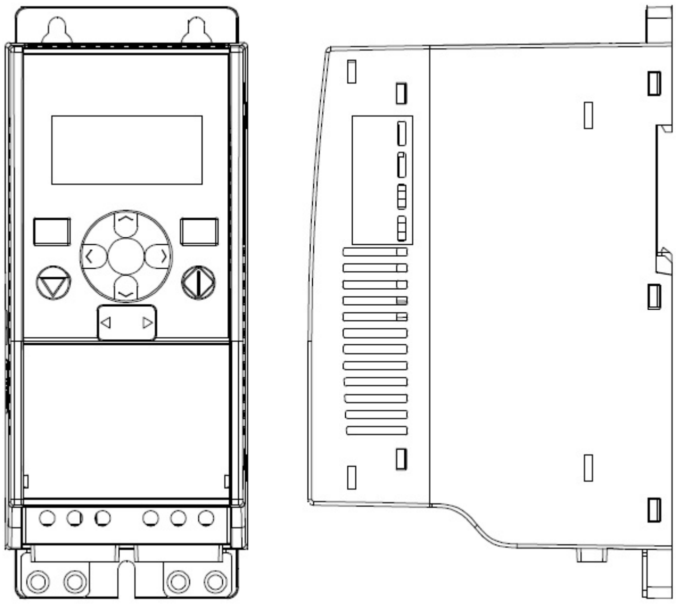


Figure 3.6. Vacon 10 Frequency inverter (Mod. Vacon 2014, p. 9).

Decided frequency inverter is Vacon 10 series frequency inverter. Frequency inverter is controlled with analogue signal to modify frequency on the motor and two digital signals to select the direction of rotation. Analogue signal range is 0-10 V. That signal tells the frequency inverter which frequency motor should be drive. Frequency range is linear and maximum and minimum frequency is possible to modify directly in frequency inverter. Frequency inverter use ramps for accelerating and decelerating motor. Those ramps times are possible to modify directly with parameters. Which shorter ramp time the motor reacts to changes of input signal. Minimum ramp time for selected frequency inverter is 0.1 s. Ramp time is always a time which is used to accelerate from settled minimum frequency to settled maximum frequency or vice versa. Deceleration and acceleration ramps can be specified separately. Basically when given voltage is 0 V the motor is driven with minimum frequency and when given input voltage is 10 V motor is driven with maximum frequency. (Vacon 2014, pp. 38, 76, 77.)

Shaft for the recoater is selected to be 25 mm diameter cold drawn S355 structural steel with ISO h9 tolerance class (BE Group 2014, p. 21). When gear output shaft is hollow shaft with tolerance ISO H8, the drive shaft can be mounted directly on gear without machining. (Valtanen 2012, pp. 628, 672, 679.) Therefore only machining which is necessary to do in a shaft is a keyways. When selected gear ratio is 30 and motor can produce approximately 5 Nm torque gear output torque is approximately 150 Nm.

$$M_{out} = M_{in} * i_{gear} \tag{3.1}$$

Output torque was calculated with equation 3.1 Where M_{out} Presents the output torque from gear, M_{in} presents the input torque to gear and i_{gear} presents the gear ratio (Valtanen 2012, p. 1194).

With maximum torque shaft maximum torsional stress was approximately 49 MPa. When yield strength for selected material is 350 MPa can be said that the shaft material and size is suitable (BE Group 2014, p. 21).

$$\tau = \frac{2 * M_{out}}{\pi * r^3} \tag{3.2}$$

Shaft torsional stress was calculated with equation 3.2. Where τ presents torsional stress and r presents radius (Valtanen 2012, p. 478-479).

Shafts was supported to floor of the main chamber with bearing units. Bearing units purpose is to decrease loses of the rotation and give end support for the shaft. Used bearing unit type is shown on figure 3.7.

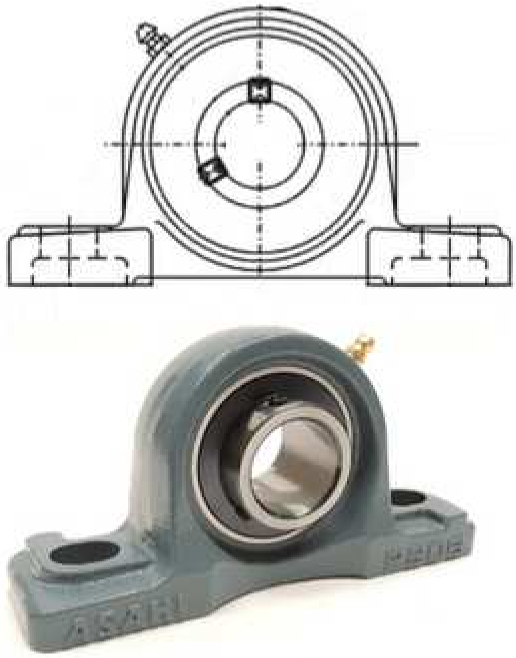


Figure 3.7. UCP bearing unit (Mod. Valurautapesällä UCP UKP UCPA UCPH).

Selected bearing units are Nachi UCP 205 pillow block units. Diameter of the shaft hole on selected bearing unit is 25 mm. One bearing can carry 7900 N load. Tolerances of the bearing shaft hole allows to insert the selected shaft without machining. Bearing block allow approximately 2 degree misalignment angle. Operating temperature for standard bearing unit is 100 °C. (Nachi-Fujikoshi Corp. 2012, p. 413, 415, 417.)

In ideal situation without losses when selected belt wheel diameter is 74.55 mm (Elatech, p. 25). Gear output torque can give in belts approximately 4030 N force. System consist two belts so maximum force in one belt is approximately 2015 N.

$$F_{belt} = \frac{M_{out}}{n_{belt*} r_{pulley}} \tag{3.3}$$

Maximum force on belt was calculated with equation 3.3. Where F_{belt} presents the force on one belt, n_{belt} presents the number of belts and r_{pulley} presents the radius of the belt wheel (Valtanen 2012, p. 478).

When recoater weight was 36 kg the maximum acceleration which is possible to reach is approximately 112 m/s². Therefor linear rails are also suitable ones.

$$a = \frac{F_{belt} * n_{belt}}{m_{recoater}} \tag{3.4}$$

Maximum acceleration was calculated with equation 3.4. Where a presents the acceleration and $m_{recoater}$ presents mass of the recoater (Valtanen 2012, p. 206).

When motor asynchronous speed was 1430 RPM and belt wheel diameter was 74.55 mm. With gear which gear ratio is 30 the recoater velocity in 50 Hz driving frequency was approximately 0.186 m/s.

$$v_{recoater} = \frac{n_{motor\ rpm}}{60 * i_{gear}} * D_{belt\ wheel} * \pi \tag{3.5}$$

Velocity was calculated with equation 3.5. Where $v_{recoater}$ presents velocity of the recoater, $n_{motor\ rpm}$ presents the motor rotational velocity in revolutions per minute and $D_{belt\ wheel}$ presents the diameter of belt wheel. (Mathway 2017; Valtanen 2012, p. 24, 1194).

3.2 Levelling of the lifting platform

One of the most important section is a building platform levelling. Building platform height movement should be very accurate. Velocity of the movement is not that critical value. Accuracy of the building platform height movement is one parameter which influence on accuracy of the layer thickness. If accuracy is poor and repeatability of the powder building platform height movement is poor it probably cause variation on printed part layers thickness and that way cause negative effect for accuracy of the printed part. When desirable minimum layer thickness is approximately 20 µm it means that to the building platform levelling repeatability should be more accurate. Lifting cylinder sizing is calculated by using 1000 kg mass which is assumed to include lifting platform, building platform, fully printed component and loose powder around the component.

When maximum component to be build is 400 x 400 x 400 mm³ in size and steel material which density is 7810 kg/m³ (Valtanen 2012, p. 312). Fully printed component weight, covering the whole build up volume, is quite close to 500 kg.

$$m_{comp} = V * \rho \tag{3.6}$$

Weight of the fully printed component was calculated with equation 3.6. Where m_{comp} presents the mass, V presents the volume and ρ presents the density (Valtanen 2012, p. 232).

When component weight was 500 kg, was assumed that the fully built building platform and lifting mechanism total weight is 1000 kg. Therefore used dimensional gravity force was 9810 N.

$$F_{dim} = m * g \tag{3.7}$$

Dimensional gravity force was calculated with equation 3.7. Where F_{dim} presents the dimensional force, m presents the mass and g presents the gravity acceleration (Valtanen 2012, p. 206).

Cylinder which create the lifting force on lifting platform was selected to be Rexroth heavy duty size 085 cylinder EMC-085-HD. Cylinder is driven with electric motor. Cylinder handle the positioning of the lifting platform. Figure 3.8 shows the principle of the drive train for selected electromechanical cylinder.

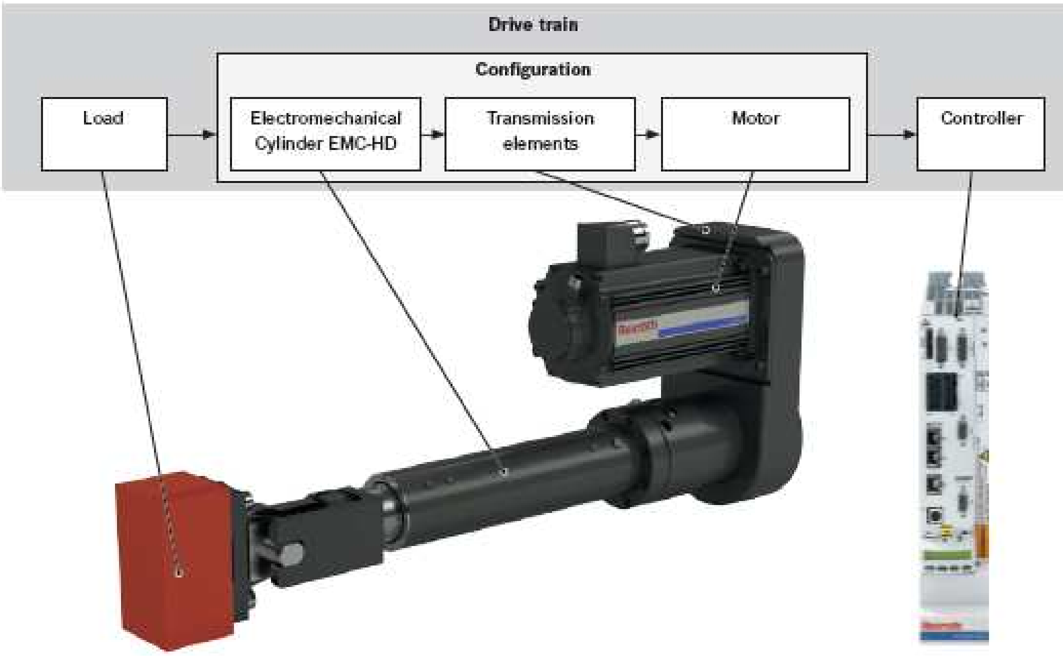


Figure 3.8. Drive train for EMC cylinder (Bosch Rexroth AG 2015a. p. 26).

Selected cylinder maximum force is 44 kN. Selected drive unit on cylinder was selected to be BASA (ball screw assembly) 40 x 10. Maximum velocity of the cylinder is 0.63 m/s. (Bosch Rexroth AG 2015a, p. 11). Other available drive unit in cylinder is PLSA (planetary screw assembly). BASA was selected because of PLSA drive unit heating will probably cause problems. Positioning accuracy in standard cylinder is 0.01 mm. (Sihvo 2016.) When dimensional gravity force is approximately 9810 N seems that the cylinder is oversized. Motion period on the machine are quite shorts which can cause problems for the lubrication (Bosch Rexroth AG 2015a, p. 68). Reject the lubrication problem the cylinder was oversized. Smaller versions are not suitable, because the life time will be quite short. (Sihvo 2016.)

Cylinder is driven with servomotor. Selected servomotor was sized via Rexroth by using they own software for sizing drives. Selected servomotor is MSK071E-0200 class motor. In order to avoid the motor overheating, in motor has added fan to intensify cooling. Servo drive which control the motor was selected to be INDRADRIVE HCS02. Selected servo controller support the additional positioning sensor. The servo controller is available in a LabVIEW library which allows to control machine with National Instruments control platform by using LabVIEW software. The position where cylinder is needed to drive will be given directly in the software and the controller handles the drive of the motor and cylinder. Communication between servo drive and National Instruments controller works via Industrial Ethernet and Open Core supports. (Sihvo 2016.)

Cylinder was selected to be with 550 mm stroke where 50 mm is a safety stroke to avoid situation when cylinder is driven on end limit. Also, in selected cylinder, the motor position was decided to be parallel with cylinder to avoid increasing length of the whole combination.

Selected rails are same type than rails in recoater. Lifting platform include two linear rails and rail blocks. One of those rails are changed to a rail with integrated positioning sensor. With that sensor it is possible to reach close to 0.0001 mm positioning accuracy (Sihvo 2016).

Building platform is lowered down each time before the new powder layer is applied. The length of this movement is a parameter setting of the printed part layer thickness. After the laser has melted the powder, platform is driven down as much as the layer thickness is such that the new powder layer has room to be spread in. When building platform is lowered it create a gap between level of treated powder layer and the new layer to come. Figure 3.9 shows the principle of lifting platform and positions of the lifting cylinder and linear rails.

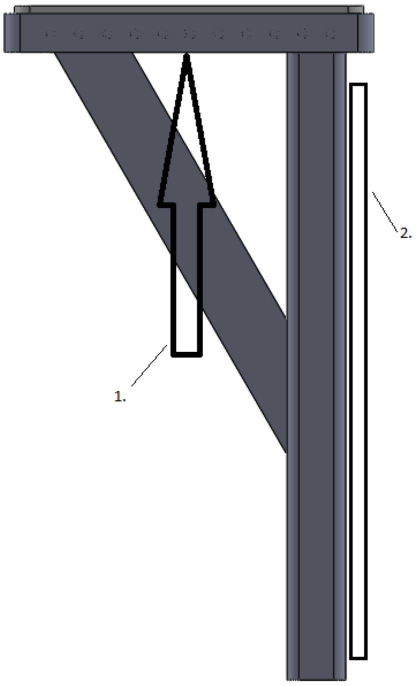


Figure 3.9. Principle of the lifting platform.

Lifting platform shape is close to L letter which is inversed. Building platform is top of the platform. Platform is mounted on a wall with linear rails. Position of the linear rails and linear blocks are shown in figure 3.9 with number 2. Mechanism will need free space on top of the platform to avoid loose powder flow between sliding components. Therefor linear rails are on vertical section. Runner blocks are on lowest position for platform so rail itself is never on higher than level of the building platform, but still rail blocks can run on the rail along whole movement trajectory. Cylinder under the platform take care the positioning in height direction. Position of cylinder end and cylinder direction is show on figure 3.9 with number 1. Accuracy of the positioning is increased with mentioned positioning sensor which measure the actual platform height position. Cylinder is in the middle of the platform bottom. Cylinder is mounted on both ends with revolute joints. Platform slides between lifting chamber walls and therefore act like a cylinder piston. Linear rails secure that the platform stays on perpendicular position against the recoater movement line.

The accuracy of the level of the building and lifting platform to horizontal is crucial to building process. One potential risk against this is bending of the L-shaped lifting platform. Lifting platform bending would influence on the deviation of the powder bed thickness. Lifting platform bending was evaluated with Adams View x64 2012 software. Figure 3.10 show the flexible model in Adams.

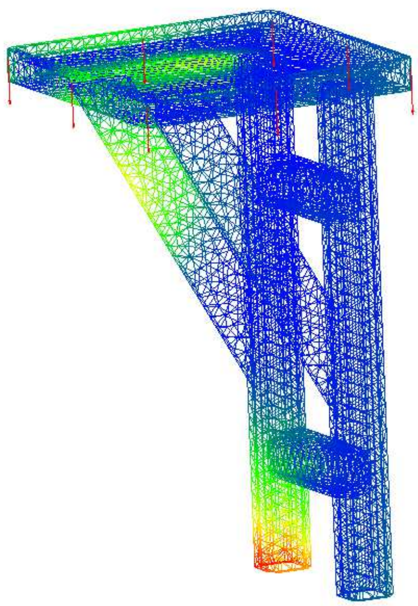


Figure 3.10. Lifting plate flexible model.

Lifting platform was designed in SolidWorks 2015 software where it was changed to parasolid format and imported in Adams. In Adams model material parameter was selected to be steel. Then model was changed to be flexible. Model has added markers on middle of the top plate and the points into which the forces will allotted. Because of difficulties to find in Adams surface force option, nine forces were add into model. One force on middle of the top plate, one force on each corner and one force on centre of each side. Each of the forces were 600 N. Therefore total force was 5400 N, which is actually close to be the same as gravity force for fully printed building platform. Which means that the printed component should be 400 x 400 x 400 mm^3 solid cube.

Maximum calculated displacement on top plate was approximately 7 µm. Simulated solution is on safe side because forces are point forces on side edges of the top plate, which is causing more bending than actual evenly distributed forces. This assumption will not take account situation when recoater hit the printed component. Also building platform which can be even 40 mm thick will be on top of the platform and it will also carry loads and resist bending. Also printed component probably try to bend building platform on other direction because of heat stresses.

3.3 Change-over mechanism of the building platform

When created component is ready the printed building platform is changed automatically. With automatic change-over mechanism machine is possible to use longer time continuously without service breaks. Also change-over mechanism increase automation level of the machine. Figure 3.11 shows the mechanism which change the building platform.

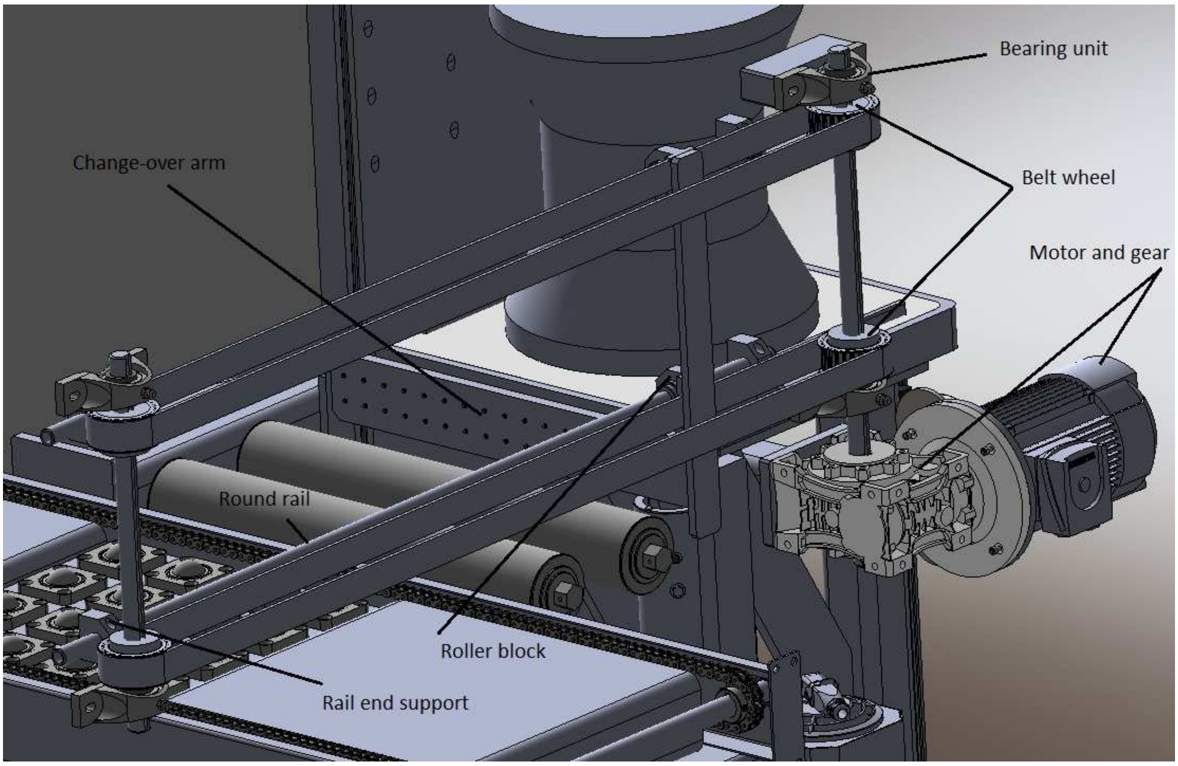


Figure 3.11. Building platform change-over mechanism.

Change-over arm pick the built plate and drag it to conveyor. Conveyor moves the new empty plate in front of change-over arm and arm pushes the new plate inside the chamber. Chain conveyor works also on building platform storage. One side of the conveyor is a built building platforms and other side of the conveyor is stored empty building platforms. Change-over arm is driven with two tooth belts. Electric motor and gear create the rotating motion to the shaft. Rotary motion is converted to linear motion on the change-over arm with belt. Change-over arm slide in two linear rails.

Change-over arm motion is made almost with the similar components as the recoater motion. Only differences are linear rails. On change-over arm movement the rails are round linear rails. Rails are supported only on ends. Empty building platforms move on conveyor under the rails. Round rails bushing and end support are shown in figure 3.12.

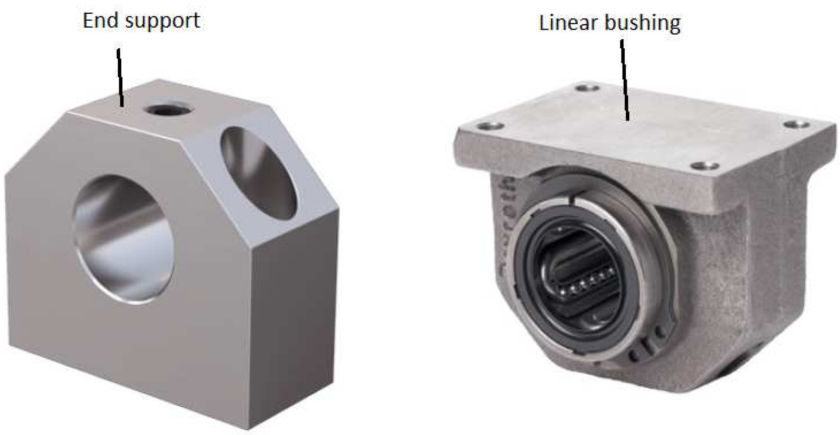


Figure 3.12. Round linear rail bushing and end support (Mod. Bosch Rexroth AG 2015b, p. 122, 237).

Rails are round hollow shafts that the example wiring over the conveyor is possible to implement inside the rail. Rail diameter is 20 mm with ISO h6 tolerance. Linear bushing slide in a shaft. (Bosch Rexroth AG 2015b, p. 200.) Rails has supported on both ends with aluminum compact shaft blocks. Shaft is attached to the block with a screw on the top and blocks are mounted on machine frame with screws from bottom of the blocks. (Bosch Rexroth AG 2015b, p. 237.)

Because the deviation accuracy is not critical value for the change-over arm movement the used linear block is standard steel housing linear bushing with viper sealing. Bushing can carry 860 Nm static load. (Bosch Rexroth AG 2015b, pp. 122-123.) Bushing purpose is to keep the movement in straight line and keep the losses of the motion small.

When power transmission components are same as in recoater motion, change-over arm maximum force is same 4030 N and it can give building platform approximately 7.3 m/s² acceleration when fully printed building platform weight is 550 kg.

$$a = \frac{F_{belt} * n_{belt}}{m_{full\,plate}} \tag{3.8}$$

Acceleration was calculated with equation 3.8. Where $m_{full\ plate}$ presents mass of the fully printed building platform and n_{belt} presents the number of belts (Valtanen 2012, p. 206).

Force which affect the change-over arm in acceleration is possible to decrease with frequency inverter. When frequency inverter is parametrized that way that motor accelerate in zero to 1430 RPM in 0.2 seconds. With 1430 RPM change-over arm has same 0.186 m/s velocity as recoater it means that acceleration is only 0.930 m/s².

$$a_{arm} = \frac{v}{t} \tag{3.9}$$

Acceleration was calculated with equation 3.9. Where a_{arm} presents the change-over arm acceleration t presents the acceleration time and v presents the velocity (Valtanen 2012, p. 205). When acceleration was decreased the force which effect the change-over arm was decreased to be 511.5 N.

$$F_{arm} = m_{full\,plate} * a_{arm} \tag{3.10}$$

Force was calculated with equation 3.10. Where F_{arm} presents force which effect the change-over arm. (Valtanen 2012, p. 206).

Selected conveyor is from company named Ferroplan. Conveyor is driven with SEW Movimot motor where is integrated frequency inverter (Räihä 2016b). Conveyor can carry 1000 kg/m load and whole conveyor can carry 2500 kg load. Conveyor total length is 3m. (Räihä 2016a.) To be able to control the conveyor velocity with analogue signal the conveyor need to be ordered with MVA21A speed control module (MOVIMOT® options).

In conveyor between chains is a roller bed. Raising rollers up, building platform can slide over the conveyor without touching conveyor chains. Rollers are lifted with two pneumatic cylinder. Cylinders lift the roller bed up when building platform is moved on or off the conveyor. When conveyor move the building platform the roller bed is down. Figure 3.13 shows cylinder.

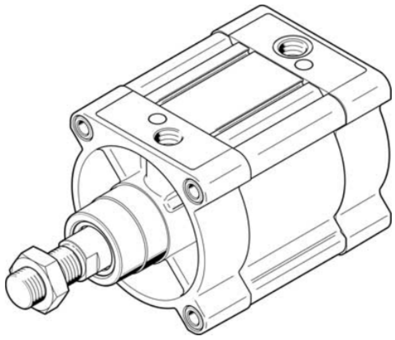


Figure 3.13. Schematic of the lifting cylinder (Standard cylinder DSBC).

Cylinder piston diameter is 125 mm and stroke of the cylinder is 20 mm. Cylinder has position sensors on both ends. (Standard cylinder DSBC.) One cylinder dimensional force is approximately 4295 N with 0.7 MPa operating pressure. Founded dimensional force is half of the cylinder theoretical force (Valtanen 2012, p. 963).

$$\mathrm{F}_{cylinder} = (\frac{{D_{piston}}^2 * \pi}{4} * p)/2 \tag{3.11}$$

Dimensional force was calculated with equation 3.11. Where $F_{cylinder}$ presents the cylinder dimensional force, D_{piston} presents the piston diameter and p presents the operating pressure (Valtanen 2012, p. 957, 963).

When there is two cylinder the force can be multiplied by two and cylinders can lift approximately 875 kg mass. With one cylinder dimensional force will be too small to lift fully printed building platform. When fully printed building platform weight is approximately 550 kg, with two cylinder lifting capacity is large enough.

$$m_{capacity} = \frac{2 * F_{cylinder}}{g} \tag{3.12}$$

Lifting capacity was calculated with equation 3.12. Where $m_{capacity}$ presents the lifting capacity and g presents the gravity acceleration (Valtanen 2012, p. 206).

Ball rollers on conveyor is a steel ball rollers. Rollers purpose is to decrease a needed force to move building platform. Building platform slide over the ball rollers. Figure 3.14 shows the ball roller.

Figure 3.14. Steel ball roller (Kuularulla).

Rollers are steel housed and ball diameter is 30 mm. One roller can carry 250 kg load. Roller can be dropped directly on 45 mm hole. (Kuularulla.) Number of the rollers on conveyor lifting platform is 16. Therefore capacity of the rollers are easily large enough.

4 POWDER REMOVAL AND HANDLING

Designed machine has automatic powder removal and powder circulating system. Powder is filled in to recoater during printing process. After component is printed the powder is removed inside lifting chamber. Removed powder is collected and oversized particles are sieved out of the powder. Cleaned powder is returned back in process.

4.1 Powder filling in the recoater

Reservoir in recoater is quite small and it need to be refilled during process. Powder has stored in mid reservoir in main chamber and fed from there on the recoater. Mid reservoir can be filled during printing process. When recoater is driven under the mid reservoir the powder can be fed on the recoater. Figure 4.1 shows the principle of the mid reservoir.

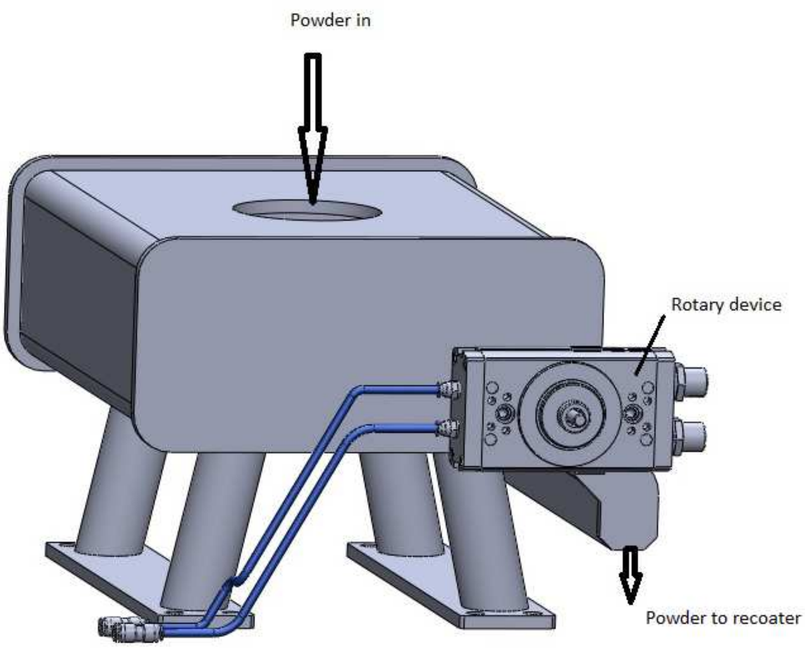


Figure 4.1. Principle of the mid reservoir.

Feeding roller shape is cylindrical which is rotated with rotary device. Roller fed the powder from reservoir to recoater. Number of the rotations control the amount of the filled powder. Roller is supported on both ends with bearings. Principle of powder feeding roller assembly is shown on figure 4.2.

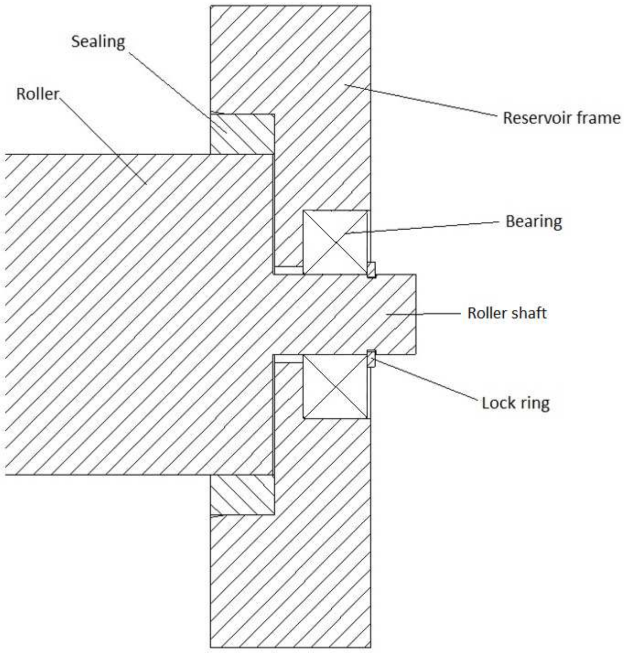


Figure 4.2. Principle of roller assembly.

Roller is supported on both ends with Nachi 6000ZZE deep-groove ball bearings. Selected ball bearings has 10 mm diameter bore and bearings are shielded from both sides to keep contact surfaces clean. Recommended maximum operating temperature for bearing is 120 °C. (Nachi-Fujikoshi Corp. 2012, pp. 140-144.) Roller is sealed with rubber seal from both ends. Purpose of the sealing is that the powder stay inside the reservoir and powder will not start to flow out of the reservoir by roller shaft holes.

Roller rotation is decided to operate with size 32 pneumatic semi-rotary drive from Festo. Actuator is based on rack and pinion operating principle (Semi-rotary drives DRRD). Figure 4.3 shows the rotary actuator working principle and figure 4.4 shows the selected actuator.

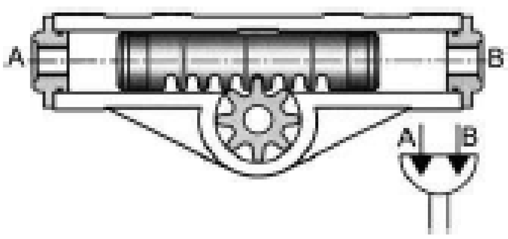


Figure 4.3. Principle of rack and pinion rotary actuator (Rabie 2009, p. 264).

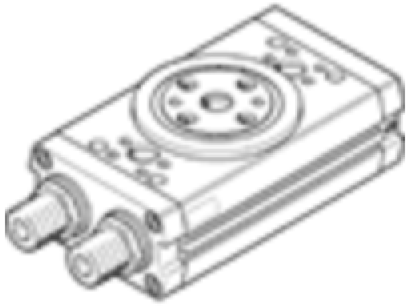


Figure 4.4. Size 32 semi-rotary drive (Semi-rotary drives DRRD).

Pressure caused piston linear motion is converted to rotary movement on the pinion (RABIE 2009, p. 264). Selected rotary device can produce 10.1 Nm theoretical torque with 0.6 MPa operating pressure. Actuator nominal rotating angel is possible to modify between 0 to 200 degrees. Recommended maximum ambient temperature for the unit is 60 °C. (Semi-rotary drives DRRD.) Rotary device rotating angle was selected to be 180 degrees, it cause that volume of powder which is fed on the recoater in one operating direction stays quite constant. Driving actuator between limit positions is possible to measure the amount of the powder which is fed on the recoater. When roller diameter is 40 mm force powder resistive force need to be approximately 500 N before feeding mechanism freezes.

$$F_{Freeze} = \frac{2*M}{D_{roller}} \tag{4.1}$$

Freezing force was calculated with equations 4.1. Where F_{freeze} presents the maximum force which rotary device can produce in roller periphery, M presents the rotary device maximum torque and D_{roller} presents the roller diameter (Valtanen 2012, p. 219).

Roller was attached to rotary unit with Metalflex bellow coupler size 24. Coupler transfer the rotational movement of the rotary device to the feeding roller. Figure 4.5 shows the used coupler.

Figure 4.5. Metalflex coupler (Metalflex-paljekytkimet).

Nominal torque for coupling is 14 Nm. Coupling is possible to order with different shaft holes between 8 – 24 mm. Coupling allow small misalignment between shafts center lines. Coupling maximum rotational velocity is 8000 RPM. Maximum operating temperature is 100 °C. (Compomac S.p.A. 2006, p. 2).

4.2 Closing lifting chamber

Powder removing was decided to do directly on lifting chamber. After created component was printed, the hole on top of the lifting chamber need to be closed such that the powder will not flow in main chamber. Figure 4.6 shows the chambers and lifting chamber closing equipment’s.

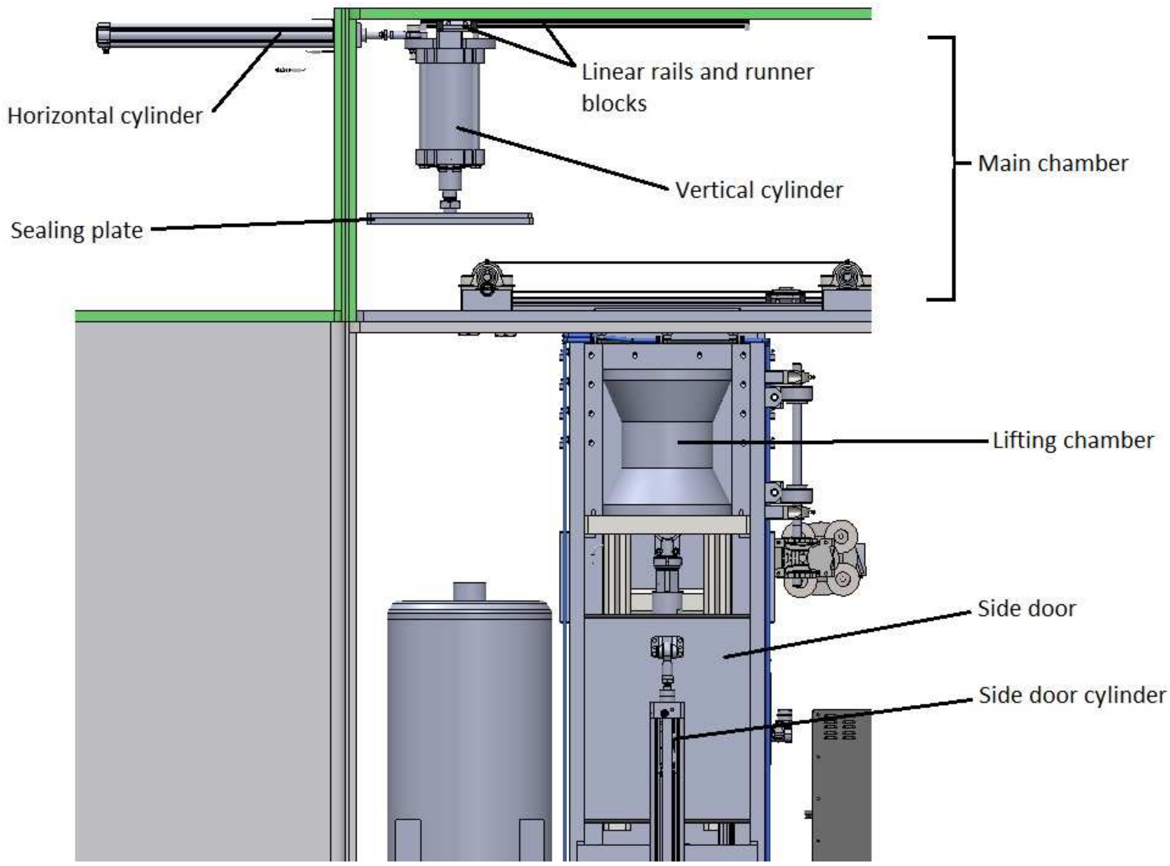


Figure 4.6. Position of the chamber, sealing plate and side door hole.

After printed part is done it is moved shortly lower that the sealing plate can seal the hole on bottom of the main chamber. During printing process the sealing plate is on side of the lifting chamber hole. Scanner head was mounted directly above of the hole and there can’t be any components between scanner head and layer which is under processing. Therefor the sealing plate should be moved horizontal way to top of the hole and vertical way on the hole. One option was to use plate which slide from wall of the lifting chamber and close the hole, but powder which particle size is quite fine could cause problems. Mechanism is not probably very reliable and mechanism can stuck because powder might go between sliding parts.

Sealing plate movements is decided to do with pneumatic cylinders. Sealing plate slide with linear rails and roller blocks. Selected rails are form Rexroth size 25 linear rails. Rails are from same series than recoater rails. These rails will not need a tight tolerances so rails is selected to be in cheapest tolerance class.

Pneumatic cylinder piston diameter for side way movement was decided to be 50 mm. Then cylinder can create approximately 1375 N theoretical force with 0.7 MPa pressure. Dimensional force of the cylinder is approximately 687 N.

$$\mathrm{F}_{cylinder} = (\frac{D_{piston}{}^2 * \pi}{4} * p)/2 \tag{4.2}$$

Dimensional force was calculated by using equation 4.2. Where $F_{cylinder}$ presents the cylinder dimensional force, D_{piston} presents the piston diameter and p presents the operating pressure (Valtanen 2012, p. 957, 963).

Vertical cylinder should be larger. Weight of the sealing plate is approximately 50 kg. Sealing plate gravity force is not critical dimensioning force. Critical dimensioning force comes for pressure increase in lifting chamber on powder removing cycle. Situation when powder removing cycle is ongoing pressure inside the chamber might increase a little bit which cause larger force requirement on down. Loses on the cylinder is not taken account, because cylinder is still and therefor assumption is that the all theoretical force is also effective force.

When selected cylinder piston diameter was 160 mm it give pressure to increase a little bit in chamber. When sealing plate size is 475 x 475 mm² and cylinder operating pressure is 0.700 MPa, the pressure difference between main chamber and lifting chamber can increase up to 0.062 MPa.

$$\Delta p = \frac{\frac{D_{piston}{}^2 * \pi}{4} * p}{A_{plate}} \tag{4.3}$$

Maximum pressure difference between main chamber and lifting chamber was calculated with equation 4.3. Where Δp presents the pressure difference and A_{plate} presents effective area of the sealing plate (Valtanen 2012, p. 230).

Side of the chamber is a door where printed component will be taken out of the chamber. Side door motion is straight line up and down. Accuracy requirements for this movement is quite low, because the motion is driven against mechanical stopper. Movement of the side door was made vertical. Side door slide in grooves and therefor vertical movement of the door is secured. When selected cylinder piston diameter was 80 mm it can produce with 0.7 MPa pressure approximately 1760 N dimensional force. Cylinder force was calculated with equation 4.2 which is shown above. When side door weight is approximately 60 kg, the cylinder can move the side door quite well.

4.3 Powder removal and powder journey

Powder removal around the created component is done automatically. Powder removal is done directly on lifting chamber. Removed powder is collected and re-used to decrease the whole powder consumption. Powder is removed on lifting chamber with gas flow and rapid pressure drops. Gas flow on the chamber is created with nozzles. Gas flow in nozzles are controlled with pneumatic valves. By using manifold assembled valve unit is decreased the amount of inlet pipes. Figure 4.7 show the example of manifold assembled valve unit.

Figure 4.7. Example of manifold assembled directional valve unit (Manifold assembly VTUG, with individual electrical connection).

In valve unit is possible to integrate many individually operated valves. All integrated valves use same compressed air input port. All valves have individual output ports and operating device. (Manifold assembly VTUG, with individual electrical connection.)

Removed powder is collected, cleaned and re-used again in process. Recycling the powder is decreased whole powder consumption. Figure 4.8 shows the principle of the powder journey.

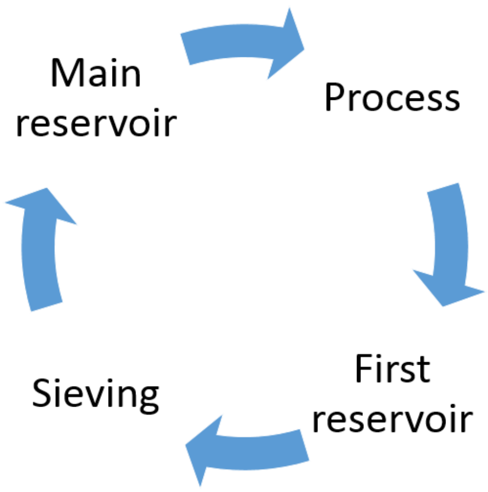


Figure 4.8. Principle of powder journey.

Removed powder is collected in first reservoir. First reservoir volume allow to collect all powder from the lifting chamber. Removed powder is transferred to sieving at the same time when new printing process is going. Sieved powder goes in main reservoir. Powder is transferred with vacuum based powder pumps. Figure 4.9 shows the operating principle of vacuum based powder pump.

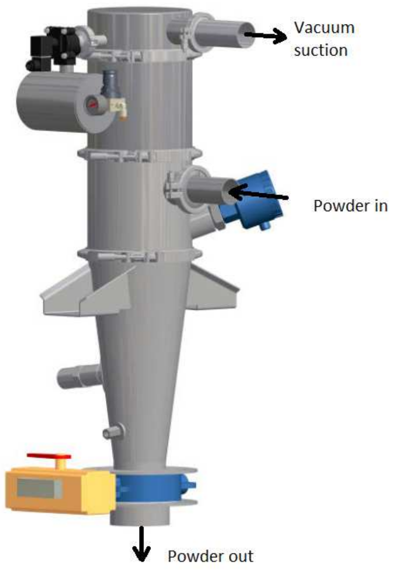


Figure 4.9. Principle of vacuum based powder pump (Mod. Putnins 2016).

Powder is transferred with vacuum based powder pumps. Vacuum source create the vacuum inside the powder pump which sucks the powder. After the receiver is filled with powder it drops the powder from bottom. Selected pump is designed to handle bulk material which minimum ignition energy is above 10 mJ. Receiver is possible to control with individual controller which has several operation functions.

When powder was transferred from first reservoir it is sieved. Purpose of the sieving is to remove oversized particles off the powder. Fine size powder can be used again in process. Figure 4.10 shows the principle of sieving.

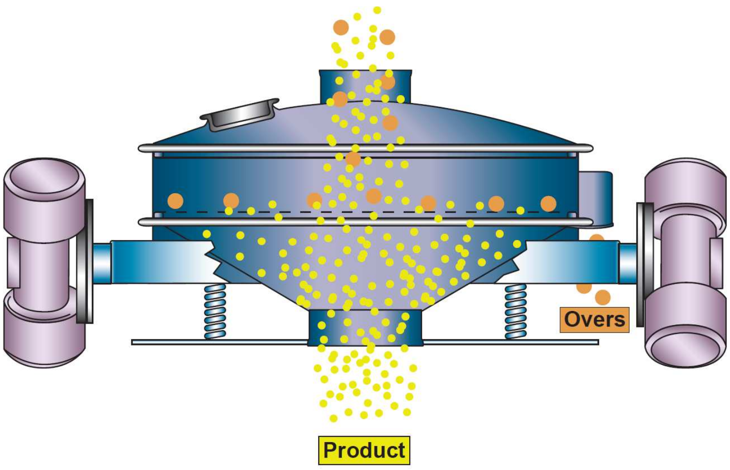


Figure 4.10. Principle of sieving (LX Illustration 2010).

Sieving station pass thru the fine size particles and remove oversized particles of the powder. Shown sieving unit works based on gravity and vibrating. Screen which separate the oversized particles off is possible to select almost freely. Screen size effect the sieving capacity of the device. To increase capacity of the sieving unit it is possible to equip with ultrasonic vibrating unit. Vibrating unit also help to keep the screen clean. (Elomaa 2016; Round separators.)

Powder pumps need vacuum source. Vacuum is created with vacuum blower. Figure 4.11 shows the illustration of the vacuum blower.

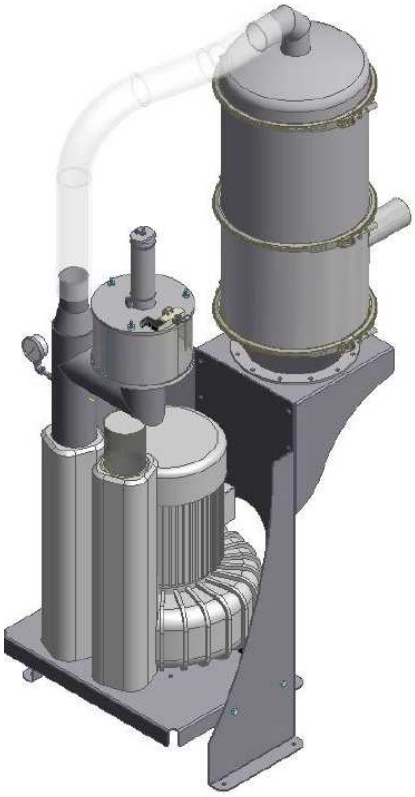


Figure 4.11. Vacuum Blower (Putnins 2016).

Vacuum blower create the vacuum suction. To secure the blower it has added inline filter to avoid powder particles flow in vacuum blower. One vacuum blower can be used to create vacuum in all needed devices. (Putnins 2016.)

5 COMPONENT BUILDING

Component building will happen in nitrogen gas atmosphere. Nitrogen is leaded in main chamber on powder bed and front of the scanner head. Nitrogen is produced with nitrogen generator which is integrated in the machine. Component building will be done with laser beam which melt the selected areas on powder bed by layer by layer. Laser beam focusing was made with adjustable focusing unit and scan head.

5.1 Building chamber atmosphere and gas circulation

Printing process is decided to do in nitrogen gas. Nitrogen flow cover the powder bed. Purpose of the nitrogen is remove oxygen from powder bed. Figure 5.1 shows the placement of the nitrogen nozzles.

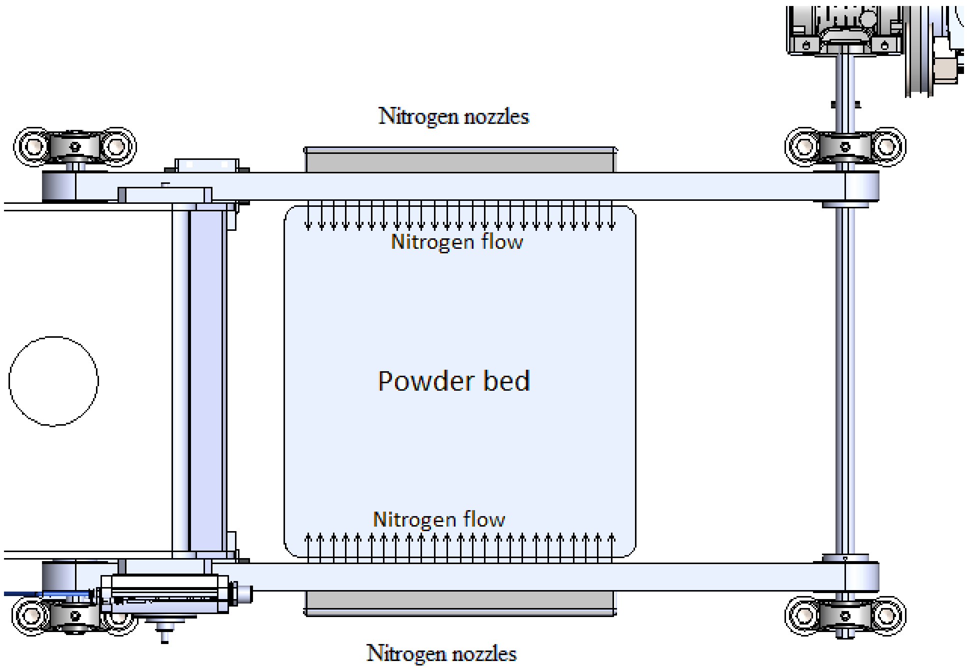
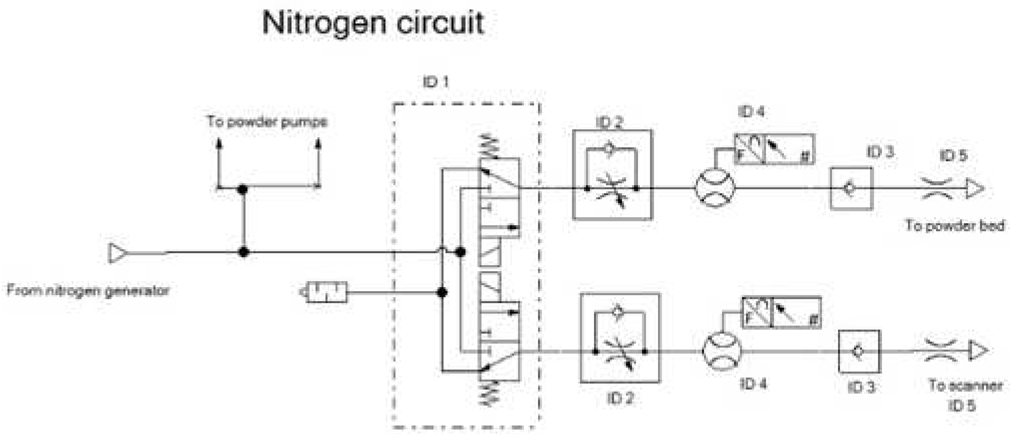


Figure 5.1. Placement of the nitrogen nozzles.

Two sides of the printing area is gas a nozzles where nitrogen flow in the chamber under the recoater linear rails and cover the powder bed. Gas flow on the chamber should be able to control and to measure. Nitrogen flow in main chamber is controlled with usual pneumatic components. Designed nitrogen circuit and used components are shown in in figure 5.2 below. Component descriptions on figure are Festo product codes.



ID	Component	PCS
1	564212_VUVG-L14-T32C-MT-Q8-U-1K9L	1
2	193970_GR-QS-8	2
3	153464_H-GS-8	2
4	565394_SFAB-200U-HQ8-2SV-M12	2
5	578287_NPQH-L-G38-Q8-P10	8

Figure 5.2. Nitrogen circuit.

Nitrogen was lead in two places of the chamber, which are towards powder bed and front of the scanner. Both lines are controlled separately. Nitrogen flow from nitrogen generator is controlled with 2 x 2/3 solenoid actuated directional valve which is ID 1 in figure 5.2. Figure 5.3 show the example image of the directional valve.

Figure 5.3. Example of VUVG directional valve (Valves VUVG).

One valve unit has two 2/3 solenoid operated directional valve which are normally closed. Both valves are controlled individually with 24 V solenoid and with spring return. Valve has fittings for 8 mm tube. (Valves VUVG.)

Volume flow of the nitrogen is necessary to be adjustable. Therefor after directional valve is a flow control valve Flow control valve is ID 2 in figure 5.2. Figure 5.4 shows the one way flow control valve.

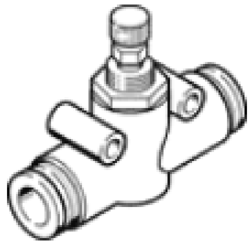


Figure 5.4. One-way flow control valve (In-line installation GR).

Valve allow to control volume flow thru the valve in one direction. Valve allow free return flow which is not controllable. Valve has fittings for 8 mm tube on both sides. (In-line installation GR).

Component ID 4 in figure 5.2 is a flow measure unit. With measuring unit is possible to know the amount of the nitrogen volume flow. When volume flow is measured it will be easier to find optimal volume flow in the process. Figure 5.5 shows the flow sensor.

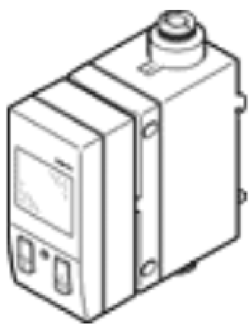


Figure 5.5. Festo SFAB flow sensor unit (Flow sensor SFAB).

Flow sensor unit maximum volume flow is 200 l /min. Sensor include analogue output port 0–10 V or 4–20 mA. (Flow sensor SFAB.) Therefore the value of the volume flow is possible to transfer in machine main controller which allow to monitor the process and give alerts for user if volume flow is not what it should be.

Component ID 3 in figure 5.2 is a check valve. Only purpose of the check valve is to reject the back-flow of the nitrogen. Rejecting the back-flow is possible to avoid the fine metal particles flow out of the chamber thru the nitrogen channels. Check valve is presented earlier in figure 4.11.

Nitrogen comes to circuit from nitrogen generator. Nitrogen generator is integrated to machine. There for it is not necessary to buy separate nitrogen bottles and that way avoid situation when nitrogen end during printing process. Figure 5.6 shows the typical nitrogen generation assembly.

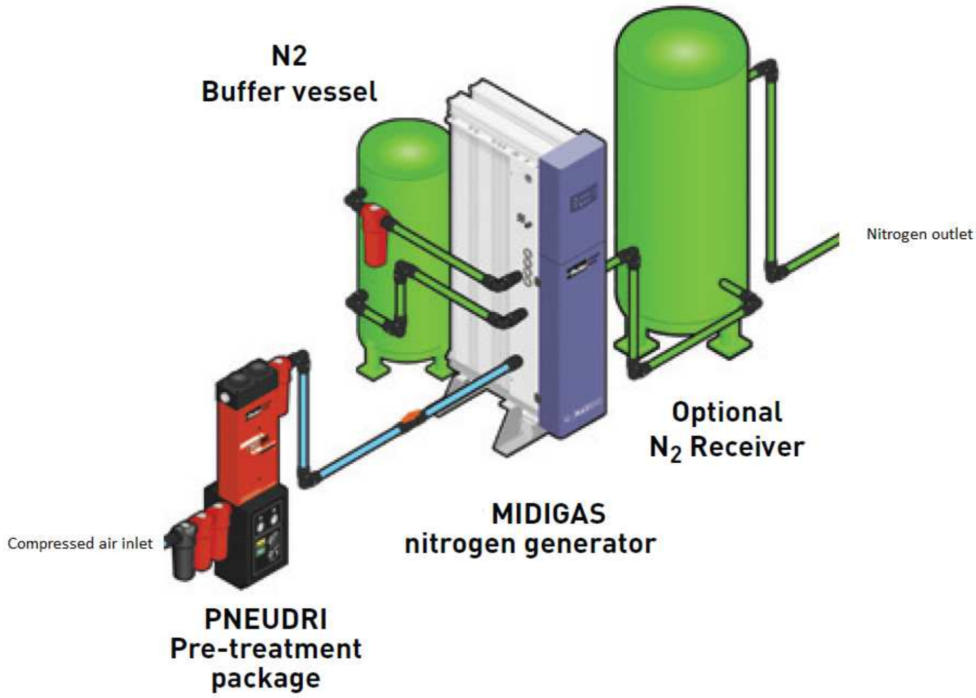


Figure 5.6. Nitrogen generator assembly (Mod. Parker Hannifin Corporation 2012, p. 8).

Nitrogen generator was selected to be quite small one and without optional receiver tank. Selected generator type is Sarlin Midigas 2. To secure quality of the inlet air the system is added air preparation unit where is air dryer and filters for air dryer. Nitrogen generator can produce 99.5 % pure nitrogen. Nitrogen generator includes separate oxygen analyser. When selected nitrogen generator is added with 50 litres mixing tank it need 0.70 MPa inlet compressed air pressure. With 0.70 MPa inlet pressure the nitrogen outlet pressure is 0.49 MPa and volume flow of the nitrogen is approximately 3 m^3/h. Nitrogen pressure and volume flow is possible to increase slightly with 200 litres mixing tank and 0.80 MPa inlet pressure. (Ruuska 2016a; Ruuska 2016b.)

To decrease the needed volume of nitrogen, the gas inside the main chamber is circulated and filtered. Gas circulation in main chamber is decided to implement with combine unit which sucks the gas from the chamber, filter it and return the gas back to the chamber. Figure 5.7 shows gas circulation and filtering unit working principle.

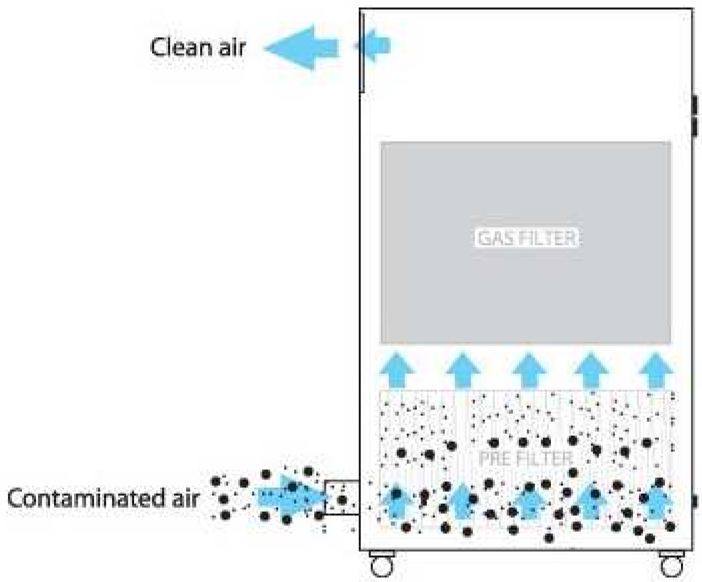


Figure 5.7. Principle of gas circulation and filtering unit (Laser Fume Extraction - AD NANO).

Selected device is Bofa AD Nano+. Device maximum gas flow is 300 m^3/h. Device is possible to get optional remote start and stop function. Device also include HEPA filter for filtering small particles. Device has automatic flow control and lasering is mentioned on typical applications. (Vänni 2016.)

5.2 Laser and optical set ups

Laser and optical set up produces the laser beam and focuses the beam onto powder bed. Figure 5.8 shows the principle of the laser and optical set up. Target of the laser beam focal point diameter on powder bead was settled to be 75–100 µm.

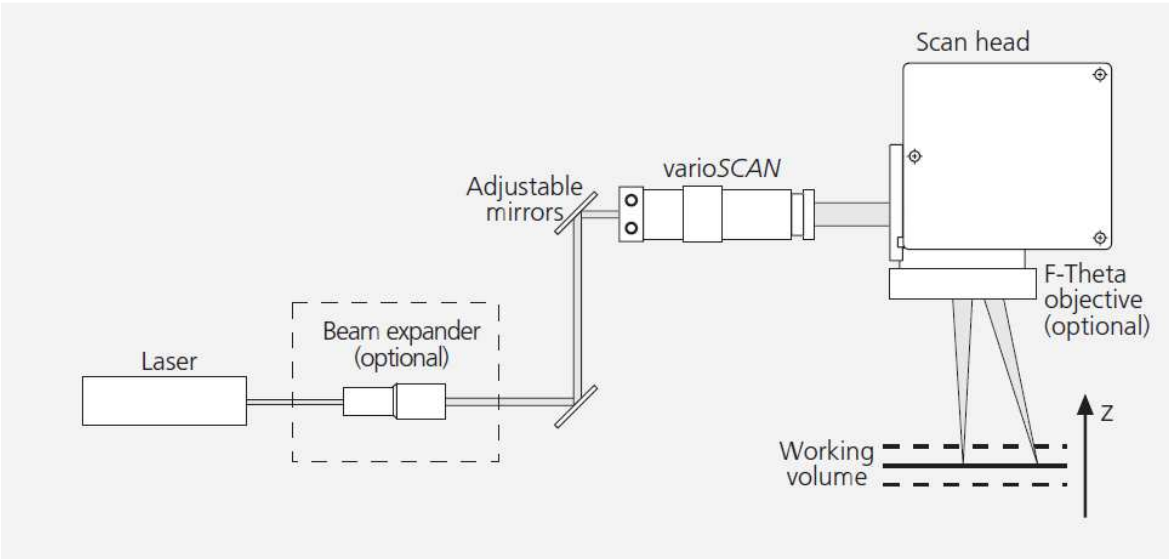


Figure 5.8. Principle of the laser solution (Scanlab GmbH 2015, p 3).

Laser unit produce the laser beam which is transferred to the scanner. Scanner handle the laser beam focal point positioning to the powder bead. Working area is decided to be 400 x 400 mm². Suitable laser unit is standard 500 W continuous wave single mode laser (Salminen 2016). Figure 5.9 shows the 500 W air cooled fiber laser unit.

Figure 5.9. 500W ytterbium fiber laser unit (YLR-AC 100-500W).

Chosen laser unit is IPG photonics 500 W constant wave ytterbium fiber laser. Laser has 1070 nm wavelength. One of typical applications this laser is additive manufacturing. Maximum output power of the laser is 500 W. Laser power is possible to adjust between 10-100 %. Beam quality value M^2 of the laser is < 1.1. Beam parameter product of the laser is 0.37 mm x mrad. Laser is air cooled. (Westphäling 2016; YLR-AC 100-500W.)

Laser produced beam need to be focused to work piece. Beam focusing was decided to do scan head and adjustable focusing optics. Figure 5.10 shows the adjustable focusing unit and scan head.

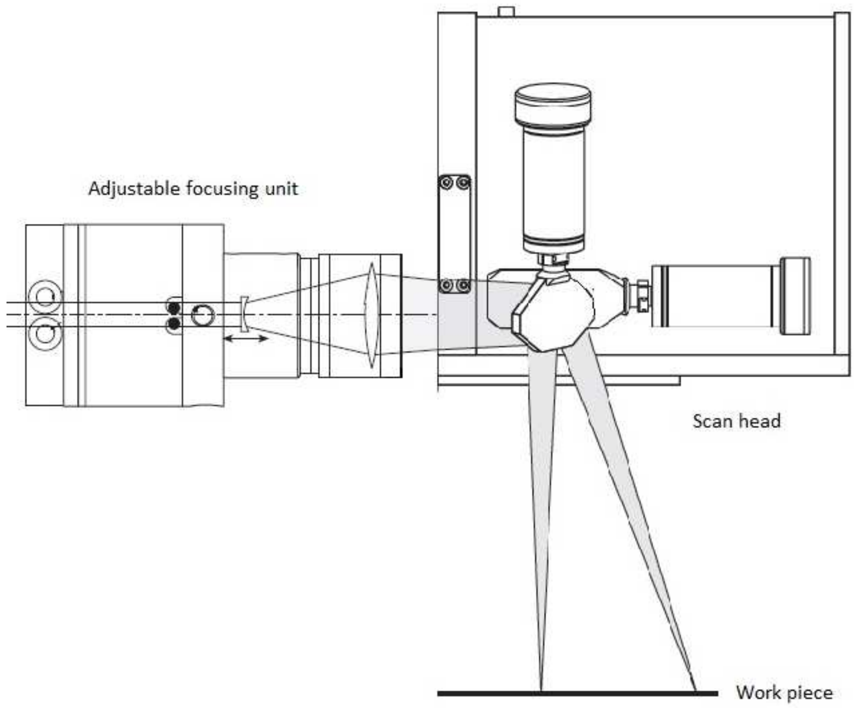


Figure 5.10. Beam focusing solution (Mod. Scanlab GmbH 2015, pp 3-4).

Selected scan head unit is intelliSCAN III 30 device from Scanlab. Adjustable focusing unit is varioSCANde 40i from Scanlab. Varioscan unit has a moving lens which handle the flat field correction to work piece. Scan head handle the beam position focusing in work piece. With selected units is possible to reach even as small as 75 µm laser beam focal point diameter when laser beam quality is < 1.1. (Vierke 2016a; Vierke 2016b.)

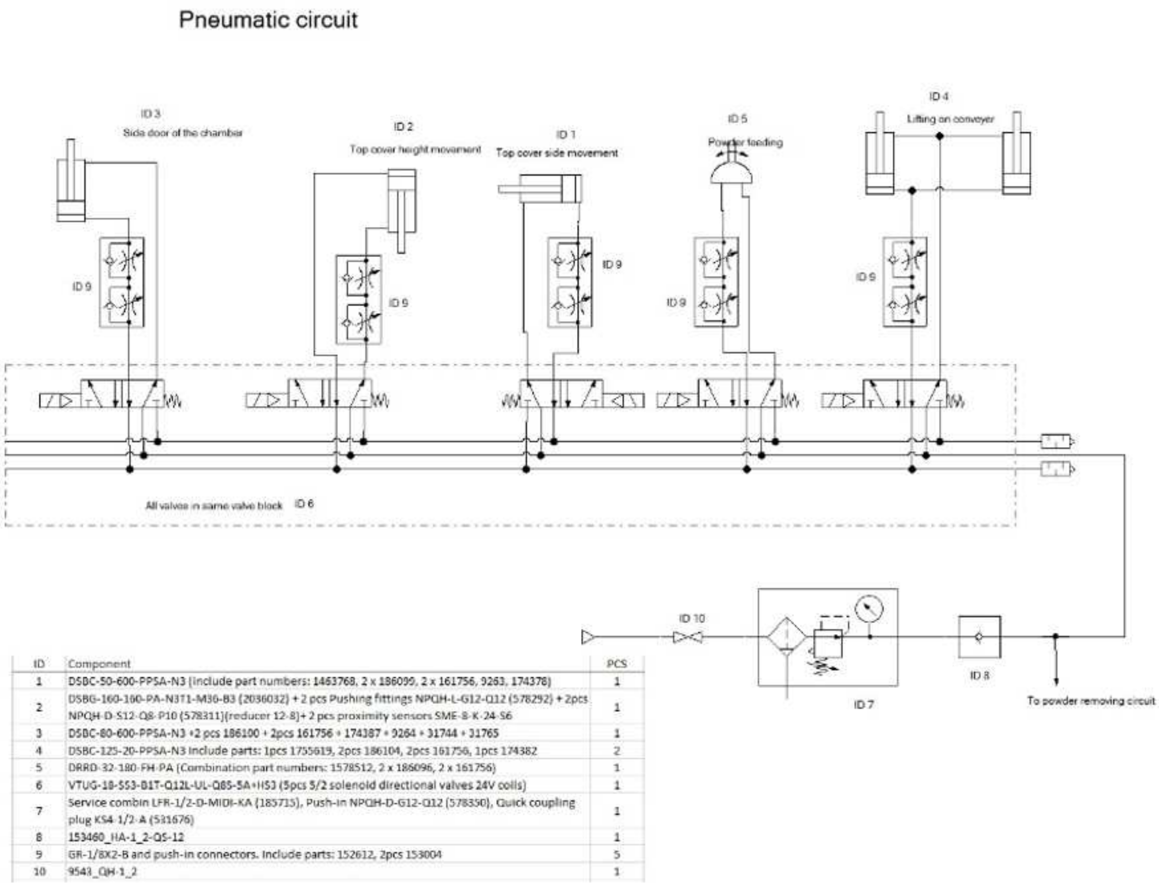
Scanner and focusing unit need water cooling. Cooling capacity required is approximately 100 W and coolant volume flow should be approximately 3 l/min. Maximum intake pressure is 0.4 MPa. (Vierke 2016b.) Figure 5.11 shows the cooling unit.

Figure 5.11. P300 Series Compressor chiller from Termotek (Termotek GmbH Chillers).

Water cooling for optics is chosen to use Termotek GmbH P307 cooling unit. Unit has 570 W cooling capacity at 20 °C water and 35 °C ambient temperature. Flow rate of the chiller is 4 l/min at 0.35 MPa pressure. Unit has integrated controller which monitors the coolant water temperature. (Termotek GmbH Chillers; Koehn 2017.)

6 PNEUMATIC CIRCUIT

Pneumatic circuit control the actuators movement. Pneumatic devices should be controlled. Velocities of the pneumatic actuators should be able to adjust with easy way. Figure 6.1 show the pneumatic circuit.



ID	Component	PCS
1	DSBC-50-600-PPSA-N3 (include part numbers: 1463768, 2 x 186099, 2 x 161756, 9263, 174378)	1
2	DSBG-160-160-PA-N3T1-M36-B3 (2036032) + 2 pcs Pushing fittings NPQH-L-G12-Q12 (578292) + 2pcs NPQH-D-S12-Q8-P10 (578311)(reducer 12-8)+ 2 pcs proximity sensors SME-8-K-24-S6	1
3	DSBC-80-600-PPSA-N3 +2 pcs 186100 + 2pcs 161756 + 174387 + 9264 + 31744 + 31765	1
4	DSBC-125-20-PPSA-N3 Include parts: 1pcs 1755619, 2pcs 186104, 2pcs 161756, 1pcs 174382	2
5	DRRD-32-180-FH-PA (Combination part numbers: 1578512, 2 x 186096, 2 x 161756)	1
6	VTUG-18-SS3-B1T-Q12L-UL-Q8S-5A+HS3 (5pcs 5/2 solenoid directional valves 24V coils)	1
7	Service combin LFR-1/2-D-MIDI-KA (185715), Push-in NPQH-D-G12-Q12 (578350), Quick coupling plug KS4-1/2-A (531676)	1
8	153460_HA-1_2-QS-12	1
9	GR-1/8X2-B and push-in connectors. Include parts: 152612, 2pcs 153004	5
10	9543_QH-1_2	1

Figure 6.1. Pneumatic circuit.

ID 6 in figure 6.1 is directional valves with manifold assembly. Directional valves are manifold assembled 5/2 solenoid operated directional valves. Figure 6.2 show the principle construction of manifold assembly.

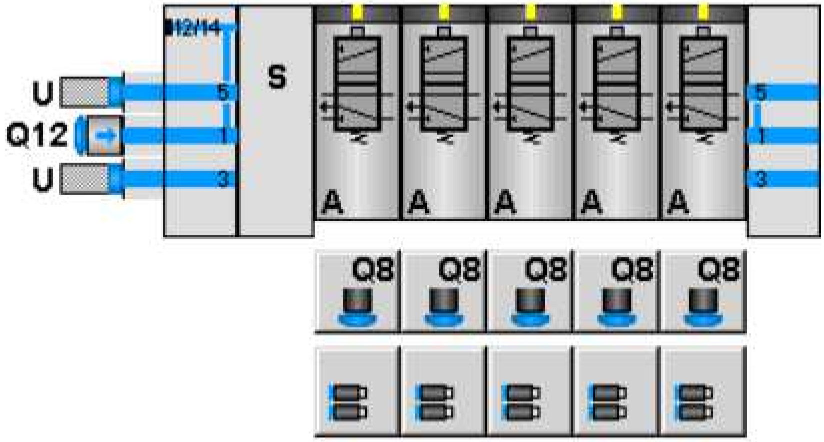


Figure 6.2. Manifold assembled directional valves (Manifold assembly VTUG, with individual electrical connection).

In manifold has five solenoid operated 5/2 directional valves. Valves are controlled individually with 24 V DC signal. Inlet port in manifold is for 12 mm diameter tube. Maximum volume flow thru manifold is 1380 l/min. Outlet ports on manifold is equipped with silencer to reduce noise when air flow out of the circuit. Outlets from the valves are for 8 mm diameter tube. (Manifold assembly VTUG, with individual electrical connection.)

ID 9 in figure 6.1 are double flow control valves. Figure 6.3 shows the flow control valve. Flow control valve is placed between actuator and directional valve.

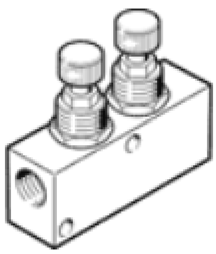


Figure 6.3. Double flow control valve (In-line installation GR).

Velocity control for actuators are made with double flow control valves. Flow control valves allow to adjust volume flow on both direction separately. Maximum flow thru the valve is

175 l/min. Cylinders which are on vertical position the flow control valve is on side where gravity force try to push air. (In-line installation GR.)

ID 8 in figure 6.1 is a check valve. Check valve purpose is to reject the return volume flow. Example if circuit allow a return flow and pressure connect is taken off the cylinder which are on vertical position might move on lowest position. Figure 6.4 show the check valve.

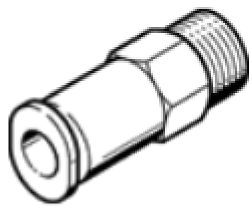


Figure 6.4. Check valve with push-in connector and thread (Non-return valves H, HA, HB).

Check valve maximum volume flow is 2230 l/min. Valve has R ½ thread on other side and other side is a push-in connector for 12 mm diameter tube. Valve allow volume flow only from thread side to push-in connector. (Non-return valves H, HA, HB.)

ID 7 in figure 6.1 is air preparation unit. Unit is a pressure inlet in a circuit. Figure 6.5 shows the air preparation unit.

Figure 6.5. Air preparation unit (Service unit combinations without lubricators).

Unit include pressure regulator, pressure gauge, manual condensate drain and 40 µm filter. Unit allow to adjust circuit pressure between 0.05–1.20 MPa. Nominal flow thru the unit is 3050 l/min. (Service unit combinations without lubricators.)

ID 10 in figure 6.1 is a ball valve. Ball valve is placed just before air preparation unit. Figure 6.6 show the ball valve.

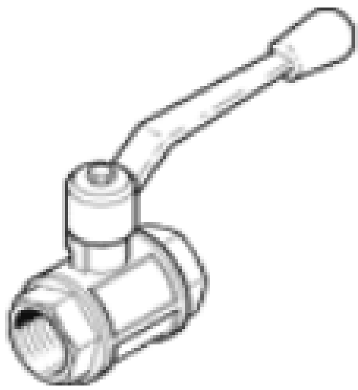


Figure 6.6. Ball valve (Ball valves QH, QHS).

Ball valve allow to shut down volume flow without removing pressure connection. Ball valve is manually operated. Maximum volume flow thru the valve is 11500 l/min. (Ball valves QH, QHS.)

7 DYNAMIC MODEL

In machine main motions was made a dynamic model with Adams View x64 2012 software. Main motions are movement of the recoater, movement of the lifting platform and movement of the building platform change-over arm. Purpose of the dynamic model is to check that forces of the components like motor torques stays under maximum torques what motor can produce. Used simulation time in Adams was 35 seconds and used number of steps was 10000 steps.

7.1 Created dynamic model

Dynamic model include totally 24 moving parts, six revolute joints, four translational joints, 14 fixed joints, one inline primitive joint, three motions and four couplers. Degrees of freedom in model is one. When all motions are deactivated the degrees of freedom is four. Each motions lock one degrees of freedom. Therefor finally when all motions are activated the whole model degrees of freedom is one. Model was also made that way there is not any redundant constraints. Figure 7.1 shows the components of the dynamic model and table 7.1 shows the descriptions of the components.

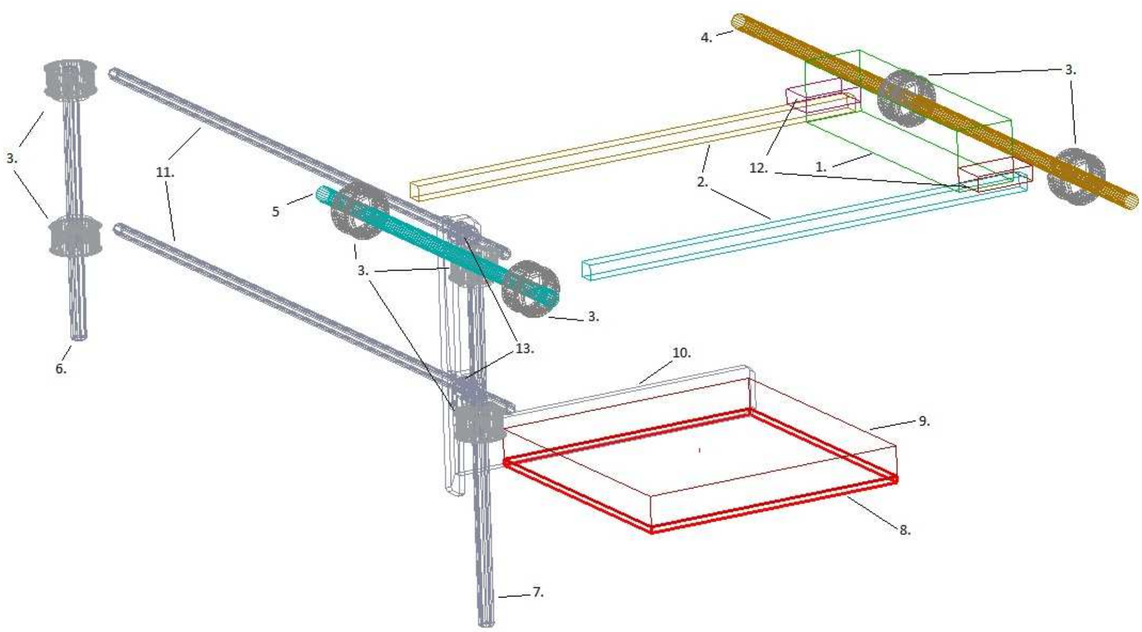


Figure 7.1. Components of the dynamic model.

Table 7.1. Dynamic model component descriptions from figure 7.1.

Item.	Description
1.	Recoater
2.	Linear rails
3.	Belt wheels
4.	Recoater drive shaft
5.	Recoater free rotating shaft
6.	Change arm free rotating shaft
7.	Change arm drive shaft
8.	Building platform lifting platform
9.	Building platform
10.	change-over arm
11.	Round linear rails
12.	Linear rail roller block
13.	Round linear rail roller block

Components physical properties was taken account by using real shape models and given material properties. Material properties are given directly in Adams and that way Adams calculate automatically all needed properties. Recoater properties are made with different way. Recoater was modelled to be solid steel block which weight is 36 kg. That way was taken account the lose powder inside the recoater. Assumption is that the whole recoater structure in real machine when it is full of powder the weight is quite close to weight which it is in the model.

Components was joined together with several types of joints. With those joints model movement are limited to be similar than designed mechanism. Motion on the model was made directly by adding motion on place where the actuator will be. Figure 7.2 shows the position of the joints and the added motions. Table 7.2 shows the joints- and motions types in figure 7.2

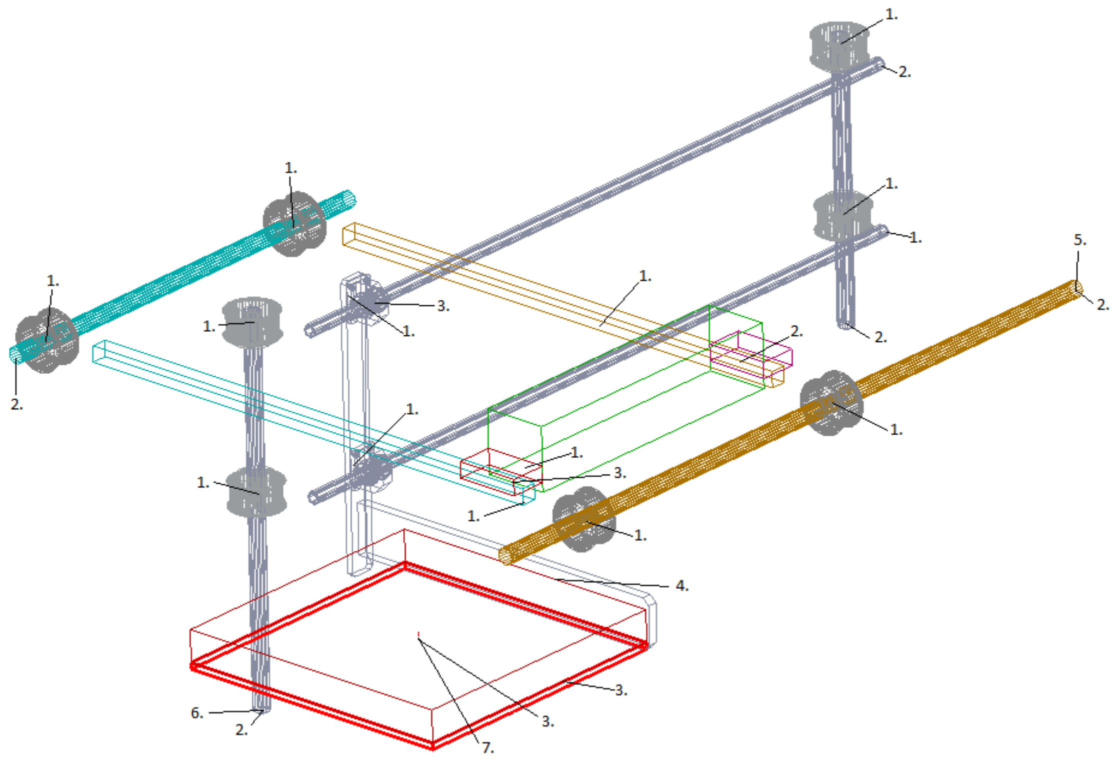


Figure 7.2. Joints and motions in dynamic model

Table 7.2. Description of joints and motions in figure 7.2

Item	Description
1.	Fixed joint
2.	Revolute joint
3.	Translational joint
4.	Inline primitive joint
5.	Recoater motion
6.	Change arm motion
7.	Lifting platform motion

Recoater motion rotate the recoater drive shaft. To take account an inertia of the shafts and belt wheels the drive shaft is connected with coupler to recoater free rotating shaft. Coupler was parametrize that way when driveshaft rotate one full circle the free rotating shaft also rotate one full circle. Free rotating shaft is connected to recoater with coupler which change the free rotating shaft rotational movement to translational movement in recoater. Coupler ratio is made that way when free rotational shaft rotate one full circle the recoater movement is same as perimeter length of a belt wheel.

$$l = \pi * D_{belt\ wheel} \tag{7.1}$$

Distance was calculated by using equation 7.1 below. Where l presents the perimeter length of the belt wheel, and $D_{belt\ wheel}$ presents the diameter of the belt wheel (Valtanen 2012, p. 24).

That the inertia for change-over arm components are taken account, the couplers between change arm motion and change-over arm was made exactly same way than couplers for recoater has made.

Model is driven with added motions. Lifting platform motion velocity and positioning was made by giving direct distance value for the motion. Because software follows directly that value the position change was made with STEP function. Figure 7.3 shows the given position trajectory for building platform lifting motion.

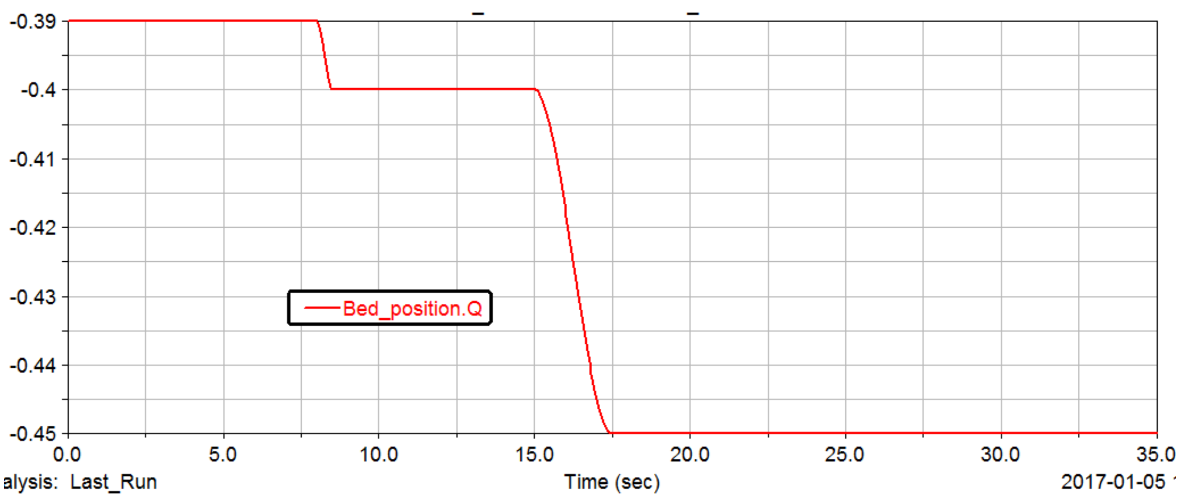


Figure 7.3. Simulated building platform height position.

Building platform was made to change position in 0.5 seconds to 10 mm. After position -0.4 m lifting platform is driven in lowest position. Motion is not exactly what it will be in real machine, but assumption is that the motion is close enough to get the simulation work properly and founded values are suitable. To get the forces which affect the lifting cylinder during operation the building platform mass was modified to same as maximum weight of the building platform with biggest possible printed component and with loose powder. Mass is sum of building platform mass, biggest possible component mass and mass of the loose powder around the created component.

$$m = V * \rho \tag{7.2}$$

Masses are calculated with equation 7.2. Where m presents the mass, V presents the volume and ρ presents the density (Valtanen 2012, p. 232).

That weight affect all the time on lifting cylinder. When printing process is ongoing and building platform is somewhere on middle of the chamber the real weight is smaller, because the component is not fully printed. Therefore the weight was reduced with opposite force which decrease total force on the lifting cylinder based on ratio how much is printed from maximum printing size.

$$if\ h < -0.4\ \rightarrow\ F_{reduce} = 0 \tag{7.3}$$

$$if\ h > 0\ \rightarrow\ F_{reduce} = \ (m_{plate} - m_{real\ plate}) * g \tag{7.4}$$

$$if - 0.4 > h < 0\ \rightarrow F_{reduce} = (1 - \left(\frac{h}{h_{max}}\right) * m_{plate} - m_{real\ plate}) * g \tag{7.5}$$

Opposite force was calculated and limited by using equations 7.3, 7.4 and 7.5. Where F_{reduce} presents the reducing force, $m_{real\ plate}$ presents the real mass of the empty building platform, h presents the height position of the lifting platform m_{plate} presents the weight of fully printed building platform and h_{max} presents the lowest platform height position on printing process (Valtanen 2012, pp. 173, 206).

Now when calculated reducing force is against the plate gravity force it correct the force which effect the lifting cylinder. With this way also when change-over arm drag the printed building platform out of the chamber the weight of the plate is in maximum value and inertia of the maximum weighted plate is taken account.

Recoater and change-over arm motion are rotational velocity motions. Frequency inverter give to motor driving frequency and motor rotational velocity depends on that frequency. Frequency inverter is controlled with analogical voltage signal. Signal can be between 0 V and 10 V. Frequency inverter can drive in both direction and direction is controlled with digital input ports. In model direction change is made by using positive or negative input voltage values. Inverter output frequency depends linearly to input voltage. When input voltage is 0 V then frequency inverter give motor settled minimum frequency which is in model 0 Hz. When input voltage is 10 V the inverter give motor settled maximum voltage which is in model 100 Hz. When input voltage change the motor frequency will change with small delay which depends the frequency inverter parametrized ramp time and shape. In dynamic model the ramp shape is assumed to be linear. Ramp time is time what frequency inverter use to accelerate the frequency from minimum to maximum frequency or vice versa. (Vacon 2014, pp. 38, 76, 77.)

In recoater movement dynamic model ramp is modelled directly in input signal with STEP function with ramp time 0.1 seconds and frequency of the motor is calculated directly to follow the input voltage. Figure 7.4 shows the input signal for recoater motion when gear ratio is 30.

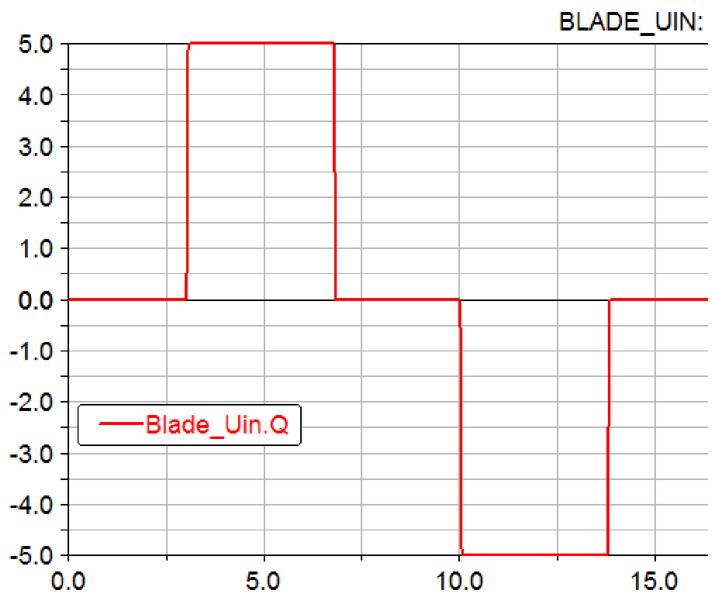


Figure 7.4. Input signal for recoater motion when gear ratio is 30.

Each step input signal change 5 V in 0.05 s. Direction change is made by using negative signal. Therefor first input signal give command to drive in one direction. After short stay still time input signal give command to drive back in other direction.

When gear ratio is changed to be 10 the input signal is modified to avoid that the recoater will not move outside of the model. Figure 7.5 shows the recoater input signal when gear ratio is 10.

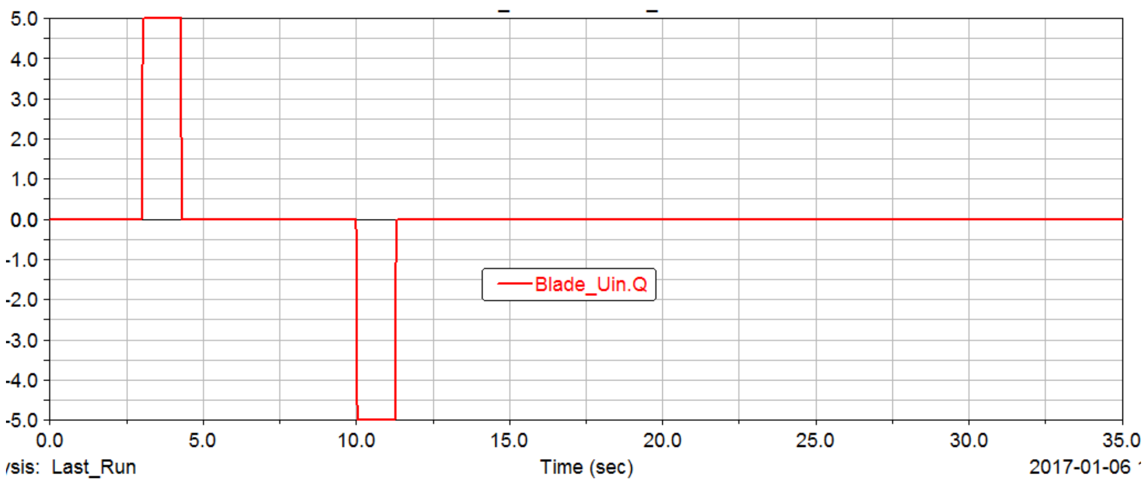


Figure 7.5. Input signal for recoater motion when gear ratio is 10.

When gear ratio is changed smaller the time when signal is 5 V is made shorter. At the same time stand still times are longer. Motions start times are same with both gear rations.

When used motor is asynchronous AC motor with 4-poles. Motor rotate 1430 RPM with 50 Hz frequency (Vem 2017). Assumption is that the rotating depends linearly for frequency and frequency depends linearly from input voltage. Motor is mounted on gear which rotate the drive shaft so that gear ration is also needed to take account. In model used gear efficiency is 0.8. Assumption is that the used efficiency factor take also account loses on bearings and linear rails.

When settled maximum frequency is 100 Hz, minimum frequency is 0 Hz and input voltage range is 0–10 V (Vacon 2014, p. 38). Therefor can be seen that the 1 V in input voltage means 10 Hz in driving frequency.

$$f_{drive} = f_{1V} * U_{in} \tag{7.6}$$

Frequency of the recoater motor was calculated with equation 7.6 which is concluded from above mentioned assumption. In equation 7.6 f_{drive} presents the motor driving frequency, f_{1V} presents the frequency when input voltage is 1 V and U_{in} presents the input voltage in frequency inverter.

$$\omega = \frac{\frac{n_{motor\ rpm}}{60 * f_{init}} * f_{drive}}{i_{gear}} * 2 * \pi \tag{7.7}$$

Recoater drive shaft angular velocity was calculated with equation 7.7. Where ω presents the angular velocity, $n_{motor\ rpm}$ presents the motor revolutions in minute and f_{init} presents the frequency when $n_{motor\ rpm}$ is true (Mathway 2017; Valtanen 2012, p. 1194).

Simulation for the recoater movement was made with two different gear rations. Initial gear ratio was 30 and other simulated gear ratio was 10. Purpose of the two different gear ratio was to check forces on mechanism if velocity of the recoater is necessary to increase more than frequency inverter allow.

Powder cause resistive force on recoater motion. That resistive force is taken account by adding force on the recoater which depends linearly from velocity of the recoater. Resistive force is modelled to be always on opposite direction than motion is. When recoater velocity is 1 m/s the force is settled to be 100 N.

$$F_{powder} = v_{recoater} * -F_{const} \tag{7.8}$$

Based on above, designed equation is show on equation 7.8. Where F_{powder} is resistive force of the powder, $v_{recoater}$ is velocity of the recoater and F_{const} presents the constant force factor.

Change arm motion components are similar than recoater motion components. Therefore the change arm motion modelling is made similar way than recoater motion modelling. Because of bigger loads the change-over arm input signal ramp time was increased to be 0.4 seconds.

With increased ramp the motion is little bit smoother. Figure 7.6 shows the change arm motion input signal.

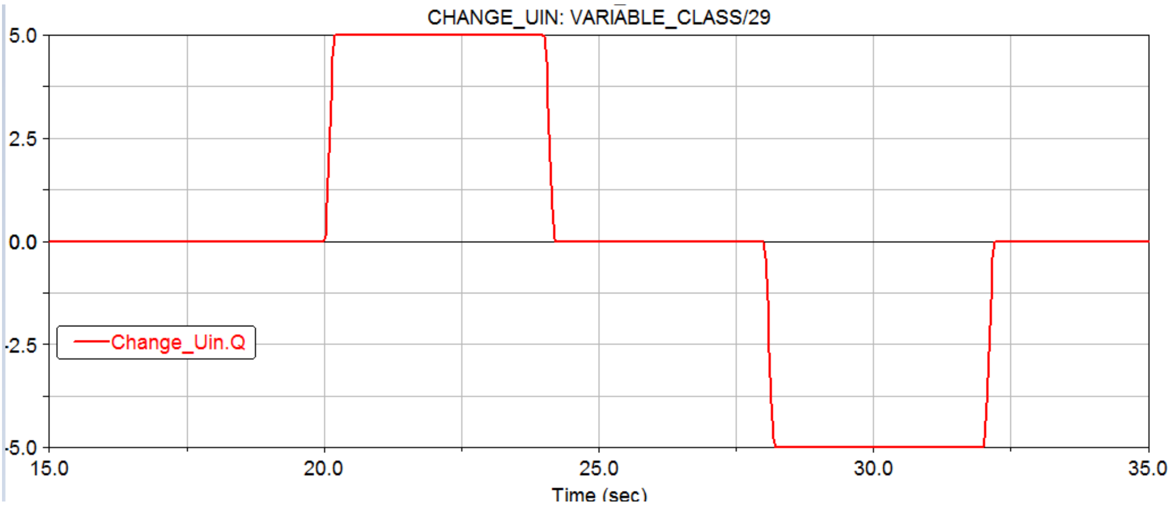


Figure 7.6. Input signal for change arm motion.

Because of ramp time is between 0–10 V input signal change 5 V on each step in 0.2 seconds. With bigger ramp time acceleration time is longer. Purpose of the longer acceleration time was to decrease the needed force of the acceleration.

7.2 Dynamic model results

After variables are created in Adams the model was simulated. Given input signal for recoater movement cause the motion for recoater. Figure 7.7 shows the position of the recoater when gear ratio is 30.

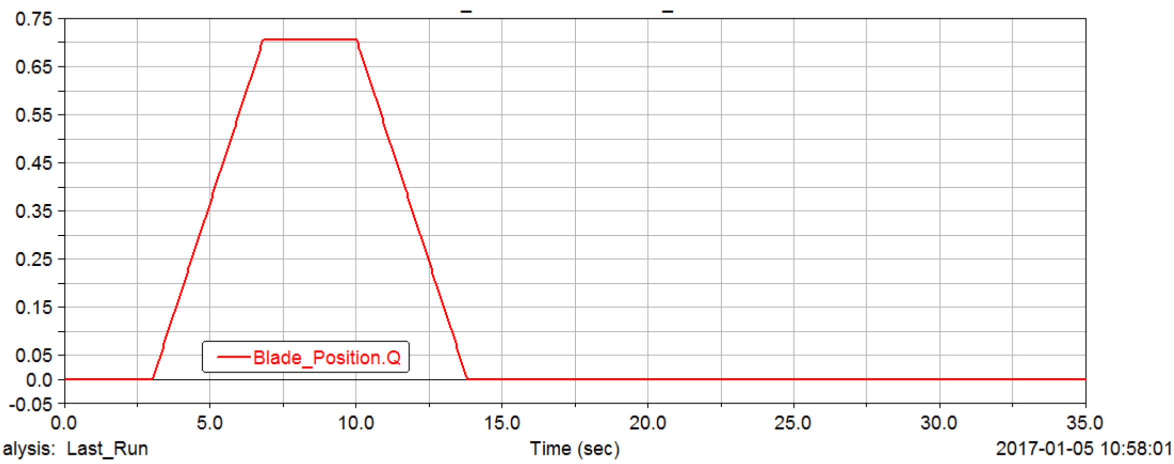


Figure 7.7. Position of recoater when gear ratio is 30.

Y-axis in the figure is a position distance in meters. When assumed building platform position is between position values 0.15 and 0.6 the recoater is over the plate between times approximately 3.8 seconds and approximately 6.25 seconds. Also in figure seems that the recoater velocity stays constant when recoater is above the building platform.

To check that is the velocity constant when powder spreading plate is above the building platform is checked velocity trajectory of the recoater. Figure 7.8 shows the recoater measured velocity when gear ratio is 30.

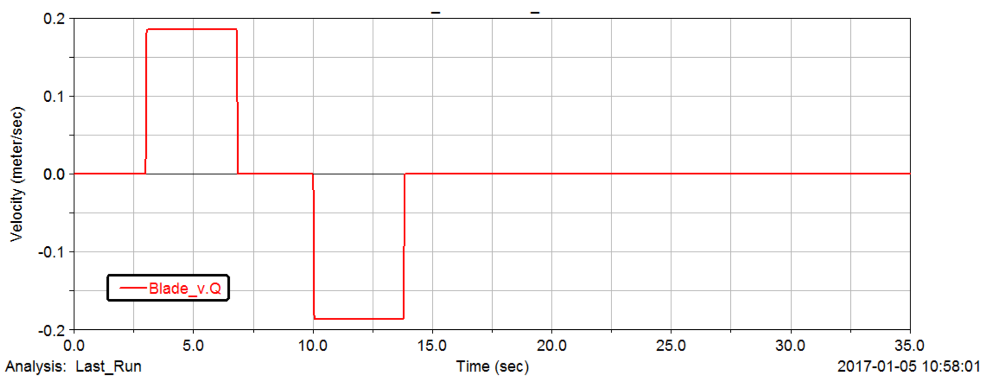


Figure 7.8. Velocity of the recoater when gear ratio is 30.

When gear ratio is 30 the constant velocity of the recoater is approximately 0.18 m/s. Figure confirm that the velocity of the recoater stays constant when recoater is above the building platform.

Belts transfer the force which cause the linear motion in the recoater. Recoater power transmission include two belts. Figure 7.9 shows the force in one belt in recoater mechanism when gear ratio is 30.

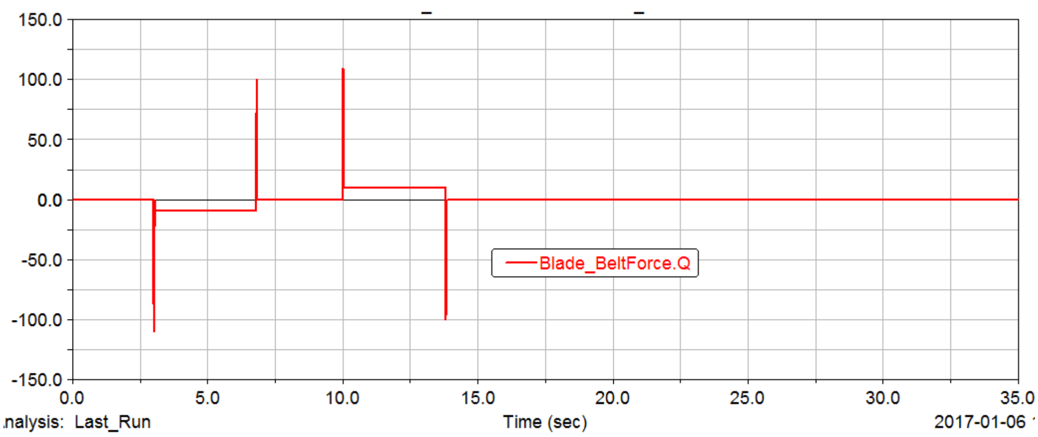


Figure 7.9. Force in on belt on recoater motion when gear ratio is 30.

In figure Y-axis is force on Newton's. Largest peak force occurs when recoater start to move and accelerate in settled velocity. When recoater has constant motion the resistive force of the powder is approximately 9 N. When recoater start decelerate the resistive force of the powder helps the deceleration and peak force in deceleration is little bit less than peak force in acceleration. Peak force in acceleration is approximately 110 N.

Force on the belts depends on the torque of the motor. To check that the motor maximum torque is not exceeded the motor torque is measured. Figure 7.10 shows the motor torque when recoater gear ratio is 30.

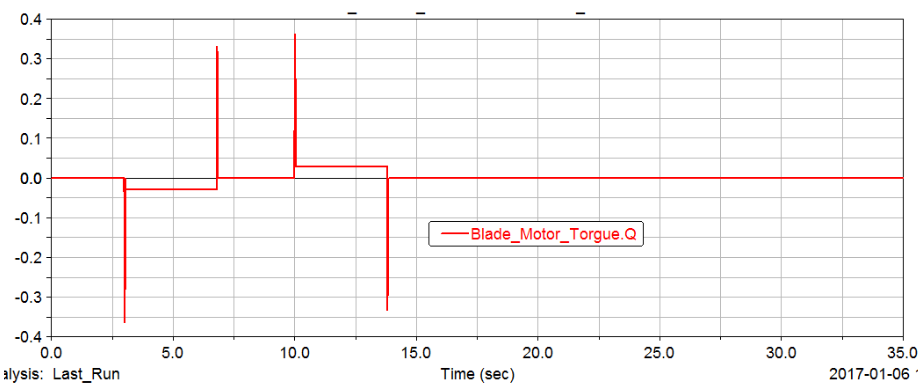


Figure 7.10. Motor torque for recoater motion when gear ratio is 30.

In figure Y-axis is torque in Nm. Peak torque occurs when recoater start to accelerate in settled velocity. Peak torque on acceleration is approximately 0.37 Nm and in deceleration peak torque is approximately 0.33 Nm.

When gear ratio is 30, motor power is clearly under the motor limits. Figure 7.11 shows the power of the recoater motor when gear ratio is 30.

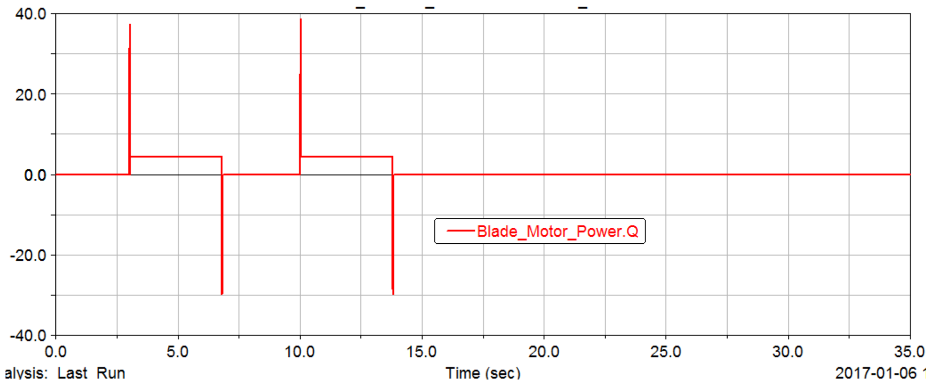


Figure 7.11. Motor power for recoater motion when gear ratio is 30.

In figure Y-axis is power on W. Peak power occurs when recoater start to accelerate. Peak power on acceleration is approximately 39 W and in deceleration peak power is approximately 30 W in negative direction.

When gear ratio is changed to be 10 the recoater position changes are faster. Because of smaller driving times, displacement of the recoater stays close to same as situation when gear ratio was 30. Figure 7.12 shows the position of the recoater when gear ratio is 10.

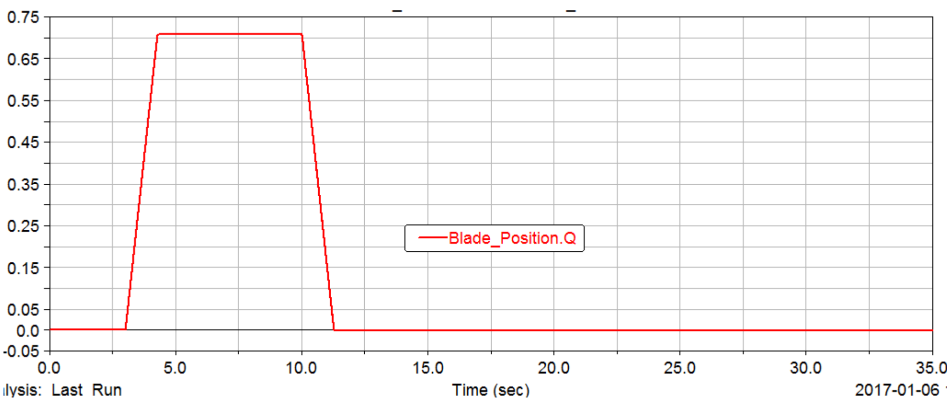


Figure 7.12. Position of recoater when gear ratio is 10.

Y-axis in the figure is a position distance in meters. When assumed building platform position is between position values 0.15 and 0.60 the recoater is over the plate between times approximately 3.3 seconds and approximately 4.1 seconds. Also in figure seems that the recoater velocity stays constant when recoater is top of the building platform.

When gear ratio is changed to be 10 the velocity of the recoater increase. Also driving times are shorter because of shorter input signal driving periods. Figure 7.13 shows the recoater measured velocity when gear ratio is 10.

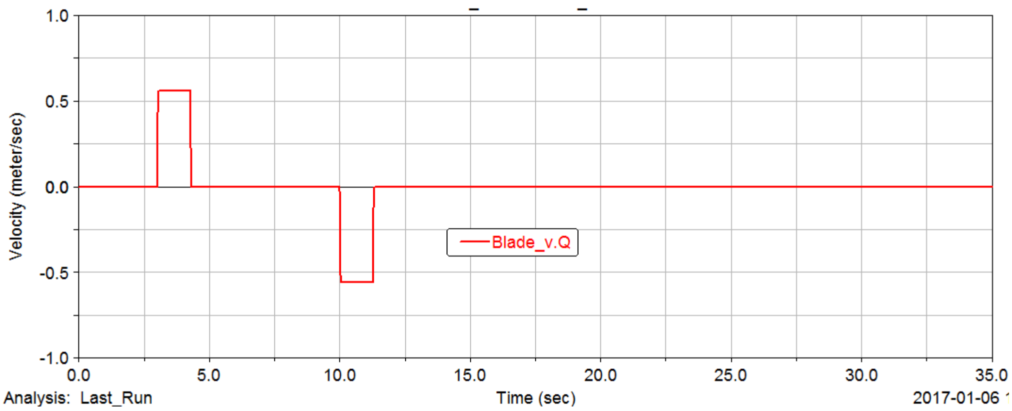


Figure 7.13. Velocity of the recoater when gear ratio is 10.

When gear ratio is decreased to be 10 the constant velocity of the recoater is increased to be approximately 0.55 m/s. Figure confirm that the velocity of the recoater stays constant when recoater is above the building platform.

Belts transfer the force which cause the linear motion in the recoater. Figure 7.14 shows the force in one belt in powder spreading mechanism when gear ratio is 10.

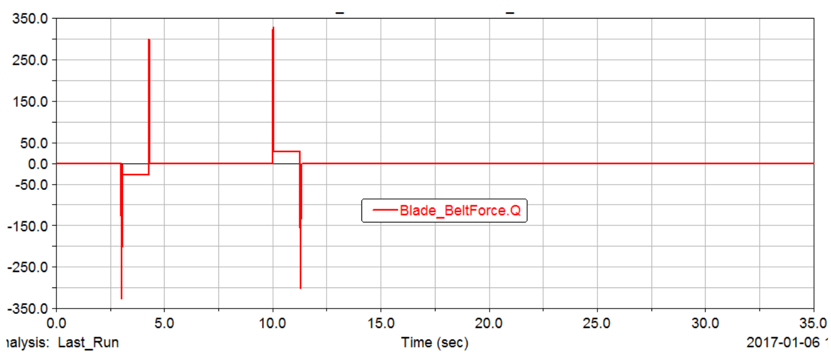


Figure 7.14. Force in one belt in recoater motion when gear ratio is 10.

In figure Y-axis is force on Newton’s. Largest peak force occurs when recoater start to move and accelerate. When recoater has constant motion the resistive force of the powder is approximately 28 N. When recoater start decelerate the resistive force of the powder helps the deceleration and peak force in deceleration is less than peak force in acceleration. When gear ratio is decreased to be 10 the peak force increase up to 330 N.

Force on the belts depends on the torque of the motor. Torque was of the motor was measured to check that the motor maximum torque was not exceeded. Figure 7.15 shows the motor torque when recoater gear ratio is 10.

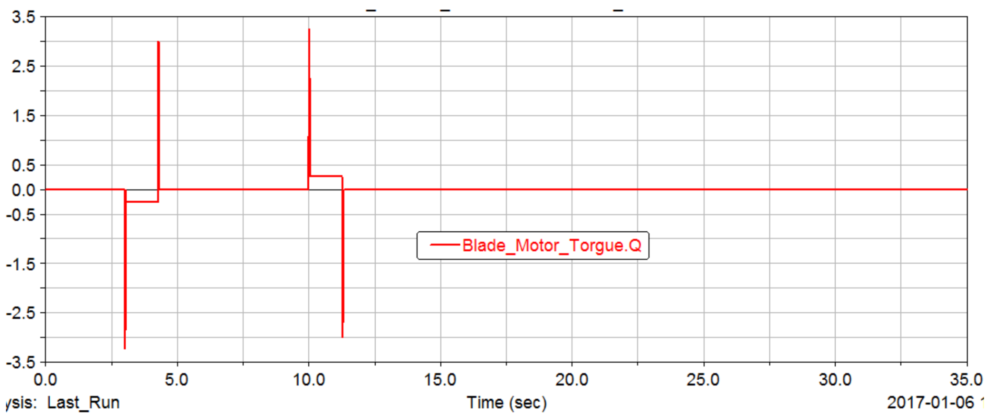


Figure 7.15. Motor torque for recoater motion when gear ratio is 10.

In figure Y-axis is torque in Nm. Peak torque occurs when recoater start to accelerate in settled velocity. Peak torque on acceleration is approximately 3.6 Nm and in deceleration peak torque is approximately 3.0 Nm.

To check that the motor power was not exceeded also power of the motor was measured. When gear ratio is 10 the motor power is closer to limits. Figure 7.16 shows the power of the recoater motor when gear ratio is 10.

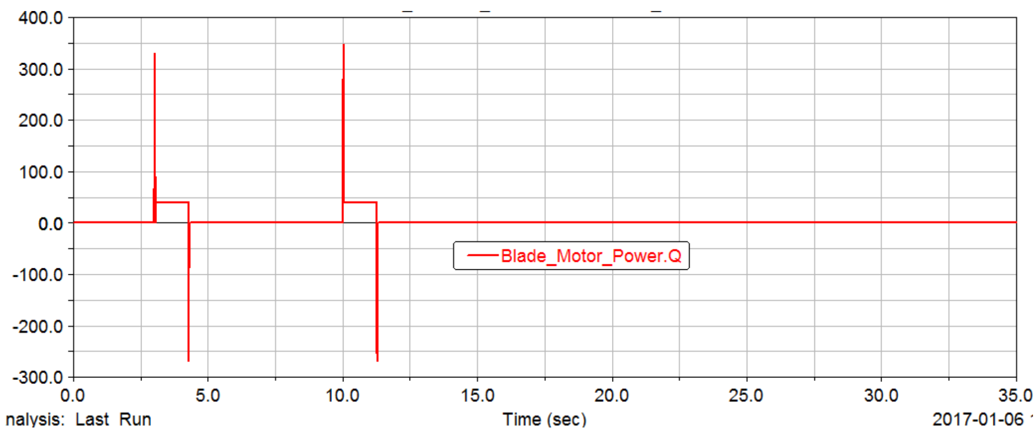


Figure 7.16. Motor power for recoater motion when gear ratio is 10.

In figure Y-axis is power on watts. Peak power occurs when recoater start to accelerate in settled velocity. Peak power on acceleration is approximately 350 W and in deceleration peak power is approximately 270 W in negative direction.

Lifting platform is driven with two different position changes. Figure 7.17 shows the lifting platform height motion over position when weight of the printed component is in largest situation.

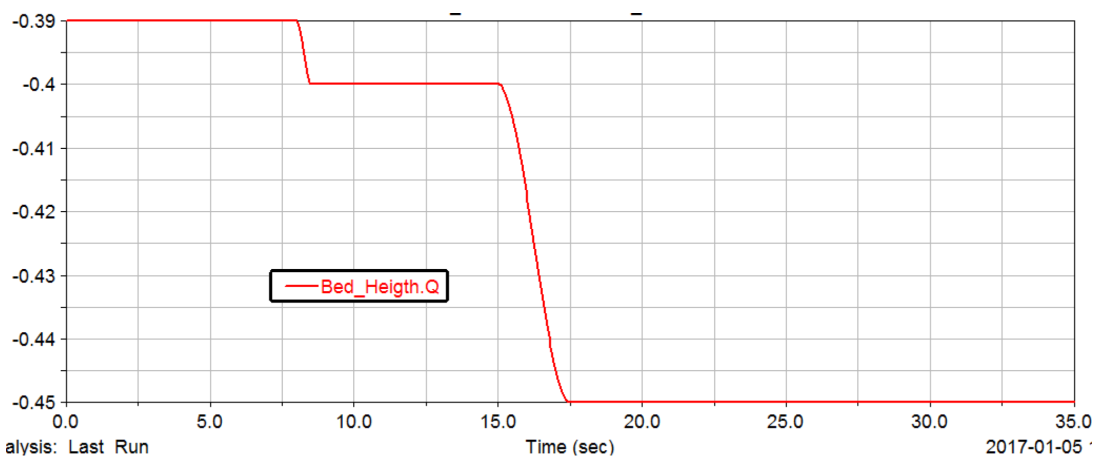


Figure 7.17. Position of lifting platform.

When building platform has reached the position -0.4 m it is in lowest printing position. After that platform is driven in changing position which is -0.45 m. Platform reach the position from -0.4 m to -0.45 m in 2.5 seconds.

Lifting platform cylinder force is clearly under the cylinder maximum force. Figure 7.18 shows the measured forces on lifting platform cylinder.

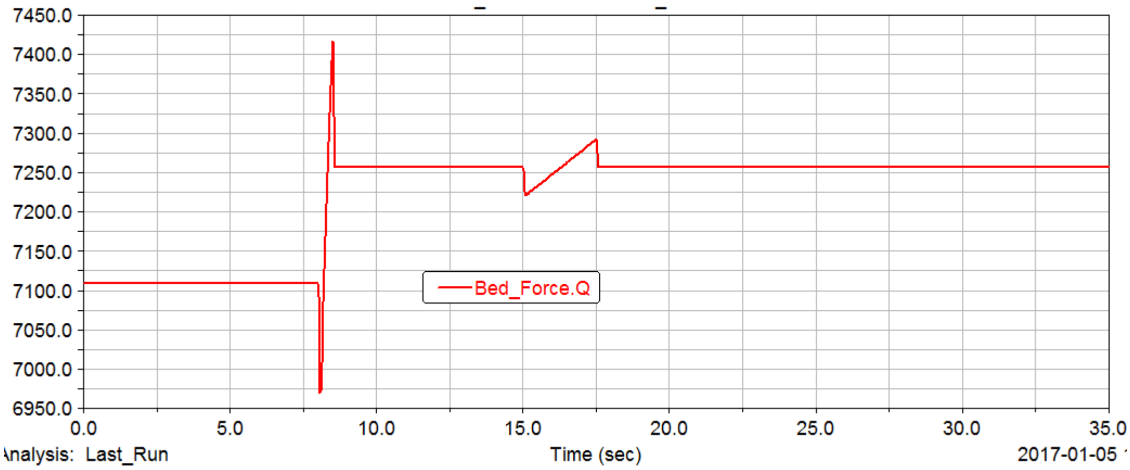


Figure 7.18. Lifting platform cylinder force.

In figure Y-axis is a force in Newton’s. When lifting platform start to move on lower position force decrease little bit. When platform is on move and it start decelerate the force increase little bit. When moving distance is longer the force behave similarly except the changes are smaller. When platform start to move from lowest printing position and building platform has not applied a new layer of powder the force after and before motion stays the same.

Change-over arm position start to move after the lifting platform is driven in change position. Figure 7.19 shows the position of the change-over arm with given change-over arm input signal.

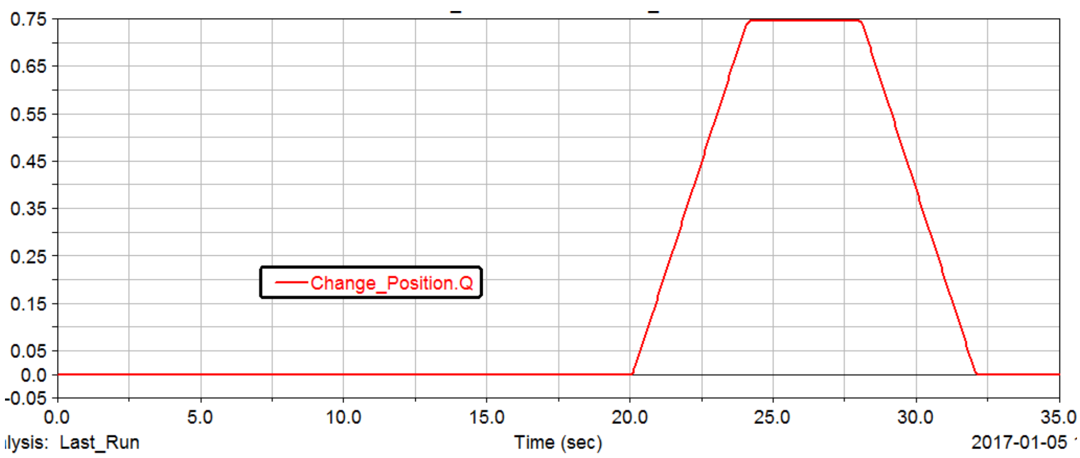


Figure 7.19. Change arm position

In figure Y-axis is position in meters. First when building platform is driven in change position the change-over arm start to move. After motion is done the arm wait a while and then start to move back in initial position.

Because of longer ramp time than recoater motion the velocity changes are slower for change-over arm motions. Figure 7.20 shows velocities of the change-over arm.

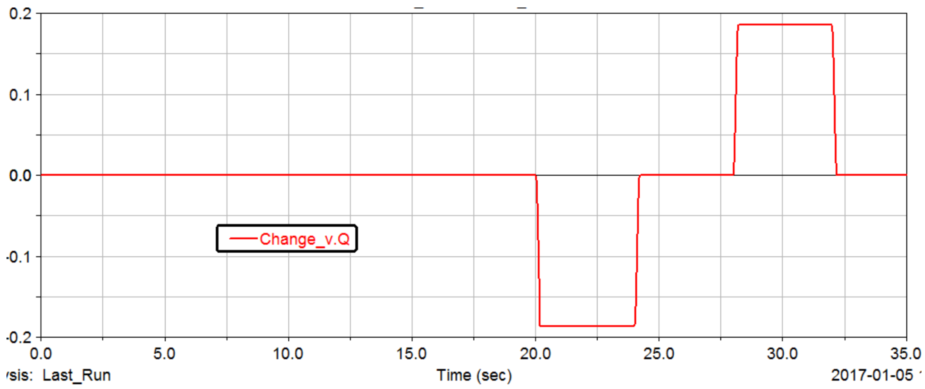


Figure 7.20. Change arm velocity

In figure Y-axis is velocity in m/s. When input signal give command to move the change-over arm velocity increase in 0.20 seconds to 0.18 m/s. Similar behaviour happen in both direction motions.

Belts transfer the force which cause the linear motion in the change-over arm. Arm power transmission include two belts. Figure 7.21 shows the force in one belt in change-over arm mechanism.

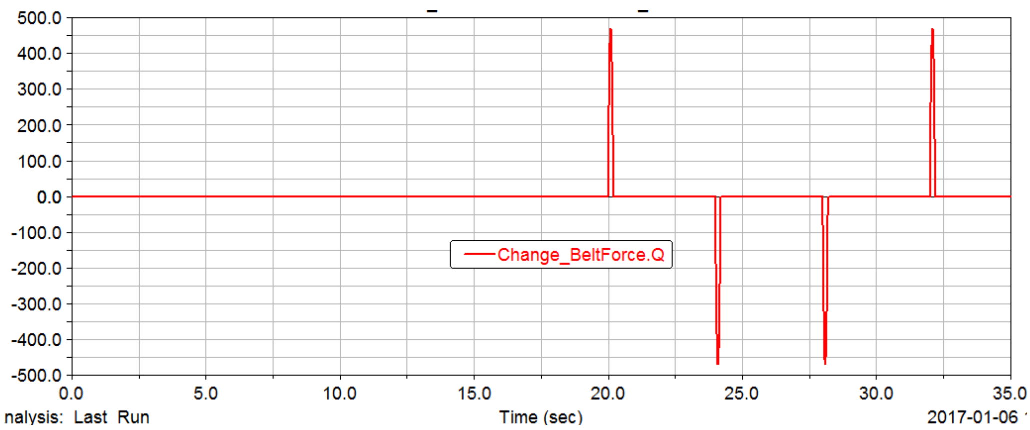


Figure 7.21. Change arm belt force

In figure Y-axis is force in Newton's. Largest peak force in the belt occurs when change-over arm motion accelerate or decelerate in target velocity. Largest peak force in the belt is approximately 460 N. In deceleration and acceleration the peak forces are quite similar.

Force on the belts depends on the torque of the motor. To check that the motor maximum torque was not exceeded the torque of the motor was measured. Figure 7.22 shows the torque of the change-over arm motor.

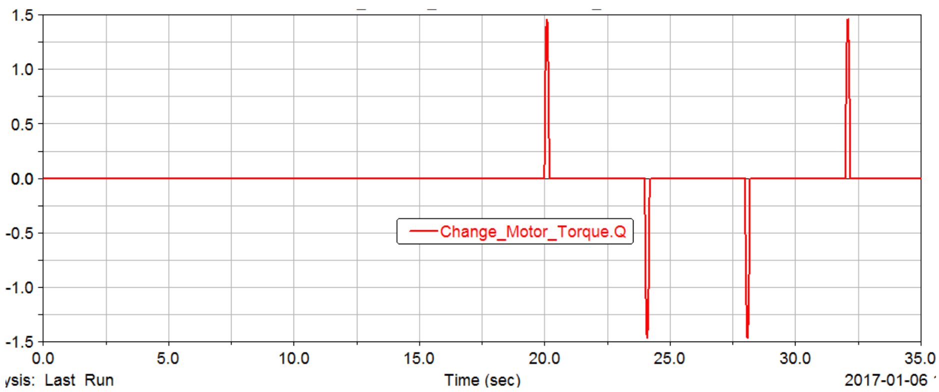


Figure 7.22. Motor torque for change arm movement.

In figure Y-axis is torque in Nm. Largest peak torques occurs at the same time than largest belt force peaks. Largest torque on change-over arm motor is approximately 1.45 Nm.

To check that the motor maximum power was not exceeded the power of the motor was measured. Motor power is clearly under the motor limits. Figure 7.23 shows the power of the change-over arm motor.

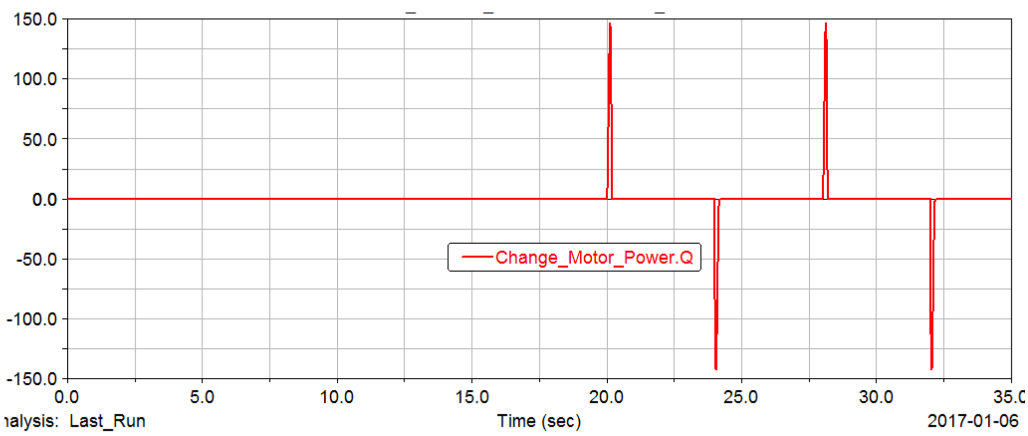


Figure 7.23. Motor power for change arm motion.

In figure Y-axis is power on W. Largest peak powers occurs at the same time as largest peak forces and torques. Largest peak power is approximately 150 W. When change arm accelerate the power is positive and motor take the power. When change arm decelerate the power is negative and motor produce power.

8 CONTROLLER

Because real machine is not built and all sensors and electrical functions are unknown the controller was created to control dynamic model. Controller was made in Matlab/Simulink R2015b software. Dynamic model was transferred to Simulink from Adams with Adams Controls add-on module. In Adams was selected the model input ports and output ports using ADAMS Plant input and ADAMS Plant output modules. Input ports for recoater motion and change arm motion are $U_{in\ recoater}$ (Recoater motion input signal in volts) and $U_{in\ change}$ (Change-over arm motion input signal in volts) variables. Third input is position target of the lifting platform. Used outputs are recoater position, change-over arm position and lifting platform position.

8.1 Controlling code

Because the frequency output of the frequency inverter is modelled to be directly depending the input voltage, in controller input ports $U_{in\ recoater}$ and $U_{in\ change}$ are added rate limiter blocks. In that block is possible to given value how fast the input value can change. That block purpose is to simulate the frequency inverter ramp time. Controller has given same ramp times which are used in dynamic model.

Controller purpose is to control the machine like real machine should work. Machine will work with cycles. Assumption is that in real machine before printing process begin is known number of layers for printed component. Therefore in controller was added constant value which is possible to change to simulate the number of printed layers. In controller was also added assumed sensors and subsystem outputs one and zero values with constants or button to simulate user activities. Those constants purpose is to simulate that the machine operating cycle can’t continue before wanted operations are done. Example change-over arm cannot pick the building platform if chamber side door is not open.

Positioning of recoater and change-over arm is made with PID (Proportional Integral Derivate) controller. For PID controller is given directly the position target where object should move. PID controller modify the frequency inverter input voltage based on error between position target and real position (Rabie 2009, p. 361). Figure 8.1 shows the designed position controller.

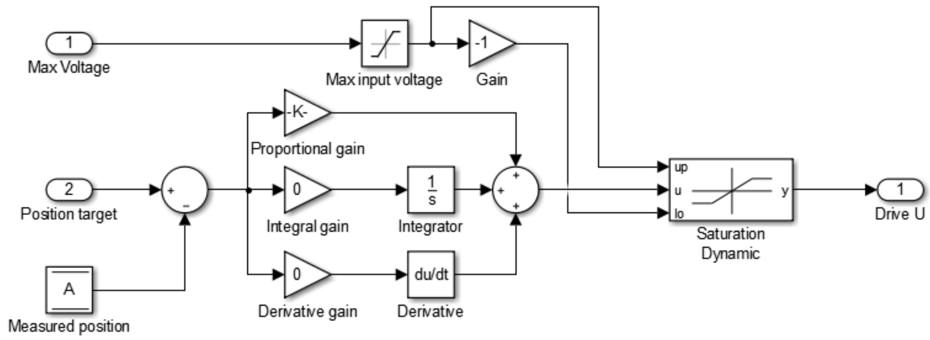


Figure 8.1. PID based positioning controller.

Because the frequency inverter maximum input voltage is 10 V and PID controller output value can be higher the maximum value of the output was limited to be 10 V and minimum value to be -10 V. Also in controller is made option to give smaller maximum voltage to get able to modify maximum velocity of the object. Still in controller was secured if optional maximum voltage is over 10 V the controller saturate maximum voltage to be 10 V. In PID controller the integral gain and derivative gain is given zero and proportional gain is given 100.

Recoater has given two target positions. Recoater was driven between those positions. Figure 8.2 shows the designed controller which give target position to PID controller.

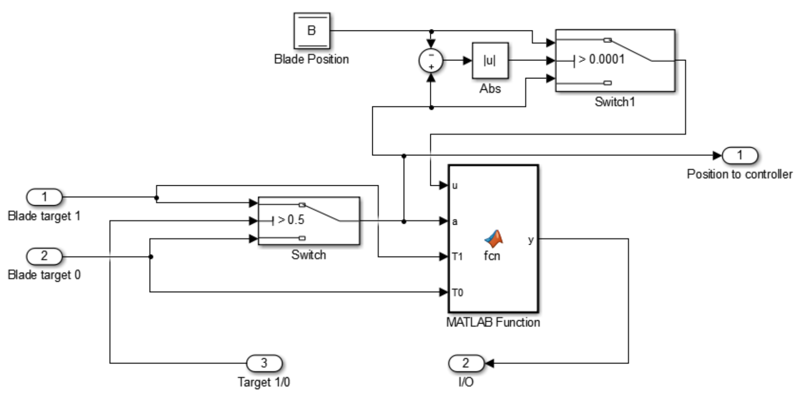


Figure 8.2. Recoater position controller.

When recoater is on target MATLAB Function give the recoater new target value. New target value goes for balloon 2 which send it to block where signal wait until the laser is done and building platform is driven in new position. After requirements are fulfilled the block send the new target value in controller.

When recoater has applied new layer of powder on powder bed. Recoater wait until the laser is melt the powder and lifting platform is reached new position. After that the recoater start the new round. When all layers are done the recoater goes in initial position and start to wait the command when new printing process can start. New printing process can't start before the building platform has changed and building platform is driven in initial position and user give a start command.

Lifting platform position is made by using direct target value. Target based on number of printed layers. Figure 8.3 shows the designed lifting platform positioning controller.

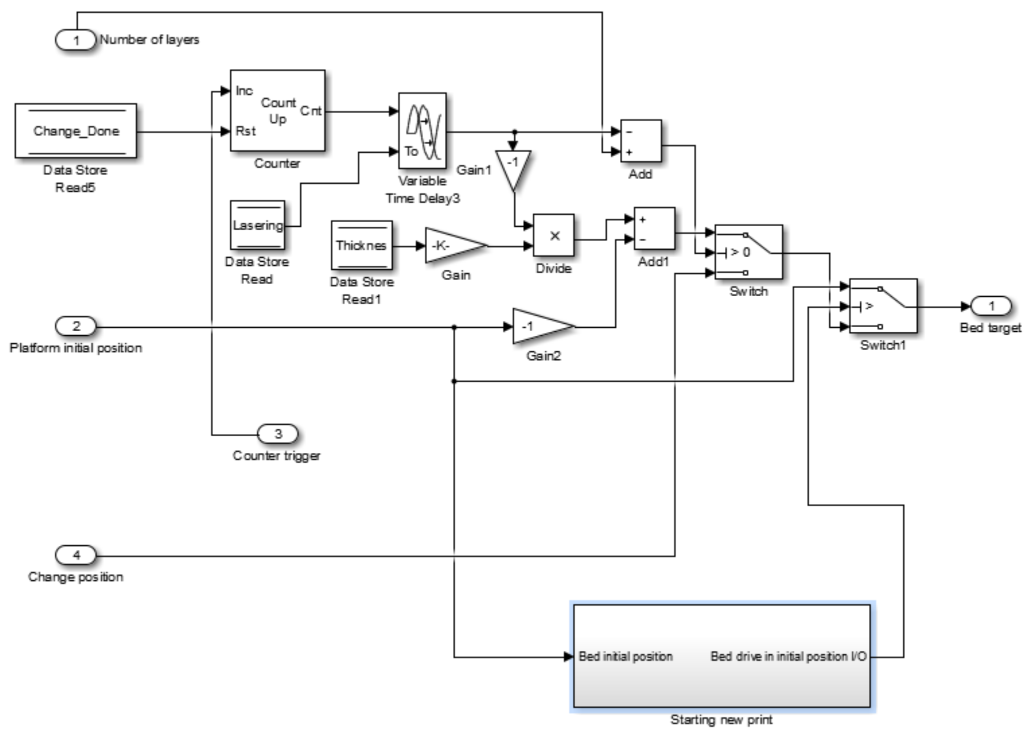


Figure 8.3. Lifting platform position controller.

When recoater has spread the powder, controller wait that when laser operation is done. After the laser operation is done controller give the lifting platform new target position. When all layers are printed the lifting platform target is settled to be in change position. In that position change-over arm can change the building platform in chamber.

After all layers are printed and lifting platform is driven in change-over position program start the building platform change-over cycle. Cycle based on steps which are change-over arm target positions. Figure 8.4 shows the designed work cycle for building platform change-over.

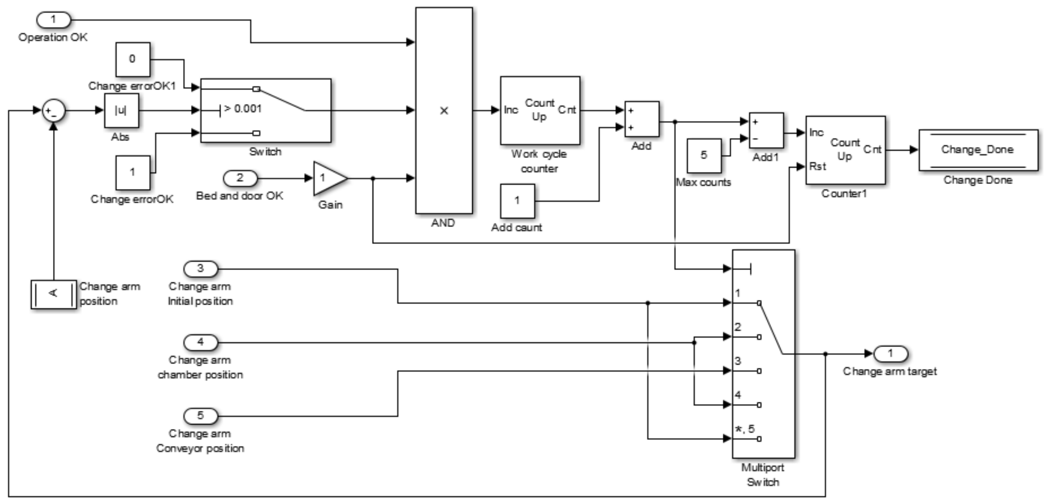


Figure 8.4. Building platform change-over cycle.

Building platform change-over controller based on five steps. When change-over arm is on initial position it wait until the side door is open and necessary other operation is done. Then it drive change-over arm on chamber position and drag the building platform out of the chamber. Change-over arm drag the building platform in conveyor position and release it. After conveyor is changed the empty building platform front of change-over arm the arm push new plate inside the chamber. After the empty building platform is inside the chamber change-over arm goes back to initial position and give signal forward that the change is done. Side door can be closed and lifting platform can be driven in initial position to wait command when new print can start. Every time when change-over arm reach the target position it wait until the necessary operations are done. Because of all additional function are not made in designed controller these steps are simulated with created button which initial value is zero and it give value one every time when button is pressed. Purpose of this button is to simulate the signal for additional controllers which tell the controller that the necessary operations are done.

Lifting platform positioning controller has subsystem which name is Starting new print. That block check when all necessary things is done and allow to start new printing process. Figure 8.5 shows the designed block to check requirements for starting new print.

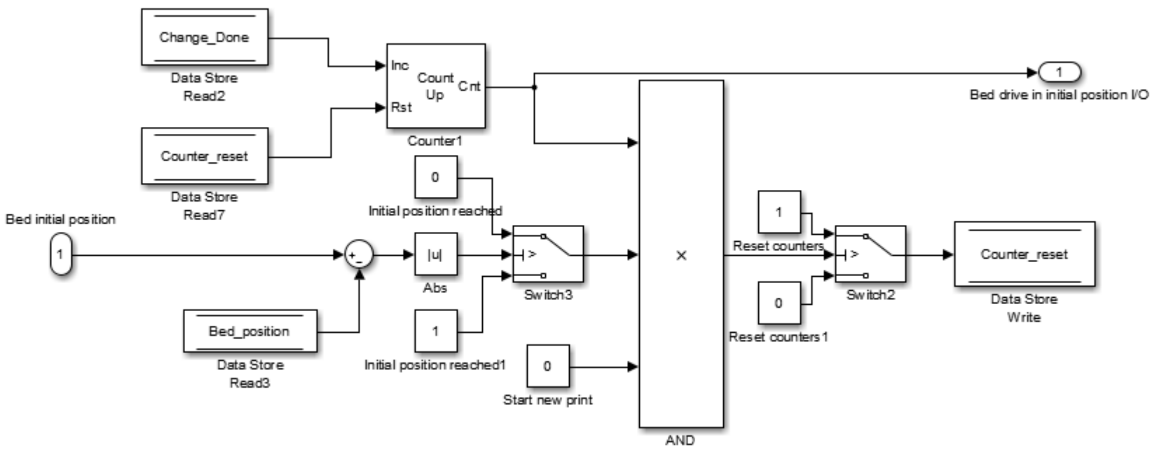


Figure 8.5. Starting new print controller.

Starting new print subsystem check that the change operation is done, building platform is in initial position and user has given command that the new print can start. When all requirements are fulfilled counter_reset block reset the counter which calculate the printed layers. Same time it reset the change_done value that the middle of the printing process is not possible to start a new print and drive lifting platform in initial position causing damage to components.

In controller is possible to modify the operating parameters. Used operating parameters are shown in table 8.1. Changing those parameters is possible to simulate different kind of situation with controller.

Table 8.1. Controller operating parameters.

Parameter	value	Unit
Layer Thickness	10	mm
Time for laser work	1	s
Number of layers	4	pcs
Platform initial position	-0.35	m
Platform change-over position	-0.45	m
Recoater initial position	0	m
Recoater secondary position	0.7	m
Recoater maximum voltage	10	V
Change arm initial position	0.3	m
Change arm chamber position	0	m
Change arm conveyor position	1	m
Change maximum voltage	10	V

8.2 Results with controller

When simulation start the recoater spread first layer of powder in the powder bed. Figure 8.6 shows the movement of the recoater.

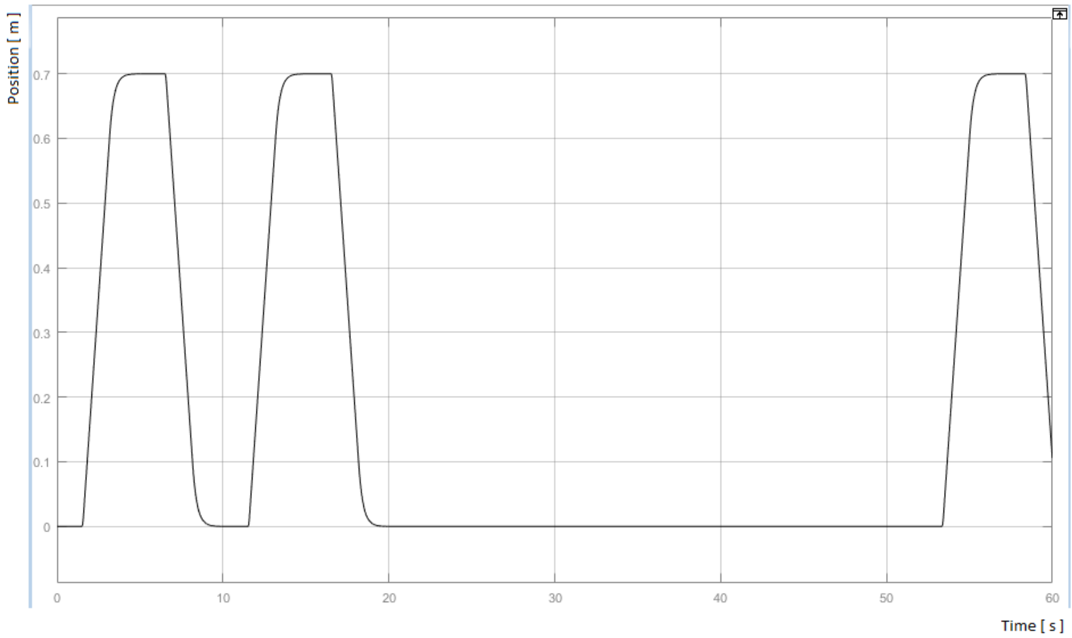


Figure 8.6. Recoater position.

Recoater move between settled end positions. When recoater has reached the target position it stand still until it get a new target value. In simulated printing process recoater move four times over the building platform spreading a new layer of powder. After time 20 s all layers are done and recoater stays in initial positon. On time 53 s user give command to start a new printing process. When user give a command for new printing process recoater start to spread first layer of powder on building platform.

Lifting platform motions depends the recoater motion and number of layers in component. Layers has seen with steps in position figure. Figure 8.7 shows the lifting platform position.

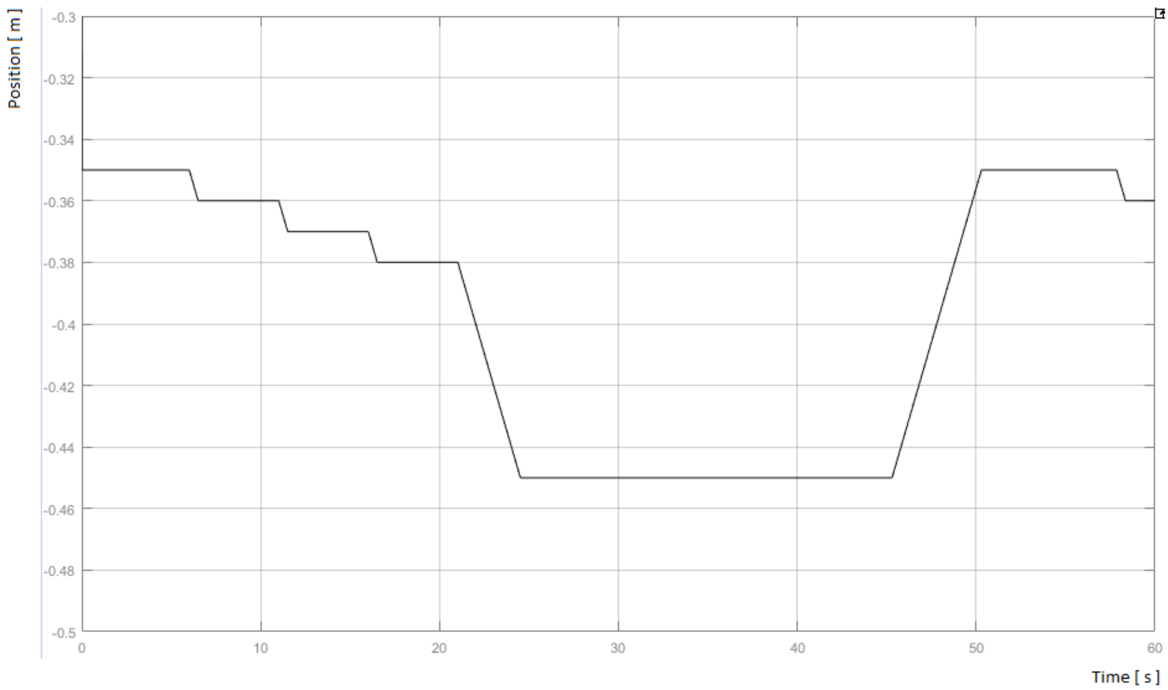


Figure 8.7. Lifting platform position.

When simulation starts the lifting platform is in initial position. After recoater has spread the first layer of powder and laser has done selective melting of the layer the platform move downwards to one layer thickness. Platform repeat that cycle after all layers are printed. After all layers are printed in time 21 s lifting platform move on building platform changing position. Platform stays in this position after the building platform has changed. On time of 46 s building platform change-over cycle is done and lifting platform start to move on initial position. After lifting platform is reached the initial position it stay still and start to wait a new command to move. On time 53 s user has given command to start new print. Lifting platform is still on initial position and on time 58 s when first layer of new component is printed, platform start to move downwards.

Change-over arm drag the printed building platform out of the chamber to conveyor. After the conveyor has changed empty building platform in front of change-over arm it push the plate inside the chamber. Figure 8.8 shows the motion of the change-over arm.

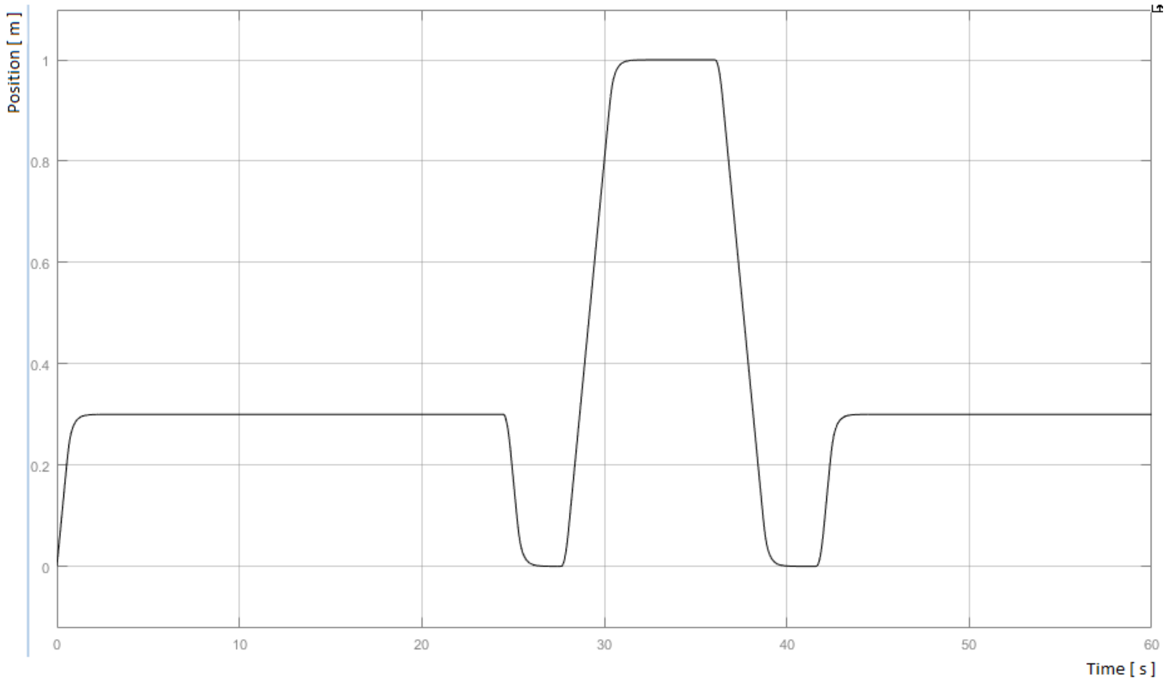


Figure 8.8. Change-over arm position.

When simulation start change-over arm is driven in initial position where it wait until the machine is on situation when building platform is need to change. In time 25 s machine is on situation when printed building platform is need to be changed. Change-over arm is driven in chamber position and there it wait until it get command that the plate is attached to change-over arm. After it get command it start to drag the plate to conveyor position. On conveyor change-over arm release the plate and wait that the conveyor has moved the printed building platform off and changed empty building platform front of change-over arm. After change-over arm get the command that the empty plate is on right position change-over arm push the plate in to chamber. After the plate is in chamber change-over arm release it and move on initial position to wait a new building platform change-over cycle.

9 DISCUSSION

Designed machine operating principle is powder bed fusion. In designed machine main functions has selected quite many different components or component combinations. Components are know where those are possible to order.

Recoater power transmission is little bit oversize on purpose. Using smaller motor will not give reasonable savings on costs. Like dynamic model shows that when gear ratio of the gear is 30 the power which is used for braking recoater is quite low. That probably allow to use motor without separate braking resistor. Also with oversized motor if powder caused restive force has variation the motor can probably keep better the velocity of the recoater to be constant. Belt ambient temperature might increase close to maximum recommended operating temperature. When operating temperature rise it might cause faster wearing of the belt. When belt is oversized it give more room to wearing and wearing is probably slower. One benefit for oversizing these components is that the often when first prototype of the machine is built, it need some modifications to work properly. Example if recoater velocity is needed to increase clearly. Velocity is possible to increase by using different gear ratio. When there is available other gear rations in same gear frame is possible to change whole gear without other changes in the machine. Like dynamic model show that the power transmission equipment’s can handle very well the motion even when gear ratio is changed from 30 to 10. One benefit more with oversized transmission is that the same components is also possible to use with bigger scale machines in future.

Motors for recoater movement and changing arm movement is possible to order with integrated pulse sensor. With pulse sensor is possible to measure the position of the recoater. Drawback is a price of the sensor. Assumption is that the positioning of the recoater and change-over arm is more cost effective to measure with additional distance sensor. Because the recoater and change-over arm positioning accuracy requirements are quite low the additive distance sensor might be much cheaper solution. Motors are also possible to order with mechanical standing brake. Motion on both solutions are horizontal and therefore the mechanical brake is not seen to be necessary.

Largest pressure difference between lifting chamber and main chamber is kept quite small on purpose. When pressure increases in lifting chamber it will cause higher pressure requirements on walls of the lifting chamber. Also with lower pressure it may be possible to avoid the situation that the under pressure equipment legislation is applied to the machine. Assumption is that the vertical cylinder act like a mechanical fuse. If pressure inside the lifting chamber increase too high, pressure force will lift the plate little bit and pressure can discharge into main chamber. This probably prevent uncontrollably pressure discharge outside of the machine and therefore prevent the human contact with a powder. By creating vacuum into first reservoir is possible to increase the pressure difference between first reservoir and lifting chamber without increasing the pressure in lifting chamber.

Nitrogen flow on main chamber is controlled with solenoid operated directional valve and manually adjusted flow control valve. Back draw for this is that the nitrogen volume flow is not possible to control from main controller even that the volume flow sensor allow to measure the volume flow. Changing directional valve to be proportional operated directional valve and removing the flow control valve is possible to control the volume flow directly from controller. Proportional valve is quite expensive and therefore in first prototype is probably safer solution to use manually adjusted flow control valve. In future one good choice is to use proportional valve to increase machine automation level.

Dynamic model show that the used components are suitable on desired purpose. When model was simulated with controller, velocity of the recoater is constant when recoater is above the powder bed. When recoater or change-over arm reach the target position, velocity decreasing shape is curve which makes the braking smoother.

In future with first prototype is necessary to research suitable metal powder properties. After the powder properties are known is possible to do experimental test to the sieving station. Sieving station screen size is depending the needed properties of the powder. Specially shape and size of the particles. Before ordering a sieving unit is recommended to make experimental test runs with powder which is purpose to use. At this moment vacuum receiver drop the powder directly to sieving unit. There is a risk that the volume of the powder is too large and therefor is necessary to add a feeder between powder receiver and sieving unit. Experimental test with sieving station supplier will show is that feeder needed. Also with experimental test is possible to evaluate the sieving capacity and that way evaluate the size of the sieving station more specific.

Largest future development will be the designing of electricity circuits and controlling code for whole machine and studying laser parameters. In future research are also included the certification of the machine. Before machine is possible to launch on the markets is necessary to study required certifications based on areas where machine are going to be marketing.

In future is also need to develop system which reject the component damages if recoater hit the printed component. One idea is to test the frequency inverter with physical model to check is there possible to use torque limiter. Therefor when recoater hit the printed component it will stop because of frequency inverter will not allow to use more force.

Machine frame and structure is quite heavy. It might be good idea to optimize in future some components like side door and sealing plate which are quite heavy. In those might be possible to use some kind of cell structure.

When first prototype is under testing it will be good to check temperatures in main chamber during process. Example if recoater belts are covered with cover where nitrogen is leaded inside the cover and nitrogen will flow from cover to powder bed. With that kind of solution, fresh nitrogen will work like coolant and also nitrogen flow will reject the fine metal dust flow to the belts and linear motion components.

10 SUMMARY

Additive manufacturing markets are growing strongly. New machine manufacturers will enter the markets and machines with new additional functions like powder removal and automatic building platform handling will be introduced. Machines for building larger size have prices quite over million Euros.

This study is scoped in several main sections of the powder bead fusion machine. Main sections of the machine are recoater movement, levelling of the lifting platform, closing the lifting chamber, powder filling in the recoater, building chamber atmosphere and shielding gas circulation, laser equipment, change of building platform and powder removal and rest of the powder journey. In each sections suitable component combination which allow to build first prototype of the machine are studied and selected.

In literature review the studied components and their properties are reported. Detailed information and price range of the components are specified via quote conversations is founded. A dynamic model for system was build and used to evaluate the suitability of the components. The created controller give information to evaluate the parameters of positioning and give guidelines to coding after the first prototype is under construction.

Recoater and building platform change-over arm movement was selected do with asynchronous AC motor, worm gear reducer which gear ratio is 30 and tooth belt convert the rotational motion to be linear. Recoater straight motion was secured with linear rails. Change-over arm straight motion is secured with round linear rails and bushings.

Lifting platform height position was driven with electro mechanical cylinder. Accuracy of the building platform height position was increased with additional position sensor. Straight motion of the lifting platform was guided with two linear rails which are oversized to get the mechanism more stable. Additional position sensor was integrated one of those rails.

When powder removing cycle start the lifting chamber should be closed. Lifting chamber has one hole on top of the chamber and other hole on side of the chamber. Automatic building platform changing is made thru that side door. Side door is closed by using pneumatic cylinder which piston diameter is 80 mm. Hole on top of the chamber is closed with two pneumatic cylinders which piston diameters are 50 mm and 160 mm. Smaller cylinder move the cover plate top of the hole and larger cylinder push the cover to the hole.

The recoater is refilled during printing process. In main chamber there is a small powder reservoir from which the powder is fed into the recoater. Feeding roller inside the reservoir feeds controlled volume of powder into recoater.

Building process will be done in shielding gas atmosphere. Machine has integrated nitrogen generator which produce nitrogen by using compressed air. Nitrogen has leaded in building chamber to replace air. With analogue signal is possible transfer information of measured volume flow to machine controller. Gas inside the main chamber is circulated and filtered to decrease nitrogen consumption. Circulation unit suck the gas from chamber and remove small particles out of the gas and return it back in to the main chamber.

Used laser is 500 W continuous wave ytterbium fiber laser. Beam is transferred with optical fiber to adjustable focusing unit and scanner head. Adjustable focusing unit take care the working area flat field correction. Scanner head focus the beam on processed powder layer. Solution give approximately 75 µm beam focal point diameter on work piece.

Loose powder over the created component is removed in lifting chamber. After the lifting chamber is closed the loose powder is removed with gas flow and pressure drops. Loose powder goes in first reservoir where is possible to create small vacuum to intensify the powder flow out of the lifting chamber. All removed powder goes in first reservoir where it is transferred with vacuum powder receiver on sieving station. Sieving station sieve oversized particles out of the powder and drop the fine size particles in main reservoir. From main reservoir powder is transferred back to main chamber and it is used again in next component.

Dynamic model and controller include three motions. Recoater motion, lifting platform motion and change-over arm motion. Dynamic model show that the used components are suitable for purpose and forces and torques are not in dimensional limits of the components.

When model is driven with controller, velocity of the recoater is still constant when recoater is above the powder bed. When recoater or change-over arm reach the target position, velocity decreasing shape is curve which make the braking smoother.

REFERENCES

Ball valves QH, QHS. [Festo www-page]. [Refered 16.1.2017]. Available: https://www.festo.com/cat/fi_fi/products_QH_QS?CurrentPartNo=9543

BE Group. 2014. Kylmavedetyt_0314 [www-document]. [Refered 20.1.2017]. Gatalogue. pitkät teräkset pp. 20-23, Avalaible: http://www.begroup.com/upload/fi/ tuotepdft/terakset/kylmavedetyt_0314.pdf

Bosch Rexroth AG. 2014. Ball Rail Systems doc: R999000485/en-GB/01.12.2014. [www-document]. [Refered 20.1.2017]. 232 p. Available: https://md.boschrexroth.com/modules/BRMV2PDFDownload-internet.dll/KSF_ G2p_EN_R999000485_2014_12_16_01_2015_media.pdf?db=brmv2&lvid=1143634&mvid=12514&clid=20&sid=2DD49AF048D6521D815564AB689DE840.borex-tc&sch=M&id =12514,20,1143634

Bosch Rexroth AG. 2015a. Electromechanical Cylinder EMC-HD, doc. R999000326/en-GB/01.12.2015. [www-document]. [Refered 21.1.2017]. 76 p. Available: https://md.boschrexroth.com/modules/ BRMV2PDFDownload-internet.dll/R999000326 _2015-12_EN-US_EMC_HD_Media.pdf? db=brmv2&lvid=1186746&mvid=12515&clid= 1&sid=663A4CFF7D8DE535BB6ACD364182E3A7.borex-tc&sch=M&id= 12515,1,1186746

Bosch Rexroth AG. 2015b. Linear Bushings, doc. R999000488/en-US/01.2.2015. [www-document]. [Refered 25.1.2017]. 244 p. Available: https://md.boschrexroth.com/modules/BRMV2PDFDownload-internet.dll/ R999000488_ 2015-02_KBF_EN-US_Media.pdf?db=brmv2&lvid=1193113&mvid=12524&clid=20&sid =BEA6C1CC81C5A174FD7E21B4809F9DDD.borex-tc&sch=M&id= 12524,20,1193113

Compomac S.p.A. 2006. Metalflex. [www-document]. [Refered 15.1.2017]. 2 p. Available: http://www.sks.fi/www/sivut/2D1B6C267766B5B6C2257AFC00220002/$FILE/METALF LEX.pdf

Elatech. 2015. Gataloque: ELATECH® M and V [www-document]. [Refered 20.1.2017]. 97 p. Avalaible: http://www.jens-s.fi/media/22624/Elatech-Metervara-M-och-V.pdf

Elomaa, T. 2016. VS: Jauheen seulonnasta [private email]. Recipient: Pasi Piispa. Sent 22.11.2016 o'clock 10.44 (UTC +0200). Attachments: "Low Profile Flow-Thru Separator.pdf", "Low Profile Flow-Thru Separator.pdf", "666002800_Ultrasonic_Screening-en.pdf"

EOS M 400-4. [EOS www-page]. [Refered 17.1.2017] Available: https://www.eos.info/systems_solutions/eos-m-400-4

Flow sensor SFAB. [Festo www-page]. [Refered 13.1.2017] Available: https://www.festo.com/cat/fi_fi/products_SFAB?CurrentIDCode1=SFAB-200U-HQ8-2SV-M12&CurrentPartNo=565394

FormUp™ machines. [AddUp www-page]. [Refered 17.1.2017]. Available: http://www.addupsolutions.com/en/machines-and-lines/#machines-formup

Frazier, W.E. 2014. Metal Additive Manufacturing: A Review. Journal of Materials Engineering and Performance, 23: 6. pp. 1917–1928.

Hammashihnap. kiinteällä navalla. [Jens-S www-page]. [Refered 23.1.2017]. Available: http://www.jens-s.fi/tuotteet/hihnakaytot/hammashihnakaytot/hammashihnap-kiintealla-navalla/

Honkatukia, J. 2016. VS: Lisää hintoja [private email]. Recipient: Pasi Piispa. Sent 20.7.2016 o'clock 15.28 (UTC +0200). Attachments: "0423_001.pdf", "0422_001.pdf

Horn, T.J. 2012. Overview of current additive manufacturing technologies and selected applications. Science progress, 95: 3. pp. 255-282.

In-line installation GR. [Festo www.page]. [Refered 16.1.2017] Available: https://www.festo.com/cat/fi_fi/products_GR?CurrentIDCode1=GR-1%2F8X2-B&CurrentPartNo=152612

Klahn, C. & Leutenecker, B. & Meboldt, M. 2014. Design for Additive Manufacturing – Supporting the Substitution of Components in Series Products. Procedia CIRP 2014: 21. pp. 138-143.

Koehn, P. 2017. Quotation P307-16707-AW-S [private email]. Recipient: Pasi Piispa. Sent 9.1.2017 o’clock 11.26 (UTC +0200). Attachments: “Quotation P307-16707-AW-S.PDF”

Kuularulla. [Witre www.page]. [Refered 25.1.2017]. Available: http://www.witre.fi/fi/wfi/kuularulla-teraskuula-o-30-mm-250-kg-14550300#descriptionAnchor

Laser Fume Extraction - AD NANO. [Vodex www-page]. [Refered 23.1.2017]. Available: https://www.vodex.co.uk/products/fume-and-dust-filtration-systems/laser-marking-and-printing-systems/bofa-ad-nano#!prettyPhoto

LX Illustration. 2010. [Sweco www-page]. [Refered 23.1.2017]. Available: http://www.sweco.com/tldr.aspx?fid=20140116085738128750Y1LOBMBZAECA

Machine search. [Senvol www-page]. [Refered 17.1.2017]. Available: http://senvol.com/5_machine-search/

Machines. [Concept Laser www-page]. [Refered 17.1.2017]. Available: https://www.concept-laser.de/en/products/machines.html

Manifold assembly VTUG, with individual electrical connection. [Festo www.page]. [Refered 16.1.2017]. Available: https://www.festo.com/cat/fi_fi/products_VI26

Mathway. 2017. Converting RPM to Radians per Second. [Mathway www-page]. [Refered 19.1.2017] Available: https://www.mathway.com/examples/Precalculus/Trigonometry/Converting-RPM-to-Radians-per-Second?id=481

Metalflex-paljekytkimet. [SKS-Group www-page]. [Refered 15.1.2017]. Available: http://www.sks.fi/www/_Servo-ja-pulssianturikytkimet&id=Metalflex_paljekytkimet

Motovario S.p.A. 2013. Motoriduttori a vite senza fine. [www-document]. [Refered 20.1.2017]. 45 p. Available: http://www.motovario.com/download_file.php?u=dXBsb2FkL2Rvd25sb2FkL2ZpbGUvZmlsZXMvMTQxMjIyMTIxOTJfY2F0YWxvZ29fc3cucGRm&f=catalogo_sw.pdf&e=1

MOVIMOT® options. [Sew Eurodrive www-page]. [Refered 17.1.2017]. Available: http://www.seweurodrive.com/produkt/movimot-gearmotor-with-integrated-frequency-inverter.htm

Nachi-Fujikoshi Corp. 2012. Nachi Ball & Roller Bearings, Doc. B2100E-4. 656 p.

Non-return valves H, HA, HB. [Festo www.page]. [Refered 24.1.2017] Available: https://www.festo.com/cat/fi_fi/products_H_HA_HB

Parker Hannifin Corporation. 2012. Nitrogen Gas Generators. Catalogue: 174004706_04_EN 09/12. 19 p. [www-document]. [Refered 29.1.2017]. Available: http://www.parker.com/literature/domnick%20hunter%20Industrial%20Division/174004706_EN_NITROGEN_GAS_GENERATORS_PIS.PDF

Putnins ,A. 2016. RE: Jauheensiirto / Thurne Teknik [private email]. Recipient: Pasi Piispa, Henrik Ramm-Schmidt (cc). Sent 1.11.2016 o’clock 7.55 (UTC +0200). Attachments: “502401-en P10.pdf”, “502401-en P10.pdf”, “501807-en LSR Controller.pdf”

Rabie, M. G., 2009. Fluid power engineering. New York: McGraw-Hill. 419 p.

Räihä, P. 2016a. RE: TARJOUS R9442_11 [private email]. Recipient: Pasi Piispa. Sent 21.10.2016 o'clock 9.50 (UTC +0200). Attachments: "R9442_11.pdf"

Räihä, P. 2016b. RE: TARJOUS R9442_11 [private email]. Recipient: Pasi Piispa. Sent 27.10.2016 o'clock 13.25 (UTC +0200).

Round separators. [Sweco www-page]. [Refered 16.1.2017]. Available: http://www.sweco.com/screener-round-separator.aspx

Ruuska, M. 2016a. RE: Typpigeneraattori [private email]. Recipient: Pasi Piispa. Sent 6.9.2016 o'clock 14.46 (UTC +0200). Attachments: "Esite_MIDIGAS_Typpigeneraattori_174004705.pdf", "MIDIGAS esite.pdf"

Ruuska, M. 2016b. RE: Typpigeneraattori [private email]. Recipient: Pasi Piispa. Sent 14.10.2016 o'clock 13.19 (UTC +0200). Attachments: "Capture 1.PNG", "Capture 2.PNG"

Salminen, A. 2016. Re: Laser on AM machine [private email]. Recipient: Pasi Piispa, Hamid Roozbahani (cc). Sent 23.11.2016 o'clock 20.11 (UTC +0200).

Scanlab GmbH 2015. varioSCAN, varioSCANde i. 5 p. [www-document]. [Refered 13.1.2017]. Available: http://www.scanlab.de/sites/default/files/pdf-dateien/data-sheets/varioscanvarioscande-en.pdf

Selective Laser Melting Machine SLM 500. [SLM-Solutions www-page]. [Refered 17.1.2017]. Available: https://slm-solutions.com/products/machines/selective-laser-melting-machine-slm-500

Semi-rotary drives DRRD. [Festo www.page]. [Refered 15.1.2017]. Available: https://www.festo.com/cat/fi_fi/products_DRRD?CurrentIDCode1=DRRD-32-180-FH-PA&CurrentPartNo=1578512

Service unit combinations without lubricators. [Festo www.page]. [Refered 16.1.2017]. Available: https://www.festo.com/cat/fi_fi/products_LFR_K?CurrentIDCode1=LFR-1%2F2-D-MIDI-KA&CurrentPartNo=185715

Sihvo, O. 2016. VL: Sähkömekaaniset sylinterit [private email]. Recipient: Pasi Piispa, Sihvo Olli (cc), Lagus Kim (cc). Sent 8.7.2016 o'clock 14.57 (UTC+0200). Attachments: ”EMC_085_HD_1_64.stp.zip”, “EMC_085_HD_1_64.pdf”, “Servomitoitus_LUT.pdf”, “MSK071D-XXX—NN-X2-UG1-XNNN-LEM-RB-140.dxf”, “32005045_1102396269_20160708_1245.pdf”

Standard cylinder DSBC. [Festo www.page]. [Refered 25.1.2017]. Available: https://www.festo.com/cat/fi_fi/products_DSBC?CurrentIDCode1=DSBC-125-20-PPSA-N3&CurrentPartNo=1755619

Technical data M line factory. [Concept Laser www-page]. [Refered 17.1.2017]. Available: https://www.concept-laser.de/fileadmin/Neue_Produkte/1610_M_LINE_FACTORY-EN.pdf

Termotek GmbH Chillers. [Termotek GmbH www-page]. [Refered 13.1.2017]. Available: http://www.termotek-ag.com/en/products/chiller/products/11/#pt11

The MetalFAB1. [Additive industries www-page]. [Refered 17.1.2017]. Available: http://additiveindustries.com/systems/metalfab1

Vacon. 2014. Vacon 10 Taajuusmuuttajat käyttöohje. Doc: DPD01318F1. Vaasa. 100 p.

Valtanen, E. 2012. Tekniikan taulukkokirja. 19th edition. Jyväskylä: Genesis-Kirjat. 1200 p.

Valurautapesällä UCP UKP UCPA UCPH. [Laakerinetti www-page]. [Refered 23.1.2017]. Available: http://www.laakerinetti.com/pystymallit-pukki-valurautapesa-ucpa-ucph-c-51_82_91.html

Valves VUVG. [Festo www-page]. [Refered 23.1.2017]. Available: https://www.festo.com/cat/fi_fi/products_VUVG_S?CurrentIDCode1=VUVG-L14-T32C-MT-Q8-U-1K9L&CurrentPartNo=564212

Vem 2017. Electronic Catalogue. [Vem motors Finland www-page]. [Refered 13.1.2017]. Available: http://shop.vem-group.com/

Vierke, T. 2016a. AW: SCANLAB Website Contact Mailer [private email]. Recipient: Pasi Piispa. Sent 8.6.2016 o'clock 13.46 (UTC +0200). Attachments: "04_intelliSCANIII_scan heads.pdf", "13_varioSCAN+varioSCANde_EN_focusing systems.pdf"

Vierke, T. 2016b. AW: SCANLAB Website Contact Mailer_Budget_A_14377 [private email]. Recipient: Pasi Piispa. Sent 22.12.2016 o'clock 17.19 (UTC +0200). Attachments: "WaterCooling.pdf", "LUT_A_14915.PDF"

Vänni, K. 2016. RE: savukaasuimuri [private email]. Recipient: Pasi Piispa. Sent 19.10.2016 o'clock 15.50 (UTC +0200). Attachments: "Bofa Nano brochure (ID 30645).pdf", "Datasheet AD Nano+ (ID 145102).pdf"

Westphäling, T. 2016. AW: fiber laser for powder bead fusion [private email]. Recipient: Pasi Piispa. Sent 12.12.2016 o'clock 12.20 (UTC +0200). Attachments: "YLR-500-AC-Y14 Specification G22-29577 rev.4.pdf", "YLR-500-WC-Y14 Specification G22-15681 rev.5.pdf", "YLR-500-MM-AC-Y14 Specification G22-29607 rev.2.pdf", "YLR-500-MM-WC-Y14 Specification G22-29584 rev.5.pdf"

Wohlers, T. & Caffrey, T. 2016. Additive Manufacturing State of the Industry. Manufacturing Engineering, 156, (5); ProQuest. pp. 45-52.

YLR-AC 100-500W. [IPG photonics www-page]. [Refered 13.1.2017] Available: http://www.ipgphotonics.com/en/products/lasers/mid-power-cw-fiber-lasers/1-micron/ylm-and-ylr#[ylr-ac-100-500-w]