Tampereen ammattikorkeakoulu

Design of a wire electric discharge machine

Roni Ampuja

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Mechanical Engineering
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TIIVISTELMÄ

Tampereen ammattikorkeakoulu
Konetekniikka
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AMPUJA, RONI
Kipinälankasaha koneen tekninen suunnitelma

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Tässä opinnäytetyössä suunniteltiin pienikokoinen ja edullinen kipinälankasaha, jota voi hyödyntää esimerkiksi vino- ja suorahampaisten hammaspyörien prototyyppivalmistuksessa ja yksittäistuotannossa. Kipinälankasahat ovat metallintyöstökoneita, joita käytetään valmistamaan metalliosia ja työkaluja tiukkojen vaatimusten mukaan eri teollisuuden aloille, kuten esimerkiksi lääke- ja lentokoneteollisuuteen. Kipinälankasahoja käytetään tyypillisimmin valmistamaan osia, joilta vaaditaan kulutuksenkestävyyttä tai hyvää mittatarkkuutta. Myös tietynlaiset muodot ovat yksinkertaisempia valmistaa kipinälankasahalla kuin muilla vastaavilla valmistusmenetelmillä.

Monet pienet pajat ja yksityiset henkilöt eivät pysty hyödyntämään hammaspyöriä suunnitelmissaan tai prototyypeissä. Tuote, jonka valmistaminen vaatii myös hammaspyörien valmistamista, edellyttää usein suuria investointeja. Lisäksi suunniteltujen osien tulisi olla käyttökelpoisia heti ilman monia testauksia, jotta suuria kuluja voitaisiin välttää. Kipinälankasahat eivät ole tunnettuja tavanomaisessa tuotannossa, ja niiden harvinaisuus ja korkea hinta ovat tähän asti olleet kilpailukyvyn esteenä muiden tuotantomenetelmien rinnalla. Hammaspyörien lisäksi myös monet yksittäistuotannon työkalut ja muut apuvälineet, vaikkapa sorvin muototerät vaativat kovien materiaalien leikkaamista tarkasti. Kipinälankasahalle olisi siis käyttötarvetta erityisesti yksittäistuotannossa.

Hinta on ollut kipinälankasahan yleistymisen este, ja tämän opinnäytetyön tuloksena saadaan parempi käsitys, kuinka edullisesti kipinälankasahoja voidaan valmistaa. Opinnäytetyön päätuloksena tuotetun pienikokoisen kipinälankasahan suunnitelma toimii hyvin pohjana selvitettäessä lankasahaamisen kannattavuutta eri mittaluokissa. Jatkotutkimuksen näkökulmasta olisi kannattavaa tarkastella laitteen älyllisen puolen kehittämistä ja myös eri valmistusmenetelmiä, jos on tarvetta valmistaa useampia kappaleita.

Asiasanat: Kipinätyöstö, Koneistus, CNC, Lankasaha

ABSTRACT

Tampereen ammattikorkeakoulu
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Roni Ampuja
Mechanical design of a Wire EDM machine

Bachelor's thesis 40 pages, appendices 5 pages
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Wire electric discharge machine (Wire EDM or WEDM) is a material processing machine, which is used to produce metal parts and tools according to strict requirements for different industries such as medical and aerospace. Wire EDM machines are typically used to produce parts that require high wear resistance or good accuracy. Certain features are also easier to produce by Wire EDM, than by other similar production methods.

The purpose of this thesis was to develop a small and inexpensive Wire EDM which can be utilized in prototype and small volume production to produce for example both bevel and helical gears.

Low budget shops and manufactures are unable to utilize any kind of gearing in development for prototypes and concept testing. Producing a prototype with manufactured gears demands huge investment and requires design to be fail proof to avoid extra costs. Wire-cut EDM machines are far from being mainstream production devices. This scarcity and high price of the machines prevents Wire EDM from being a viable option of manufacturing. Many tools and jigs in prototype building require the ability to cut hard materials, such as Lathe form tools.

This Wire EDM design helps better understand how affordably Wire EDM machines can be produced. Design of this small size Wire EDM serves as a good basis for determining the profitability of Wire EDM in different scales.

It is worth paying more attention to machines electric control before making multiple copies, it is also advisable to utilize different production methods if there is a need to manufacture multiple parts.

Key words: EDM, Machining, CNC. Wire EDM

SISÄLLYS

SPECIAL VOCABULARY

EDM	Electric discharge machine
WEDM	Wire electric discharge machine
RamEMD,	SinkerEDM Or Conventional edm. Edm usually controlled by single axis machining for transforming negative and positive mould
EDMdrill,	Could also be referred as hole popper. Another type of single axis EDM preferred for deep hole drilling and start hole drilling for WEDM.
Dielectric	Electrical insulator which can be polarized. (Here usually used to refer the insulation properties of the dielectric fluid)
G-Code	Programming language for CNC and NC robots.
CNC	Computer Numerical Control Used for wide array of different robots and machines. Most commonly associated with material processing machines and robots programmed by G-code.
CAM	Computer Aided Manufacturing most usual meaning being for computer program used to generate g-code.
Servo	Electric motor with feed back loop for accurate positioning
FR,	Feed rate, speed of which cutting element or part to be cut is moved relative to each other
MRR,	Material removal rate, rate of material being cut by volume. usually given in cubic millimetres or cubic inches per minute

1 INTORODUCTION

EDM is material processing method which is not widely used despite first production capable machines being produced in 1960. EDM is wildly different from other machining methods which are used to produce different parts. Unlike milling, spinning, sawing or other cutting methods like waterjet EDM doesn't rely on mechanical cutting action to shape or form the part. EDM and particularly WEDM can be considered, to be close to laser or plasma cutting since these methods vaporize or melt the material accurately in the cutting point. The scientific phenomena which happens in the sparking process of EDM is not fully explained or understood yet although the mechanics of this action is predictable and can be controlled and tuned easily to pre-determined and tested values for different processing cases.

With the methods many advances such as extremely high accuracy and capability to cut any material that is conductive the slow nature of EDM process has been the common disincentive restricting its growth to become common method for normal part production in factories and in job-shops. As a mechanical device EDM is fairly simple and easy to use machine. For WEDM the negligible cutting reaction forces means much easier part fixturing compared to milling or grinding. In 2d and 4d cutting WEDM. takes the win of being more accurate than plasma, laser, or water cutting which means that a part that would need to be milled or grind because of high tolerance can be cut much easier with a WEDM.

2 THEORY

2.1 History

Very first occurrence of discharge machining dates back to 1770 when an English scientist, philosopher, theologian, chemist and a political theorist Joseph Priestley, presented his findings to the English royal society. In his papers was described how electrical discharge can erode metals. (Schofield (1997), 227, 232–38;) It is told that the development of first Edm:s started in 1940's. In 1943, soviet scientist B.R. and N.I. Lazarenko discovered that wear of the tungsten electrode could be controlled by immersion in dielectric fluid. Apparently at the same time in United States Jack Beaver, Harold Stark, and Victor Harding where developing an EDM to remove broke taps and drills from cast aluminium parts. By current knowledge the advancements where made independent from each other.

Earliest Wire EDM machines where punch-tape machines which used a computer to follow simple instructions punched into a tape. First versions and prototypes where converted from a milling machine. (imts history of CNC EDM) First wire EDM machine become available to the consumers in 1967. Which was developed in the Soviet Union. (American wire EDM early history of wire EDM) These first machines produced liaison in with Lazarenko operated in the resistance capacitance circuit principle. (imts history of CNC EDM) In 1971 Andrew Engineering company filed a patent of a type of WEDM machine which was able to produce a part tracing master drawing mounted to a glass plate. This very early version of a WEDM used an optical tracer and slave motors to cause an tungsten or other type electrode to be moved through workpiece. (United States patent n. 3,614,372)

Andrew engineering company's 1971 patent didn't actually describe a wire cutting through workpiece instead a solid relatively thick rod was used which could be slowly oscillated back and forth to induce even wear on the electrode. Tungsten was usually good choice for the electrode since it's resistance to wear. This machine was only small step away from what could be described as a wire EDM.

Running wire unmounting from a spool would have required minimal effort to incorporate into the machine and at the time with the technological improvements was fully feasible to implement.

2.2 Different types of EDM

There are three common different types of EDM ram, hole drilling and wire. In reality these machines can be companied to work as multiple machines with still being one physical machines. For example, hole drilling is easily done also with Ram EDM with an attachment of rotating head and some WEDM have a hole drilling attachment installed.

Photo 1. Old type Ram EDM with separate PCU (https://www.purplewave.com/auction/191016/item/FI9630 2021 2021)

Photo 2. Water drained out of WEDM (http://www.imsmfg-llc.com/page/wire-edm-8.html 2021)

Photo 3. Cheap EDM drill only for hole making (https://www.indiamart.com/proddetail/edm-drill-machine-15249154797.html 2021)

Ram EDM is commonly for mould making and might be least used of the tree different types of machines. Other than start hole drilling EDM drills are used to drill deep holes for example in turbine blades. In this thesis we are concentrating on WEDM which can be used purely to produce ready parts without the need of other machines. We'll be concentrating on developing cheap to manufacture 4axis WEDM mainly with the goal of lowering the bar for angular and bevel gear production which would allow hobbyist car enthusiast job-shops and motorsports teams to easily produce their gearing without the need for complex and expensive milling and surface grinding machines.

The cost of manufacturing single bevel gear is by conventional ways is much more expensive than using WEDM to produce a single part. The underlying benefit added to this is you do not need to hire or train personnel to use WEDM as it’s so simple to use. With WEDM you can cut the cost of milling machine, grinding machine and two operatives although when speaking at the scale of making gearing for a machine the milling machine is a must in other areas in this kind of production environment.

2.3 **Working principles of wire EDM**

Basic operation principle of a wire EDM is very simple. In practical terms wire EDM works on the same way as a jigsaw would work when cutting pieces for jigsaw puzzle. Differences here are that the saw blade is a consumable material which is unwound from a spool to provide new fresh cutting “edge”. Instead of mechanical cutting for example saw blade tooth wire EDM uses eighter electromechanical cutting method or electrochemical phenomenon to cut through work piece. In both methods an electrical potential difference in cutting wire (electrode) and workpiece is used. In electrochemical machining a chemical reaction is induced by high flow of amperage trough a cap in electrode and work piece. In electromechanical machining same theory applies but machining occurs by supplementing the workpiece and as a result also a tiny amount of the tool. Electromechanical machining uses sparking with the frequency of around 10khz each spark is forced trough nonconductive fluid in the (TOOLCAP) this results a heat around 8000-13000C. Tiny particles of bought tool and works piece are left to be flushed with constant flow of dielectric water. Tool is set to have the negative terminal from power source and workpiece positive terminal. This results in electrons moving away from the cathode and positive ions toward the cathode from the workpiece. Specific parameters and fine-tuning results in the optimal amount of material being removed from workpiece with minimal to none being welded back to the surface. Too high voltage or too high spark on time could result in wire breakage in WEDM. (Sciencedirect electrical discharge machining 2021)

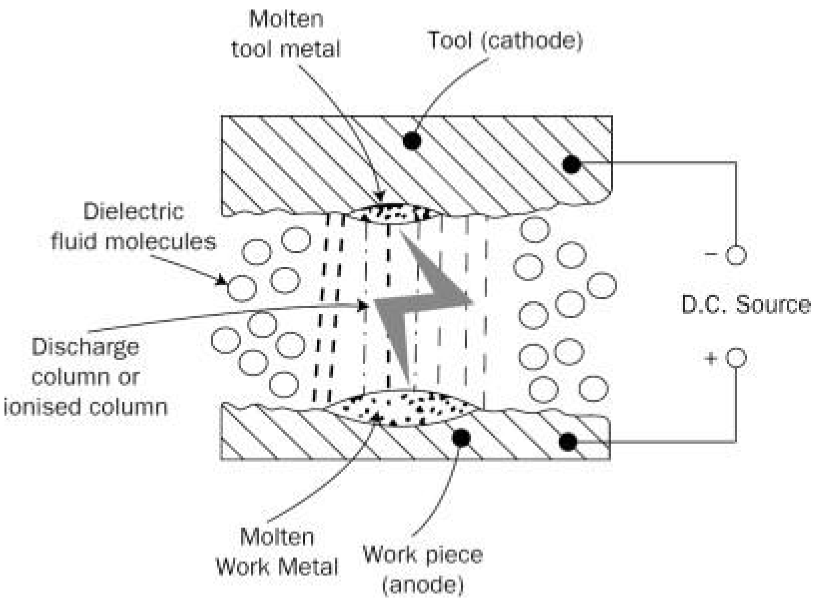

Photo 4. Visualization of Chip forming (https://ars.els-cdn.com/content/image/3-s2.0-B9780857091543500052-f05-01-9780857091543.jpg 2021)

2.4 **Types of wire used**

Incidentally WEDM tool electrode selection is driven by same factor as used to select EDM sinker electrode but contrariwise the materials are selected from opposite end of spectrum. Instead of high melting point a relatively low melting point is actually desirable for EDM wire. In mold making for sinker EDM it is optimal that the electrode would not wear and would maintain its structure and tolerance to produce part where minor features from the tool electrode are preserved. Wire in WEDM operates in different principle where the material which is being removed from electrode is hoped to sublimed quickly in order not to get tine particles stuck between the work piece and wire which does the cutting. (Sciencedirect electrical discharge machining 2021)

2.4.1 **Brass wire**

Brass wire is most common wire used. Alternation from this wire is usually only done for rare and specific reasons such as: Very small corner radius, no allowance for zinc or copper contamination, tight tolerance in wall straightness. Different hardness brass wires are available eighter for better taper cutting performance or to reduce barreling (The effect of wall curving due to wire deflection). Alloyed zinc in brass wire allows for higher cutting speed due to zincs low melting point. Unfortunately, brass wire with high zinc content is difficult to manufacture. Special method of diffusion-annealing has been developed to produce wire with zinc content of almost 50%. (Novotec-edm wire selection 2021)

2.4.2 **Copper Wire**

Used to be the only wire available, copper was chosen for its high conductivity but it hasn’t been shown to offer any particular benefit. Low tensile strength and low cutting speed caused the downfall of copper wire in WEDM use. (Novotec-edm wire selection 2021)

2.4.3 **Molybdenum wire**

Wire with high melting and vaporization point. Molybdenum’s high strength aids in the use of small diameter wire. Molybdenum wire is one of the options to go to when zinc or copper contamination is not allowed. Molybdenum wire can be used to cut very small corner radius features. (Novotec-edm wire selection 2021)

2.4.4 **Tungsten wire**

Tungsten wire is hardest wires to cut with, but sometimes may be the only option to use if very straight walls with high tolerance are required. Tungsten wire can also be used when copper and zinc contamination are not allowed. High price of tungsten wire also limits its use for only very special applications. (Novotec-edm wire selection 2021)

2.4.5 **Steel-core wire**

Steel-core wires are made to have high zinc content brass coating. This offers the steel wire the brass wire cutting capabilities and also has a high tensile strength which helps in making very deep cut's and lessens the occurrences of wire breakage. (Novotec-edm wire selection 2021)

2.4.6 **Coated wires**

Coated wires have a small coating usually of zinc to improve cutting capabilities. wire is coated either by Electro-galvanization or by hot-dipping. Electro-galvanization is more precise but also electro-galvanized wire is more expensive. (Novotec-edm wire selection 2021)

2.5 **Typical parts produced by wire EDM**

There are many reasons why WEDM would be preferred method of manufacturing.

Reason to use WEDM
1. Hard/tempered or difficult to machine material
2. Small internal corner radius/high aspect ratio
3. Multiple parts can be cut with stacking
4. Fragile part difficult to clamp
5. High precision/surface finish needed
6. Other small features such as very small slots or hex holes etc.
7. Easy lights out operation and otherwise very save to operate. Majority of crashes will only result in wire breakage and not damage the machine.

WEDM has many obvious advantages. Many manufacturing methods have some kind of downfall as does WEDM. Milling, turning and grinding is only possible if the tool is harder material than the part being machined. Harder tools are more expensive more fragile and slower to use. Milling and turning introduce high forces into the part being produced which requires bigger more rigid machine and often more complex mounting of the part. Grinding is more accurate and produces superior surface finish, some ferrite iron parts can be easier to mount with the use of magnetic table. Where grinding forfeits the game is in the material removal rate and complexity. Often only straight surfaces are grind. Multi axis grinding machines are expensive and are hard to use.

Cons of WEDM
1. Slow material removal rate
2. Certain topological limitations some shapes only possible from certain direction some not possible at all

If part is impossible to be manufactured with WEDM this does not mean WEDM couldn’t aid in the manufacturing process. Many parts have some feature that makes them easier to be produced with two different methods. Such as axle with keyway can be turned and the keyway cut with WEDM.

Photo 5. WEDM produced parts with small slots that would be nearly impossible to produce by any other means.
(http://www.precisionmachineryparts.com/supplier-387911-wire-edm-parts 2021)

photo 6. Gear teeth which require precision and have complex form can be cut with wire EDM and rest of the part can be machined with conventional means. (https://www.directindustry.es/prod/maedler-gmbh/product-66929-1572034.html 2021)

3 Design

3.1 Machine category

The goal of the thesis is to design and produce a 4-axis wire cutting EDM. There are multiple manufacturers producing wire cut EDM's yet affordable easy to use and small WEDM is difficult to find.
Along with the rise of consumer 3d printer's desktop routers, waterjets, laser cutting machines and even 5 axis mills have been produced for hobbyist and low level production shops.
The goal in this thesis is to produce a free-standing machine with 250mm x 250mm x 100mm work envelope.

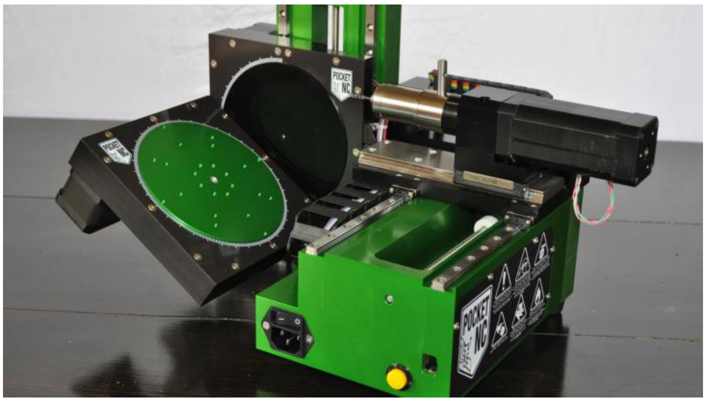

Photo 7. 5-axis mill for consumers.
(https://www.kickstarter.com/projects/1090944145/pocket-nc-the-first-5-axis-cnc-mill-for-your-deskt/posts/1509963 2021)

Photo 8. Desktop waterjet.
(https://fi.pinterest.com/pin/282179351453196487?nic_v1=1asoAGvLm6Z3lZgJw%2BJjPCdSNp%2FB%2F0vXui2XwH462kGgplx8S46kto0HHFx55Dagx6 2021)

3.2 Accuracy class

Most wire EDM machines are capable of working on sub-micron accuracy. Part 3d features are usually impossible keep at this level of accuracy. Only measuring display is under one micron.
Common difference wire EDM's must have compared to other CNC machines is the capability of reading code backwards in case of wire breakage to engage the material again.

Coal is to produce and design machine with mechanical composition that is capable of producing parts to 0.01mm accuracy repeatably.

3.2.1 Dynamic changes

WEDM does not experience a lot of forces or heat. Regardless some commercial EDM's have for example cooled ball screws since such a high precision is demanded. These allow the machine to be greatly more accurate and many times more accurate than milling machine would be even with cooled linear components. EDM's best feature is the low forces inside the machine. Dynamic compliances come from weight and wire tension.

3.2.2 **Necessary functions**

Maximum required rapid speed is 300mm/min.
Maximum required wire feed speed is 16000mm/min
Other required features and functions that need censoring are wire tension monitoring, spark cap monitoring, short-circuit monitoring and automatic g-code back tracking. Machine needs to be able to independently monitor the conductivity of water.

3.2.3 **Added functionalities**

Without a doubt the most complex extra function which the large industrial machines have is auto threading that was obviated from the design for its complexity, machine was build keeping easy hand threading in mind.

3.3 **Different designs**

3.3.1 **Tilting head design**

It was clear from the start that 4-axis could be done by two different ways. When moving table was count out because adding too much critical surfaces. If not casting a machine base the common frame plate is an obvious solution to keep most machine surfaces parallel or perpendicular. Tilting head would have an C type arc that dips in to the dielectric pool. This type of design has the benefit of not needing to make complex moving seals to the tank. Negative about the Tilting C arc has that it’s difficult to make centrical and it not being a common type of control would be more difficult to make.

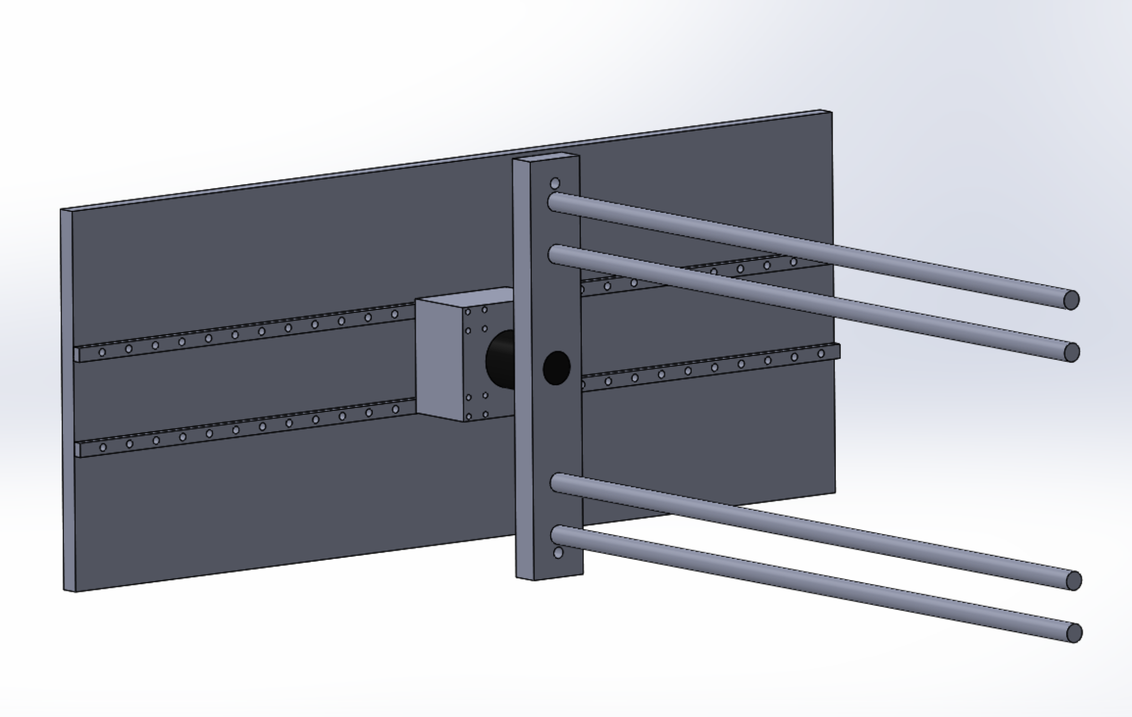

Photo 9. Representation of tilting C-arm (Roni Ampuja 2021)

3.3.2 **Indipendent gantryes desing**

Independence gantry design has two separate diamond guides that move in X and Y direction. Independent gantry design has the benefit of having less critical machine surfaces. The most challenging part is the dynamic sealing of the work tank. Design where upper and lower booms moved independently was chosen since it can be produced more accurately. This design is also closer to standard type of WEDM so control for this type of machine is easier to make.

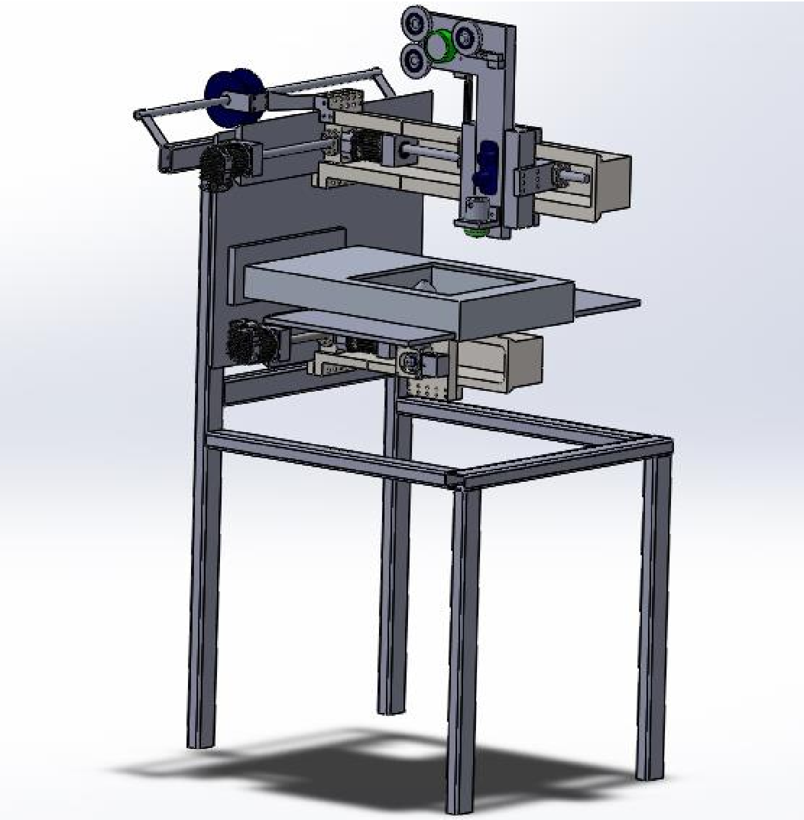

Photo 10. WEDM design with independent upper and lower gantry (Roni Ampuja 2021)

3.4 **Designed parts**

3.4.1 **Base Plate**

Machine will use one base plate where all critical surfaces can be done by single fixturing in 3-axismill.
Dovetail surfaces and table mount surface are designed to be on same plane so that they can be easily scrapped and tested buy engineers blue on granite surface plate.

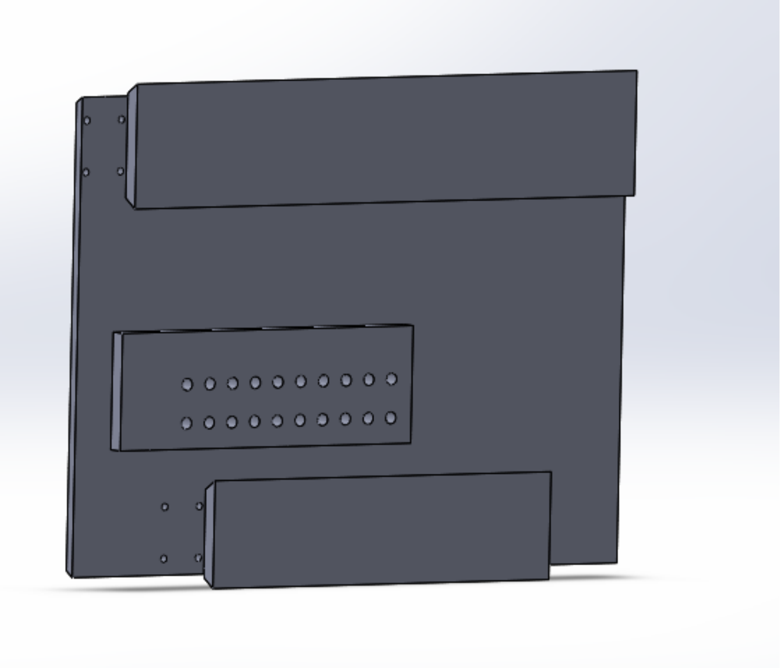

Photo 11. The two dovetails are easily machined barrel due to single fixturing. (Roni Ampuja 2021)

Photo 12. Base plate had to be done by manual mill since big enough CNC was not available. (Roni Ampuja 2021)

3.4.2 **Table**

All parts moving parts will be measured referring to the worktable, but this does not mean worktable is the dominating surface in assembling. The table is stationary in this design so with it having a single flat surface easiest to orient it with the other moving axis.
Table needs to withstand being submerged in water constantly. Stainless steel would be good choice for this but is very difficult to work on so to easy the prototype building aluminium was chosen instead. As a big block form aluminium ends up being cheaper especially when comparing price to volume ratio.
Usual sealing method is to seal lower boom arm trough tank wall, but this hardens the installation process of wire, sealing the tank at table level leaves the lower boom arm to be free.

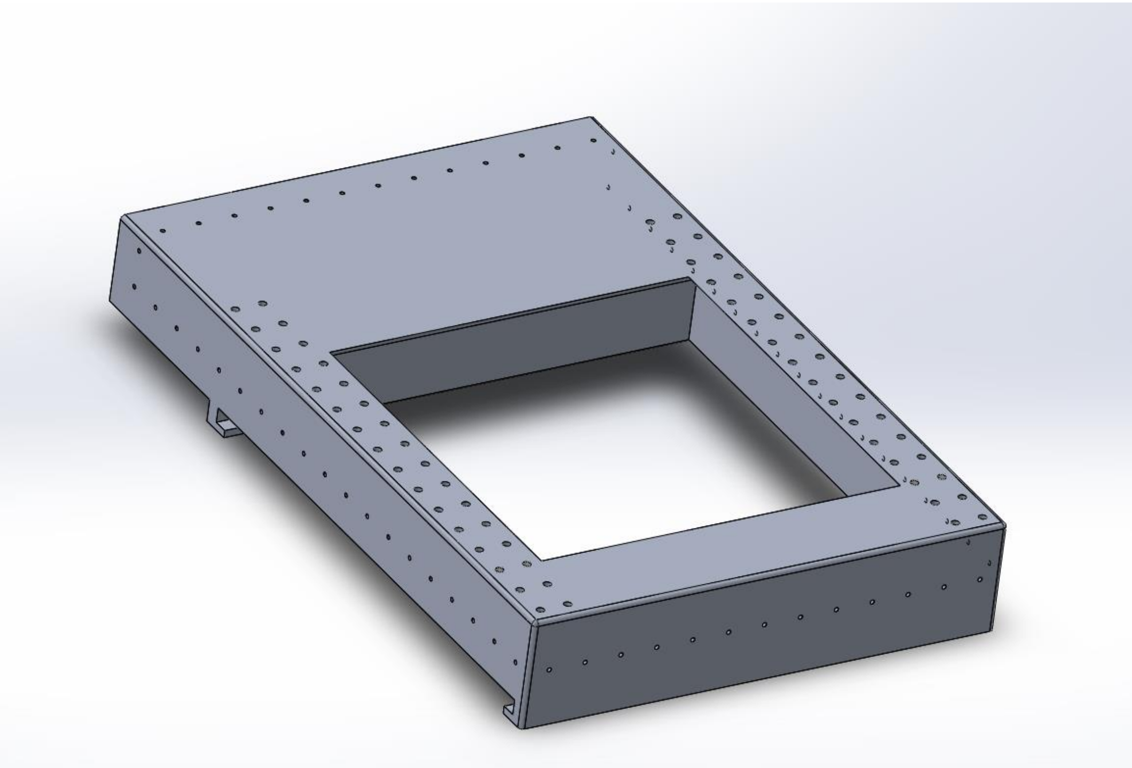

Photo 13. Aluminium table

3.4.3 **Linear Ways**

For budget reasons linear guides were neglected from the design and dovetail ways where used instead. Dovetails have the benefit of being very cheap if produced by self. Dovetails also have the freedom of making them as accurate

as desired in any situation. For this machine they are scraped to perfection for most accuracy.
It is common for industrial WEDM's to have the possibility to do compensation for the linear inaccuracies in ball screw travel this requires higher mathematics and complex code and for that reason accurate ball screws were bought instead. Compensation is easy to add later since it does not need any physical changes and leaving it for the future saved much time in this particular situation.

3.4.4 **Upper and lower boom**

The upper and lower boom are the two biggest and most important parts after base plate. Here they are designed in such a way that the critical surfaces can be machined by single fixturing. Boom dovetails as all other dovetails in this machine use 60 Degree dovetails. Booms also feature internal oil canals. The flushing of the cutting chips requires flushing cups close to the material being cut therefore z-axis adjustment needs to be inserted into the upper boom.
Z-axis adjustment in upper boom adds more special alignments that need to be set perpendicular to certain reference points (in this case orientated with the worktable) Lower boom only requires two accurate mounting angles which are 90 degrees.

Photo 14. Upper Boom (Roni Ampuja 2021)

Photo 15. Internal oil channels required long drills. (Roni Ampuja 2021)

3.4.5 **Ball screws**

Ball screws were chosen first with accuracy in mind. All options where with 5mm lead. Weight and movement speed determined the ball screws to be used. Contractors came with two options 16mm or 20mm which bought are exceedingly rigid and capable in this situation. In practice there is now use in optimizing to the lowest thickness, Savings are minimal and risk of creating a source of vibration increases. One thickness is used here which allows cutting from a one saw stock and unfirming different parts within the product itself.

3.4.6 **Z-axis moving element**

When adjusting z-axis up or down it should not change the cutting angle of the wire this would be the case if z-axis ways do not run perpendicular to x and y axis.

3.4.7 **Table sealing method**

Water sealing is big fundamental design challenge in WEDM since wire needs to run through the table and tank which holds water. Most commercial wire EDM machines have lower boom and gantry which is sealed. In this design sealing point was inserted right into the table which is easier to manufacture and cheaper to build.

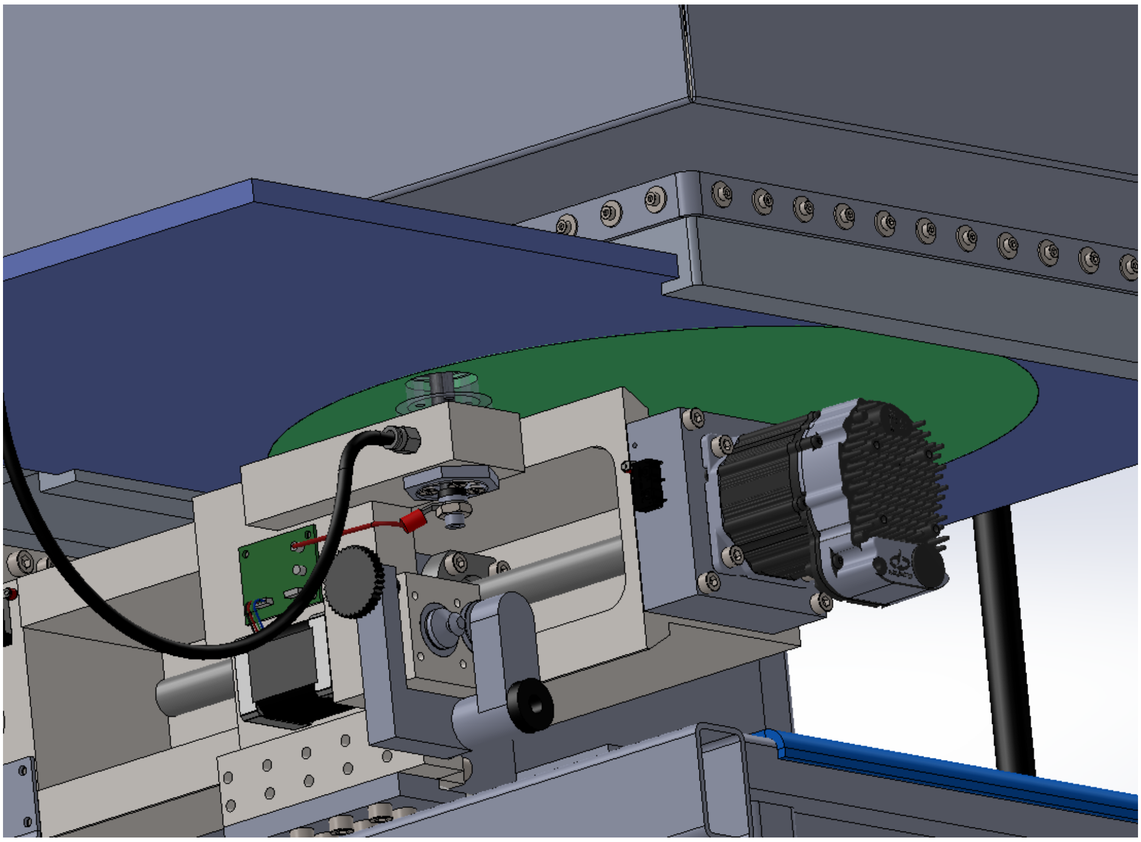

Photo 16. Large dynamic tank bottom plate (light blue) moves left to right (x-direction). Round plate (green) is mounted to the bottom plate with offset hole for lower wire guide. Round plate works as a cam with offset hole and allows y-direction movement. (Roni Ampuja 2021)

3.4.8 **Wire feed system**

Since part that is being cut is on the worktable and is connected to the ground the wire can only make contact to the ground trough the part. This requires the wire to be insulated from rest of the machine all the way from the spool to the collection bin. Mainly plastic insulator rings were used to insulate the wire. Wire feed system works by having a lower pull motor which pulls and unwinds the cutting wire all the way from spool. After the wire spool and before upper diamond guide there needs to be electrically controlled break to provide sufficient tension to the wire.

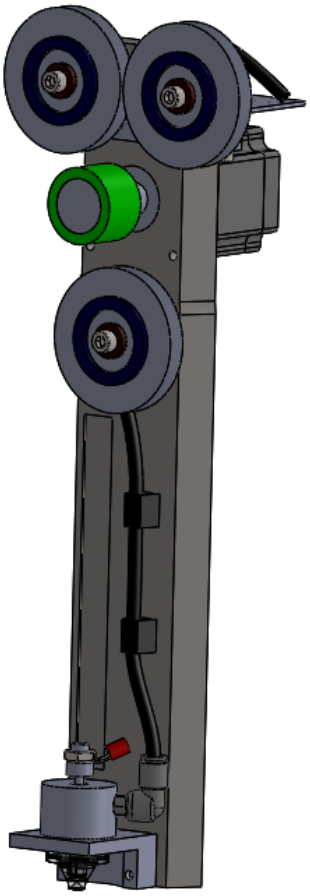

Photo 17. Upper wire guide and brake system. (Roni Ampuja 2021)

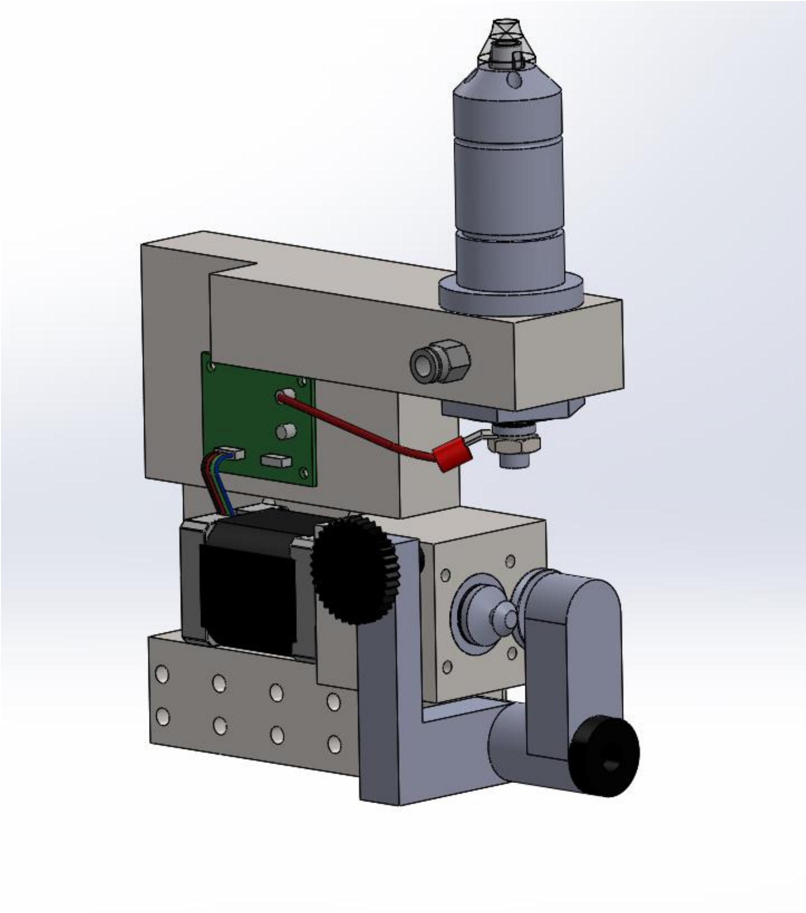

Photo 18. Lower wire guide and pull motor which controls wire speed. (Roni Ampuja 2021)

3.4.9 **Upper and Lower wire guide**

Since thousands of meters of wire will be fed through the machine and they need to be guided accurately small diamonds are used as guides. Sodick diamond wire guides are used in this design.
Wire also needs an electrical contact point so that electricity can be conducted in to the wire. This contact point is ideally as close as possible to the diamond guides so that there is not unnecessary resistance when traveling trough extra wire, this also needs to keep the wire cool and avoid expansion of the wire.

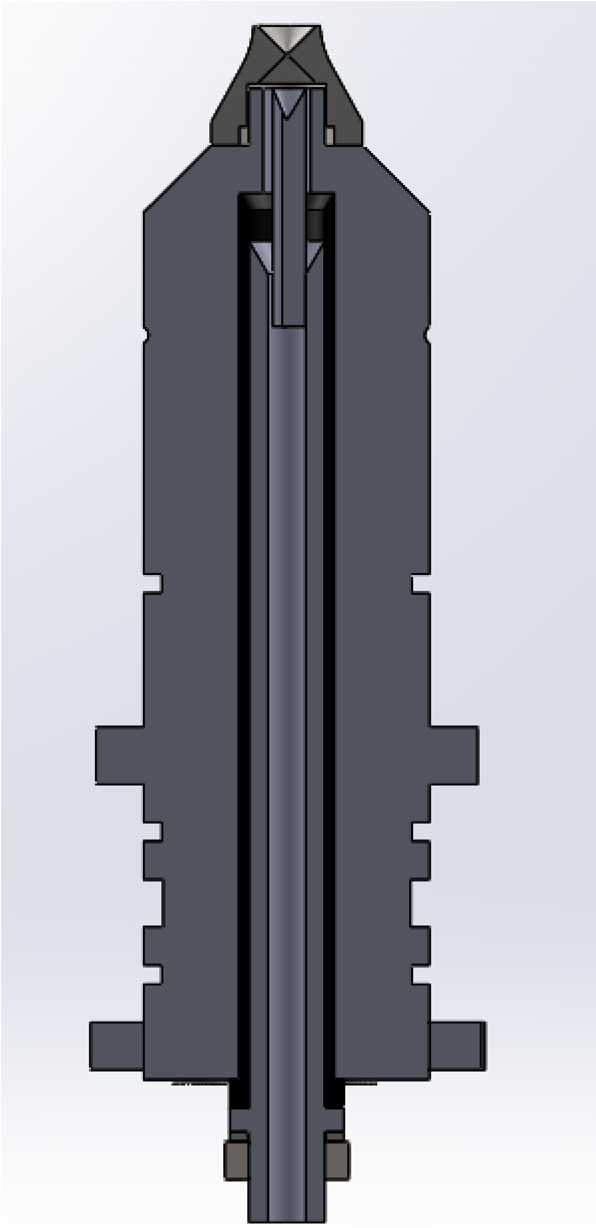

Photo 19. Half section view of the lower wire guide. Insulation needs to run from bottom all the way up to the diamond guide. (Roni Ampuja 2021)

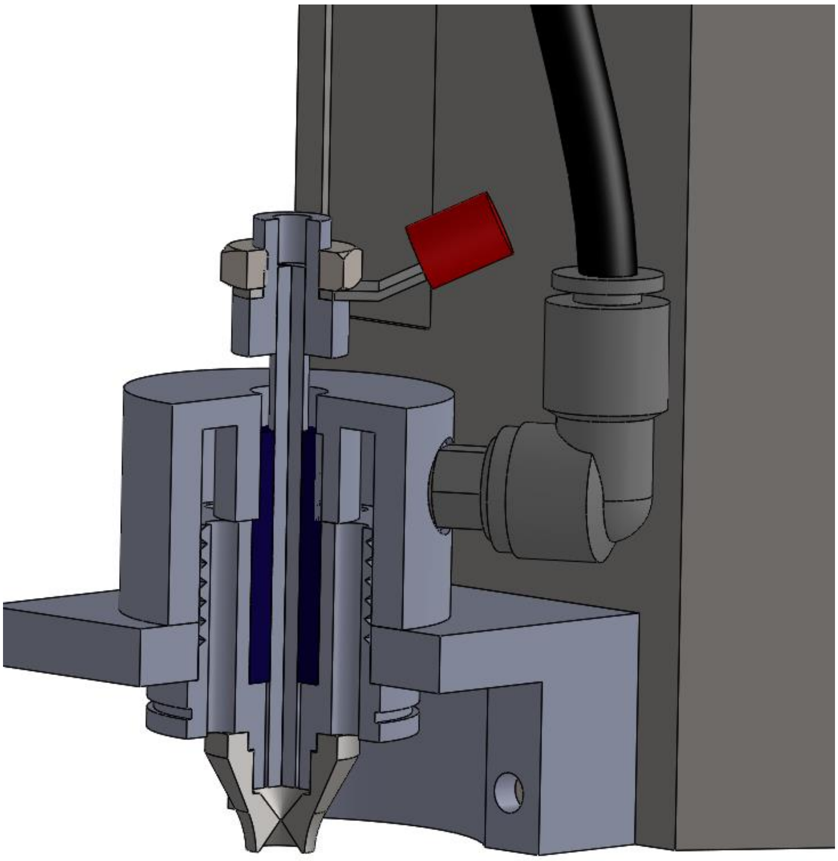

Photo 20. Quarter section view of the lower wire guide. (Roni Ampuja 2021)

3.5 **Calculations**

3.5.1 **Servos**

Ball screw lead, weight, friction, and direction relative to G are determining factors in required torque of servos when coupled with the mass to be moved and friction of the linear ways.
Required constant speed torque is calculated with formula.
(linearmotiontips.com how to calculate motor drive torque for ball screws 2021)

	$\mathrm{Tc} = \frac{M \cdot g \cdot \mu \cdot \mathrm{Ph}}{2\pi \cdot \eta}$	

Where Tc is the required constant speed torque
Where M is mass of the beam and mounted parts (kg)
Where μ is friction in dovetail ways
Where a is required angular velocity
Where Ph is lead of the ball screw
Where η Is efficiency of ball screw
Where g is acceleration due to gravity

Plain bearings have a friction coefficient of 0.05 to 0.1 (linear motor tips 2021) Best servos determined by availability easy of use and customer support were found in teknic. Here the smallest servo was a well within the required parameters. Same servo is used for uniformity and fact that lower quality option was not selectable. Teknic clearpath servo CPM-SDSK-2310S-ELN is capable of 1.6Nm peak torque and 0.3Nm constant. ELN comes with position resolution of 6400. Clearpath servo in itself is programmable and was extremely helpful feature to ease the coding and simplify the use by the fact that virtual positioning resolution could be set to 5000 to synchronize with 5mm lead in the ball screw resulting in one micrometre per step.

3.5.2 **Feed Motor**

Feed Motor pulls the cutting wire from wire spool by stepper motor mounted with rubber pulley. Feed motor must be abele generate 22 newton normal load to the cutting wire and be able to produce 8000mm/min wire feed speed.
Required Feed motor torque is calculated by following formula

$$\mathrm{Tf} = r \cdot Nw$$

Where Tf is required torque
Where r is radius of the feed motor pulley
Where Nw is required tension for cutting wire
Required Feed motor speed is calculated by following formula

	$Fw = \frac{Sw}{2\pi r}$	

Where Fw is the required revolutions per minute

Where Sw is the required feed speed

Attached calculations show that torque of 0.11Nm and turning speed of 255 rpm is needed. Nema 14 stepper motor is used for its small size. Most nema 14 are capable of producing previously mentioned values.

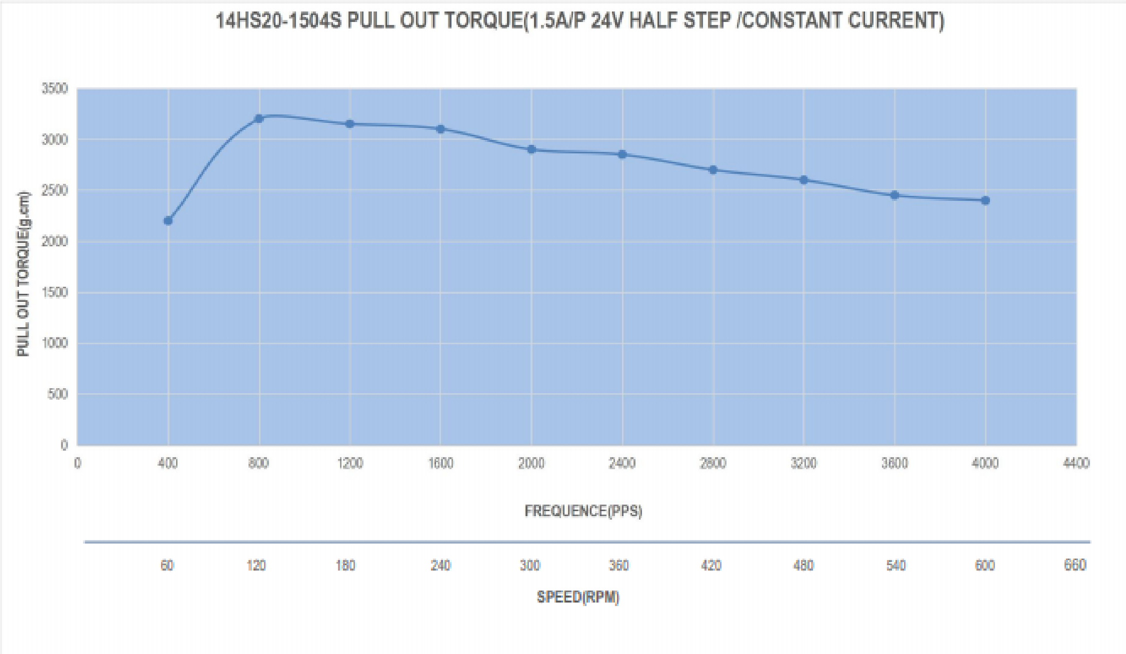

Photo 21. Torque curve of 14HS20-1504S nema 14 motor. Image shows that torque at 255 RPM is over the required torque. (https://www.omc-stepperonline.com/nema-14-stepper-motor/nema-14-bipolar-1-8deg-40ncm-56-7oz-in-1-5a-4-2v-35x35x52mm-4-wires.html 2021)

3.5.3 **Inaccuracies of the machine**

Ball screws are from Slovenian company called Tuli. Two ball screw were order and split to make four pieces all bought ball screws had an accuracy of 8μ per 300mm. Dovetails were scrapped against surface plate with deviation of 3μ. All parts can be expected to bend slightly in different loading scenarios to cause inaccuracies. Practical testing would be required to determine is accuracy of 0.01mm cross whole table feed obtained.

4 DISCUSSION

Machine was designed mostly manufacturing in mind. Attention was given also to the machines that where in use. Parts are designed with optimised cutting radius, length of cut to diameter ratio, required tool changes, Fixturing, and parts are also easy to machine with 3 axis capabilities.
For high mass production could be made by focusing on computer-controlled compensation and less accurate linear parts. Also casting would be preferable manufacturing method for some of the parts if multiple parts would be made.

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Attachments

Attachments 1. Calculation of required servo torques

Required torque to move upper X-axle

$M_{ux} := 22kg \qquad \mu := 0.1 \qquad P_h := 0.005m \qquad \eta := 0.95$

$$T_{cux} := \frac{M_{ux} \cdot g \cdot \mu \cdot P_h}{2\pi \cdot \eta} = 0.018\,N\,m$$

Required torque to move upper Y-axle

$M_{uy} := 6.7kg$

$$T_{cuy} := \frac{M_{uy} \cdot g \cdot \mu \cdot P_h}{2\pi \cdot \eta} = 5.504 \times 10^{-3}\,N\,m$$

Required torque to move lower X-axle

$M_{lx} := 15kg$

$$\frac{M_{lx} \cdot g \cdot \mu \cdot P_h}{2\pi \cdot \eta} = 0.012\,N\,m$$

Required torque to move lower Y-axle

$M_{ly} := 4.5kg$

$$\frac{M_{ly} \cdot g \cdot \mu \cdot P_h}{2\pi \cdot \eta} = 3.697 \times 10^{-3}\,N\,m$$

Attachment 2. Required wire feed motor torque and rpm

Required feed motor torque

$r := 5mm \qquad N_w := 22N$

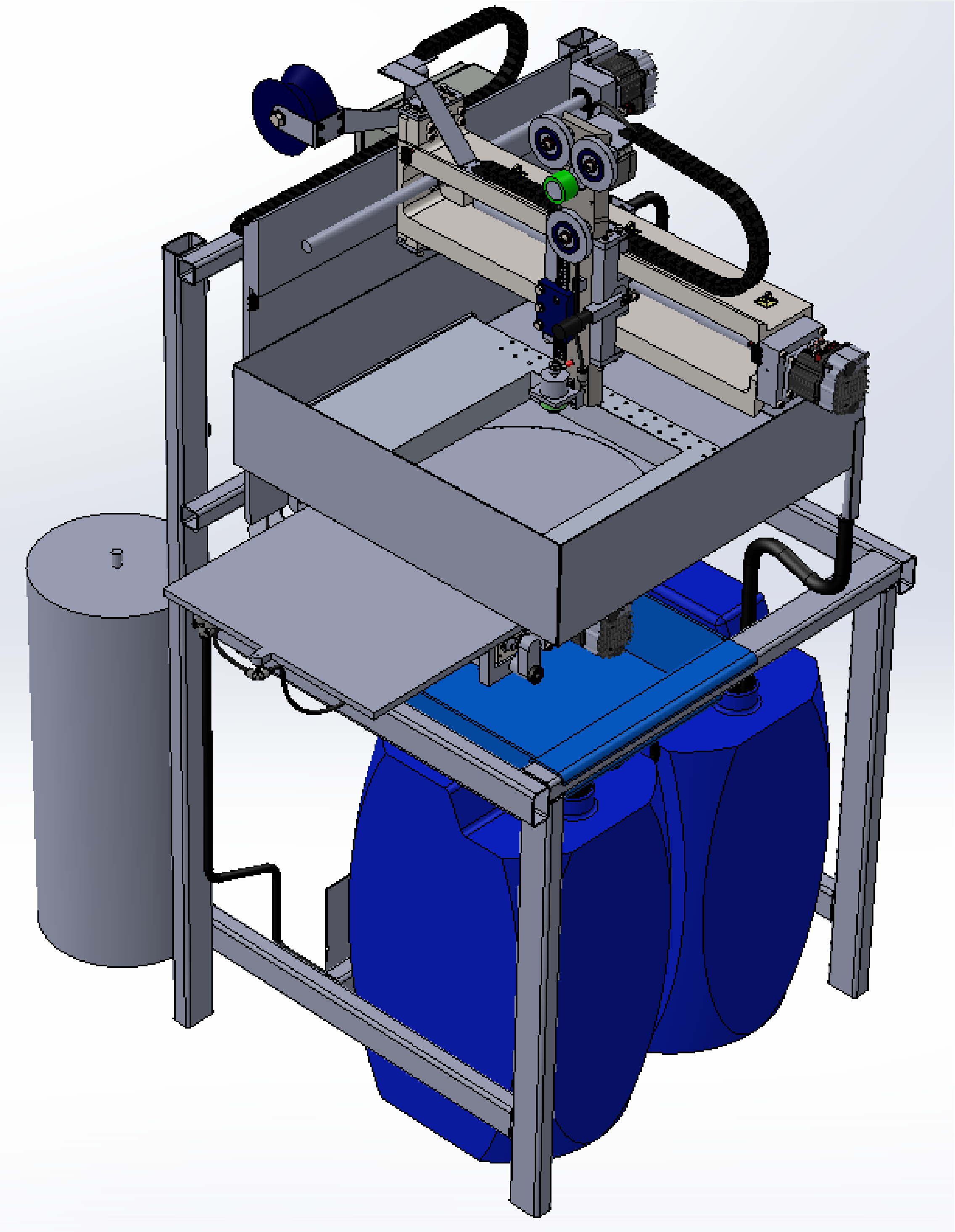
$T_f := r \cdot N_w = 0.11\,N\,m$

Required motor RPM

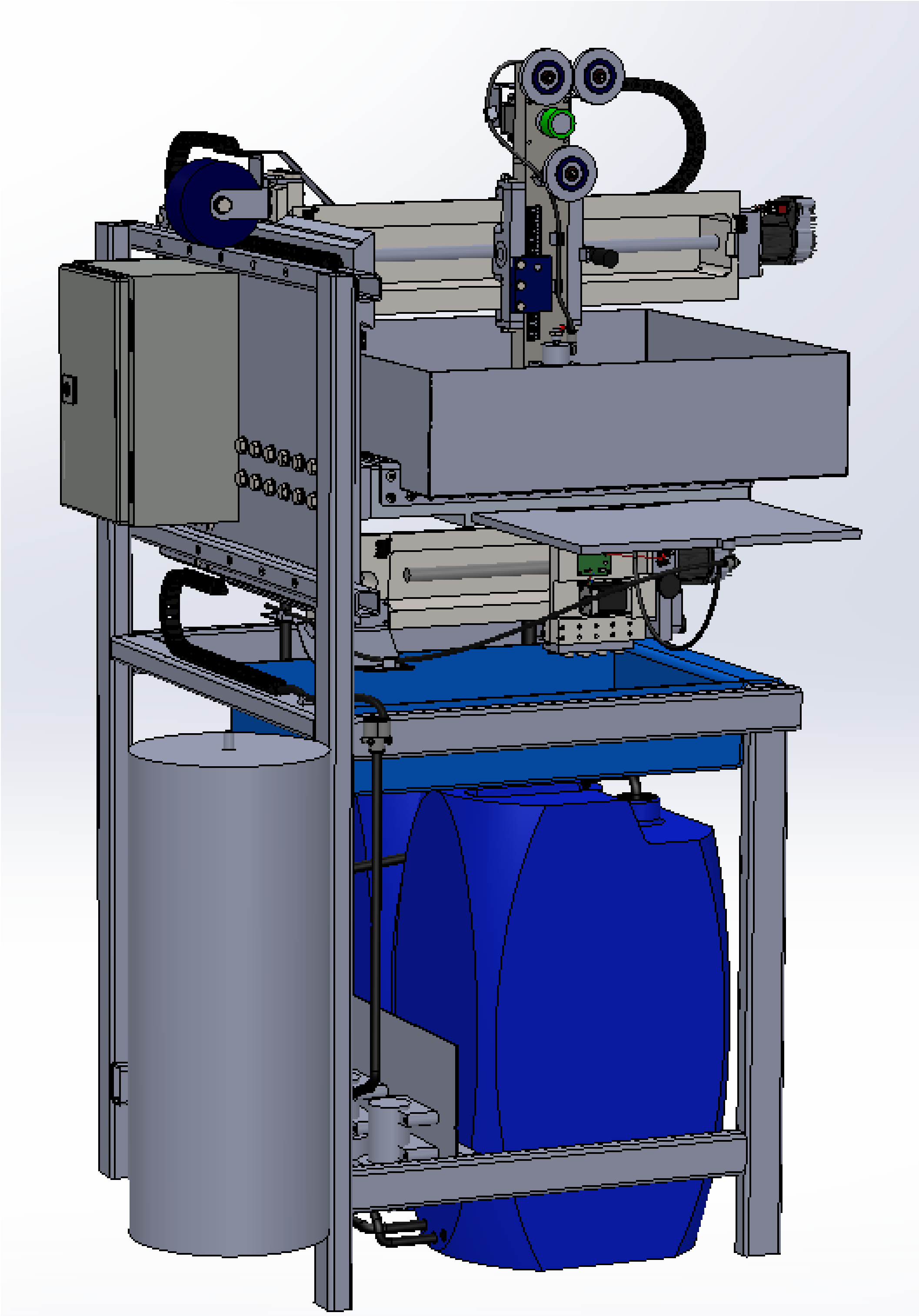
$$s_w := 8000\,\frac{mm}{min}$$

$$F_w := \frac{s_w}{2\pi \cdot r} = 254.648\,\frac{1}{min}$$

Attachment 3. View 1 of the machine



Attachment 4. View 2 of the machine



Attachment 5. View 3 of the machine