Adaptive CNC

Self-aware milling machine

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Abstract

CNC milling machines have long been a type of work that only experienced operators can handle. With many different setups, parameters, tools and materials, it becomes hard to manage and start milling. The risk of breaking the milling tool or the workpiece is high when the parameters are not correctly set. Moreover, tool wear is greater at wrong settings. This thesis questions if it is possible to monitor the milling process with simple sensors and hardware attached to any milling machine to warn the user and stop the machine before it breaks anything. Implementing this will make it less dangerous and simpler for any operator to use. Lowering the knowledge and experience needed to use a CNC milling machine making it safer, less expensive and more accessible.

Contents

List of Figures

List of Tables

Abbreviations

A/D - Analog to Digital

CAD - Computer Aided Design

CAM - Computer Aided Manufacturing

CNC - Computer Numerical Control

FDM - Fused Deposition Modelling

IC - Integrated Circuit

kNN - k Nearest Neighbours

OEE - Overall Equipment Effectiveness

PCB - Printed Circuit Board

PWM - Puls With Modulation

RPM - Revolutions Per Minute

SVM - Support Vector Machine

Acknowledgement

I want to thank my supervisor Mats Erling Høvin for all the great help and motivation during this thesis. I also want to thank my fellow students and my family for keeping up with me during the writing of this master thesis.

Part I

Introduction

Chapter 1

Introduction

1.1 Introduction

3D printers have in the last couple of years become a machine everyone can own and operate. From a part being designed in a 3D modeling program or downloaded from the Internet to become a part you can touch and feel. The way the 3D printer has gone from a machine that needs a lot of adjusting, repair and attention to a machine you can send a file over the network and take it out of the machine a few hours later complete without any setup. CNC milling machine has potential to do so many things since it can make parts from so many different materials the parts you get from the milling machine are often stronger and more durable than things that are 3D printed. This way you can use it not only as a rapid prototyping machine but also make strong replacement parts or new working things you need. However, CNC milling machines still require much knowledge of milling and tables of settings of what is necessary to get the job done. A common result of the wrong setup is that the milling tool breaks [7]. This is an expensive and potentially dangerous result that also can destroy the part being milled or worst case the machine itself. This thesis will examine the possibility to create a system that warns the user and stops the milling machine before any harm is done. This will result in a safer, easier, and more cost-effective milling-process. Moreover, will lead us in a direction where a milling machine will become a tool that more people will be able to use.

1.2 Motivation

Hopefully, where there is placed a 3D printer now, it will also be placed a CNC milling machine in the future. So students, hobbyist, makers, designers, inventors and other can enjoy the great results that a CNC the milling machine can give you. Moreover, people already using CNC milling machines could easily implement the design discussed in this thesis on their machines to make it more reliable and safe to use. Reducing the need for "babysitting" the machine when milling. This way we can have the same revolution of the CNC milling machines as we had with 3D printers. Moreover, it will give birth to new ideas and products we could not imagine before.

1.3 Goals of the thesis

This thesis will take a look at several things.

- The first being the possibility of making a CNC milling machine from the ground up with easy to get and cheap parts. Using 3D printers and laser cutters as rapid prototyping tools to make custom parts and minimal other expensive tools to get the job done. Keeping it simple and learn about this type of machine in the process.

- Second goal is to find a cheap and easy way to gather information from the running CNC milling machine that can be used to determine how the machine is performing. What type of sensor, and what kind of information to gather will be discussed.

- Third will be to find algorithms to analyzed all the data to find patterns in wrong behavior when milling. Processing time is a major factor for the system to be able to stop the machine before something goes wrong.

1.4 Outline of the thesis

This thesis consists of five chapters and will elaborate the process of making a milling machine and implementing learning algorithms to sense the machine's performance. The chapters are divided into (i) Introduction, that will give a light introduction to the thesis. (ii) Background, telling the necessary theoretical background needed. (iii) Implementation, where all the components are described, the building of the machine is explained and the implementation of the programming. (iv) Experiments, explains how the tests were conducted and the results are shown. (v) Conclusion, gives the results, the discussion and how future work could be done.

Chapter 2

Background

2.1 Previous work

The need for monitoring milling jobs are a big topic and is required in the industry today. This section will take a look at some work that has been done in this field of study. With the Overall Equipment Effectiveness (OEE) in mind as the factor that pushes this research forward.

$$OEE = SystemAvailabilityRate * PerformanceRate * QualityRate$$

OEE Describes how efficient a manufacturing process is. Moreover, the problem of tool breakage and tool wear is directly affecting the performance Rate and if tool wear is not attended to the effect of Quality Rate goes down as well. Significant research has been done on tool monitoring in turning machines, but not so much in the milling field [1]. Figure 2.1 show some of the options for sensor use on the CNC milling machine and some of them will be mentioned in this section. The measurement of cutting force is widely researched [8] [9] [10] and is often measured with dynamometers attached to the table of the milling machine with the ability to measure forces in three dimensions. This is proven to be very successful in finding relations between machining parameters and cutting force but is expensive and hard to implement. Shuaib et al [11] Used in his article a dynamometer to detect torsional strain between the spindle and milling tool with an electric wire strain gauge.

The other approach is to use spindle torque measured out of the current drawn by the spindle motor under load. Like Bertok et al [12] did in his

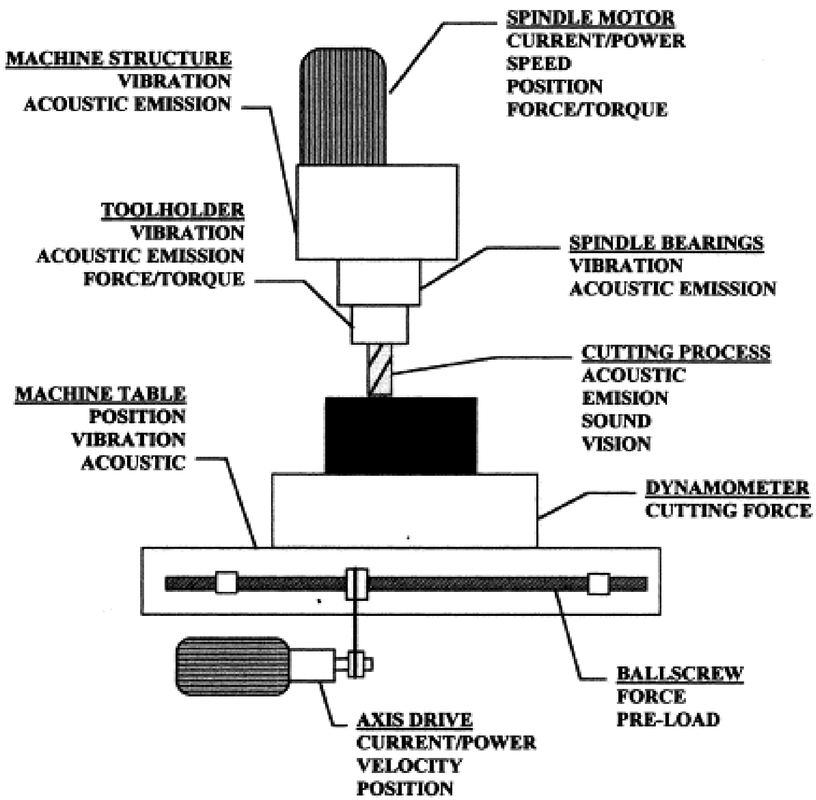


Figure 2.1: Different types of sensors and placement [1]

article where he made a model of the process to predict spindle motor torque. Moreover, then measure deviations from his predictions comparing them to the running machine to predict a fault in milling such as tool breakages.

Kim and Klamecki [13] used shaft vibration to find tool flank wear during milling. They found two components of the vibration. One natural frequency component and a forced frequency component. The latter one increased as tool flank wear increased.

Tlusty and Tarng [14] used both vibration and acceleration placed next to the lower front spindle bearings to measure tooth breakage. They found out that the vibration better gave an indication of tooth breakage than the acceleration could give.

Piezoelectric AE transducers is a sensor for high-frequency oscillation that occurs when metals are fractured or cut. AE transducers is a very efficient way of monitoring lathe work. Moreover, is tested on face milling as well [15].

2.2 CNC milling

CNC stands for Computer Numerical Controlled and is a way to make machines move its parts without a machine operator. Ordinary machines can often be converted into CNC machines by adding motors to the movable axis. This is a common practice and is often a cheaper solution than buying a complete CNC machine. Often you just take off the manual turning wheels and insert a motor instead, making this an easy conversion. There is a lot of different CNC machines available, Lathes, grinders, cutters, drillers. All of them remove material from the workpiece in various ways, making it a subtractive process. This thesis will concentrate on CNC milling machines.

Figure 2.2: A large industrial cnc machine shows the difference in size and form from a desktop CNC machine[2]

Milling machines are versatile and can be used in many ways to solve problems in the workshop. There are a lot of different types of milling machines in many different sizes. Figure 2.2 shows a large industrial CNC machine, this thesis will look at smaller desktop machines like the one in Figure 2.3, they often have more problems with vibrations and tool-breakage because they are not as sturdy as large industrial models. Milling is a cutting process using rotary tools to remove material from a workpiece. It is similar to a drill machine in that it can use the same tools and drill holes in the axis of the rotation of the tool. However, it can also cut at an angle of the axis. This is possible because the tool and workpiece can move in relation to each other. Movement of the machine is defined by how many axes of freedom it has. Normally a milling machine has three axes of freedom. More axis makes the machine more unstable, so sometimes it is better to flip the workpiece manually than to add a fourth axis.

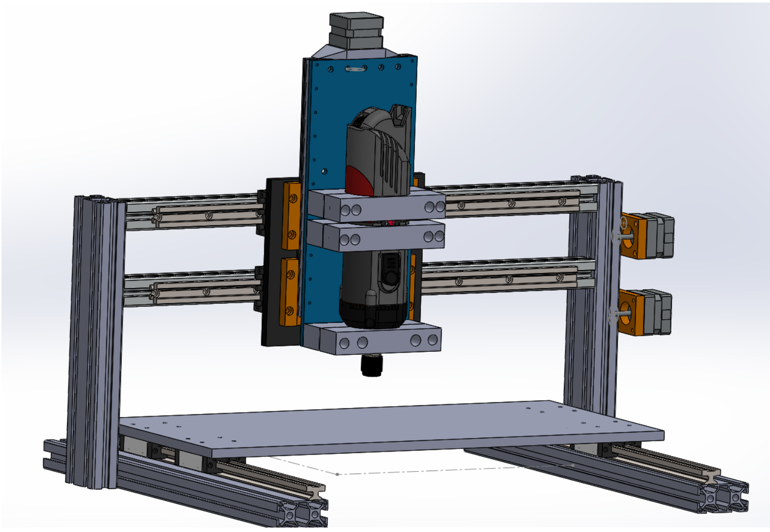


Figure 2.3: Model of the desktop CNC milling machine made in this thesis

2.2.1 Tool path and Gcode

The control over the movement is done with computer code called Gcode. Defined by Electronics Industry Association (EIA) in the 1960's [16] Gcode is a simple code with short commands telling the machine what to do [17]. An example of a gcode command is G01 x10 y10 telling the machine first with the G01 that this is a linear interpolation move. Moreover, it moves from where it stand now and to the new coordinate x10 and y10. By adding a F400 at the end of the line of code, it tells the machine that it should move at a speed of 400mm/min to the new location. There are also commands for spindle speed, coolant, moving in particular ways and a lot more [18].

Parameter	To slow	To fast	good balance
Spindle speed	use longer time cutting	burn the tool with friction	smoother sounds
Feed rate	wear out the tool by rubbing	can ”bite” and break the tool	even small chips

Table 2.1: Choosing the right parameters [6]

2.2.2 Milling strategies

Milling is the process of removing material from a workpiece with a rotating cutter. The objective is to shape a piece into the form desired. The material of the work-piece places a big role in what kind of strategies used. Milling in hard metals can lead to many problems. Things to take into consideration is.

- Safety
- Tool wear
- Surface finish
- Volume of material removal
- Heat
- Interaction with the machine

Time taken to make a part can be critical when in a big production, but other cases the finish of the piece is more important. Spindle speed, feed rate and type of milling are all features that affect the result [6]. Spindle speed is the RPM (Revolutions Per Minute) of the cutting bit and depends on the milling bit placed in the spindle. The feed rate is how fast the bit moves trough the material. Figure 2.1 shows a table of errors that can occur if the parameters are wrong. Skilled machinist calls the perfect balance ”the sweet spot” and it is where the machine is making only good smooth sounds. The ability to hear the sweet spot is one thing of what makes a good machinist. The look of the Metal Chips coming of the cut is another indication. They should be small and not long strains. The color of the chip is also a good indication[19]. The theory behind chips in milling operations is hefty and will be left out of this thesis.

When having so many different parameters and different machines to use. There are many possibilities for how the part get made. Moreover, finding the right way to do it can be hard. Optimizing the machine for the particular job is important for not breaking the machine and saving time. Different ways of milling as shown in Figure 2.4 cause different stress on the machine. Stress produces different sounds and vibrations. While the Plunge milling is causing most of the stress in the axis of the tool rotation leaving little stress sideways, the side milling causes much stress at a right angle to the axis of rotation. Side force makes the bit vulnerable to bending or breakage.

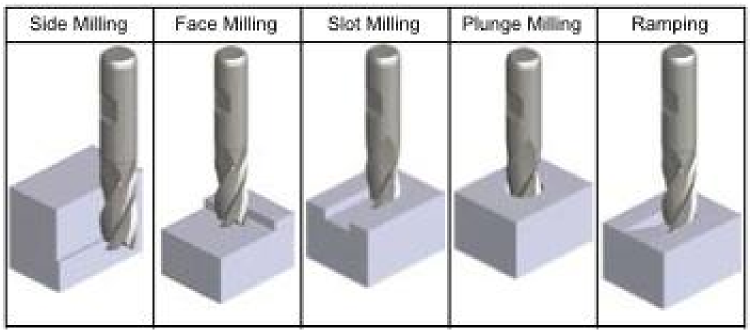


Figure 2.4: Types of milling strategies

2.3 Python

Python is a high-level programming language, with a large variety of packages [20]. The sklearn package [21] has all the most used learning algorithms implemented, this makes it easy to use and test different algorithms in the thesis. It also has a good implementation for sound manipulations.

2.4 SolidWorks

SolidWorks is a great CAD program with all the features needed to design. By great meaning that SolidWorks has almost become the standard when it comes to 3D design. From when the company started in 1995 it reached one million users in 2009 [22]. It also has the HMS works extension that makes CNC milling paths. Both of theses are essential tools for being able to make something with a CNC milling machine.

2.5 Machine learning

2.5.1 Sample data

For any algorithm to work, it needs some input. Learning algorithms require data in the form of samples to get smarter. Theses samples represent different scenarios that the machine may face later. The samples need to be constructed in a certain way, so it is usable for the learning algorithm to be able to build a suitable model of it. The data should represent the different classes or outcomes with close to an equal number of samples each [23]. Moreover, have little random noise that could lead to the wrong classification later. A Higher number of samples is good as it gives the model a higher chance of making the right predictions. It is also good as it usually gets split into two groups. One group is the training set and is used to build the model by trying to find a similarity between the different inputs and trying to fit this to the model to match the output. Fitting is usually done in several iterations until a criterion is met. Then the test set is used on the model. This set is unknown for the model and is used to measure the performance and accuracy [24].

2.5.2 Supervised learning

There is three main types of learning.

- Supervised Learning
- Unsupervised Learning
- Reinforcement Learning

They represent different ways of creating the model with different types of sample sets. This thesis will only make use of Supervised learning algorithms, so the two others will not be explained here but are mentioned to understand the concept and versatility of machine learning better.

Supervised learning has the benefit of knowing the answer to what should be the result of each sample when training the model. Here the data set contains not only samples but also a label for each sample. Labels give the algorithm an advantage and do not have to guess the answer, but can instead find a generalizing function to that answer right to the samples. The downside of supervised learning is that it is not always easy to make a big enough data set for the machine to train on since this usually has to be done by humans as it in in the case of this thesis. If the data set had an infinite number of labeled samples, it would not be any problem finding a suitable function, but the fewer the samples, the harder it gets generalizing the function. Fitting will be talked more about in the section about Over- and under-fitting.

2.5.3 Classification

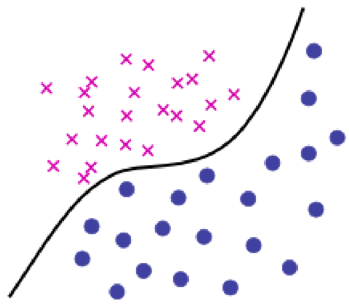


Figure 2.5: Model of classification [3].

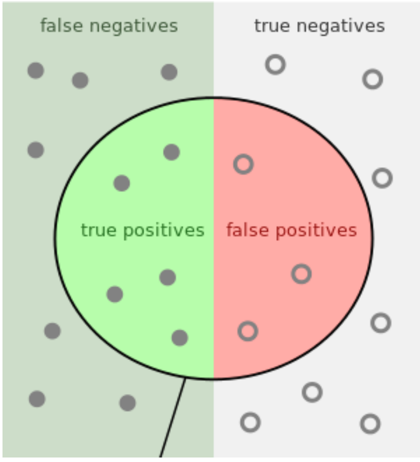
How samples get classified is what defines the learning algorithm and is an important part of machine learning. Classification is the prediction of where each sample belongs. In Figure 2.5 the circles and X's are the samples and the line is the classification function. The function tries to make a separation between in this case the two classes with the line as far away from the closest samples as possible, so the chance of wrong predictions minimizes. To measure how well the models is doing we have certain formulas to compare results with each other. In two-Class classification or binary classification, as is the case in this thesis the use of accuracy, precision and recall are used as well as F-Score. Figure 2.6a shows how the samples are categorized to explain the formulas.

$$Precision = \frac{tp}{tp + fp}$$

$$Accuracy = \frac{tp + tn}{tp + tn + fp + fn}$$

$$Recall = \frac{tp}{tp + fn}$$

$$FScore = \frac{Precision * Recall}{Precision + Recall}$$



(a) Visual representation of samples[25].

2.5.4 Over- and under-fitting

A big issue when the dataset is sparse, or the training gets to run too long is that the problem of over-fitting occurs. When the dataset is small, the problem of random noise can be overwhelming cause the training to fit the model to the noise as well. Noise causes the model to be overly complicated and not be generalized to the actual data. Figure 2.7 illustrates with a green line the over-fitted model. Moreover, the black line as a balanced model of the dataset. Under-fitting happens if the training does not get to work on the data long enough.

2.5.5 Feature selection

Feature selection is important for machine learning, it is what is used to segregate the classes and is the input to the model. [26] Benefits of feature selection[27]

- Increase classifier performance
- Reduce storage requirements
- reduce training time

Types of feature selector methods

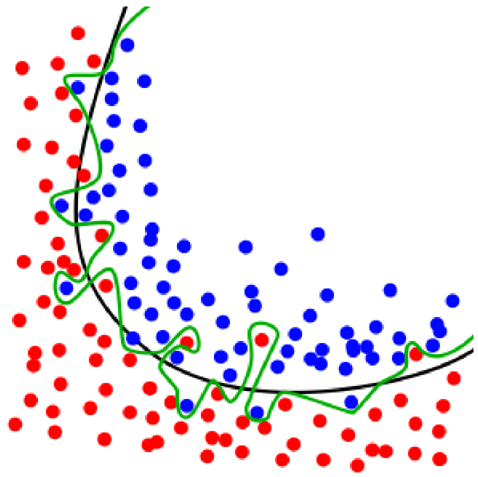


Figure 2.7: Illustration of over-fitting[4]

- Filters
- Wrapper methods
- Embedded methods

2.5.6 Support Vector Machine

Support vector machine algorithm is considered to be an advanced algorithm so that the presentation will be the general idea of the algorithm. When predicting new data, the algorithm tries to find out on what side of the decision boundary it lies on. Sometimes the new data lies to close to the border, so the chance of misclassifying the data becomes greater. The goal is to have the decision boundary as far away from the nearest data point in the training set, trying to maximize the margin of error. Cortes et al [24] wrote about the maximizing of margin is only a dependent of the dot product of the input vectors. To separate the different classes, the SVM algorithm can transform the data into a higher dimensional space where the data is easier to separate. Since the decision boundary is the only dependent on the dot product of the feature vectors the transformation function only computes the high-dimensional dot-product. The function that does this is called the kernel function and is a critical component of the SVM classifier. There are many different kernels to choose from. Using cross-validation is an automatic process for finding a good kernel [28]. SVM is a good classifier on reasonably sized dataset [29]. It is also very robust against high dimensionality and a low ratio of training examples to the dimensionality of the input data [30].

2.5.7 k Nearest Neighbours

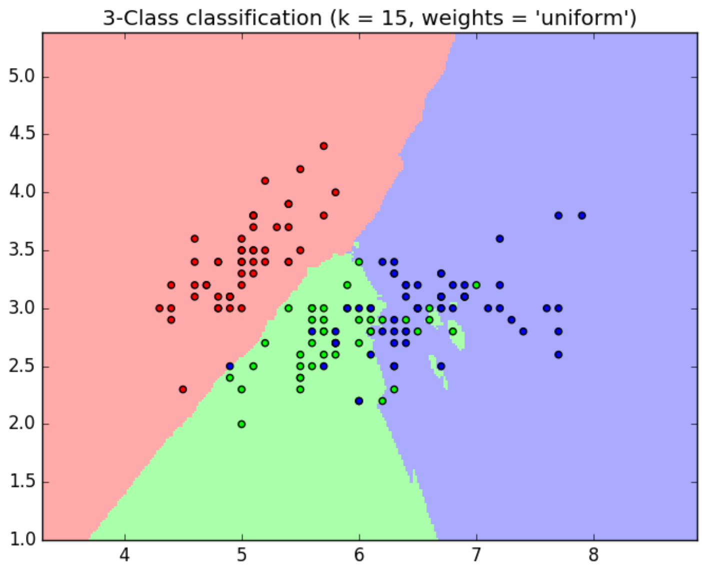


Figure 2.8: Picture showing the different classes in different colors in the feature space [5].

K-Nearest Neighbours is one of the more easy learning algorithms to understand. It is an instance-based or lazy learning, meaning it does not train an explicit generalization, but rather compares new problems directly with instances seen in training [31]. This also makes it a non-parametric method the way the parameters grow with the size of the training set [32]. This way there is easy to add more or remove samples from the model making it adopt while running. The downside is that this is very memory consuming. Training kNN is only to store the labeled feature vectors to memory. To classify a new unknown sample, the algorithm places the sample in the stored feature space and finds the nearest neighbors to the new sample. k is user defined and represents how many neighbors to check. The majority class of the neighbors gets assigned as the new samples class. Using some weighting scheme can help give better classification. A common weight is distance measurement; this helps if the set has many outliers. A common distance metric is Euclidean distance.

Part II

Implementation

Chapter 3

Implementation

This chapter will take a look at the different components of the machine, building the milling machine, and how to implement the detection software.

3.1 Components

3.1.1 Sensors

The milling process with a CNC machine can be very messy, noisy and cause many vibrations depending on different factors. All of this unwanted effects can be used to decide whether the machine is running well or not. A skilled milling operator can listen to the machine or look at the chips from the cut and tell if the machine is working well or not. Both the sound and vibration are movements of particles and can be measured in many ways. Microphones can be used to measure the sound frequencies. Vibrations are more complex with more components as displacement, velocity, acceleration, and frequencies [1]. Often used sensors for vibration are piezoelectric accelerometers. The usage of Driver current monitoring has also been used to measure breakage of the tool [33]. A contact microphone [34] could also be used, with the upside that it is attached directly to an object and hear only the sound vibrations of that object with no interference from surrounding noise. This type of sensor is not that common and is more expensive than a microphone. Using this will not give better sound samples because noise from the machine itself is so much higher than any surrounding sound, so the need for noise reduction is not necessary. A vibration sensor is so complex and not that easy to come by cheap types, so it will be left out of this thesis instead a microphone will be used as the sensor. The choice of microphone came down to the microphone installed on the Macbook Air computer. There is not much information available about the microphone. Because Apple keeps information like this to themselves. However, from testing the microphone, it proves that it can detect all the frequencies needed to make this test possible.

Either way, the sound has to be decomposed so we can gather more information. The amplitude alone is not enough to determine the machine condition because amplitude depends on so many other things as the type of cut, travel speed, and depth. Joseph Fourier found out that complex periodic functions could be decomposed to simple sines and cosines waves. Using this function called the Fourier Transform on the sound signal we get from the microphone, we can look at all the frequencies the machine is making and get a larger picture of what is happening. Now the algorithms have more features to work with.

With the standard microphone, we can measure frequencies from about 20Hz to 20kHz, but the built-in A/D converter on the computer is the limiter, with a sampling rate of 16kHz knowing the Nyquist frequency [35] we can only find frequencies half the sampling rate. So the frequency specter we will look into is between 20Hz and 8kHz. We can not look at all the frequencies by them self, that would be too much to process and would not be of any use either as no sound is perfect and will resonate in many different frequencies on either side of the main frequency. That is why we group them into bands. The size of the bands may affect the results. Using fewer and bigger bands gives faster computation, and more bands provide higher accuracy. If the difference between a good working machine and a bad working one is small in the frequency range, we have to use more bands.

3.1.2 Spindle

The spindle used on The CNC machine is a Kress 1050 FME-1. It has a very rigid axial with steel motor flange with double bearings, making it an ideal motor for the job. The choice of using this is because of the compact design. Long and thin is perfect for mounting to the milling machine. Other choices would be cheap spindle motors from China, but they often have a too low effect to work in this situation. Water cooled motors were also evaluated, but the need for more hoses and a water tank would make it bigger than needed.

Kress 1050 FME-1	
Watt	1050Watt/230V
RPM	5000-25000
Mounting	Ø 43mm
Sound Pressure	78dB(A)
Noise Power level	89dB(A)

Table 3.1: Specifications for the Kress Spindle.

3.1.3 Linear guide system

The guide system used in this machine is the DryLin T. It does not have ball-bearings giving it high dirt resistance and low vibration and noise [36]. The rail is made of hard-anodized aluminum making it strong and reliable. Other options would be ball bearing gliders; these come in square types or round types riding on round tubes rather than a square rail. The downside of those is space usage as they tend to ride higher from the base. This again gives loss in stability.

Figure 3.1: DryLin T glider used on the milling machine in this thesi.s

3.1.4 EasyDriver

The choice of driver for the motors came down to either the RepRap Driver with the A4988 chip or the Easy Driver with the A3967 chip. The choice of using the Easydriver was because it was available in the lab, and the knowledge of it was better than the RepRap driver. The EasyDriver is made by Brian Schmalz as an open source hardware project. The stepper motor driver is compatible with 4, 6, and 8 wire stepper motors of any voltage between 6V and 30V. It is compatible with any PWM capable device, runs currents up to 700mA/phase [37]. The decision to use the drivers is because they are known to work great with the stepper motors utilized in this thesis, they are cheap. Moreover, is also compatible with the GRBL software. If one breaks down under any circumstance, it is easy to swap it out for a new since it is a separate circuit board. They are known to break if the motor is detached while the driver is powered. The IC on the circuit board gets hot when in use, so a fan is attached to cool the drivers while the machine is running.

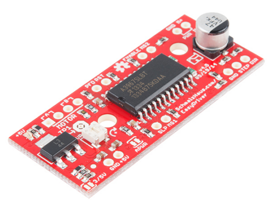


Figure 3.2: The stepper motor driver used is the EasyDriver shown here.

3.1.5 NEMA 17

Stepper motors from Mercury motors called NEMA17 stepper motors with bipolar coils and 1.8degree per step, it draws a max current of 350mA at 12V [38]. The motor are ideal for desktop milling machines because of the small form-factor and very stable radial axis with no give in the bearings, making it very accurate without external bearings on the ball-screw shaft. This minimizes the need for more parts. They are easily available and used in many other CNC builds making them well tested for this application.

3.1.6 ATmega328

ATmega328 microprocessor is a commonly available microprocessor found in many applications, also many homemade CNC machines [39]. The Arduino Duemilanove and other Arduino type prototyping-board use this chip. It is

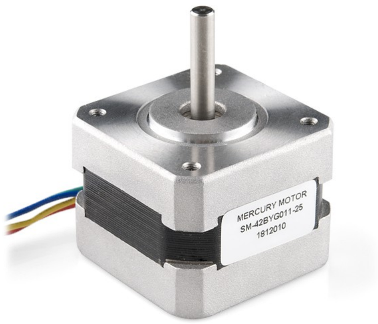


Figure 3.3: NEMA 17 stepper motor.

a very popular prototyping board for people not too familiar with programming with its programming IDE and language that makes it simple to get started with. However, is also a super versatile chip for advanced users with its many features. The GRBL program is made to run on this chip utilizing every smart integration the chip has.

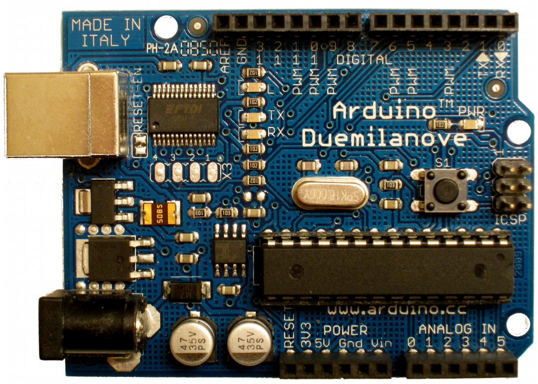


Figure 3.4: Arduino Duemilanove development board

3.1.7 GRBL and Universal Gcode Sender

Norwegian programmer Simen Svale Skogrud was the founder of GRBL and started the community that now runs as an open source project on GitHub under the leadership of Sungeun K. Jeon. This program reads Gcode sent from the computer and makes it into motion on the machine. It supports all the necessary Gcode commands needed for this project. With it written in optimized C utilizing every clever feature, the Atmel chips on the Arduino has to offer. It can run at 30kHz step rate making it very smooth. To send all this code to the GRBL, there has to be a program that can communicate with the GRBL program. Most gcode senders have support for GRBL. The Gcode sender I am using is called The Universal Gcode Sender and is an open source program made in Java to work with GRBL. It has all the features needed to run this milling machine. Especially needed are a stop function that can halt the machine at an instance; was implemented in the latest version of the GRBL software. There are many ways to make it stop. Using the pause/hold feature already written into the GRBL program is an effective way of making the machine stop when we want to [17].

3.1.8 Rapid Prototyping

Rapid prototyping is the process of fast development and design [40]. The idea is to design the part in a CAD (Computer aided design) program such as SolidWorks, Autodesk Inventor, 123D or others, and use this to get the part made physical and tested. This method of using software to aid in the manufacturing process is called CAM (Computer Aided Manufacturing) [41]. Making the part fast is done with 3D printers or laser cutters or other manufacturing machines. Available machines during this thesis are mentioned in Table 3.2.

Type	Name	Version
FDM 3D printer	Ultimaker	2, 2+, 3, Go
FDM 3D printer	Stratasys Fortus	250mc
Laser Cutter	Epilog Zing	16

Table 3.2: Prototyping tools

3.2 The machine

Making a CNC milling machine from scratch was a decision made, so there is more control over every part of the machine. This way you learn all the weak spots of the machine. There will always be some places where the machine is flexing or bending more than other locations. This gives errors and flaws in the part and vibrations in the machine. Knowing where this weak-spots are there is easier to measure sound and vibrations later in the process and try to eliminate the known errors. Several designs of CNC milling machines were studied before building this machine. The number of axes was discussed. What was the number needed to be able to do the tests. Fewer axis makes it easier to build, and more sturdy. If the machine is sturdy, it will not bend or flex as much, and it will be harder to measure sound and vibrations later. With fewer axis, there is not possible to run all the milling strategies. To make a plunge cut the machine needs a Z axis. Moreover, to face- or side-mill it needs X or Y axis. This is why most milling machines have three axes. This makes the machine very versatile. However, keeps it strong and compact for better precision.

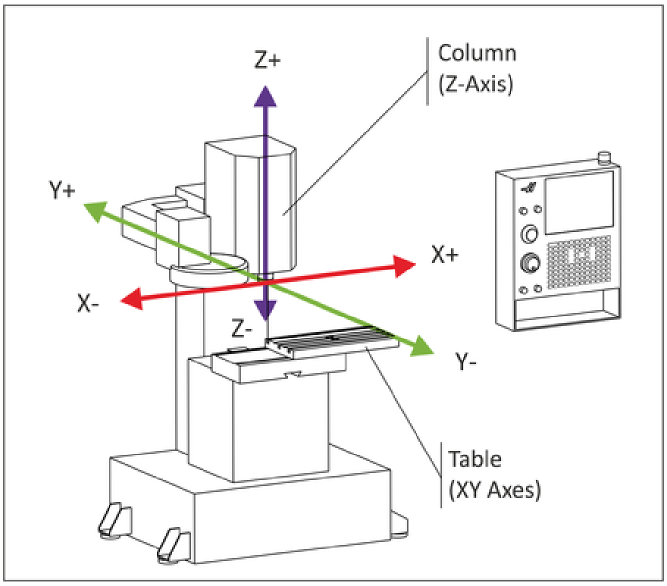


Figure 3.5: The coordinate system of a CNC milling machine

Several iterations where made on the design of the machine trough the design process shown in Figure 3.6. Discovering weaknesses along the building process made for alternative variations of the design. In all there where four iterations of the machine, all with there own strength and weaknesses. Available parts were a big factor in how the design came out.

Some key features the CNC milling machine should have.

- three axes of freedom
- available parts
- able to cut hard plastic
- able to cut soft metals
- made to fit the Kress spindle motor
- compact
- large work surface
- rigid

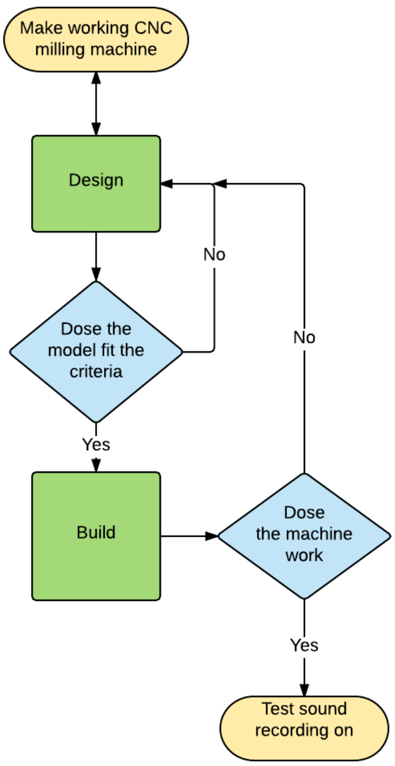


Figure 3.6: Design Process

3.2.1 Design 1

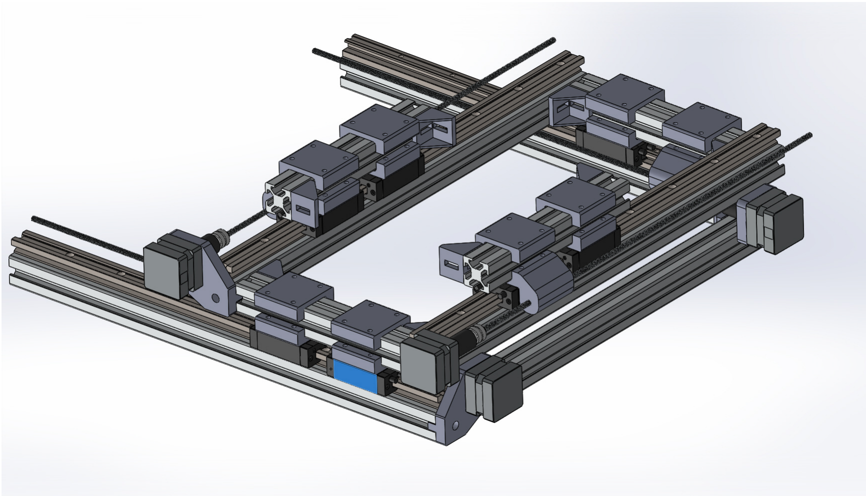


Figure 3.7: First design

The first design was a flatbed where the use of aluminum extrusions where the main building blocks. To fasten these together with the use of angle brackets were used. Motors were attached to the side of the carriages. Here the Y axis rides on top of the X-axis, a very common design. The problem with this is that all the weight of Y axis is on the X axis gliders, and has to balance on the width of the gliders from the X axis. Making it more unstable. The compromise here is travel distance vs. stability. Z-axis placement is the challenging part of this design, and with the argument to keep the machine compact the first idea of having a large overhanging gantry was out of the question. Table **??** shows the criterion for the design and what design one did not accomplish and that is why this design was stopped.

3.2.2 Design 2

The second design was made to better compensate for a Z axis. Now the whole system was raised up, and a big "box" was added under the X/Y axis. The Idea of this design was to keep all the dirty, dangerous parts inside the box to make the machine cleaner and safer to work with. With all the rails and ball screws over the spindle, the chance of getting debris in sensitive

Criteria	
3 axis of freedom	NO
available parts	YES
able to cut hard plastic	not tested
able to cut soft metals	not tested
made to fit the kress spindle motor	NO
compact	NO
large work surface	NO
rigid	YES

Table 3.3: Criteria for the first design

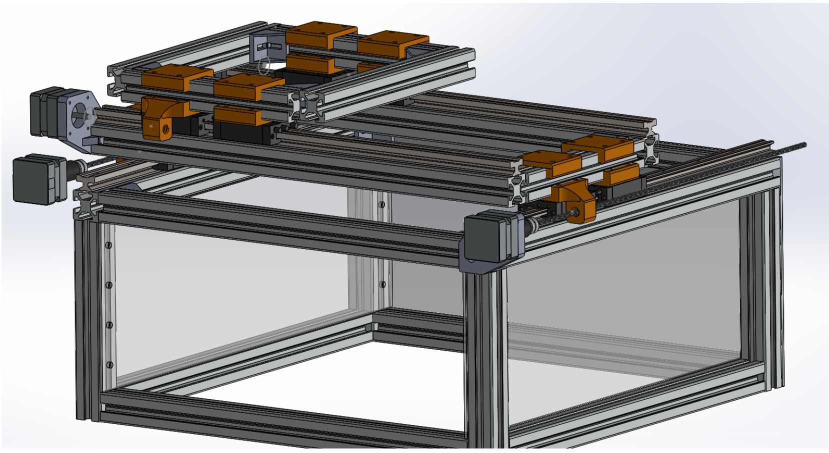


Figure 3.8: Second design

parts is less likely. Z axis was supposed to go inside the square box on top Figure 3.8. However, even tough the spindle motor is small there was no room for the Z axis inside that square.

Other reasons not to use this design is shown in Figure 3.9. Parts displayed in Orange is custom 3D printed parts made to support the aluminum extrusion bar on top of the glider, and also work as the fastener for the ball-screw joint. These parts were not robust enough to carry this much load. Moreover, it also made the machine much higher as seen in Figure 3.9 they raise the system up a few millimeter, this results in a more unstable machine. So these parts were scrapped.

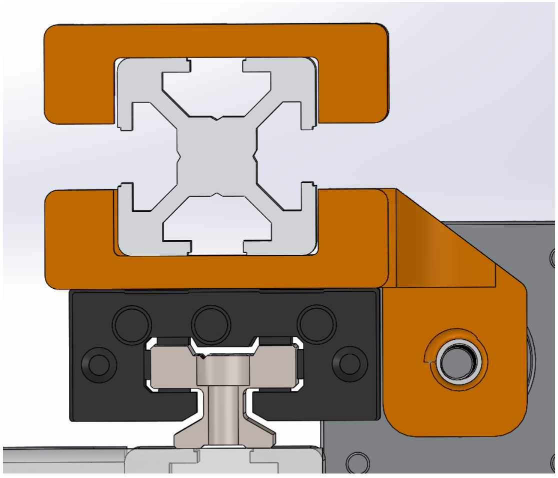


Figure 3.9: Closeup of the problem with the design

Criteria	
3 axis of freedom	YES
available parts	YES
able to cut hard plastic	not tested
able to cut soft metals	not tested
made to fit the kress spindle motor	NO
compact	NO
large work surface	YES
rigid	NO

Table 3.4: Criteria for the second design

3.2.3 Design 3

Trying not to have 3D printed parts as the main construction but use other methods and materials, design three became very different. Now the X and Y axis is separated. The X axis is at the bottom moving the work-surface. With four glider spaced far apart in all directions makes the work-surface very stable.

As Figure 3.10 shows a gantry is placed to hold the Y axis over the moving work-surface. With this, both glide rails for the X and Y axis is statically attached to the same construction making it very stable. The X axis only has to move the weight of the workpiece and the work-surface.

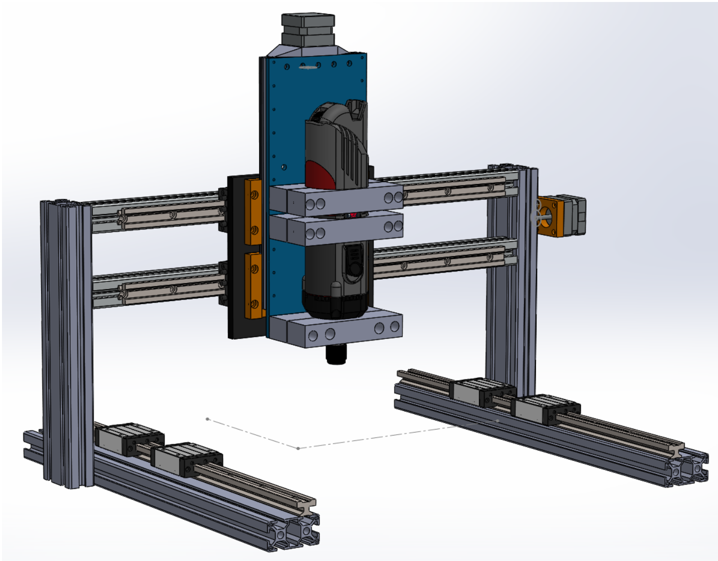


Figure 3.10: third design

The Y axis moves the weight of the Z-axis and spindle motor dividing the weight, so the motors do not have to work as much.

The work-surface is directly attached to the gliders and ball-screw fasteners with no weak 3D plastic parts in between. Same goes for the Y axis, where the bolts in the gliders of the Y axis is attached to the gliders of the Z axis. With only a strong laser-cut acrylic plate in between the gliders. So the force is directly transferred trough the machine via strong parts.

When testing the design, the weakness was shown to be the guide rails of the X axis was too far apart, so the work-surface flexed in the Z axis when force is applied in that direction.

3.2.4 Design 4

Figure 3.11 shows the final result of the milling machine. With the X-axis and Y-axis not connected you get a more stable construction with no sacrifice in the workspace. The design is as compact as it can be, with the workspace not much smaller than the machine itself. The gliders in the X-axis is moved closer together from the previous design to make the work-surface not flex as much in the Z direction.

The weakness of this design is the Y gantry. It has the most flex in the

Criteria	
3 axis of freedom	YES
available parts	YES
able to cut hard plastic	not tested
able to cut soft metals	not tested
made to fit the kress spindle motor	YES
compact	YES
large work surface	YES
rigid	NO

Table 3.5: Criteria for the third design

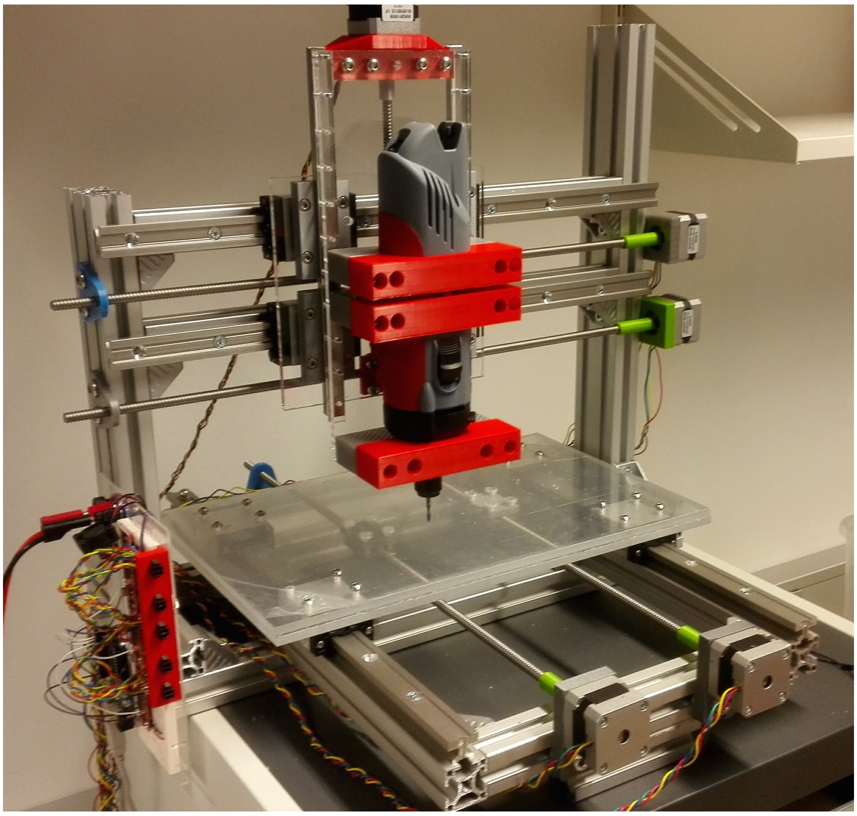


Figure 3.11: fourth design

direction of the x-axis. This is the weakest part of the design and can be improved by making a bigger gantry up from the base plate. When testing it is more likely that running in the X direction will cause more vibrations

Criteria	
3 axis of freedom	YES
available parts	YES
able to cut hard plastic	YES
able to cut soft metals	NO
made to fit the kress spindle motor	YES
compact	YES
large work surface	YES
rigid	YES

Table 3.6: Criteria for the fourth design

than running in the Y direction.

3.3 Wiring

The wiring of the machine is shown in Figure 3.12 where you can see that there are two stepper motors for the X-axis and the Y-axis. This is to make the machine stronger and also to reduce the chance of the machine jamming on the diagonal. This can occur if there is only one motor and the rail is far apart. Wiring is simple when all the components come on separate PCB's with all the inputs and outputs labeled. This also makes it easy to change out the parts if they are broken. With the motors using 350mA max at 12V the Easy driver with a max draw of 2.5Amps at 12V can run two stepper motors at the same time.

3.4 The Programming

The thesis consists of several small programs design to do specific tasks. Here are a list of the most important ones.

- Program for recording test samples of sound from the machine in different milling jobs. The program was designed to record small samples of 5 seconds and with the possibility of labeling each sample.

- Program used to convert sound data and test the samples on different learning algorithms. This program was used to determine if the

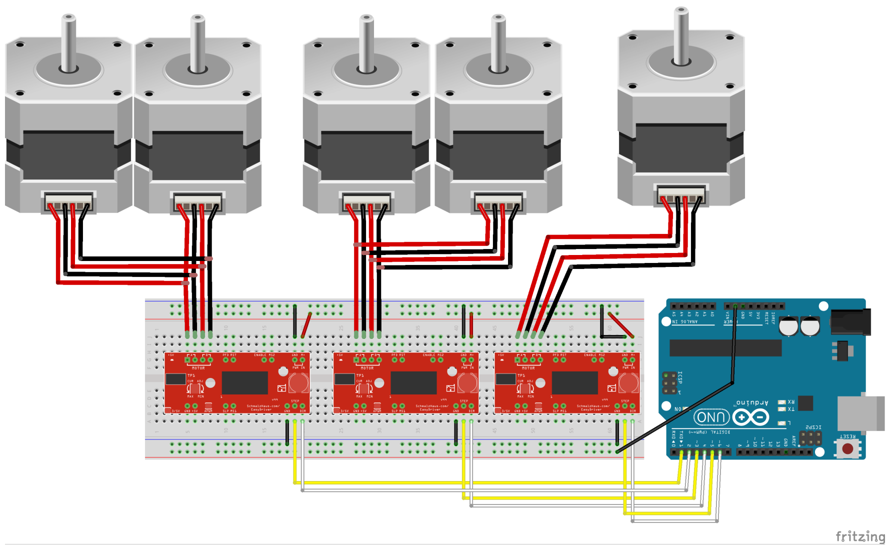


Figure 3.12: Wiring Diagram

hypothesis that a learning algorithm could classify the samples.

- Program used to run beside the machine and analyzing sound real time while the machine was working.

3.4.1 Learning algorithm

The learning algorithm was made to be used separately from the machine not running live to see if it was possible to classify the different milling-patterns of the machine and detect if something went wrong with the machine. Figure 3.13 shows the iterations of learning, where each algorithm gets evaluated after each run to see any progress before either tweaking the parameters or changing to another algorithm.

3.4.2 Real time analysis

The real-time analysis system is made to be implemented on the CNC milling machine to run in real time while the machine is milling. The system needs to be fast to be able to predict if somethings goes wrong before they do. With a microphone connected directly to the computer running the analyzing software, the response time goes down. If the computer detects something wrong, it immediately sends a stop signal to the Arduino telling it to shut

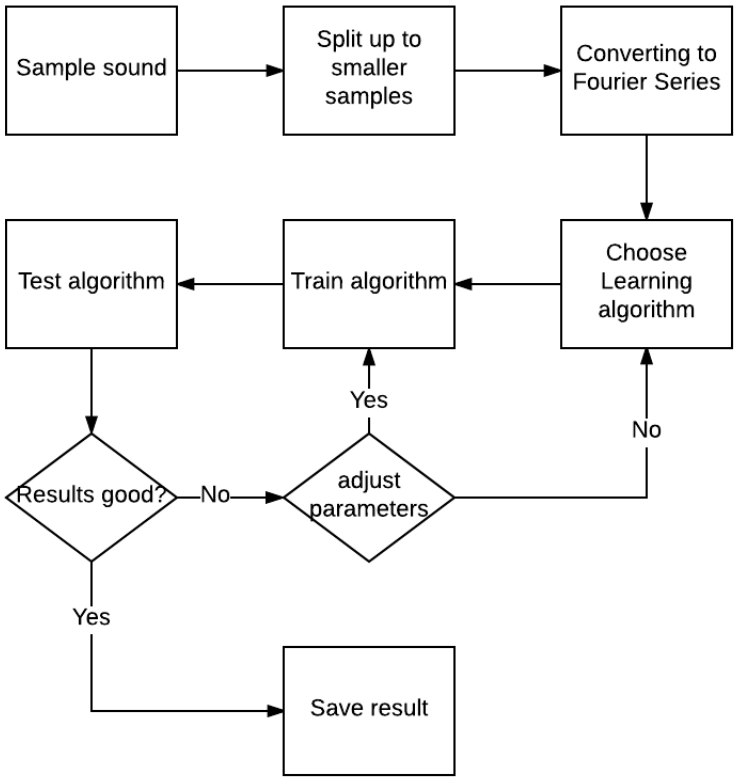


Figure 3.13: Design diagram of the Machine learning program

down the machine. The design of the code is shown in Figure 4.4.

Microphone and A/D converter

The microphone is an analog sensor giving out signals of a variable voltage at different frequencies; this has to be converted so the computer can understand and save it. This is done with an Analog to Digital converter module. As mention before this limits the resolution of the sound sample. This is a hardware component and will not be discussed further. However, the processing of the samples after digitized is important to understand what features the algorithms have to work with later. All the samples are 5 seconds long, then get split up into smaller samples of 16000 measuring points with an overlap of 4000.

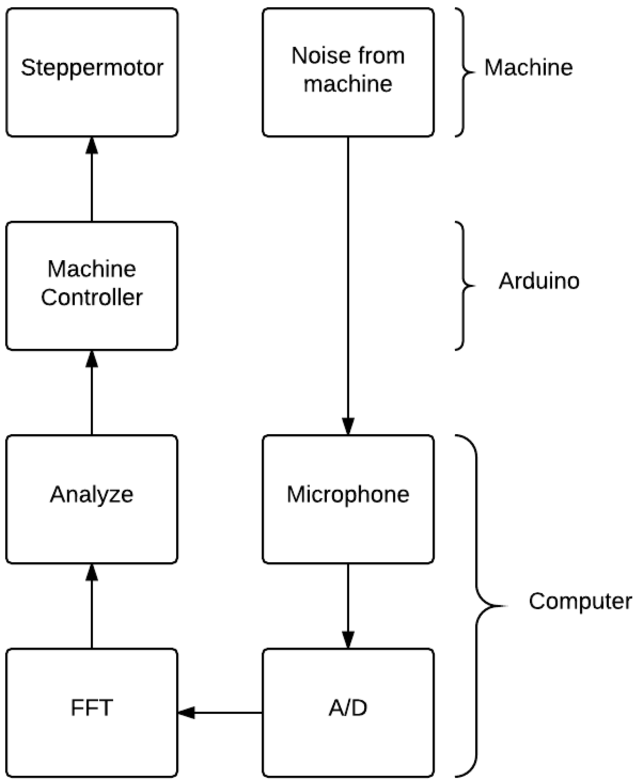


Figure 3.14: The design of the real time analysis system for the CNC milling machine

Fast Fourier transform

The windowed samples are then sent to the Fourier transform [35], where the function takes the sample and calculates the Fourier series of the signal. The resolution of the Fourier is originally 8000 different frequencies, but in this analysis, we take thesis and gather them into groups ending with 15 bands in the Fourier. These are the 15 features the learning algorithms are going to work on.

Analyze

Analyzing this is done with the sklearn package imported into Python. This package let's the programmer easily change between different learning algorithms to test different classifiers. Only the SVM and kNN will be used in this thesis because they are known to do well in this kind of situations.

Chapter 4

Experiments

This chapter takes a look at the testing process, how it was done and shows the problems encountered while testing. There had to be taken several different tests along the way. Before the final

4.1 Parallel gliders

All axis of the machine must run perfect level and trough to each other. This is important, so the machine will not jam if it goes out of parallel. Moreover, to leave less stress on the motors. The finish surface of the workpiece is also a result of the machine being tough. Getting all rails parallel to each other and at right angles where done using precision calipers and angle squares. This process of checking squareness was done several times when assembling the machine so the error would not continue when building on. If the machine starts off not parallel or square, it will only get worse. This is a crucial part of making a CNC machine and must be perfect for the best result. If not square or parallel the machine can make various vibrations and noises in different regions of the cut making it harder to analyze the data later on in the thesis.

4.2 Adjusting the movement

When building a CNC machine from the ground up and using different parts, it is important to adjust the distance the machine move per step of the motor. In GRBL this is the steps/mm parameter for each axis. If not adjusted the size of the cut will not become the correct dimensions. This parameter can be found using this function.

$$stepsPerMm = (stepsPerRevolution * microsteps)/mmPerRev$$

To see if this is correct each axis is marked and moved exactly 50mm then measured with a caliper as seen in Figure 4.1. Then moved back again to see if there is any backlash in the axis. This step is done several times in different locations on each axis to verify the result.

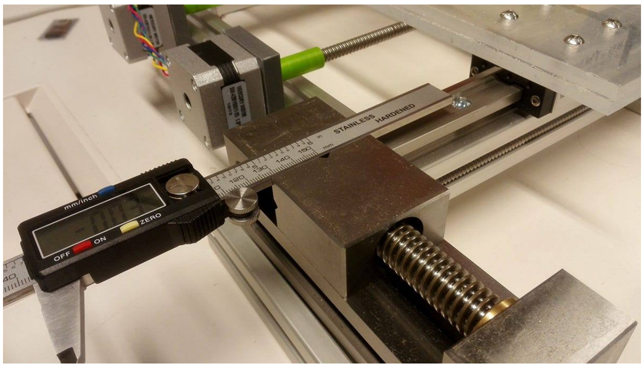


Figure 4.1: Caliper measurement of the distance travel on the X axis

4.3 First cut

For the first cut with the milling machine, a two-flute bit was used to cut in Styrofoam. Figure 4.2 shows the result after the first test. As seen in the picture, the cut was not completely round, because some of the parameters were not set correctly.

4.4 Recording sound

4.4.1 Placement

The goal of the thesis was to be able to get the computer to understand how the machine is performing when milling. The decision was made to use a microphone as a sensor. Testing this is a multiple stage test. Many different sounds are coming from the machine. Getting the right ones are necessary to get good results. Placement of the microphone is therefore critical. Tests

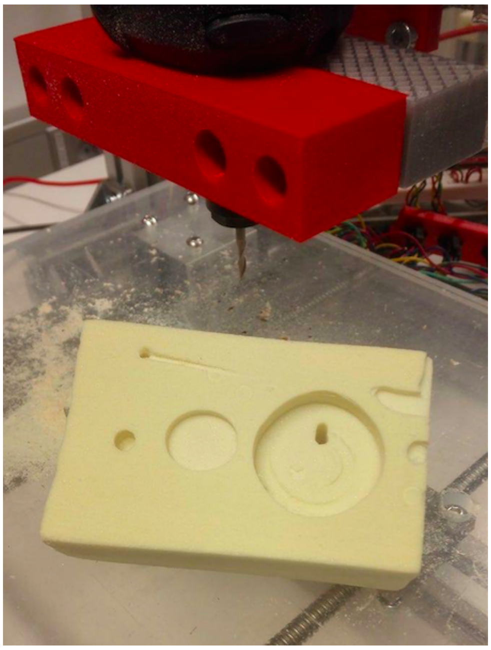


Figure 4.2: Picture shows the first cut in Styrofoam with the finished milling machine.

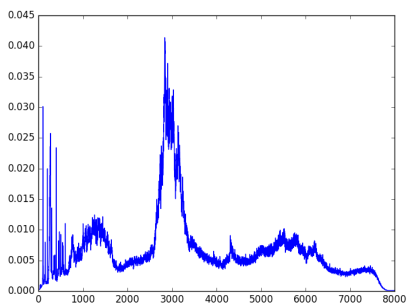
show that the microphone should be placed as close to the milling tool as possible to get the right sound. Even tough the sound frequencies from the engine are necessary for the data. The microphone needs to capture vibrations sound from the tool as well. Tool vibration sounds are lower in amplitude, that is why the microphone must be closer to the milling tool.

4.4.2 Test Samples

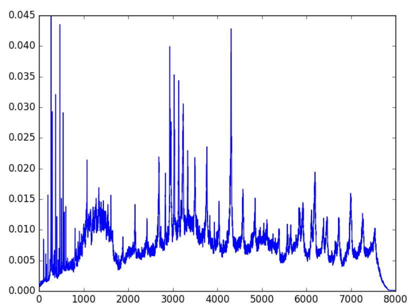
Large varieties and quantities of sound need to be gathered to get better results in the analyzing of the data. Samples taken are labeled into categories after what kind of milling strategy is used and if the machine is operating right or wrong. The number of samples taken is limited because of the time required to test. All samples are divided into two main categories. The main types are good sound and bad sound. Under-categories is there for deeper studies if needed. The main objective is to find out if the machine is running well or not.

4.4.3 Milling test

Testing the bad samples are inconvenient because testing this would require breaking many milling tools to get the sound before this happens. This is not only an expensive test but also a very dangerous test. The alternative to this is a more gentle way. Tool breakage as described in the background happens when the force becomes too strong between the workpiece and the cutting edge of the tool and the spindle slows down causing changes in the sound frequency of the motor and the frequencies generated by the energy release between the metals colliding. The noise of the motor beginning to stall can be replicated with tightening a strap around the spindle. The first bad samples are done using this method. Other good samples are done with plunge-cut, side milling, and slot milling. Figure 4.3a and 4.3b shows the Fourier transform from the sample data.



(a) Fourier transformed data of the sample labeled bad sound



(b) Fourier transformed data of the sample labeled good sound

The recording was done on the computer with a self-written Python program that recorded 5 seconds samples with different labels after what button was pressed. This way it was easy to take samples at various stages when milling. All samples were saved as an independent .wav file. The good and bad sound were stored in different folders.

4.4.4 Learning Algorithms

The next step is to use this data in learning algorithms to see if there is a way to classify the different sounds. The test were all done in Python, where the program read all the sample files and converted them into arrays. Overall

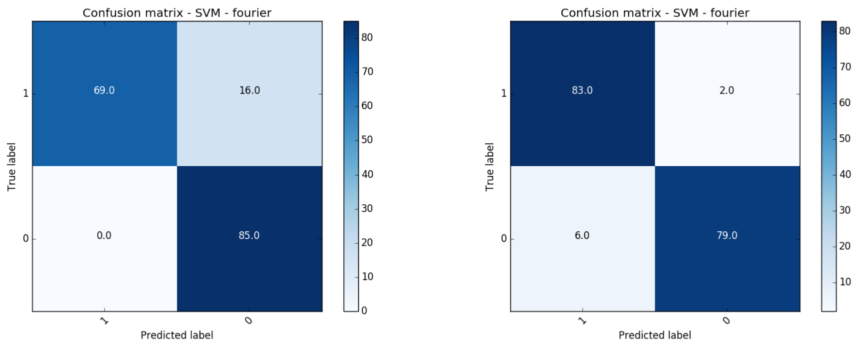
SVM with raw sound data	F1	0.49	+/- 0.15
	Accuracy	0.54	+/- 0.10
	Precision	0.63	+/- 0.11
SVM with Fourier data	F1	0.95	+/- 0.10
	Accuracy	0.95	+/- 0.09
	Precision	0.99	+/- 0.02
SVM with mean of Fourier data	F1	0.83	+/- 0.38
	Accuracy	0.87	+/- 0.23
	Precision	0.98	+/- 0.07

Table 4.1: Test results from SVM with different input data

amplitude alone is not enough to determine the machine condition because amplitude is only one feature and depends on so many other things as the type of cut, travel speed, and depth. Joseph Fourier found out that complex periodic functions could be decomposed to simple sines and cosines waves. Using this function on the sound signal, we get from the microphone we can look at all the frequencies the machine is making and get a larger picture of what is happening. Now the learning algorithms have more features to work with. In all the Fourier with the windowing chosen gave 15 features along the frequency specter. Support vector machine with a linear kernel and k Nearest Neighbours with a k=5 was tested on different input data. Trying raw sound data against Fourier transformed data will test if it is necessary to use the Fourier transform. The difference is evident in the test with SVM shown in Figure 4.1. Where raw data only got an F-score of 49% against SVM with Fourier transformed data that got 95% F-Score. This did not have as much effect on the kNN algorithm as shown in Figure 4.2.

kNN with raw sound data	F1	0.90	+/- 0.07
	Accuracy	0.90	+/- 0.07
	Precision	0.96	+/- 0.05
kNN with Fourier data	F1	0.96	+/- 0.08
	Accuracy	0.96	+/- 0.08
	Precision	0.98	+/- 0.03
kNN with mean of Fourier data	F1	0.94	+/- 0.20
	Accuracy	0.95	+/- 0.16
	Precision	0.98	+/- 0.07

Table 4.2: Test results from kNN with different input data



(a) SVM algorithm used

(b) kNN algorithm used

Figure 4.4: This matrix shows the distribution of the samples and what is correctly predicted.

4.4.5 Problems with the experiments

- The number of samples are a common problem in machine learning and was also an issue in this thesis. The number of different sounds was not sufficient enough to make a good guess of how well the algorithms would have done in a real test.
- The machine was not able to cut in metals, so an actual test sample of metal cutting was not possible. The reason for this was the 3D printed parts not handling the forces on them.
- The sounds made the peak value of what the microphone could capture during some of the tests. This resulted in unwanted noise in some samples.
- Not being able to break the milling tool gave no samples of that scenario.

Part III

Conclusion

Chapter 5

Conclusion

This chapter concludes the thesis with a discussion of the project, a summary of the test results and mentions of future work.

5.1 Discussion

The first goal was to build a CNC machine from scratch. Some may question the relevance of making a machine to be able to conduct the tests needed in this thesis. However, the part of the thesis involved with building the machine gave a much better understanding of how advanced a CNC milling machine works and what is needed to make it run perfectly. All the parts have their strengths and weaknesses; this gives more understanding of the big picture than a documentation of a milling machine can give. This knowledge came to good use later in the thesis. With this fresh in mind, the future processes of the thesis were also more inspiring. The building process proved to be harder than expected, giving more respect to others that have built machines before. With this and the waiting time for parts, this phase took longer than anticipated.

The process of building was an iterative process, of designing, testing and redesigning. During testing weaknesses in the design was found. One of the reasons the machine could not cut soft metals was the ball-screw joint between the stepper motor and the balls screw. The joint shown in Figure 5.1 was made on the 3D printer and had a weakness when force was applied to the axis of rotation away from the spindle motor. This is because the 3D printer prints in layers and the weak point becomes the joint between each layer. When the machine was running the joint cracked in between the layers.

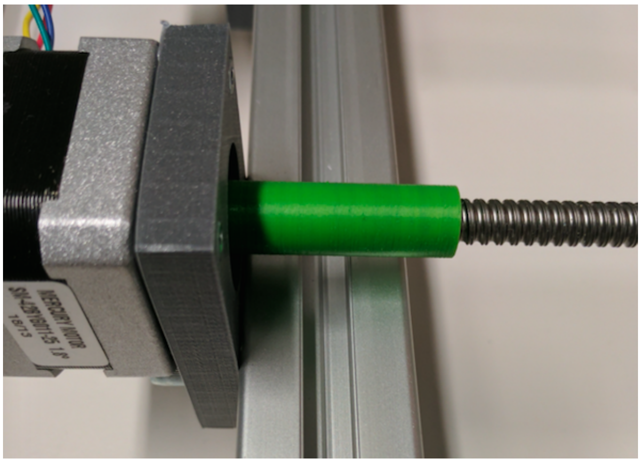


Figure 5.1: Weak 3D printed joint between Stepper motor, and the ball-screw is the green part

The second goal of the thesis was to find suitable sensors for sensing the machine. The use of a standard computer microphone to record sound was implemented. Moreover, the results were at a satisfactory level. The question about pollution from surrounding noise was disproved when tested as it showed that the sound from the machine was a lot higher than anything else. Other problems that could occur was that the microphone was not able to capture all the sound, but this was rather a problem with the A/D converter. The microphone did cut out when the amplitude got to high contaminating the samples. However, even tough the need for more expensive sensors as contact microphone or others seems not to be needed.

Lastly was the goal of finding an algorithm that can determine the machine's behavior. The way the learning algorithms performed had a great deal to do with the quality of the sample data. Thankfully the samples were at a satisfactory level, so the learning process gave good results as shown in the experiment chapter. The need for more data is preferable to make the models more generalized. However, proved sufficient enough to have a 96%

score on the test data. With the argument that both the training and test data was limited.

5.2 Conclusion

The need for babysitting when milling is a time consuming, and boring task, and the effort to make it easier and the more fail proof is shown in all the research done surrounding this subject with their different ways of handling this problem. The need is there, and the solutions will save time, money and make it easier for everyone to use CNC milling machines. The process will also be safer with the machine being able to warn others and shut itself down if needed. This thesis has shown that it is possible to make a system using a conventional microphone placed beside the machine and with some lines of code be able to predict to some extent if something goes wrong. There is still more work to be done before it can be a reliable system, but the tests have shown that it is possible to predict some of the behaviors of the machine using sound to some extent. More data and tests are needed to conclude anything. However, this thesis has shown that the use of only sound as data is possible, proving that simple sensors can be used to do the same job.

5.3 Future work

Microphones with higher frequency range could make a difference; there could be sounds we can not hear that has much impact on the results of milling, that may lie between what a microphone can hear and what acoustic emission sensors pick up. However, without the equipment needed this was not tested.

Processing of the sound from the microphone could be better. With an A/D converter with higher sensitivity and range, the samples would have had more information. Moreover, the learning algorithms would have more to work with.

With more time, there could be done more tests of different learning algorithms. The algorithms used in this thesis was chosen because they are good at these types of problems, but others may do better with more work in building the right models.

With this as a good start the possibility of future implementations on the machine and algorithms this could become a self-adjusting CNC machine, with the need for "babysitting" at a minimum. With more accurate classifications on the machines performance and more specific classes, the algorithms can send commands to adjust parameters on the machine such as Feed rate, spindle speed and more, to continuously optimize the milling process. The need for more sensor may be necessary, but the need for sound sensors as used in this thesis is important to understand the big picture of the machine.

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