Master's Thesis
MAS500
New Approach to produce special purpose visual aid Glasses

A custom designed 5-axis Mill

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This Master's Thesis is carried out as a part of the education at the University of Agder and is therefore approved as a part of this education.

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Summary

The thesis problem formulation is given by the company ProVista. ProVistas area of expertise is mainly the rehabilitation of visually impaired. This includes research, training of opticians and sale of supporting materials such as glasses with magnification. The thesis problem is a part of the research to give their customers a better product with much shorter delivery time. Today the customers normally have to wait several weeks to get their visual aid glasses. The reason for this is that the holes are milled manually. With CNC mills existing some decades now, the visual aid community should also benefit from the advantage of CNC milling. Both producer and customers will benefit from a new automated small five axis mill, especially ProVista that has started this paradigm shift. ProVista wants the opportunity to mill holes in their own glasses. Today they are depending on two foreign companies to mill the holes. This is both time consuming and costly for ProVista and their customers.

This master thesis comprises the study, design and manufacturing of a five axis mill. The decision to build a five axis CNC mill was made early in the process, this was done by integrating a three axis CNC mill with two extra rotations axes. The project incorporates the main areas within mechatronics such as designing and building mechanical and electronic parts and the interplay between them, control system for controlling and tuning the motors. The mill shall produce different holes, mostly circular with angles so that the binoculars achieve the correct focal point in accordance to the user's needs. The users are mainly surgeons and dentists, who depend on magnification provided with two binoculars, focused at an item to performer their work more efficiently and correctly. In ProVista sub market the users vary from hobbyist using binocular glasses to paint tin soldiers, old people reading the paper and other people that are visually impaired.

The solution this project presents is a new small five axis CNC mill special designed for milling in glasses. The mill is based on the High-Z S400 purchased from CNC-Step in Germany. The chosen design for the two extra axes is a two axis rotary table design also known as trunnion. The trunnion table was fitted with two stepper motor, from the same producer used on the High-Z S400. The stepper motors were chosen mainly for their low cost and ease of use. There has been made a control box with motor drives and power supply for the trunnion table. The control box is also fitted with serial ports, parallel port, fan, emergency button, fuse and power connection. A new fixture for glasses is also designed and built. This will most probably be the first milling fixture for a pair of glasses in the world.

The software used in the project is Excel and Mach3. Excel was used to generate the G code from the position, diameter and the angle of the holes. After this the data is saved in a txt file, making it readable by Mach3. This process has been made as user friendly as possible so that a user can operate the milling machine without problems. The Mach3 CNC program already has a good enough interface, and only needed to be modified with a six axes interface. The Excel spreadsheet is been made simpler and the user may only change a few variables, the transfer of the G code is also been done simpler by adding the possibility to save the column with G code as txt file. The most typical holes that ProVista needs are circular holes and oblong holes (prism).

After implementation several test were carried out to verify that the different parts obtained the requirements. Among the tests that were carried out was: resolution and repeatability for the mill, and the backlash for the trunnion table. In the last test it was milled holes through glasses to verify that the final product met the requirements

All tests met the requirements with good margin, except the last test. The problem will be fixed and the test will be redone before handing over the machine to ProVista.

With the new automated mill ProVista will be able to offer high quality visual aids on the world market. Their products will be made quicker and at a lower cost, benefiting both ProVista and the customers. ProVista will also have a new tool in their further research, which may result in new methods to help visually impaired so they may have a better quality of life. With the newly acquired high capacity to mill holes in glasses, ProVista would be able to take in orders from other visual aid companies.

Further work may involve reducing the size of the mill since a large portion of the work area is unused.

The user interface should be something similar to HMI (Human Machine Interface) where the users do not see the Mach3 or Excel and just put in the desired position, diameter and angles on a touch screen. The fixture should also be modified so that the glasses are self centred, this will reduce any minor errors. A new spindle should also be refitted to reduce noise level.

Preface

This report is written as a part of the master's thesis course MAS500. A project idea was formulated together with the special optician Hallgeir Aronsen of the company ProVista. The idea was to automate a process that up today has been done manually.

The project took place at UIA Grimstad, where both the required equipment and knowledge are present. The project consisted of preliminary study, concept selection, integrating different sub system into one system, and testing and validation.

The inspiration for working on the topic of automation is because both members of the group have a great interest in automation, especially CNC controlled machine that became the final solution of the project.

The group would like to give thanks to the supervisors project manager Stein Bergsmark and special optician Hallgeir Aronsen, and to the staff at the engineering workshop Roy Folgerø and Lars Erik Jåvold.

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1. Introduction

In the medical field doctors and dentists often have to work with tasks that can be very hard for a trained eye to see, examples of that could be, but not limited to do surgery or drilling in teeths. For this they have a wide variety of remedies to help them in that work and one of remedies is the visual aid glasses. Visual aid glasses are also used by other professionals such as jewellers, watchmakers, photographers and other [7]. Visual aid glasses is made of a pair of ordinary glasses with or without magnification. In addition there are mounted one or two small binoculars for magnification in them. In order to make a pair of visual aid glasses there are a critical factor in making the holes for the binoculars. The holes have to be placed correctly on the glasses with correct angles in order to get a correct focal point or else the user will experience diplopi (double vision). Incorrect focal point will also give the user a incorrect posture. A research shows that with binocular glasses the users get a better posture, this results in reduced health related problems caused by poor posture. The research also showed that the use of binocular glasses give a small increase in the quality of the work[12].

Figure 1.1: A varity of Visual aid Glasses

This chapter gives the reader an introduction about the company that assigned this master thesis, the problems are described in detail with short information about the current practice, and why the problem has arrived. A literature review is performed to find the best solution for the problem, and the problem solution will be based on this research.

1.1 Background

Today Univet in Italy and Design for Vision in USA are the two leading companies within the field of visual rehabilitation community, as ProVista is in Norway. When fitting glasses with magnification, these two companies depend on craftsmen with several year experiences. These craftsmen use a manual mill, and place small boxes underneath the glasses until they get the desired angles. ProVista in Arendal does not have enough work related to milling, to educate their own craftsmen. So most of their milling related work ends up at either Univet or Design for Vision. ProVista wants to change this, and have the opportunity to mill their own glasses at Arendal. The new machine shall mills angular holes with ease and high accuracy. When it is delivered to ProVista it would give their customers a quicker delivering time, and the machine will in time show itself to be more cost effective than the current practice.

1.2 Problem statement

The project proposal has been given by ProVista. ProVista is a Norwegian company established in 1999 at Arendal, and their headquarters is still at Arendal. They have since 1999 established branches in Oslo and Gothenburg in Sweden. Currently they are looking at getting established in China.

Today ProVista depends on Univet in Italy and Design for Vision in USA to do the milling for them. With this arrangement their customers have to wait several weeks for their binocular glasses. And if they are not satisfied with the focal point or the magnification, ProVista has to do the procedure over again. This is the main reason why ProVista wants their own tool to mill angular holes.
Angular holes in this case are rotations around two of the axis of a normal coordinate system X, Y and Z. This means designing a mill with five axes.

1.2.1 Goal

In order to solve the problem stated above, the main goal of the project is:
Design and build an automated five axis mill
for milling in polycarbonate.

1.2.2 Objectives

From the statement above, the corresponding objectives can be derived;

OB1: Establish a theoretical background on the different parts/modules.
This objectives means that the team acquire components knowledge on the most common parts of automated five axis mills.

OB2: Combine different parts/modules into a working system.
The project will rely on parts from different supplier and may not have been designed to be used together.

OB3: Design hardware and software.
Custom made mechanical components and programs have to be designed or redesigned.

OB4: Construct a working system.
All the different components will result in a full functional 5 axis mill.

OB5: Testing and Validation.
The test has to be performed to ensure that the mill meets the requirements set at the start of the project.

OB6 Extra: Engraving.
If time allows the team will try to implement an engraving feature on the mill, the engraving will be done on curved surfaces.

OB7 Extra: Publish a paper.
If the team can finish the OB6, the spare time will be used to write and publish a paper.

1.3 Key Assumptions and Limitations

In order to design and build a five axis mill during the spring semester, certain assumptions and limitations had to be applied.

- The mill will only be used to mill in polycarbonate.
- The mill will be built without coolant, this is to reduce complexity and cost.
- The mill will be operated by persons with some knowledge of milling.
- There will only be made one type of fixture that will be universal for all relevant glasses.
- It is possible to find and integrate components within given specification and cost frame to realize an automated mill fo glasses.

1.4 Literature review

The project will be solved with the use of an automatic five axis mill, this means performing a literature search on the topic of five axis milling. The source that has been used in this project includes books, scientific publications and internet pages. Internet pages shall mostly be used for reviewing the specifications of parts and machines, otherwise articles publish on internet pages are used for theoretical information on the different parts. Books will be use to supply the theoretical part of the report. Scientific publications are used to find the level of research in the field of five axis milling. This section will be a review of different papers that have been written of the topic and a short review on the other topics this report contains.

The team has reviewed four different papers, found after a search on www.ieee.org. The overall subject of all the papers are the problem of continues five axis milling and the different solution that exist to generate a tool path. First of continues milling is used when processing complex surfaces as aeronautical turbine blades, impellers, die and molds[11]. [11] Presents a method called Non-Uniform Rational B-Spline (NURBS), with this method it is possible to reduce the number of NC code that is normal used. And still machine more effectively with a high accuracy. [9] Achieve the same result when applying the AKIMA method to enchant the milling compared to the existing five axis linear interpolation methods. [15] Presents a solution for non linear error problem in ultra precisions multi axis machining with a new control called TCP (Tool Center Point) that is integrated into the CNC system. [14] has developed a computer software program to calculate the contour errors and to simulate the actual tool trajectory for multi axis machine tools, their general idea is to use this analysis to produce more accurate five axis tool paths for the advanced CAD/CAM system.

After a short review it seems like the area of research is on the tool path and the errors, and how to improve these. The review also contained an article that may be used later in the report. The article [14] includes the equations to find positions in planes when rotating around axes. This will be needed when programming a script of G-codes in Excel for positions in the five axis space. Since Excel is used in this project, the project would not contribute further on the topic of continues milling, but rather on how to build a custom five axis mill for a specific usage.

Another important topic is the fixture, the finished system needs a fixture for glasses independent on the type of five axis system selected. A literature search did not prove to be successful, and the team has to make use of other methods in order to get ideas for a design.

At the start of the project the team was informed by the ProVista that the polycarbonate melted very quickly when they tried to mill polycarbonate in the past. The search for literature on the topics of milling in polycarbonate generated only hits from tool manufactures, LMT Onsrud LP had publish an article on the topic of milling in polycarbonate, their conclusion is that polycarbonate is relatively easy to machine if a proper tool is selected. They also conclude that best result is achieved with good routing practices such as rigidity and proper programming.

On the topic of binocular glasses the team came across a scientific paper on the benefits of using binocular glasses in the dentist profession [12]. Through the research most of the subjects in the case study had an increase in their quality of work and an improved posture when using binocular glasses. So this type of aid is important for the health of dentists and the dental care of patients.

1.5 Problem Solution

The task ahead is to automate a work that up to this day is performed manually by professional craftsmen. The main question would be if is possible to mill the holes automatically, and maybe there is a reason why the procedure is still done manually. In order to complete this task, five axis CNC machine or a robot arm are considered. Both CNC machine and robot arm consist of electronics and mechanics element. Either of these is put together by several mechatronic elements such as control system to control the electronic motors, mechanic to design a working machine and computer to program the machine. This is the main reason for choosing this project. Also the prospect of making a machine that has a commercial value is exciting.
In order to complete the task, the team takes the integrator role. This means that the most of the parts/modules are purchased instead of using time on designing and manufacturing. It still will be small

parts that need to be custom made to ensure that everything fit together.

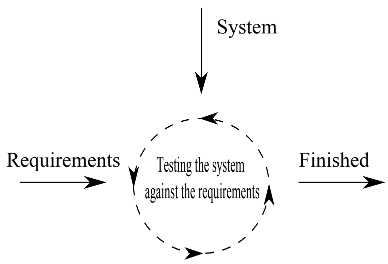

Figure 1.2: Development Method

Figure 1.2 shows the development method used by this project. With this method the idea is to test the system against the requirements, if the system is not within the requirements. It must be taken back and forth with tweaking and redesigning, before it can be retested. This continues until the system is within the requirements, and the final system emerges.

1.6 Contribution

This project will contribute with a two-axis platform integrated with a three axis mill. The machine will consist of different subsystems such as a three axis mill, a two-axis platform, a fixture, and control software. The different subsystems can be divided down to different components.

Some subsystems can be purchased "ready to install" or they has to go through modifications to be adapted to the final machine. Other subsystems will have to be designed and built from scratch where components have to be found, evaluated and chosen.

In order to get the different systems to work together an integrator role has to be played. The components within a subsystem will have to be integrated to work together and the subsystems has to be integrated to work as a automatic five axis machine that mill holes trough the glasses.

1.7 Report Outline

Chapter 2 begins with introducing some general information and market survey of small milling machines, such as robot arms and CNC mills. Their motion control has been explained, and how their performance can be measured.

Chapter 3 introduces the solution to the given problem. The chapter includes the steps the team had to take to design and build a five axis CNC mill. The chapter features the specifications of the different parts, including the models and explanations of how the system is built. Chapter 3 also includes system verification and testing, this is done to secure that the machine is within the requirements.

Chapter 4 introduces the new procedure to mill holes in a pair of glasses. The chapter explains the new procedure step by step. The chapter features a normal user case. This user case will be the base for the new procedure.

Chapter 5 gives the startup procedure and a user case were actual data for holes in visiual aid glasses is tested on the new machine.

Chapter 6 presents the conclusion of the thesis and suggestions for future work

2. Small Milling Machines

Since the size of the glasses is rather small, a more compact and small mill would be preferable. With a small milling machine the power consumption will be reduced compared to larger milling machines. The required accuracy will also be achieved at a lower cost, since smaller tools is better to mill small holes. Today both hobbyists and professionals use mills to create new parts or refurnish old parts. Hobbyists tend to go for small 3 axis cnc mills driven by stepper motors due to the low cost, and they normally mill in lighter materials. Professionals tends to go for high end mills, such as 5 axis cnc mills and robots but still keep the larger 3 axis cnc mills for larger workpieces.
In this chapter the different small multi axis mills have been researched, including the motion control and performance.

2.1 Multi Axis System

Most people are familiar with the x and y coordinate system, this coordinate system is used to describe several different data ranging from geometrics to economics. When it comes to more complex data such as surfaces a three axis system is used to describe the surface in the three dimensional space. The three axis mill is the most common mill on the market today.

Figure 2.1: 6 axis system

In this project extra rotations have to be used to drill angular hole in three dimensional space. The ordinary x, y and z coordinate system has up to three extra rotations, one for each axis. Rotation around x-axis is called A, and rotations around y and z axis are called B and C. With these rotations the system become a six axis system shown in Figure 2.1. For this project a five axis mill is sufficient enough.

2.1.1 Robot Arm

In the industry the robot arm has already made a huge impact by taking over tasks that most people see as unsafe, hazardous, repetitive, and unpleasant. Further it has made an uprising when making several workers jobless by taking over jobs like welding, painting and packaging[6].

A robot arm has several joints, the number of joints is determined by the task it is set to do. In this project a robot arm with five joints is needed, this provides the required five axes.

A research has been done to find a suitable five axis robot arm that is within the required accuracy and cost. The research consists of small and medium size robot arms and one from each category have been discussed.

Figure 2.2: Dremel 4000: 175 Watt, 5000 to 35000 rpm

The robot arm should be able to lift a drill. The dremel 4000 shown in figure 2.2 is weighing 0.533 kilogram, meaning that the robot arms payload capacity has to be higher than the weight of the drill. Further the accuracy for the hole placement should be better than ±0.1mm, the machine shall use a single phase connector with less than 16 ampere consumption, and have a maximum size of 1x1x1m.

Figure 2.3: Harmonic Arm 6M with 5 or 6 degrees of freedom and 0.1mm Repetition Accuracy
and the LR Mate 200iC with 6 degrees of freedom and 0.02mm Repetiton Accuracy

One of the smallest robot arm found was the harmonic arm 6M Model 450 shown in figure 2.3. This machine has the required accuracy, size and a single phase power connection lower than 16 ampere. But with a payload capacity of only 500 gram, the machine does not fit the project requirement. (www.aai.ca/robots/h_arm.html)
Small robot arm means that the payload capacity will be limited, bigger robots provide a higher payload capacity.
The medium size category the robot arm LR Mate 200iC shown in figure 2.3 has a payload capacity of 5 kilogram, this arm can be fitted with a larger and more powerful drill than the Dremel 4000. The robot arm meets all the requirements mention above. [3]
Overall the project can be solved with a robot arm. The research concludes that a very small robot will struggle to meet the project accuracy and the weight of the drill. But if the robot grows in size, the accuracy and payload capacity normally increases, so do the cost. So for the ratio between cost and accuracy in ProVistas case, the workload is not high enough to justify the use of a robot.

2.1.2 Engraving Mill

Engraving mills are used by engravers to make signs nameplates, badges etc in materials like brass, plastic, copper and steel materials. An engraving mill usually is a small 3 axis mill controlled by cnc. They are usually small with limited height in z direction which does not allow many options for two extra rotational axes at the working table. Thus they are very accurate with high resolution in xyx direction. An option is the High-Z S-400 from CncStep Germany shown in figure 2.4 which is a multipurpose 3 axis mill, also as an engraving mill, which has an unlimited height in Z-direction. With this mill it is possible to add two extra rotational axes under the spindle. This mill will be further considered.

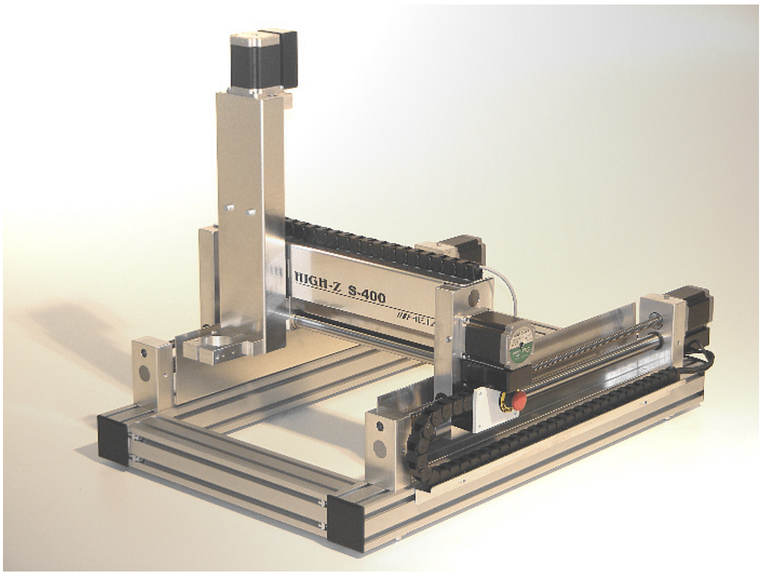

Figure 2.4: High-Z S-400 with open base and Traverse Paths: X=400 mm; Y=300 mm; Z= 110 mm

2.1.3 Small CNC mill

Typical the ordinary mills are made to be versatile. In other word the mills have the capability to mill hard metals. To machine hard metals the mills normally have coolant, self lubrication and a high torque spindle. In order to accommodate some of these abilities a small CNC can topple over 100 kg in total weight. Generally small mills have a smaller table size than small engraving mills, because engraving mills have more use of the x and y axis than the z axis. An example of a capable small mill is the Sieg KX1 Hobby CNC Mill in figure 2.5. As seen the mill has a tray to gather and recycle the coolant, the mill also has a 500W Closed Loop Brushless DC Spindle Motor, when most small CNC mills use universal electric motors such as the dremel. The main drawback of Sieg KX1 is the limited space that can be modified for two extra rotation axes, but the mill will be taken in to consideration in the finale decision.

Figure 2.5: The Sieg KX1

2.1.4 Rotary Tilting Table

Today it exist several products that can transform an ordinary three axis mill to a modern five axis mill. Thus reducing the set up time, this also means there will be an increase in accuracy due to fewer set ups. A company with a five axis mill will also be able to process more glasses in shorter time than a company with a three axis mill. Similar the company ProVista will have a higher capacity with their new automated five axis mill, than other company that still mills their holes manually.

Figure 2.6 shows the most common method to upgrade a three axis mill, called index table and trunnion table.

Figure 2.6: Indexer and Trunnion 2 axis with 160mm table

These tables can be set up in a 1+4 system where z moves up and down while every other axis moves in series underneath. Next setup is a 3+2 system where z, x and y axis move in series and the rotations of the rotary table move in series. A system that has many axes in series will have a buildup of errors trough all the joints making the system less rigid and accurate. A parallel system on the other hand will not suffer from this problem, since the axes are independent from each other. Given example would be the 3+2 mill that is both a serial and parallel system. Where both the 3 axis and the two axis are in series, but are parallel to each other. So the obvious choice would be a 3+2 mill, since it is more rigid and accurate.

Figure 2.7 shows another possible solution namely a spindle head attachment that gives the spindle two extra axes.[5] This solution would give the opportunity to mill larger and heavier work pieces, but will also make the spindle less rigid and accurate compare to the ordinary spindle.

Figure 2.7: Head Attachment with additional two axis and 0.0042° Repetition Accuracy

2.2 Motion Control

In automated machines the axes are normally controlled by electrical or hydraulic motors since these motors can get their power or oil supply from external sources. In this project either dc servo or stepper motor are evaluated. There is a short introduction on each, and how to control them. The most common gear used in compact automated machines has also been reviewed.

2.2.1 Stepper Motor

Stepper motors are used for position control, and is widely used by hobbyist due to the high accuracy compared to the cost. Due to the open loop operations of stepper motors there are no need for sensors, resulting in large savings. Stepper motor is also a bit larger than dc motors with same or higher rated power.

Stepper motors come in three categories: variable-reluctance motors, permanent magnet motors, and hybrid motors. The variable-reluctance motor is built up with a stator and a rotor that both have different magnetic reluctance among various radial axes, they also have a different number of poles. The permanent magnet motor has a permanent magnet rotor, and one winding has the same number of poles as the rotor. But since the motor has two phase windings, this motor also has a different number of poles between rotor and stator. The hybrid motor is built on principles from both variable reluctance and the permanent magnet. [13]
Stepper motors moves in steps, and its resolution is dependent the number of steps per revolution. The most common resolution is 1.8 degrees per step.

2.2.2 Servo Motor

Servo motor is controlled in closed loop, either by speed or position. It is used in precision applications were high torque is needed, for example larger cnc machines. A simple rule geckodrive gives their customers is that if your application require 200 watts or more choose a servo motor, if it is below 100 watts choose a stepper motor, and in between either of the motor will be sufficient enough.

Servo motors come in two categories brushed and brushless. The brushed motor is build up by a permanent magnet stator and a rotor with windings, a set of brushes use commutator on the axles to distribute the required current to each winding, and this is commonly called mechanical commutator.
The brushless is build up opposite compared to the brushed motor, the brushless has a permanent magnet on the rotor and the windings on the stator. With a rotor without windings, The brushless uses electrical commutator to distribute the required current through the windings, this is achieved by the use of either optic encoder, hall sensor or using the voltage generated by a spinning motor (EMF).[13]
Of course there exist several different types of dc motor, but in this section only the most common have been explained.

2.2.3 Motor Driver

To use an electric motor in an automated application, a motor controller is normally necessary. Figure 2.8 shows a example of a small motor controller for stepper motor made by the company Geckodrive.

Motor controllers are used to start and stop the motor, selecting forward or reverse rotation, selecting and regulating the speed, and regulating the torque. More expensive motor controllers also limit the torque and protect it against overload and fault. [8]

A research has been carried out on the motor controllers for small dc motors such as servo- and stepper motor. With an emphasis on controllers that suit the power consumption of small milling machines, and that stepper motor is normally operated in open loop and servo motor in closed loop.

In order to control a stepper motor, there should be two control signals, one signal for direction and the other signal for stepping. Direction is controlled by a signal that goes high and low, and with programming it is possible to assign which direction should be high or low. Further on the movement of the stepper motor is controlled by pulses called step, one step correlates to one step on the motor. The movement itself depends on steps per revolution, the most common is 200 steps per revolution. One step would then be the same as 1.8 degrees. Further on it exist drivers that raise number of step through something called microstepping. The most common is to have up to ten micro steps. This will give a smoother motor than with full step. Ten micro steps means that the resolution increases from 200 steps per revolution to 2000 steps per revolution, giving a resolution of 0.18 degrees per step.

In order to control a dc motor, most of the control is done with one signal/supply. This is done with the PWM (Pulse width modulation) signal. Long and short pulses both control their designated direction and the pulse between these two stops the motor. The magnitude from the stop pulse regulates the speed of the motor. To control the motor position the dc motor is dependent on an encoder. The encoder counts the number of ticks the motor has moved. An encoder with many ticks per revolution has a higher resolution than one with few ticks per revolutions. In order to reach the desired position, the system has to be in a closed loop.

Both stepper- and servo motor are controlled by some sort of pulse signal. A stepper motor controlled in full step would look very similar to a normal PWM signal, but will get smoother pulses with micro stepping. To regulate the speed on a stepper motor it is possible to either increase or decrease the steps per seconds. When it comes to the servo motor, it is not necessary to increase or decrease the number of pulses to adjust speed, just simple adjust the width of the pulse hereby the name pulse width modulation (PWM).

The simplest servo motor controller is an on/off switch, but there are some limitations to the number of applications where it can be used. More complex and costly controllers uses H Bridge design to generate the pulses.

2.2.4 Gear

Gears are mainly used to increase the torque and increase the resolution in small milling machines. This is because most of the small electrical motor on the market has very high rpm and low torque, and with a gear any rotary or linear motor can be adjusted to fit for their application. The main drawback when using a transmission is the backlash, backlash appears due to the play in between the contact teeth of the gear,

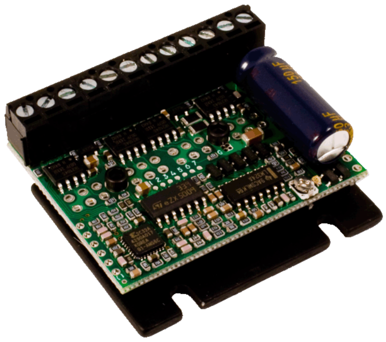

Figure 2.8: G251 Stepper Motor Driver with 1/10 microstepping and 3.5 amp capability

backlash will be discussed further in the section performance.

The most common gear used in small electrical motors is the planetary gear in figure 2.9. The gear wheels consist of one sun, four planet carriers and a ring. Both the sun and the planet carrier can be an input, as for the output either the planet carrier or the ring can be an output, giving this specific planetary gear a total of three gear ratios.

Due to the number of gear wheels, planetary gear can transfer high amount of torque compare to its compact size. If an application requires more torque, the planetary gear can be made with more stages. But this effect the backlash that increases with each stage. So to achieve a low backlash the planetary gear should stay at one stage of gears. [10]

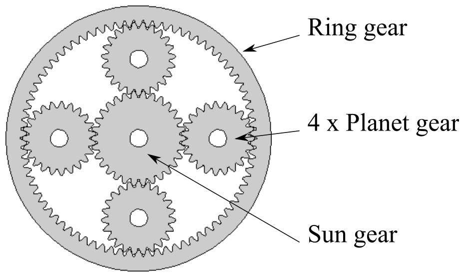

Figure 2.9: Planetary Gear

If the application requires zero backlashes, there exists a gear called harmonic gear. Compared to planetary gear a harmonic gear with a 1:100 ratio gear has the same volume as a planetary gear with a 1:10 ratio. Due to high cost it is rarely used, and has the drawback of wind ups and degeneration due to the flexible gear. See figure 2.10 [4]

2.2.5 G-Code

G-code is a programming language used in computer numerical control (CNC). It was developed in the 1950's and is used widely in the machining industry today [1].

The G-Code library consists of numerous different commands and in this section only the commands that may be used in this project are explained. Other commonly used G-Codes can be found in Appendix Creferanse.

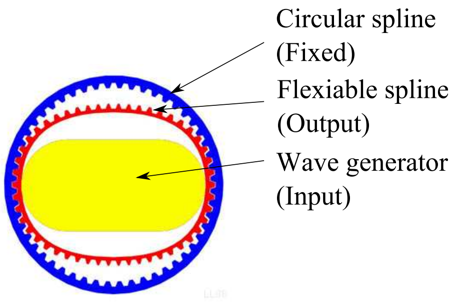

Figure 2.10: Harmonic Gear

The G-codes correspond to different motions and commands, such as linear interpolation (G1) and rapid positioning (G0). For example if the tool starts at (0,0) and the next point is (50,20), a G1 command will make the motion linear while a G0 command will go with max speed on each axis and may differ from the path from a G1 command. G1 is the most common command, since most milling will be linear, G1 commands also respond to the feed(F) command, so that different feed rate on each program line can be used. G0 on the other hand will override the feed command, this is important to know in order to prevent collisions between the tool and the work piece.

Other commands that are useful in this project is the commands for arc and circle interpolation, both have clockwise and counterclockwise motion. This research only looks at clockwise motion.

First the arc command (G2) shown in figure 2.11, this will be use to make oblong holes and prism along with the common G1 command. Next is an example on an oblong hole with G-code, the tool starts at (0,0,0).

```
N01 G0 X10 Y10
N02 G1 Z-1 F300
N03 G2 X10 Y22 I0 J6
N04 G1 X40 Y22
N05 G2 X40 Y10 I0 J-6
N06 G1 X10 Y10 ..................
```

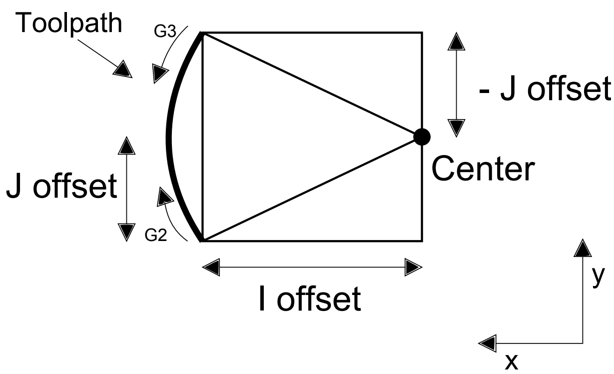

Figure 2.11: G2 and G3 commands

The code can be repeated several times if a deeper cut is needed. This set of codes mills a 1mm cut. Furthermore the G2 is used for clockwise arc interpolation. The G2 should contain the end position of the arc and the center of the arc in X (I) or Y (J) dependent on the start of the arc.

Second is the command for circular holes G12 shown in figure 2.12. An example on a circular hole are shown below, the tool starts at (0,0,0).

```
N01 G0 X10 Y10
N02 G1 Z-1 F300
N03 G12 I5.......
```

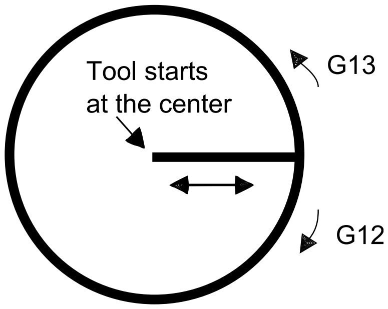

Figure 2.12: G12 and G13 commands

With this code only I(radius) is needed compared to the G2 command. Same as the G2 programming this can also be repeated if a deeper cut is needed. The program starts with a rapid motion out to the center of the circle and the tool goes 1 mm down in to the work piece with a feed rate of 300 mm/min. The G12 command then tells the cnc mill to make a circular motion with a radius of 5mm. The tool starts in the center and moves linear the distance of the radius. It then moves either clockwise(G12) or counterclockwise(G13), since the programming contains G12, the tool moves 360 degrees clockwise and then moves towards the center after one revolution.

Normally the industry depends on CAM (computer aided machining) programs to make the g-code from a CAD (computer aided drawing) file. In this project Excel is used instead, as seen the programming is repeatable and simple so Excel will be the better alternative.

The two examples contains a code 'F300', this is one of the many variables used in G-coding. In this case F refers to the Feed rate in mm/min, one other common variable is the S that refers to the spindle speed in rpm.

Other code used in CNC programming is the M-code, M-code is used to stop and start functions. For example to end a program, start and stop coolant and spindle. These are normally put at the start and the end of the programming, for setting different parameters and ending the program.

2.3 Performance

Prefomance is a non-fuctional requirement set. It is a measurement of how well a machine performs its tasks. In this report the machine is a precision machine, and its performance is measured by backlash, repeatability and accuracy. More common performance issues such as power savings and noise level has been overlooked. A precision machine with low backlash, high repeatability and high accuracy has good performance, but a precision machine with the opposite traits has an inferior performance. This section will give a short introduction of the terms backlash, repeatability and accuracy.

2.3.1 Backlash

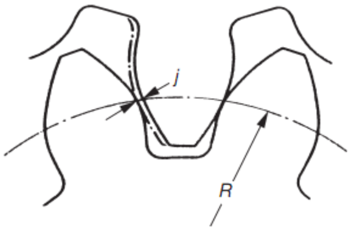

Figure 2.13: Backlash

The term backlash describes the play between two teeth in two gears in figure 2.13. This backlash is necessary to avoid jamming and to get space for the lubrication. To achieve a lower backlash the gears must be machined with high accuracy or the center distance between two gears must be low.[2]

2.3.2 Accuracy and Repeatability

In precision machines the ability to performer the same task over and over again is important. If a milling machine has to mill the same hole in several work pieces, the hole should be in the same position all the times. But this will almost never happen, due to different aspects, one of them being the backlash. The milling machines ability to hit the same spot over and over is measured as repeatability. If the mill has a low spread of hits the repeatability is high as shown in figure 2.14

Figure 2.14: Accuracy and Repeatability

The figure also shows the term accuracy. Accuracy is the difference between reference value and obtained value. Low difference gives a high accuracy while a low accuracy means a high difference between reference value and obtained value as seen in the middle and right target.

3. Solution

Based on the problem statement, a five axis mill machine will be created and verified during the project. The solution is a 3+2 axis mill, based on a small three axis mill with a custom made two axis trunnion table. The system is designed to be controlled with a bare minimum knowledge on how to control a CNC machine. The most difficult part of the CNC operation is the G coding. In the industry, the G code is generated with a CAM (Computer-aided manufacturing) program. The CAM program generates the G code from a part drawn with a CAD (Computer-aided design) program. To simplify the procedure, both these programs are scraped in favour of Excel. With the help of formulas and scripts, the user should be able to generate a script of G code with only the coordinates and the angles of the holes. In contrast to existing five axis mills, that are designed to be versatile when it come to the weight and size of the work piece. The small five axis mill in this project is special designed to mill in polycarbonate glasses. With this limitation it is possible to create a small mill machine that can be placed inside a laboratory and not in a machine shop.

3.1 User Requirements

The requirements are given by ProVista, and some are derived after a discussion between ProVista and the project team. The team has sorted them into functional and non-functional requirements. Functional requirements are requirements which describe the functionality the user wants from the mill. The non-functional requirements are requirements which ProVista may not see, but these requirements are still important.

3.1.1 Functional Requirements

FR1: Mill holes with an angle This is the basic problem in this project. The angles should be within ± 40 degrees in b and c directions.

FR2: Mill holes in polycarbonate
ProVista glasses are made of polycarbonate plastic.

FR3: Five-axis design
In order to get two extra rotations (angles) the mill should have five axes.

FR4: Fixture
Some sort of contraption has to be implemented to secure the glasses during milling.

FR5: Minimum working area
The working area of the mill should be at least the size of a pair of glasses, the size of an ordinary pair of glasses is ca 160 mm x 80 mm.

FR6: Hole size range
The machine should be able to mill holes between 4 mm and 40 mm in diameter.

FR7: Accuracy
The mill should have a maximum error of ± 0.1 mm.

FR8: Hole placement accuracy
The given distance between the holes may only have an error of ± 0.125 mm.

3.1.2 Non Functional Requirements

NFR1: Maximum current consumption
The mill may only draw electricity from a standard household type outlet. 16 amps @ 230VAC.

NFR2: Maximum system size
The mill may only occupy a space equal to 1x1x1m

NFR3: Noise level
The mill is supposed to be placed inside a laboratory environment, so the noise level should not exceed the noise level of other application in the laboratory.

3.2 Design Selection

The different concepts were chosen in the mini project, the project was a part of the course MAS503 product development. The different concepts were chosen based on how well they fulfill the different user requirements presented in the previous section. The next step is to design and build a prototype based on the selected concepts.

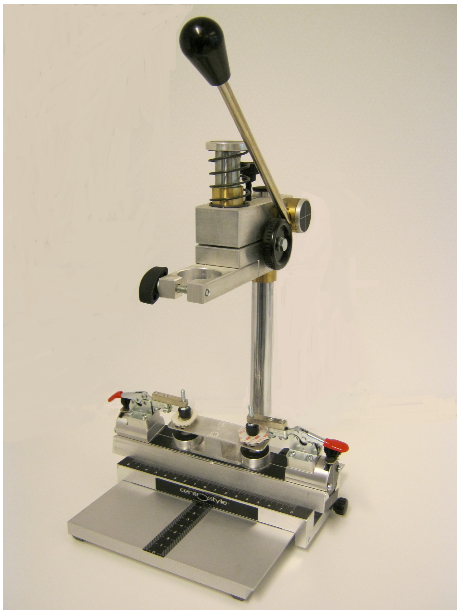

Figure 3.1: Centrostyle Drilling System

The first concept was a fixture for glasses, in the mini project it was decided that the glasses is going to be secure by the help of clamps. At the start of the master thesis the team used a drill rig from Centrostyle shown in figure 3.1 as templet when designing the fixture. It was determined that the design should be based on the clamps that were used in the Centrostyle drill rig. The tilting mechanism was also implemented into the new fixture in order to secure glasses with different curvature. The size of the fixture was design to be long enough to get the clamps at the edge of the glasses, next the width was design to fit both the clamps and the glasses.

The second concept was the selection of which type of mill that was going to be used. Through the selection of concept the 1+4 axis system got the highest score, where the idea was to upgrade a compact 1+2 axis mill. The 1+2 axis mill has a tool that only moves in the z-axis while the table moves in x and y axis. The two extra rotations were at this point a choice between a two axis rotary table in figure 3.5 and a tilting table with linear actuators with a ball joint at the center of rotation shown in figure 3.2. After an evaluation the trunnion table was the best alternative since this is a proven design that has been a conventional solution in the industry for a long time.

Figure 3.2: Cardboard mockup of linear actuator tilting table

At this moment the team realized that the compact 1+2 axis mill would not have the required space for a two axis rotary table. This meant that the concept with second highest score was chosen. This meant a 3+2 axis mill, this mill has a tool that moves in all linear axes and the trunnion table is fixed at one position. The mill that was purchased is presented in the next section.

3.3 System Specifications

This section features the specifications on the parts of the system. The system consists of hardware and software, some of the parts are purchased and some are custom made for this project. The different parts are introduced with a short specification and pictures. The custom made parts are also given a more detailed introduction by adding the whole design procedure.

3.3.1 Hardware

The hardware consists of the three axis CNC mill and the two axis trunnion. Both are presented with specifications, features and pictures.

3 axis CNC mill

After an evaluation the high Z S-400 mill from CNC step has been selected. The high Z S-400 is designed as a milling and engraving mill, and is capable to mill in aluminum and lighter materials. The mill has a high repeatability, high resolution and has an open base beneath the mill unlike many other small CNC mills. With this open space it would be easy to fit the mill with a two adittional rotation device.

When delivered the CNC mill comes without a spindle, but the retailer had several different spindles ranging from routers to high end spindles. A router of the brand Trend see figure 3.3, model T3E where purchased from the same retailer as the mill. It is small and compact and has a neck of 42mm and came with an adaptor for 43mm mounting bracket. The spindle speed is variable between 8000-32000rpm. If this should lead to melting when milling it is possible to add some coolant or reduce the spindle speed with a frequency converter.

Figure 3.3: The Trend T3E

Otherwise the CNC was ready to be used out of the box, and was integrated with the Mach3 CNC software without any problems.

Features for the mill

- 2 motors for constant tension and compression during milling operation on X-Axis
- Feed through of long work pieces possible, because there's no belt drive at the end of the X-axle
- Reference- and limit switch on all axes
- Double safety emergency stop button
- Energy chain for clean cabling
- Modular frame for universal application

Table 3.1: Specifications for the High-Z S-400 three-axis mill

Table size	730 x 400 mm
Traverse Paths	X=400 mm; Y=300 mm; Z= 110 mm
Traverse speed of rapid feed	3000 mm/min
Testing Motion support	Guide ways X and Y axle 22 mm / Z Axis 16mm, grinded and with 61hrc hardened surface
Driver screw	Ball bearings at both sides of trapezium spindles Tr. 12x3 mm flank lead
Technical resolution	0,00187 mm
Repeatability	± 0,03 mm
Drive	4 x Nanotec stepping motor 1600step/rev (1/8 microstepping)
Spindle motor	Trend 550 W router with collets (3 mm, 6 mm, 8 mm, 1/4")
Spindle speed	Fixed speeds from 8000 to 32000 RPM
Total dimensions including motors	L x W x H = approximate 730 x 520 x 500 mm
Weight	31 kg

The table 3.1 shows that the mill is fairly small in size, and the actual working space is smaller. But as stated earlier this mill meets the requirements of the project. Further on the traverse speed explains the maximum speed of the axes, normally achieved with the command G0(rapid movement) or if the variable F command is used. The mill has different sizes of guided threads, but ball bearings on all the axes to secure low backlash. Technical resolution means the number of millimetres one of the axes travels per step, in this case the resolution is 0.00187 mm per step. So if the mill is milling a line with 45 degrees across the xy-plane, the line would be a set of steps with a size of 0.00187 mm. With a repeatability of ± 0.03 mm, this CNC mill is a precision tool. The axes are all driven with Nanotec stepper motors with 1600 steps per revolution, the motors has original 200 steps per revolution but is controlled with 1/8 step(microstepping) from the motor driver in the control box to get its 1600 steps per revolution.

Mill Control Box

The CNC mill is delivered with a microstep controller figure 3.5, the controller has the ability to control up to four axes. It also has two power outputs one for coolant and spindle, both can be operated manually or through the CNC program.

Technical data of included microstep controller:

- 4-channel control
- Power up to 4 x 2.4 A
- Micro pacing 1/8-Step / 1600 steps / rev.
- 4 ports for 4 stepper motors
- Connection to parallel port or USB WIN PCNC Economy to USB port
- Sleep function for power reduction in standbyProtect against high voltage spikes
- E-stop button, 2-way secured
- Control of 2 outlets up to 1200 watts via software switchable (from WIN PCNC Economy), 230 V, 8A
- Power Supply Relay / Cooling
- Aluminum heatsink / 2 active fans 60 and 40mm
- Ability to connect a total of 5 end-and reference switches / stop button
- Ports motors and control line through D-sub 9-pin.

Figure 3.4: Control Box for the mill

Modifications

Since the CNC mill has an open base there was fitted a 8 mm thick aluminum plate as base. This base will be used to secure the two axis rotary table. Further the base has been fitted with rubber knots, this is done to give the mill a better contact with the surface, this resulted in a noticeable reduction in noise level due to less vibrations.

2 axis trunnion table

In order to achieve the two rotational axes in addition to the three axes mill there had to be added a device that fulfill this. Different systems from different companies were evaluated but none of these were preferable because of cost and size. For example a trunnion table from the company Haas in Germany were one of the smallest had a weight of 181 kg and a cost at 17.600 €. They are designed for other applications and heavier work and has a high cost. This repeated on all trunnions that were considered. Therefore it was decided to design and build a trunnion that are custom designed for this project. First a cardboard mockup was made to illustrate that the function works and the size is acceptable. See figure 3.5

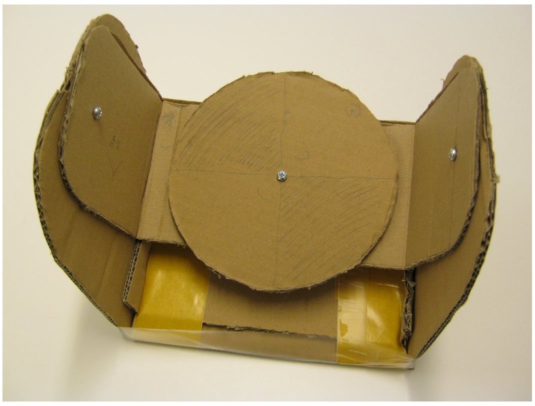

Figure 3.5: Cardboard mockup

After the verification with the cardboard model of the trunnion table it was drawn in SolidWorks and the calculation of the force that the stepper motors would be loaded with was calculated. A larger motor on the turntable would lead to more torque on the trunnion so the calculation went back and forth to both motor sizes were acceptable. In the calculation a safety factor of times two was included in case of unforeseen details that may affect the torque. The complete trunnion table in SolidWorks is shown in figure 3.7. Figure 3.6 shows the gear that had to be added since a motor that had to hold the torque alone would be large in size and would not fit in the three-axis mill. The gear was calculated to hold the torque and the amount of stages was to be held as low as possible to obtain low backlash.

The trunnion was drawn with 8 mm and 5 mm aluminum plates with 8 mm thickness in sidewalls and bases

Figure 3.6: Nanotech Gear single stage planetary ratio 8:1

and 5 mm in the turning table. Ball bearings were calculated and added in all rotating joints for extensive wear and rigidity.

Stepper motors

To power and control the trunnion two motors are required, one for each axis. Two alternatives are possible, stepper and servo. Steppers were chosen because they are easier to control and they are needs less wiring. The requirements came from the weight of the trunnion and the weight of the fixture and glasses. The forces from the spindle are also an important factor. The resulting forces on each axis were calculated and the stepper motors could be chosen. Because the torque at the B-axis is many times larger than the moment on the C-axis this would lead to a large motor on the B-axis. Since the speed of the motors was not an important factor it was decided to mount a gear on the B-axis stepper motor to increase the moment and reduce the size of the motor. Suitable stepper motors are available with 200 steps per and 400 steps per revolution. The Nanotech ST5909 stepper motors were selected. This is a compact motor with a high torque and a resolution of 400 steps per revolution.

The complete trunnion table with stepper motors in SolidWorks is shown in figure 3.7 and the specifications is presented in table 3.2.

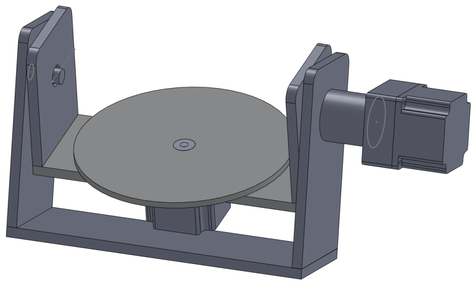

Figure 3.7: Trunnion in SolidWorks

Table 3.2: 2-axis Trunnion Specifications

Tilting	
Drive	Nanotec ST5909X2508 400 steps/rev with (1/10 microstepping) 60 Ncm torque
Gear	Nanotec 1-stage planetary 38 Nm output torque
Gear ratio	8:1
Tilting Degree	To be found deg
Rotating	
Drive	Nanotec ST5909X2508 400 steps/rev (1/10 microstepping) 60 Ncm torque
Rotating Degree	360deg
Diameter of table	170 mm
General Dimensions	
Dimension LxWxH	346 x 170 x 156 mm
Total weight	ca 2 kg

Stepper motor drivers

The stepper motors needs drives to run and to be controlled by a computer. There is a wide variety of drives and distributors of these drives. The requirements are set by the motor. The motor consumes 1.77 amp and this is the main factor for choosing a driver. A drive that can deliver 1.77 amp or more is then required. After a search of motor drives the choice is a drive from http://www.geckodrive.com. The G251 can deliver 3.5 amp and operates between 15 and 48 volts. It also has a 1/10 micro step feature which means that it can micro step ten times per step on the stepper motor. This gives a resolution of 0.09degree per micro step on the stepper motor. It has screw terminals which make it easy to connect it. It also has a heat sink with two mounting hole to mount on other units. It is compact in size with dimensions 42.5x40x15 mm. Another important factor is that it is very affordable with a cost of 69$ per unit.

Control Box and cabling

In order to process the trunnion table there are motor drives to control it. These motor drives need power and safety system in order to work in a safely way. It was considered if it was possible to mount the motor drive in the same control box as the three-axis mill. The conclusion of this is that the power supply in the control box is designed to power three stepper motors and not five. So it was not desirable to mount them in the same box. Therefore it was decided to design and build an own control box for the trunnion. First the size of the power supply was calculated then the safety items were chosen such as fuses and safety switch. Signal connectors were chosen to be db25 parallel connector between the control box and computer. Between the motors and control box there are de9 serial ports. After all the components were chosen, the required size of the box was calculated. A box in cast aluminum was chosen because these are easy to machine in such a way that all the components fits the box. All components were ordered from www.elfa.se Schematics of the control box is presented in Appendix A.

Fixture

The glasses had to be secured during the milling procedure. After evaluating a couple of fixtures it was decided to make one. The alternatives of fixtures considered for example the Centrostyle fixture in figure 3.8

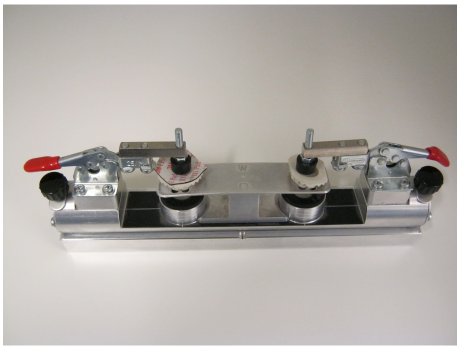

Figure 3.8: Centrostyle fixture

The fixture were too wide with the clamps sticking out on each end and then consumed too much space in the mill. The fixture were also open in both ends with no support for centering the glasses. A new fixture was drawn by hand and a cardboard model was made to verify that the dimensions would fit the mill. Afterwards the fixture was drawn in SolidWorks to make working drawings for machining the parts in aluminum. See figure 3.9 The major difference from the fixture from Univet is that the holding clamps are turned 90 degrees to decrease the width. There are also a back wall for centering and supporting the glasses. The design is solid and no further calculations were needed.

3.3.2 Software and Interface

The software used in this project is Mach3 and Excel. The modification that was done in Mach3 was mainly to set up the right pins and ports. In Excel there was used both scripts and formulas, interfacing with excel was done more easy by letting the users only change a few variables. Saving the G code was also designed to be simpler.

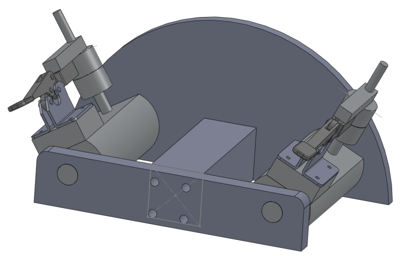

Figure 3.9: Fixture in SolidWorks

Excel

To find the position were the mill shall go on the glasses the geometry is divided in a global and a local coordinate system. The global coordinate system represents the three axis mill and the local coordinate system represents the trunnion. Imagine a point on the rotating table has coordinates x,y,z. When the trunnion turns around the y and z-axis, the x,y,z coordinates changes. In order to find the new coordinates three equations are set up.

$$x = A \times \sin b + B \times \cos b \times \cos c$$

$$y = B \times \sin c$$

$$z = -A \times \cos b + B \times \sin b \times \cos c$$

b is the wanted angle around b-axis. c is the wanted angle around c-axis + the actual angle of z in the xy-plane. When stating a point in the xy-plane this forms a Cartesian triangle between the point, the x-axis and the origin from where the z-axis points out. With $\arctan \frac{z}{y}$ the actual angle is found.

A is the length on z-axis from origin in the local coordinate system to the point on z-axis were the mill shall start. B is the length of the hypotenuse that is formed from the starting point in the xy plane to the origin, also explained in the previous section. Now the new coordinates when the trunnion moves are found. These coordinates is then added to the global system for the mill and the mill knows where to go.

Due to the simple geometry of holes and oblong holes there is no need for high cost CAD and CAM programs to generate the G-code. Most of the G-code programming repeats itself very often, for example milling a hole would mean a repeated set of command dependent on the set of cut, so a hole that requires five cuts would have five repeated commands, the only differences will be the Z (the depth of the cut). So for repeated commands Excel is a perfect tool in order to generate G code fast and simple. The idea is to generate g-codes from inputs such as position and angle, and that the formulas derived earlier in this report generate the proper position when the angles are being adjusted. Figure3.10 shows th different elements in the Excel program.

The generated g codes are then place inside one column by the help of a script shown in figure 3.11, this script also add letters such as x, y and z.

To simplify the procedure even further the Excel spreadsheet has been fitted with a macro that saves a selected set of columns and rows. The macro is execute with a button on the spreadsheet shown in figure xx, when pushed a message appears asking the user to select the data that are going to be exported to a text file shown in figure xx. This text file can then be open inside Mach3 and the milling can start.

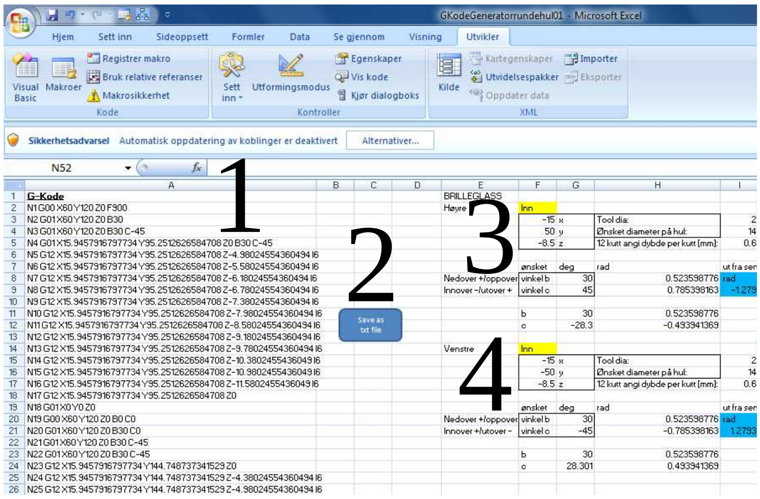

Figure 3.10: Illustration of Excel program: 1. Colum with G-code 2. Save the G-code as txt file 3. Input right glass 4. Input left glass

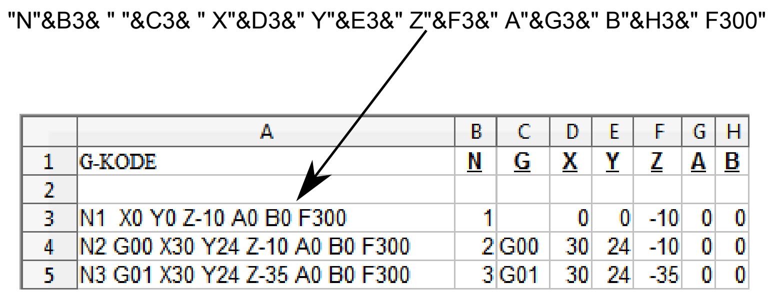

Figure 3.11: Script in Excel

Mach 3

In this project Mach3 is used instead of the WIN PCNC that was provided from the producer of the High-Z S400 CNC mill. Early on it was discovered that the WIN PCNC only supported 4 axes control. Mach3 on the other hand support up to 6 axis control.

Mach3 default interface may only have 4 axis displayed, but with an upgraded interface the other two axis can be displayed. The six axis interface was found on the Mach3 support site. This interface is sufficient enough for this project. The six axis interface is shown in figure 3.12 where: 1. Display G-code 2. Display tool path 3. Adjust feedrate 0-300% 4. Tool coordinates 5. Start and stop and other miscellaneous commands.

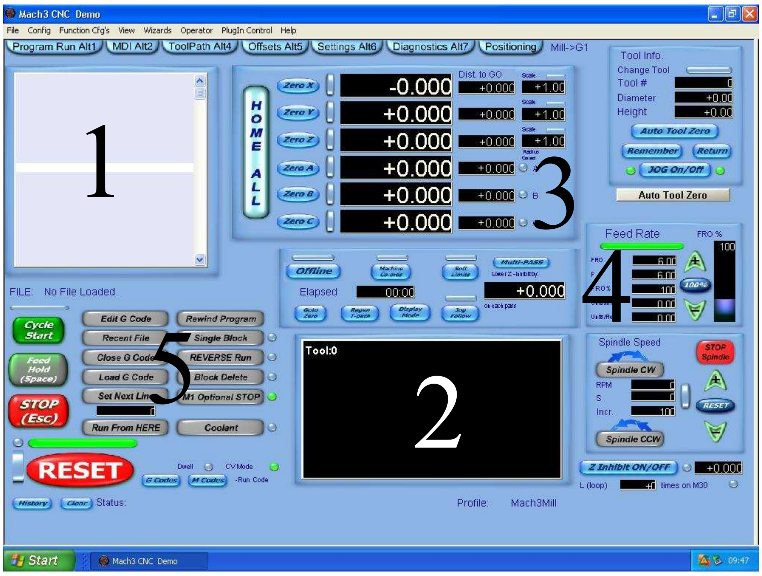

Figure 3.12: Illustration of Mach3 screen

MACH 3 uses parallel port shown in figure 3.13 for the connection between itself and the motor drivers, compared to WIN PCNC that uses a USB connection Mach3 parallel port connection may seem old fashion. The problem with this is that almost none of the new motherboards come with a parallel port as standard, to solve this either an old PC must be used or I/O card with parallel port. A five axis system needs two parallel port connections, so in this project an old PC with an extra I/O card was used. It should be mention that figure 3.13 only shows the male connector, and that the different between the male and female connector may cause some problems if they get mix up. Mach3 set up consist mainly of selecting port numbers and pin numbers. Each motor uses two pins, one for step and one for direction shown in figure 3.14.

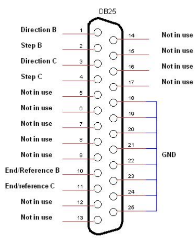

Figure 3.13: DB 25 Pinout

These two signals can either be Active on a low or a high signal. Similar the reference and limit signals and emergency stop are assigned pins and ports in the input signals. The output signals are used for spindle control and other output such as coolant.

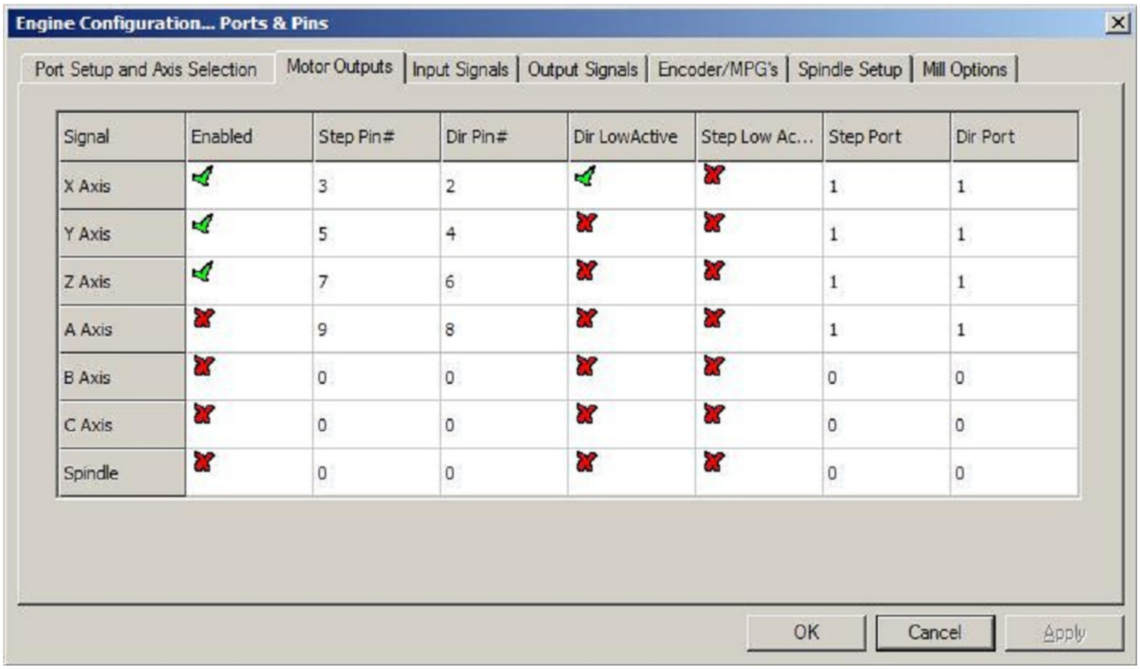

Figure 3.14: Pin Configuration in Mach3

Each axis has their own movement profile in Mach3 shown in figure 3.16, where both velocity and acceleration are adjusted. Steps per mm is also defined in this setup, to find the steps per mm these formulas are used:

Lead = pitch*starts

Steps per mm = steps per revolution/Lead

The CNC mill has lead screws with 2 starts and 3mm pitch giving a Lead equal to 6mm, the Lead describes the linear distance the nut travels in one revolution. Further on the 1600 steps per revolution is divided on the distance resulting in the steps per mm for this CNC mill, in this project all the axes have 266.667 steps per mm.

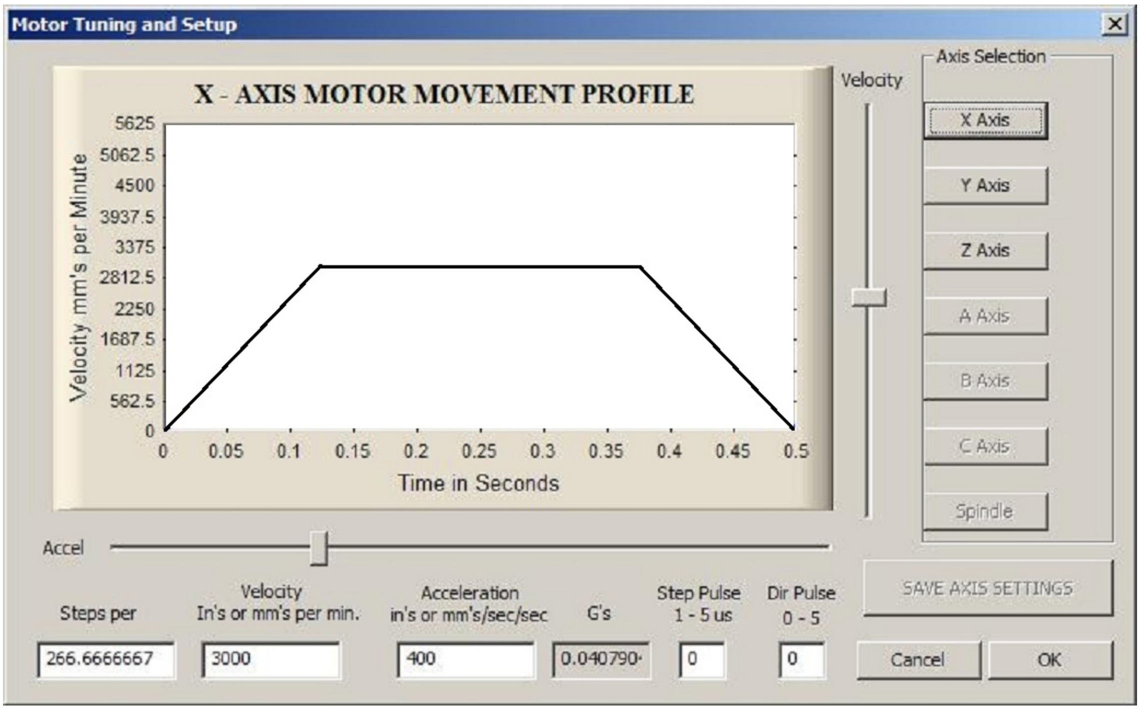

Figure 3.15: Motor tuning in Mach3 8:1

Figure 3.16 shows the setup screen for the motor home and the soft limits. Soft limits are limits that are optional limits such as a yellow light in traffic light. The soft limits stops G codes that travel further than the given soft limits, but it does not stop when operated manually with a jog. Slow zone is the area where the mill slows down before it reaches the home switch. Home negative defines the direction the mill should move when given the order to move home. The tool auto zero turns all the axes to zero when they are returned home. Speed is the homing speed, and is define with a percentage of the maximum velocity set in motor tuning and setup. For a more comprehensive set up, look at the reference Mach3 Configuration for High-Z S400 in the appendix.

Figure 3.16: Motor home and soft limits

3.4 Implementation

After the design of the system and all the specifications was found it was ready for ordering, producing and implementation. The trunnion and the fixture had been drawn in SolidWorks and most of these parts where to be produced in aluminum. All the aluminum was purchased from a local shop. The SolidWorks drawings where used to make cnc code and the parts were then machined in the university machine shop by the staff there. All work that had to be cut on the lathe, threaded by hand and grinded was done by the group members. Afterwards all the components were put together.

Trunnion

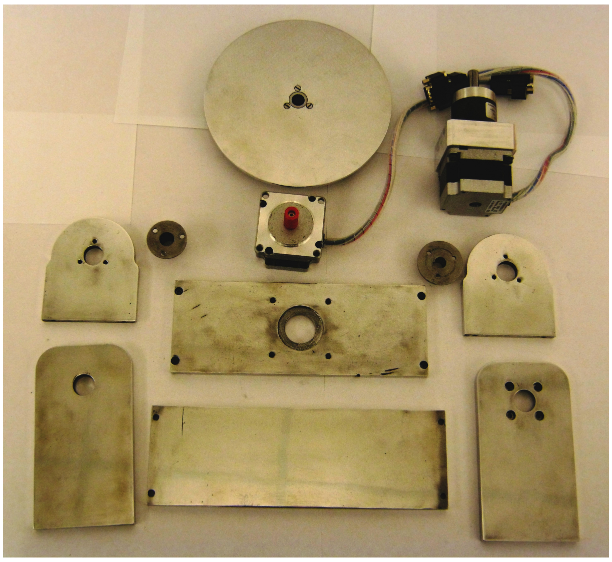

Figure 3.17: The different parts for the trunnion

After the trunnion had been drawn in SolidWorks the different part were made. Figure 3.17 shows the different parts that were made + the stepper motors and gear. All the sidewalls and the two base plates are machined of 8 mm aluminum plate. The round rotating table plate is machined of 5 mm aluminum plate. To connect the sidewalls to the base plates it was bored and threaded in the sidewalls and screwed together. To connect the inner trunnion and the outer frame and the gear there were made two axels on the lathe that are screwed on to the inner trunnion. One is connected to the outer frame with a bearing and the other are connected to the gear with a parallel key and set screw. The rotating table is connected to the inner trunnion base plate and stepper motor with an axle that is cut on the lathe. Three is bored and threaded on the rotating table and axle to connect them together. An axial and a radial bearing are pressed on the axle and the axle with the bearings is pressed on to the inner trunnion base plate. Then the motor is connected to the axle with a collet. The second stepper motor is connected to the gear which is connected to the outer frame. The motors came with JST-XHP-8 connectors but these were cut off and replaced by db9 male connectors. Insulation was placed around the wires to protect and collect them. The figure 3.18 shows all the parts mounted together after being polished.

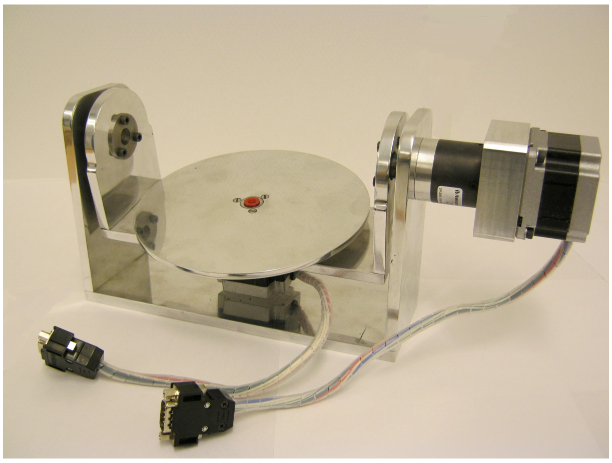

Figure 3.18: Complete trunnion mounted together

Fixture

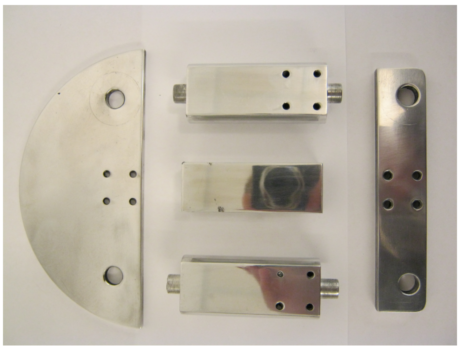

Figure 3.19: The parts for the fixture

The fixture that had been drawn in SolidWorks consisted of several components. The clamps with the rubber pads were ordered from the company Electro-Drives link. The supporting back plate where machined of 5mm aluminum plate and the front plate is machined of 8mm aluminum plate. The round turning devices that hold the clamps are made out of round 40mm aluminum bars. They are first cut on the lathe and afterward milled to get the flat sides. The clamps are then mounted on the round bars with screws by boring and threading in the round bars.The parts that were made is shown in figure 3.19 and the complete fixture is shown in figure 3.20 Afterward the fixture and trunnion were paced in the mill, shown in figure 3.21

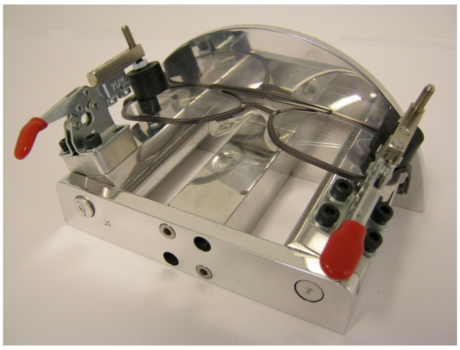

Figure 3.20: Complete fixture with glasses

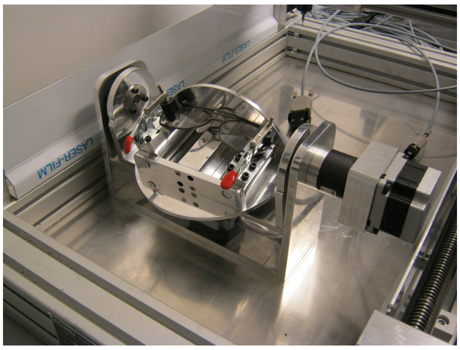

Figure 3.21: The trunnion and fixture in the mill

Control box

To capsule all the components it was started with an aluminum box with dimensions lxwxh: 275X65X175 mm. The plans of component placement were used to bore and grind holes for them in the aluminum box. Afterwards the components were placed in the box at their respective places. Then the cabling could begin. For the power side of the circuit it was used cables with cable eyes as the components were designed for. On the signal side it was used wires from a signal cable. It could have been used wires with a smaller cross-section but this would be harder to work with. The wires were soldered to the contact ports and connected to the Gecko drives with screw terminals. The aluminum box is connected to ground (earth) trough the power cable. Figure 3.22 and 3.23 shows the aluminum box after all the components are fitted.

Figure 3.22: Aluminum Box after components were fitted

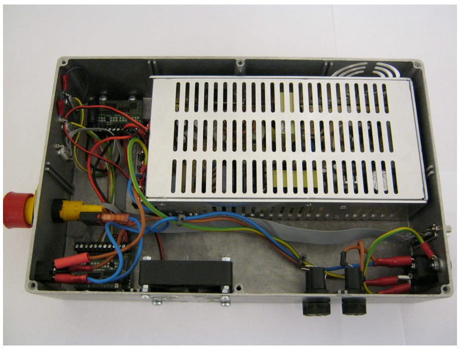

Figure 3.23: Inside the aluminum box

The control box was entirely made out of component purchased from Elfa[link] and Gecko Drives[]link See appendix for component list. To connect the motors to the control box it was used a signal cable with 0.25mm cross section which can lead the power. It was soldered a male and female DE-9 connectors in both ends. See 3.24.

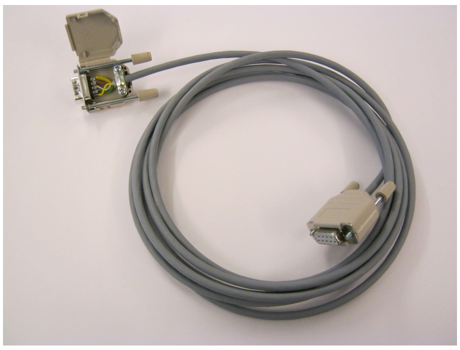

Figure 3.24: Screened cable fitted with DE-9 connectors

3.5 Test Procedures

Tests were performed to ensure that the purchased machine meets the specification set by the producer and the requirements set by the project. The rotary table was also tested for backlash since the B axis is fitted with a planetary gear.

3.5.1 Backlash

The figure 3.25 shows the basic concept of the backlash test. The idea is to use the already fitted cradle wall to measure the backlash at the end of the wall. This measurement will be calculated into an angular measurement and compared with the angular backlash given by the gear producer. The backlash test will be preformed with a dial gauge when there is current flowing trough the motor windings.

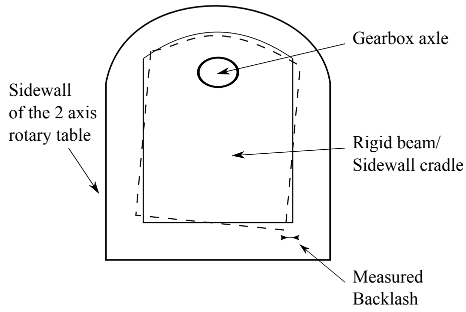

Figure 3.25: Example of backlash testing

3.5.2 Roundness

This test will verify if the CNC mill can produces round holes. This test requires a rigid fixture such that the work piece does not move around during the milling. After the milling a sweep with a slide caliper verifies if the hole is perfectly round.

3.5.3 Resolution

The resolution will be check by milling 45 degrees linear line through a work piece, the 45 degrees line will ensure that each axes move with one step each, similar to a set of stairs. From the specifications the mill has a technical resolution of 0,00187 mm, so one stair will then move 0.00187 mm in both x and y direction. The tool path should look similar to the figure 3.26. But since the resolution is very high the steps may not be visible, not even under a microscope.

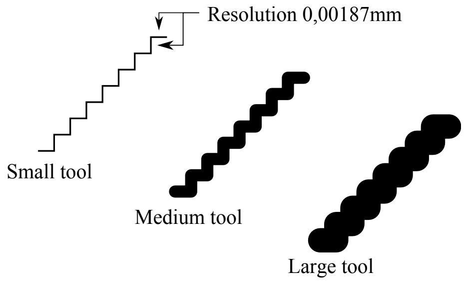

Figure 3.26: Resolution testing

3.5.4 Repeatability and accuracy

The CNC mills repeatability and accuracy will be tested by drilling several holes along a line. For each hole the tool has to go back to its home position before drilling a new hole along the line. Afterwards the position of the holes will be compared to the drawn line. If the holes align into a line the repeatability is high, but if the holes are not close enough to the reference line the accuracy is low figure 3.27.

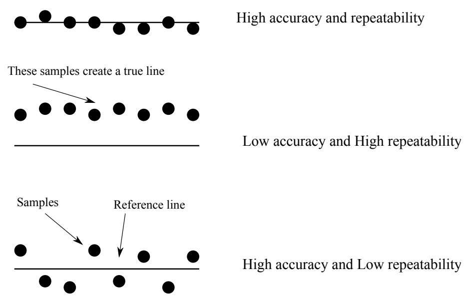

Figure 3.27: Example of accuracy and repeatability

3.6 Validation

The results from the test procedures where compared to the user requirements and suppliers specifications and verified that they were within the limits.

3.6.1 Backlash

Figure 3.28: Dial Gauge used to measure the backlash

The backlash was measured with a dial gauge shown in figure 3.28. It was chosen to measure every 45 degrees, the different deflections are shown in table table 3.3, the orientation and the angles are shown in figure 3.29. The test shows that the backlash varies from 0 mm to 0.37 mm. Other angles were tested to see if there was more backlash. At 25 degrees a deflection of 0.39 was found. This deflection is used to find the backlash in arc min, arc min being degrees divided on 60.

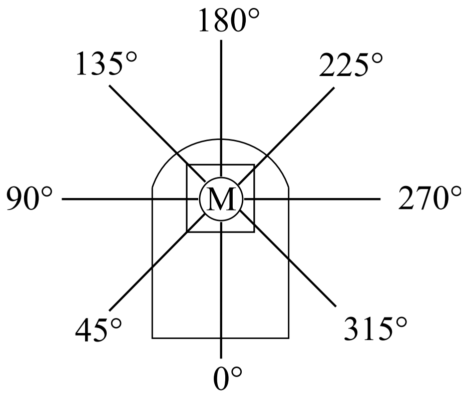

Figure 3.29: Orientation of the mill when testing the backlash

Table 3.3: Backlash test measured values

Degree	Deflection [mm]
45	0.37
90	0.36
135	0.30
180	0.15
225	0
270	0.10
315	0
360 0	0

The point that was used in the test was located 73.8 mm from the rotation center. This was calculated from the 62 mm down to the table and 40 mm out to the point. The calculated backlash in arc min is

$$Arcmin = \frac{deflection \times sec \times deg}{2 \times \pi \times radius}$$

$$Arcmin = \frac{0.39 \times 60 \times 360}{2 \times \pi \times 73.8} = 18.17$$

The producer says that their planetary used in this project has a backlash lower than 24 arcmin, this means that the gear is within the rated backlash.

Roundness

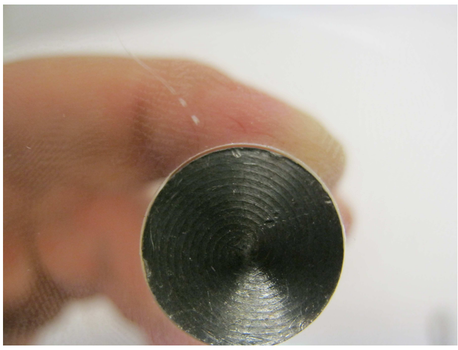

Figure 3.30: Gap

Since the CNC mills holes with a small tool, there has to be done a test to see if the hole is perfectly round. The hole was set to be 14 mm in diameter, to test the roundness a drill equal to 14 mm in diameter was placed inside the hole as shown in figure 3.30. After a close inspection it turns out that the holes is a bit oblong, but it is within the ± 0.1 mm accuracy. It will be searched for faults later.

3.6.2 Resolution

To be able to see a pattern, the mill has to make some sort of mark in the material to show the resolution pattern. The problem is that this leaves a groove, so with a technical resolution of 0.00187 mm it is impossible to see a pattern under a microscope. With a lower resolution a pattern may have been visible.

3.6.3 Repeatability and accuracy

Figure 3.31 shows the test results, both the x and y axis were tested. In the test the G00 and G28 commands were used. G00 is rapid movement out to the position given and the G28 is rapid movement to the home position. Both run at maximum velocity of 3000 mm/min rated by the producer, these commands were used to stress the stepper motor to see if they were skipping steps. Only the Z axis was run at reduced velocity,

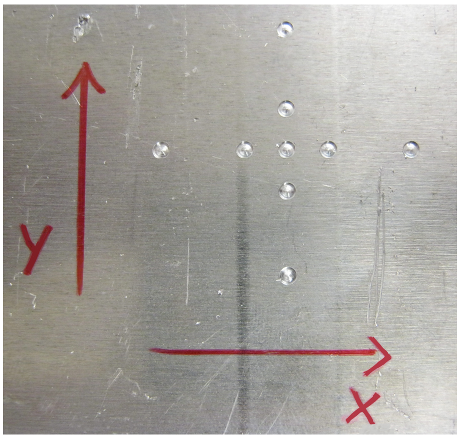

Figure 3.31: Test Holes with 2mm tool

this was done to reduce the risk of tool breakage. The tool was a 2mm three flute end mill, spinning with 8000 RPM. Since the test only needed markings, each cut was only 0.5mm deep.

In order to check the repeatability and accuracy the apparatus shown in figure 3.32 was used. The apparatus had several lenses similar to those in a mirror reflex camera, at the end it was fitted with a camera named Jenotik ProgRes SpeedXt core 3. This was connected a computer, allowing for picture to be taken.

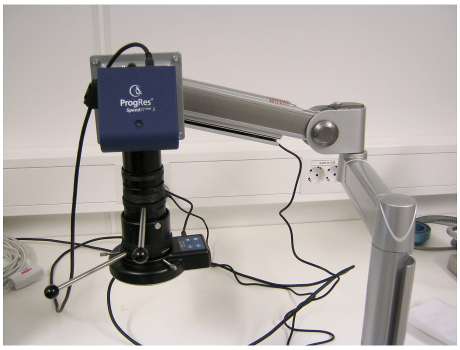

Figure 3.32: Jenotik ProgRes SpeedXt core 3

Only the holes closes to the center were used to ensure a more precise measurement shown in figure 3.33. It should be emphasis that some of the holes varies in size when look up on with magnification, this can be due to that aluminium is a softer material compared to steel and is easier to damage.

The figure 3.34 and figure 3.35 shows the holes distance from the reference line. All the measurements are shown in micrometer. In figure 3.34 the first hole from left has an error of - 4.5 μm the other two have errors of 13 μm and 12,6 μm, all are within the $\pm$ 30 μm reversal error of the mill illustrated with the boarder lines. In figure 3.35 the errors are - 0.5 μm, 16.8 μm and 20.95 μm so all the samples are within $\pm$ 30 μm. When it comes to the accuracy the drilled holes are within the boarder lines.

3.6.4 Hole placement

Figure 3.36 shows the deviation from the set distance. The deviation lies in the area around -0.06 mm and -0.04 mm all within the limit of $\pm$ 0.125 mm set by the FR8. The deviation may have been lower since the

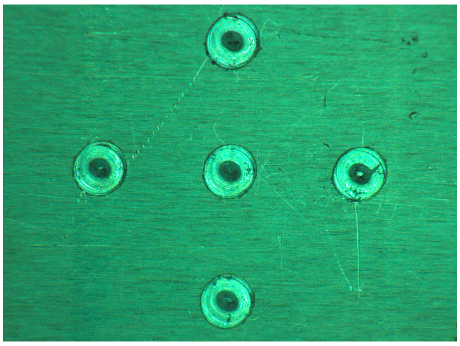

Figure 3.33: Detailed Holes from figure 3.31

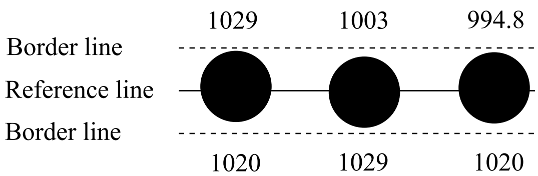

Figure 3.34: X-axis repeatibility in μm

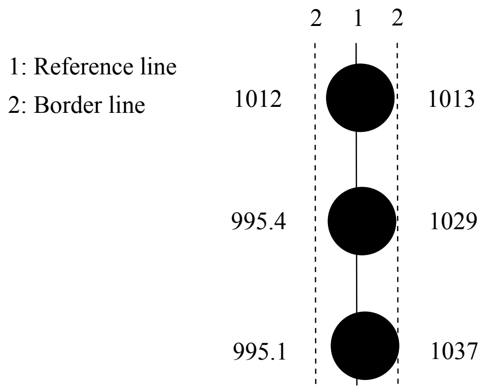

Figure 3.35: Y-axis repeatibility in μm

slide calliper tends to expand the holes and thereby decreasing the distance between the holes.

3.6.5 Spindle speed, feed rate and cut depth in polycarbonate

There was performed three milling tests, the reason for the low number of tests are because the first cut showed a good result. This meant that the optimal milling parameters were within sight. The different cutting parameters are shown in table 3.4, all the tests were performed with a 1.2 mm cutting tool special made for milling in polycarbonate.

Table 3.4: Test of feed rate and cut depth

Test#	Spindle speed [RPM]	Feed rate [mm/Min]	Cut depth [mm]
1	16000	450	0.8
2	16000	450	0.4
3	16000	900	0.4

The first test showed sign of breakage in the edge of the hole, the reason for this can be the cut depth. So for the next test the cut depth was set to 0.4 mm instead of 0.8 mm. Test number two had the finest cut with no visible breakage at the edge. So the next test was to find the upper limit for the highest feed rate with a 0.4 mm cutting depth. Test number three showed small signs of breakage at the edge of the hole. The sign of breakage at the edge do not necessary mean that the holes cannot be used. The breakage is an indication of the quality of the cut.

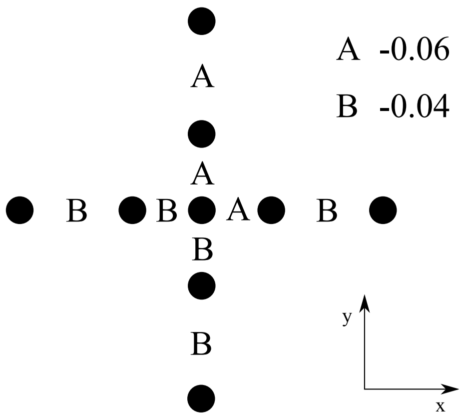

Figure 3.36: Deviation in hole placement in mm

4. User Case

4.1 Startup Procedure

Step 1 is to ensure that all the axes are connected to their designated connection, including the connection between the computer and the control boxes. After this the power can be turned on.

Step 2 the user should select the correct Excel spreadsheet in accordance to the wanted shape of the hole. Inside Excel the user is prompt with the positions, diameter and angles of the holes. After this has been filled out this, the G-code is generated. Next the user has to mark and select the G-code and push save as txt file button. It is important that the user remember the path and name of the file since the txt file has to be loaded into Mach3. After the G-code has been loaded into Mach3, the user should scroll through the codes and look at the simulated G-code to see if everything looks fine. All the AXES should be homed and set to zero before proceeding to next step.

Step 3 the glasses are mounted onto the fixture and centered by aiming the nose bridge to be align with a center line located on the fixture wall. After this the glasses are clamped and secured.

Step 4 the user should put the feed rate at 10% or low enough to see if the tool starts milling at the correct location. It should also be mention that anyone that use or are in close proximity to the mill under operation has to wear protective glasses.

Step 5 the milling can now commence, if everything looks fine the feed rate can be increased but if something do not look right the feed rate should immediately be decrease to minimize the chance of tool breakage.

Step 6 when the milling is finished and the tool has gone to the home position the procedure is repeated if the other glasses are being processed. If the milling is finished, the power is turned off and the computer is turned off.

Important

It should be mention that the three axis CNC mill's moving parts should be lubricated at regular interval to maintain the high performance of the mill, the service interval can be found inside the manual that is delivered with the three axis CNC mill.

4.2 User Case

A typical user case will be tested with a work piece that is easier to secure than a pair of glasses. The test will be use to verify the different subsystems. The test utilizes the G-code from the Excel spreadsheet. The test is to mill two circular holes with declination and convergence similar to the reading glasses. The normal angles used in reading glasses are presented in appendix E. The declination is determined by the usage and the convergence is determined by the distance between the glasses and the magnification point. Normally these distances are 30 cm, 40 cm and 50 cm.

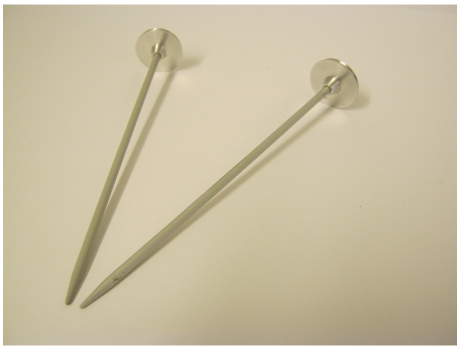

Figure 4.1: Testpins

With a thick work piece the convergence angles can be verified by the use of pins fig 4.1 place inside the finished holes.

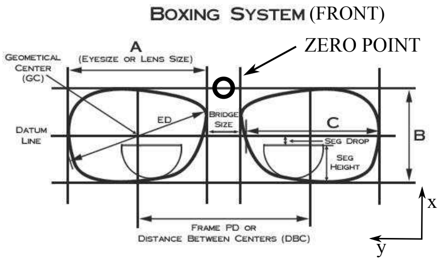

Figure 4.2: Boxing

The user case is as following: The holes will have a convergence set to 14.48 degrees and a declination set to 12 degrees, the declination is similar to the data in appendix E. The positioning of the holes makes use of the boxing system shown in figure 4.2. The zero point on the glasses is set on the middle of the nose bridge and is local coordinate system. The holes coordinates are (-20 mm, 35 mm) and (-20 mm, -35 mm). With a hole to hole distance of 70 mm and a convergence of 14.48 degrees the magnification point is 135.55 mm in front of the user. The idea was to measure the cross over point of the test pins and compare it against the magnification point.

But after a visual check and test with a dial gauge it was verified that the test pins were not straight enough for testing and verifying the angles of the holes. Instead a pair of 15.5 diameter drill bits were planned to be used, since the drill bits were shorter than the test pins the convergence angles had to be increase to 25.9 degrees.

The substitute material for polycarbonate glasses was a six mm thick piece of nylon plastic. The test went without a hitch until the first hole was almost finished. The problem was that the tool was too short for a six mm thick work piece that was resting in two different angles. The tool's shank is wider than the actual tool, this cause the tool's shank to increase the friction between the tool and the work piece. This friction made the C axis table jump out of steps. The table was reset for the next hole, in Mach3 the required steps were made to start the program at the correct programming line. Overall the existing tool may be sufficient enough for milling in glasses since these have a thinner material thickness. But it should be an assessment on the possibility to invest in new tools, since the existing tool has a limitation in the areas of material thickness and high angles.

The Excel G-code generating worked just fine, the milled holes had the same distance between them even after both the B and C axis has been changed twice.

When the user case test was finished, it was discovered that the holes have a smaller angle than it should have. This was especially related to the convergence. The fault is located and will be corrected before the machine is handed over to ProVista.

5. Discussion

This chapter gives the discussion on the user requirements, tests, cost, ease of use and the user case. The user requirements are evaluated and discussed one by one.

FR1

In order to mill holes with angles an ordinary three axis mill must have two extra two rotations axes. But could also have been solved with a robot arm, but small CNC mill was chosen because of better ratio between cost and accuracy in ProVista's case. Earlier in the process the choice stood between a tilting table with linear actuators and a trunnion table. The trunnion table has no limitation in the achievable angles, but the designed tilting table was limit by the play of the linear actuators and the ball joint at the middle. So to ensure that the final machine satisfy FR1 the trunnion table was chosen, it was also chosen because it is a proven design that has been used in the industry for a while. The problem is that commercial trunnion is designed for heavy pieces, so it was decided to build a trunnion table special made for glasses.

FR2

In order to achieve perfect result when milling in polycarbonate a two flute end mill special made for milling in polycarbonate was ordered. The end mill is supposed to be used in the hand mill dremel, so the tool is made for spindle speed between 5000 and 35000 rpm. So the it was decided to perform a test to see which parameters gave the best result, with the limitation of not using coolant it was exciting see if the milling could be done without coolant. Optimal parameters such as spindle speed, feed rate and cut depth were found, but if the quality of the edge is less important all the test parameters can be used. The most interesting discovery was that the milling did not melt the polycarbonate. Neither the milled holes nor the tool displayed any increased temperature.

FR3

With FR3 the choice stood between number of different five axis mills, but mainly between the robot arm and the CNC mill, the main reason for choosing the CNC mill has been mentioned above. But it should also be mentioned that a robot arm would had resulted in more programming. But since the team is more interested in mechanical designing and building, the solution was to modify a three axis mill with a trunnion table. With a trunnion table from the FR1, and the purchase of a three axis CNC mill the final product is a five axis CNC mill thus satisfying the FR3.

FR4

Independent of the type of mill, the mill would need a fixture. To the teams knowledge it does not exist any commercial fixture for a pair of glasses. So the fixture had to be custom made, the Centrostyle drill rig was used as template and several elements were used in the design such as the clamps, rubber pads and the tilting mechanism. The design also incorporates that ProVista delivers two types of glasses with binocular, so the fixture is design to secure two types of glasses with minor modifications. The glasses are restrained in one direction by a wall. All other directions are secured by the clamps. The nose bridge is centre against a mark on the fixture wall. This is done by visual estimate. This may lead to some inaccuracy, but according to ProVista the human eye can correct such minor inaccuracy very easily.

FR5

The size of the fixture was based on the FR5, the length of the fixture is based on the length of a pair of glasses and that the rubber pads are placed at the edge of each glass. The width is designed to fit both the clamps and the glasses. The trunnion has been made with a 170 mm diameter turntable thus satisfying the FR5.

FR6

With a mill it is possible to mill large holes, the size of the holes are limited to the size of the mill's working area. In this case the working area is greater than 40 mm. The smallest holes is limited to the size of the tool, in this project a 1.2 mm tool is used. The smallest hole size achievable will then be 1.2 mm, this means that the hole size range are within the FR6.

FR7

The High Z S-400 was purchased because it had a reversal error of ± 0.03 mm, this is within the FR7. Still it was decided to test the purchased mill to see if this was correct. The test was to mill five holes in a string in both directions, the mill went back and forth between the work piece and home position on each hole. The largest deviation after testing was 12.6 μm on the x axis and 20.95 μm on the y axis, both these are within the specification and the FR7.

FR8

In the same test the hole placement was tested. The highest deviation was 0.06 mm which satisfies the FR8. But the deviation can in reality be even smaller, since the slide calliper may have expanded the holes during measuring and thereby the distance between them.

NFR1

The High Z S-400 control is powered through a standard household type outlet, the same is the custom made control box for the trunnion table. This means that the complete system satisfy the NFR1.

NFR2

The CNC mill should not exceed the size set by NFR2, so the mill was suppose to be large enough for the trunnion table and small enough for the NFR2. With external dimensions of 730 mm x 520 mm x 500 mm, the purchased mill is well inside the NFR2. Even if it later is decided to build a cage around the mill the external dimensions will still be within the requirement.

NFR3

The noise sources on the new mill are the stepper motors, the spindle and the control boxes. The stepper motor emits most noise at low speeds and get quieter when they run faster. The control boxes emit a constant noise level due to the fans. The main problem is the spindle which masks out every other noise source. There have been fitted rubber pads underneath the mill, so the vibration noise gets lower. Other step may involve minimizing the running time of the spindle, meaning that the spindle stay turned off when the tool travels between the different milling tasks. The feed rate can also be turned up to reduce the milling time. Later upgrades like a new and quieter spindle may lower the noise level, or the entire mill can be built inside a soundproof cage. Since the NFR3 is not quantified it is hard to tell if the noise level is low enough compared to the other apparatus inside the laboratory and thus satisfying the NF3.

Overall the user requirements have been satisfied, except the NF3 which can be satisfied if the mill is fitted with a spindle that runs quietly.

Roundness test

Another test that was performed was to find out if the mill could mill perfect circular holes. By placing 14 mm diameter drill through the 14 mm diameter milled hole, it was discovered that the circular hole is a bit oblong. In the oblong direction the hole has a diameter of 14.1 mm, in the other direction the diameter is 13.94 mm.

Backlash test

The three axis CNC mill has been tested and validated, and delivers the required performance. The next source error in the new five axis mill is then the trunnion table. The trunnion table is fitted with a planetary gear to increase the torque output on B axis, when using a planetary gear there will be some backlash in the trunnion table. The gear retailer informs that the planetary gear has a backlash of 24 arcmin. From the testing the highest backlash was measure to be 18.17 arcmin, so the backlash is lower than rated backlash. The most interesting was that the backlash varies in size through the different angles. From 0 degrees to 180 degrees there is higher backlash than from 180 degrees to 360 degrees, the reason for this may be that the purchased planetary gear normally varies from 0 to 18.17 arcmin, or the trunnion table is not aligned properly. But with this test is possible to use the range of angles that has lowest backlash.

General discussion

The finished machine is special made for a specific usage, compared to industrial five axis mills that are made to be versatile. The cost has been reduced by designing the size of the special made machine after the specific usage. The trunnion table size has been reduced considerably compared to ordinary trunnion table have a weight over 100 kg, a smaller trunnion mean less cost on materials, bearing, gear and motors. The selection of stepper motor also reduced the cost, compared to servo motors that are dependent on sensors in a precision tool as a CNC mill. The combination Mach3 and Excel were also chosen due to the low cost compared to a CAD and CAM programs.

Design is also build on the principal on ease of use. The most difficult element of CNC milling is to generate the G-code. A big effort was made to make the process at effortless as possible. It has also been added a save button in the spreadsheet to eliminate the process of manually copying and pasting the G-code into a txt file. The path of the G-code is even display in Mach3 after it has been loaded into the program. This will make the user able to evaluate the tool path before proceeding further.

The user case test indicated a fault in the trigonometric functions in excel, the problem is that the output angles for the convergence is not equal to the angles set in the excel spreadsheet. The assumption is that the convergence angles can be used at an input. Extra calculations are needed so the turntable turns the required angles set by the needed convergence.

The necessary steps will be done to fix the problem before the machine is delivered to ProVista.

6. Conclusion

The background for this master thesis proposal was that Provista saw a large potential in designing a mill that would be a more time and cost effective method to make their visual aid glasses.

The requirements that ProVista had for their new machine were that it had to be of limited size, be able to mill holes in different types of glasses with different angles in two directions and being easy to operate. The holes must have an error less than ±0,1 mm in diameter.

6.1 General Conclusion

The solution presented for solving the user requirements was a machine with five degrees of freedom that are needed to mill a hole with a path in the three dimensional room and to be turned around two axes that would represent the angles for the hole. The machine is based on a three-axis mill which was extended with a custom made a two-axis trunnion to be able to achieve the five degrees of freedom. Also there was made a custom fixture to secure the glasses during the milling process. In order to control and steer the milling process all five axes where powered with stepper motors and motor drives. These are controlled by two programs on a computer. First an Excel script is produced where desired position, angle and hole size are typed. The Excel script then produces a set of G-code for the milling trajectory to produce the desired holes. The second program Mach3 uses the set of G-code to issue control signals to the stepper motor via the motor drives.

After some test procedures including accuracy and repeatability for the machine and final tests involving user cases with milling of actual holes with angles, the conclusion would be that the machine mills the holes with correct positions. The mill is small with a size of 700x520x550 mm and has a user interface which has only four steps: 1. Type coordinates, angles and size of hole 2. Save G-code as text file 3. Load G-code in Mach3 4. Adjust the feed rate and push start. With this machine ProVista will be able to offer high-quality visual aid glasses at a highly competitive cost and short delivery time.

6.2 Future Work

Elements that could be improved in future work are suggested to find a more silent spindle since this is the largest source of noise on the machine. Other factors that could be improved are the fixture to centre the glasses. The fixture could also need some extra supporting pillars for certain types of glasses. The size of the mill can be further reduced since a large area of the mills work area is unused. The operating of software on the computer could have a more user friendly interface. Instead of operating two programs it is possible to merge these into one user screen were the operator only has to fill in angles and position and push start.

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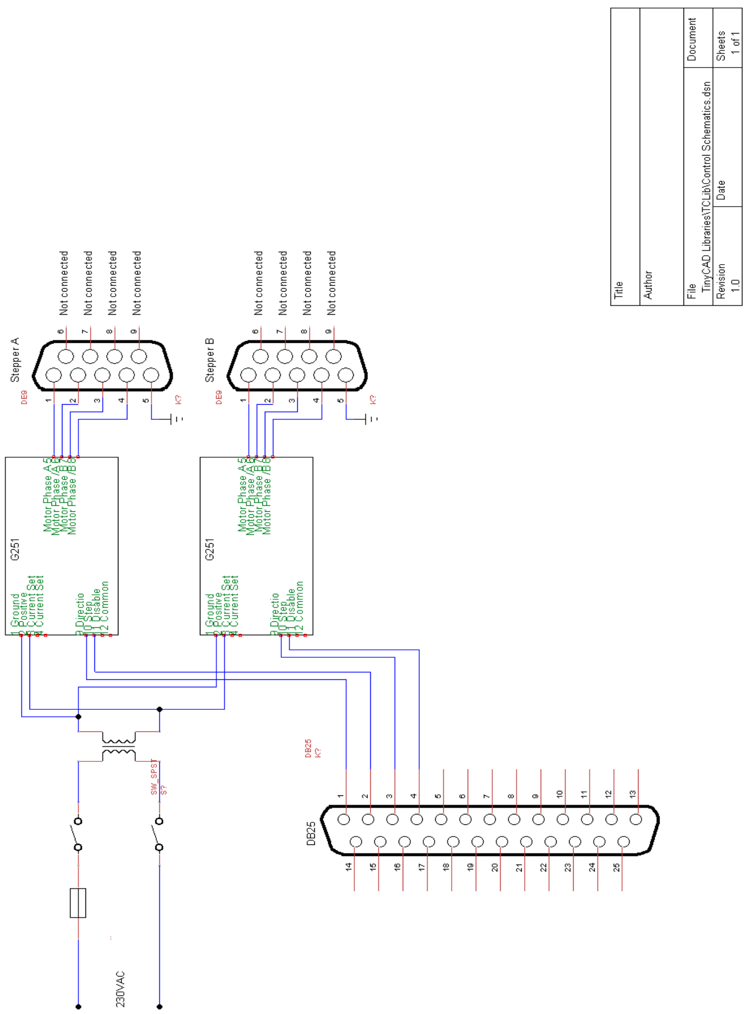
A. Schematics



B. Part List

Part list

CNC mill; High Z S-400; CNC-step.de

- Aluminium base; Thomic Aluminium

Custom made Trunnion table

- 2xStepper Motors; Nanotec
- 8:1 Planetary Gear; Nanotec
- Aluminium; Thomic Aluminium
- Bearings; KSH Arendal
- Micro switches; ELFA
- Steel; UiA
- Screws; UiA

Custom made fixture

- Aluminium; Thomic Aluminium
- Clamps; Electro-Drive.no
- Rubber pads; Electro-Drive.no
- Screws; UiA
- Steel; UiA

Custom made control box

- Aluminum box; ELFA
- DB25 Parallel port; ELFA
- DE9 Serial ports; ELFA
- Emergency button with sign; ELFA
- Fuse holder; ELFA
- Power connector; ELFA
- Power supply; ELFA
- Stepper motor drives; Geckodrive.com
- Cables; UiA
- Power button; ELFA
- 60 mm fan; ELFA

Cabling

- Screened cable; ELFA
- DE9 connectors; ELFA

C. Standard G-Codes

Power Automation America

Standard NC Programming Codes

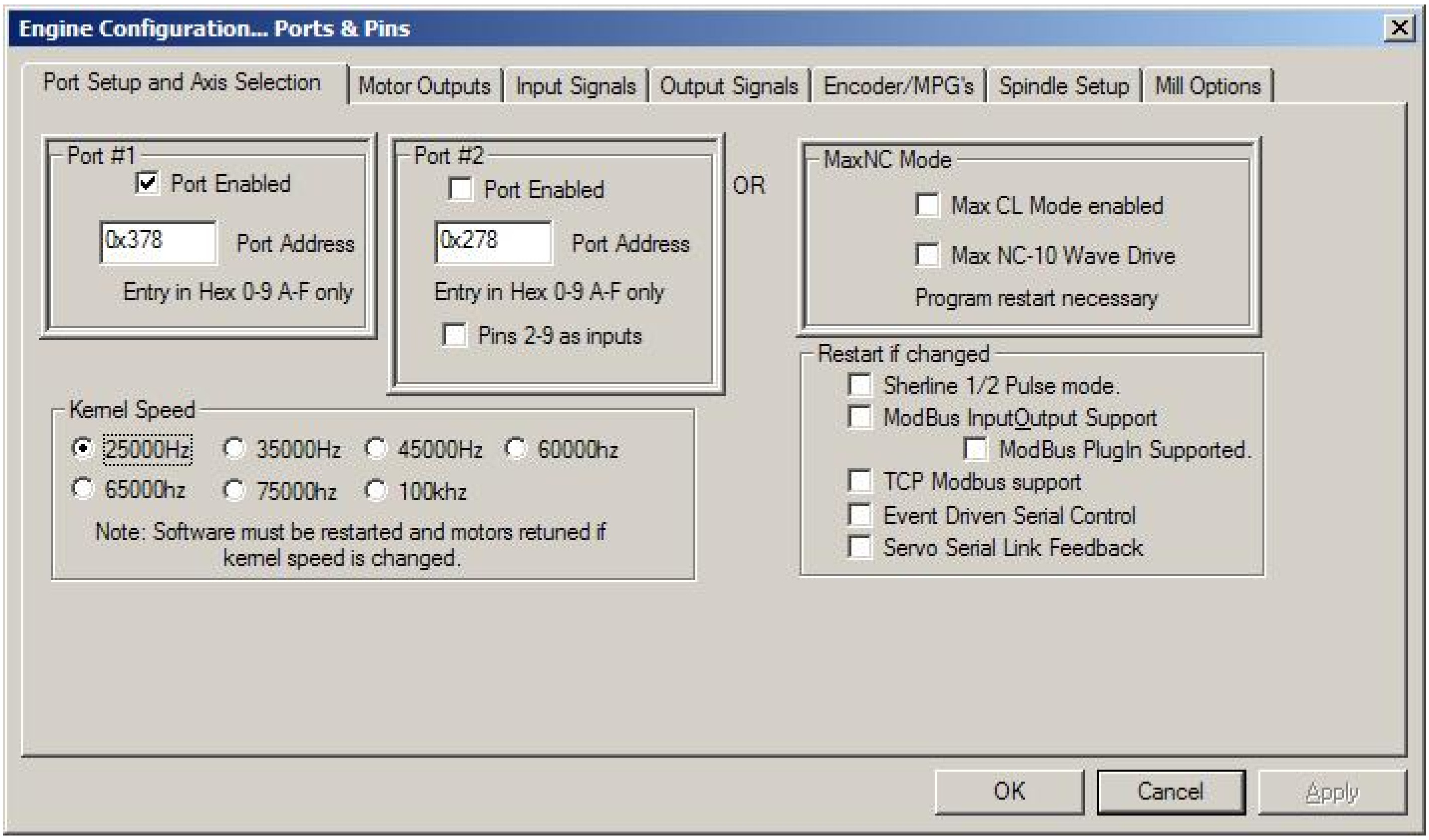
NC Programming as per ISO (DIN 66025) and RS274

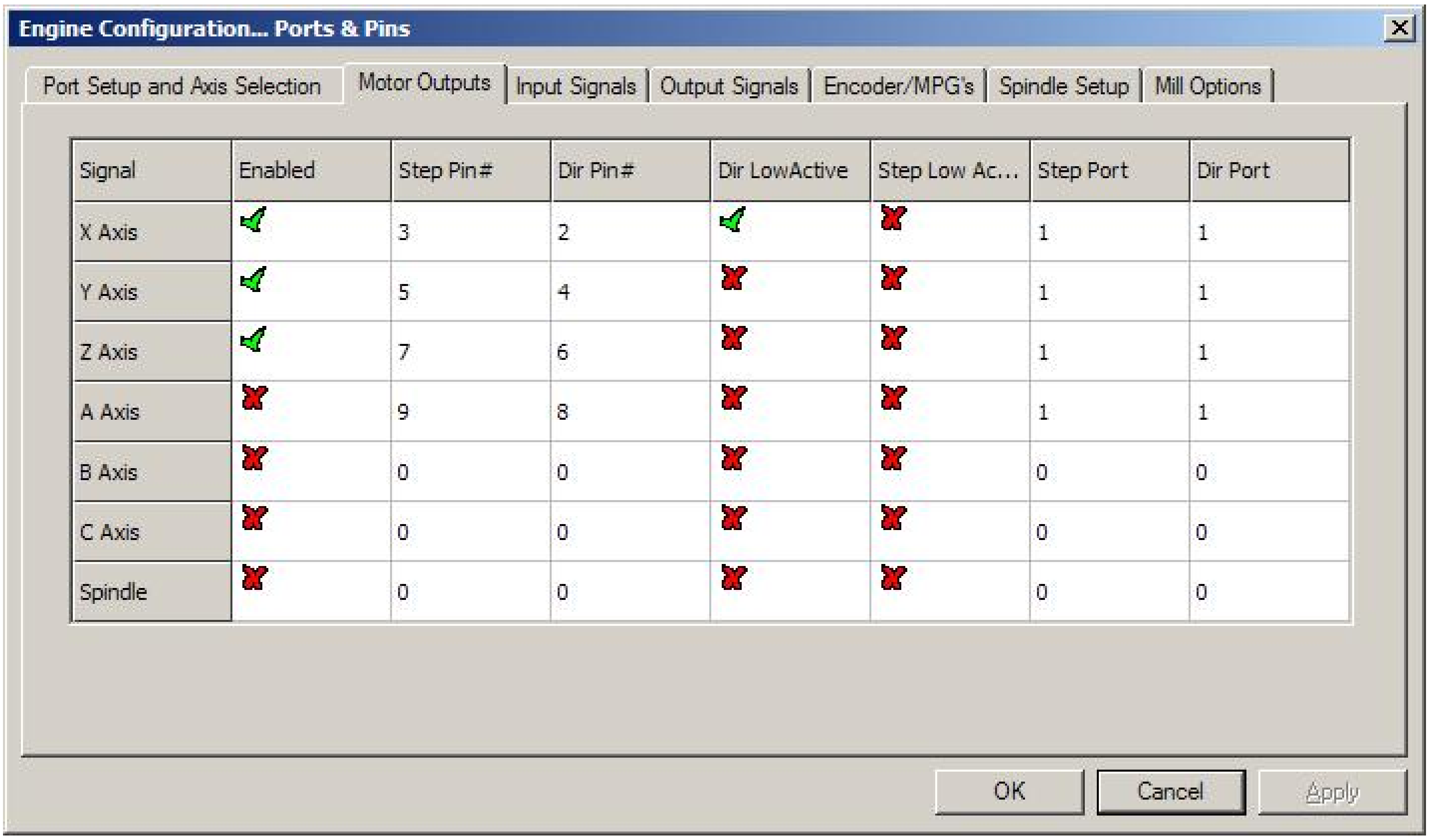
G00	Rapid traverse
G01	Linear interpolation
G02/G03	Circular interpolation
G04	Dwell
G07	Tangential circle interpolation
G08/G09	Path control mode (ramp at block transitions) and "Adaptive Look ahead"
function	
G10/G11	Block pre-processing control
G12/G13	Circular interpolation with radius input
G17-G20	Plane selection
G33	Thread cutting/rigid tapping
G36/G37	Programmable feedrate limitation
G38/G39	Mirror image
G40-G44	Tool radius compensation
G50	Scaling
G51/G52	Part rotation
G53-G59	Zero offsets
G63/G66	Programmable feed rate/spindle speed override
G70/G71	Inch/metric dimensioning
G72/G73	Interpolation with in position stop
G74	Home position
G80-G89	Canned cycles
G90/G91	Absolute/incremental programming
G92	Position register preset
G94/G95	Feedrate
G160-G164	ART learning function
G186	Programmable tolerance band
M00	Program stop
M01	Optional stop
M02/M30	End of program
M03/M04/M05	Spindle control (cw/ccw/stop)
M06	Tool change (M-code depends on PLC)
M19	Spindle orientation
M40-M46	Spindle gear transmission steps

D. Mach3 Setup

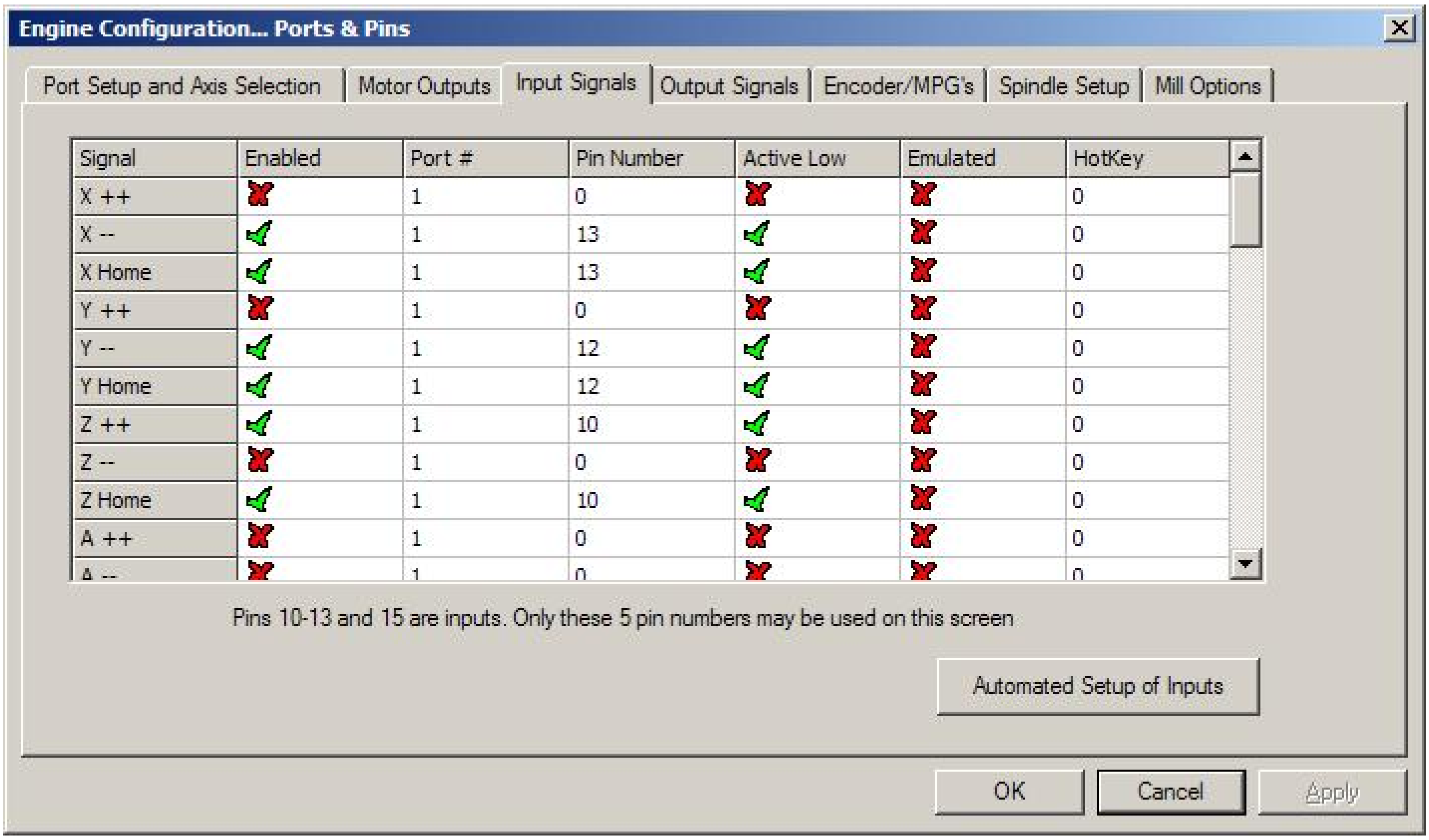
Marc3 Configuration for High-Z S400

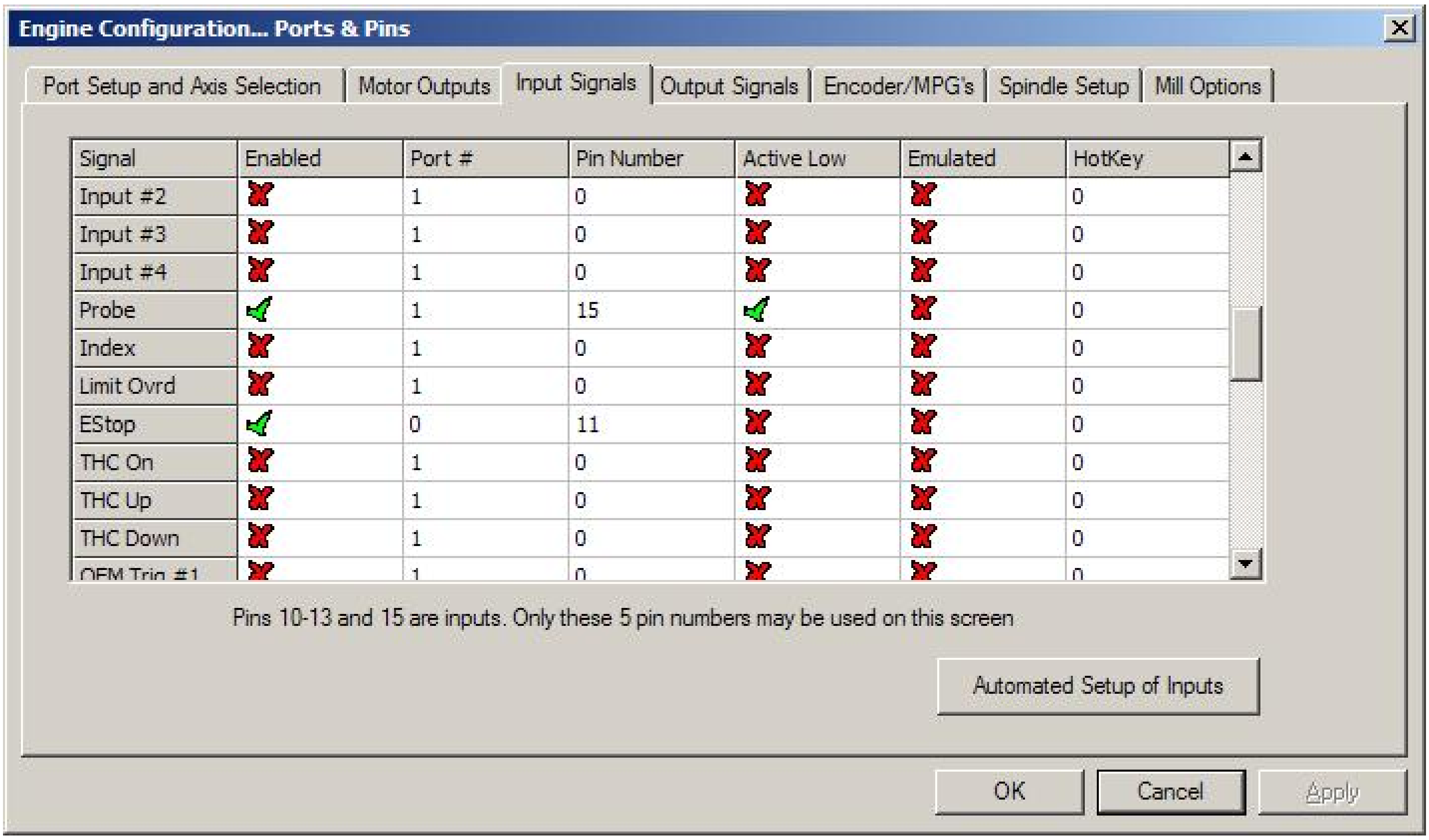
Mach3 menu: Config -> Ports & Pins



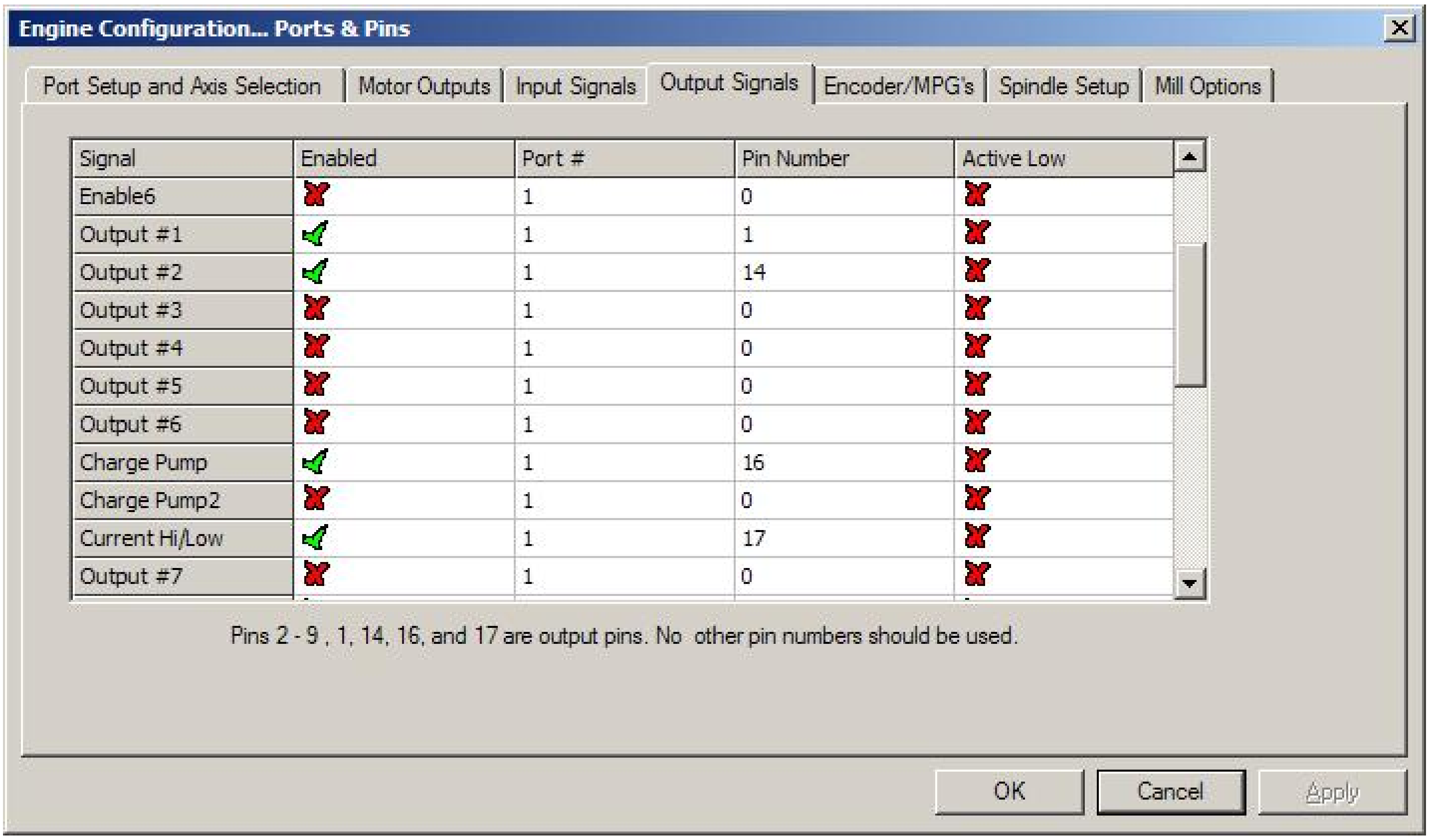


Signal	Enabled	Step Pin#	Dir Pin#	Dir LowActive	Step Low Ac...	Step Port	Dir Port
X Axis	✔	3	2	✔	✘	1	1
Y Axis	✔	5	4	✘	✘	1	1
Z Axis	✔	7	6	✘	✘	1	1
A Axis	✘	9	8	✘	✘	1	1
B Axis	✘	0	0	✘	✘	0	0
C Axis	✘	0	0	✘	✘	0	0
Spindle	✘	0	0	✘	✘	0	0





Only shown inputs is set, all others is off.
There is an EStop input on pin 11 but it is unstable and triggers unwanted random EStops.

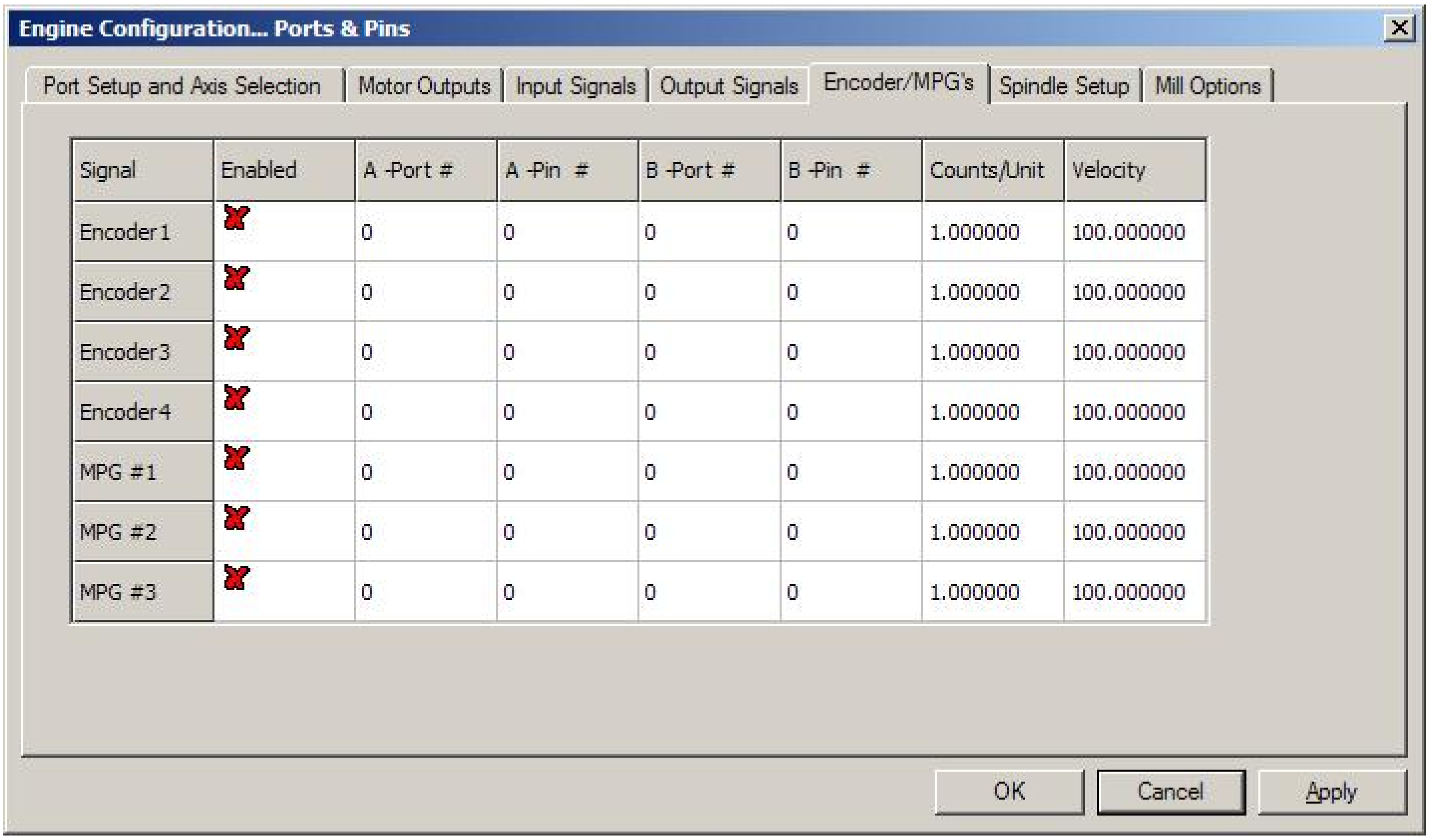


Signal	Enabled	Port #	Pin Number	Active Low
Enable6	✗	1	0	✗
Output #1	✓	1	1	✗
Output #2	✓	1	14	✗
Output #3	✗	1	0	✗
Output #4	✗	1	0	✗
Output #5	✗	1	0	✗
Output #6	✗	1	0	✗
Charge Pump	✓	1	16	✗
Charge Pump2	✗	1	0	✗
Current Hi/Low	✓	1	17	✗
Output #7	✗	1	0	✗

Output #1 is used for spindle relay and output #2 is for mist/flood relay control. They uses the same relay. Chargepump on output #16 is wired on the controller diagram but I don't think it is working.

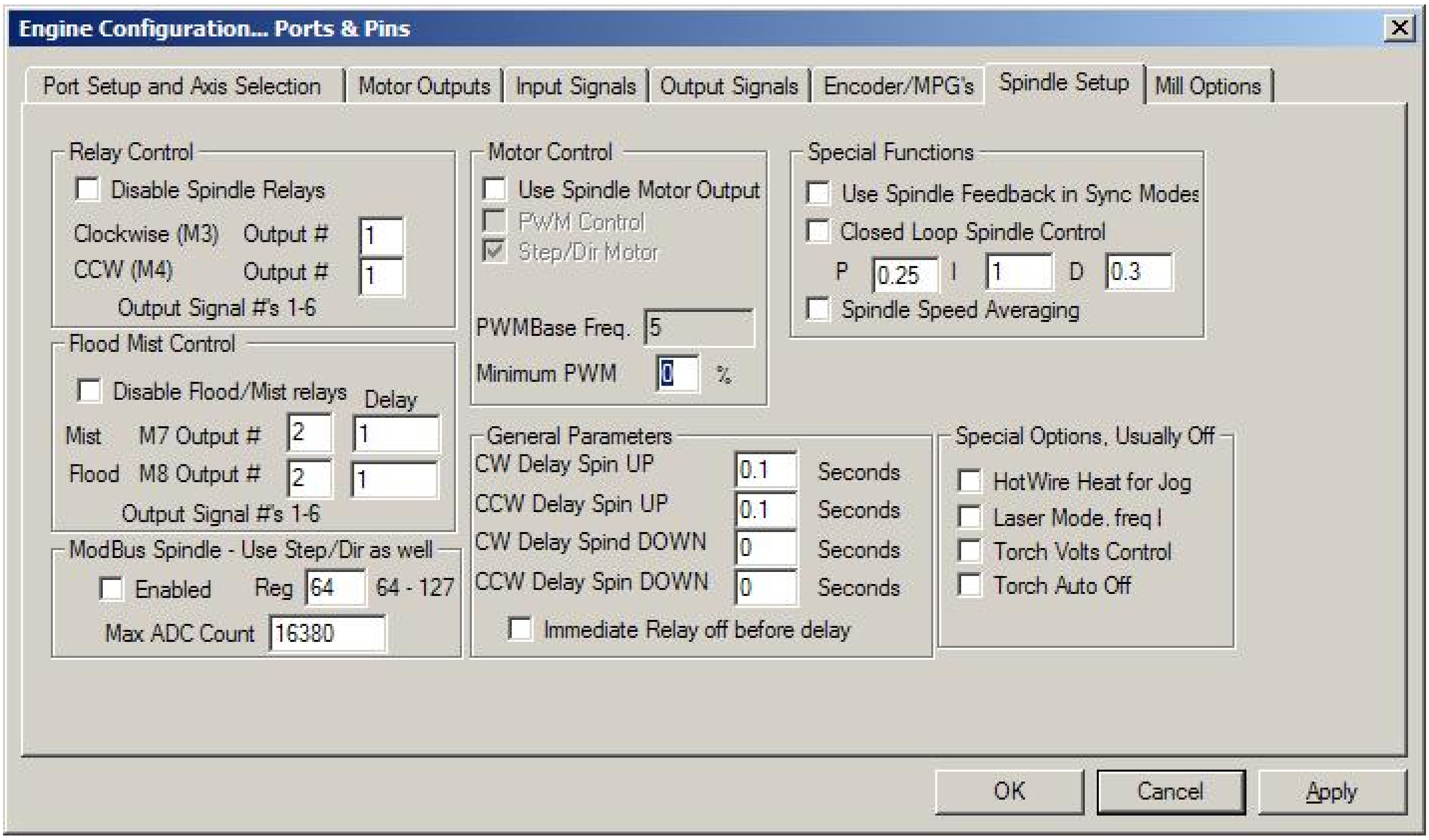
Output #17 id used for controlling "power save" on controller and reduces the noise when the motors is not running.

All other outputs is off (or not configured).

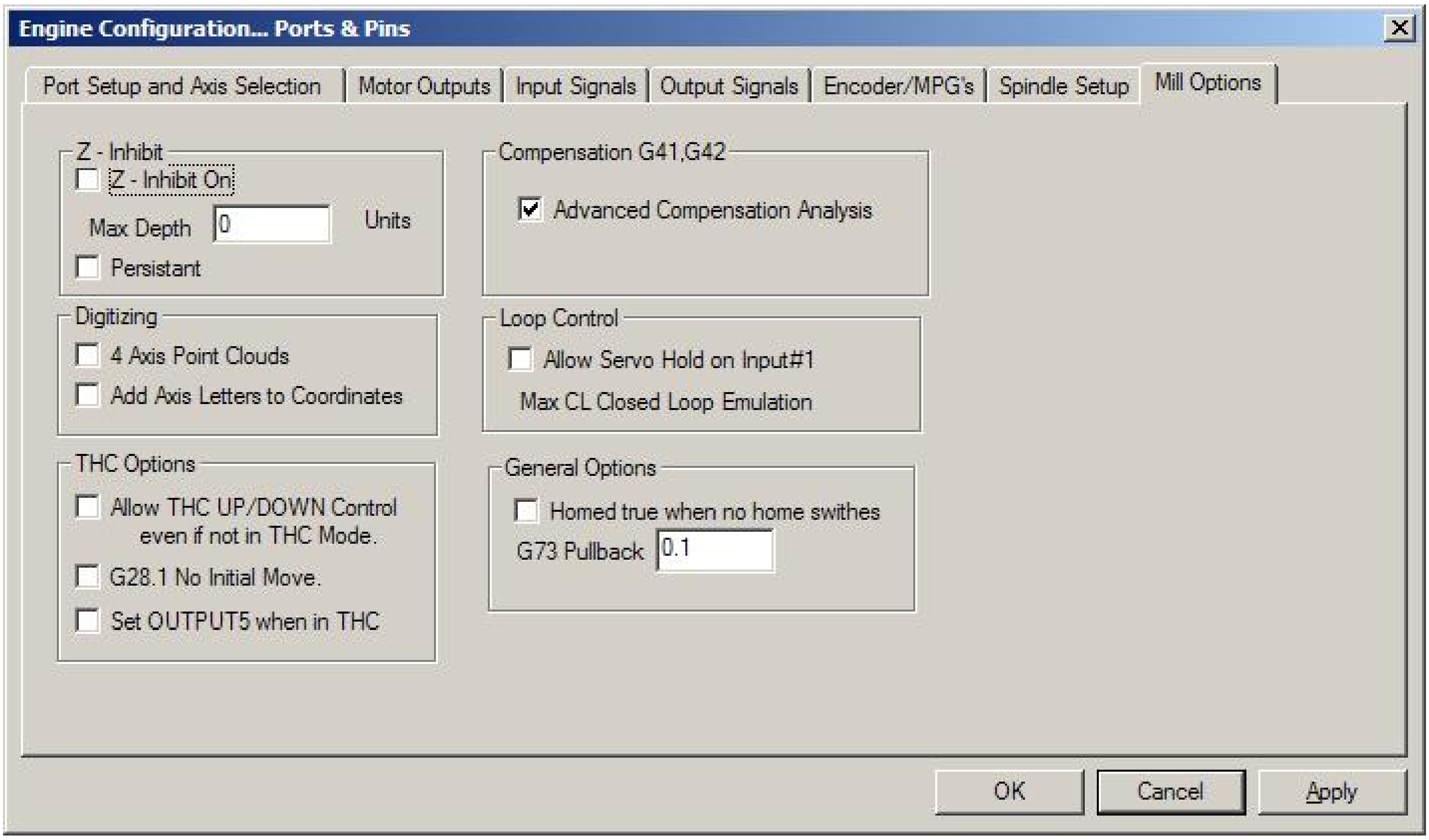


Signal	Enabled	A -Port #	A -Pin #	B -Port #	B -Pin #	Counts/Unit	Velocity
Encoder1	✗	0	0	0	0	1.000000	100.000000
Encoder2	✗	0	0	0	0	1.000000	100.000000
Encoder3	✗	0	0	0	0	1.000000	100.000000
Encoder4	✗	0	0	0	0	1.000000	100.000000
MPG #1	✗	0	0	0	0	1.000000	100.000000
MPG #2	✗	0	0	0	0	1.000000	100.000000
MPG #3	✗	0	0	0	0	1.000000	100.000000

Encoder/MPG's is not used in my configuration.

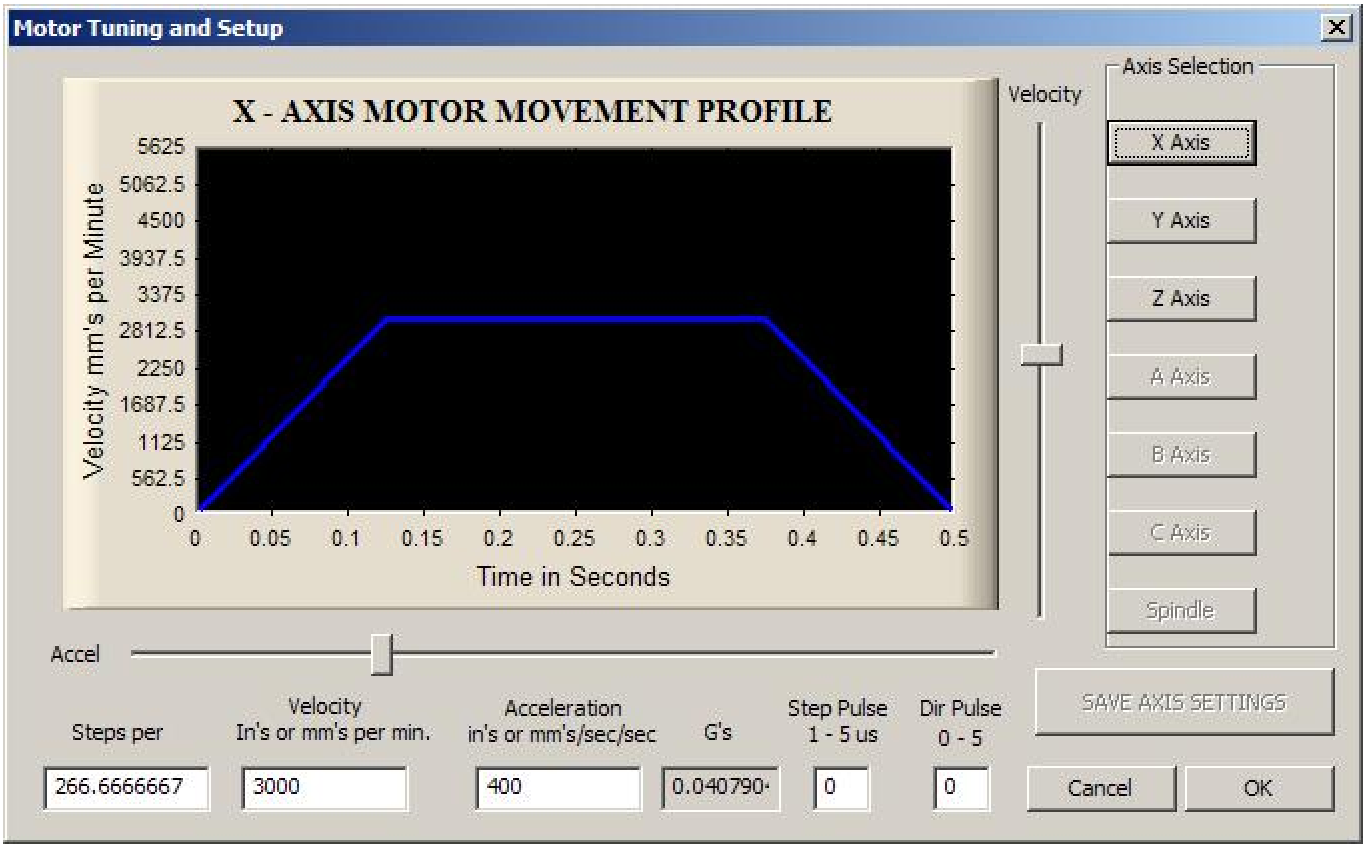


Here spindle (output #1) and mist/flod (output #2) is setup.
Values for spin up/down may need adjustment.



All set to default settings.

Mach3 menu: Config -> Motor Tuning



All axes have same configuration.
Note max velocity for S-720/S-1000 is lower and higher for T models.

Mach3 menu: Config -> Homing/Limits

Axis	Reversed	Soft Max	Soft Min	Slow Zone	Home Off.	Home Neg	Auto Zero	Speed %
X	✗	400.00	0.00	3.00	0.0000	✓	✓	20
Y	✗	288.00	0.00	3.00	0.0000	✓	✓	20
Z	✗	0.00	-110.00	3.00	0.0000	✗	✓	10
A	✗	100.00	-100.00	1.00	0.0000	✗	✓	20
B	✗	100.00	-100.00	1.00	0.0000	✗	✓	20
C	✗	100.00	-100.00	1.00	0.0000	✗	✓	20

E. Data for Glasses

BIFOCAL MICROSCOPES

GENERAL

Bifocal Microscopes are microscopic lens systems designed to be used in bifocal form, and they come in powers ranging from 2X (+8.00 D.) to 10X (+40.00 D.). Composed of a doublet lens system, Type I in design (two plano-convex lenses with the convex sides facing away from the eye—see schematic), they are mounted low in the carrier lens and function in the same manner as a flat-top bifocal. Two styles are available:

Type E Segment: 13 X 23 mm
Type R Segment: 19 X 25 mm

These Bifocal Microscopes are ideal for people who must be constantly alternating between distance and near vision, e.g., students, businessmen, etc.

The patient's distance prescription can be incorporated into the system, as well as a tint for light sensitive patients.

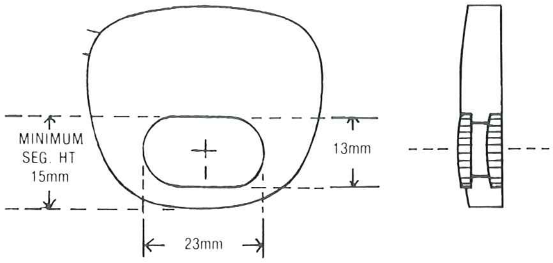
FITTING

Bifocal Microscopes are fit in the same manner as standard bifocals, with some restrictions. They can be set at the patient's near P.D. within the physical limitations of the frame's eyewire, although this is not recommended for the higher powers because of the short working distance. There is also a minimum segment height: 15 mm for the Type E system, and 22 mm for the Type R system. For optimal results, however, the bifocal should be set as high as possible, even as high as one would set a trifocal segment—especially on the higher powers. This, along with increasing the pantascopic angle of the frame, will allow you to position the segment in such a manner that the system's optical axis is very close to, if not coincident with, the patient's visual axis, i.e., when the patient reads through the bifocal microscope, he should be looking perpendicularly through the center of the system, or as close to it as possible.

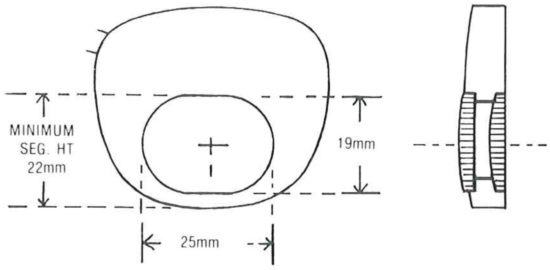
The Yeoman 6 is the frame of choice for the Bifocal Microscope.

POWERS AVAILABLE

Type E Segment: 2X–10X
Type R Segment: 2X–10X



Type E Bifocal Microscope
(in carrier lens)
2X — 10X



Type R Bifocal Microscope
(in carrier lens)
2X — 10X

Two Type E Bifocal Microscopes
mounted in the Yeoman 6 frame

Two Type R Bifocal Microscopes
mounted in the Yeoman 6 frame

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BIOPTIC TELESCOPES

GENERAL

The Bioptic Telescope (also Galilean, as are the Full Diameter Telescopes) provides the patient with the benefits of a telescopic system while still maintaining his mobility. Mounted high in the carrier lens, the telescope is "out of the way" while the patient is moving about or doing his general work, but is always available for distance spotting simply by the patient dropping his head slightly to bring the telescope into alignment with his eyes. This is important, because the patient does not use the telescope all the time (as he would with the Full Diameter Telescope), but only when he wants to see a distant object magnified. With this principle in mind, one can see why Bioptic Telescopes have been prescribed for students who need to view the chalkboards in the classroom while still being able to see up close, for people who need to spot distant signs while moving, for drivers who need to spot signs in the operation of a motor vehicle—indeed, for any situation requiring a greater flexibility in the patient to meet constantly changing visual demands.

As with the Full Diameter Telescopes, different designs are available in the Bioptic line, depending on the needs of the patient. The standard Bioptic Telescopes (Model I) are available in powers of 2.2X, 3.0X, and 4.0X. There is also a Model II Bioptic Telescope, available in only the 2.2X power, which is markedly smaller than the Model I 2.2X Bioptic Telescope. This is particularly suited for the patient who is more sensitive to the cosmetic appearance of the telescope. All of the standard Bioptic Telescopes are constructed of glass lenses mounted in a plastic housing. It should be noted that the Full Diameter 3.0X and 4.0X Telescopes and the Bioptic Model I 3.0X and 4.0X Telescopes, respectively, are physically the same telescope. The difference is in where the telescope is mounted in the carrier lens—centrally or superiorly.

The Wide Angle Bioptic Telescopes are available in powers of 2.2X and 3.0X. Because of the larger physical size of these units, compared with the standard Bioptic Telescope, the visual field is larger.

It should also be noted that all of the Bioptic Telescopes have round objective lenses, with the exception of the Model I 2.2X and both Wide Angle telescopes (2.2X and 3.0X). These three telescopes have rectangular objective lenses.

While the Bioptic Telescope is generally used for distance tasks, closer working distances can be achieved by applying a reading cap over the front end of the telescope. The reading cap will focus the telescope for any desired working distance (intermediate or near), based on the power (focal length) of the cap. As with the Full Diameter Telescopes, in some cases the Doctor will have to prescribe more than one reading cap to satisfy all of the patient's visual needs.

The patient's distance prescription can be incorporated into either the telescope, the carrier lens, or both. For best results, it is recommended that this be done. It should also be noted that a bifocal carrier lens can be prescribed for the patient. The Executive style bifocal is the one that is customarily ordered. It is also possible to have both a Bioptic Telescope and a Bifocal Microscope or Reading Telescope in the same carrier lens. This is referred to as a Trioptic System, and will be discussed in a separate section of this catalogue.

The telescopic units can be supplied with either a clear or black housing. For patients with a glare or light sensitivity problem, a tint can be incorporated into both the

(over)

telescope and/or the carrier lens, as well as the reading cap. Drilled Sunfilters are also available.

FITTING

Bioptic Telescopes are generally mounted in the carrier lens such that the optic center of the ocular lens is 9 mm below the top of the carrier lens. They are laterally decentered to the patient's P.D., and have a standard drilling angle of inclination of 10° upward from the horizontal plane. Any position or angle, however, can be special ordered. Bioptics can be ordered in either a "clear" or "black" housing—this must be specified on the order blank.

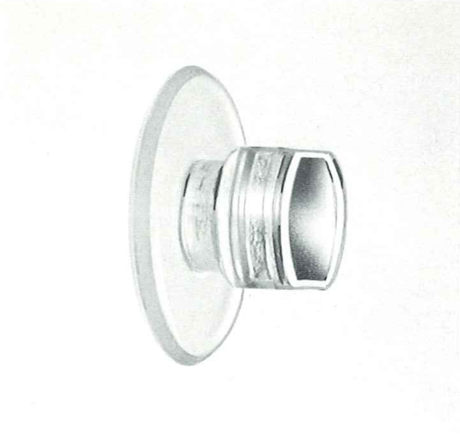
When using a bifocal carrier lens, care must be taken in the placement of the bifocal segment. This is not as important if the patient is going to be using only the telescope and the bifocal segment, but if it is also desired that the patient be able to see at a distance through the carrier lens, at least 8 to 10 mm should be available between the telescope and the top of the bifocal. Thus, a frame with adequate vertical dimension must be chosen for the patient. The Designs for Vision Yeoman 6 is especially suited for this purpose.

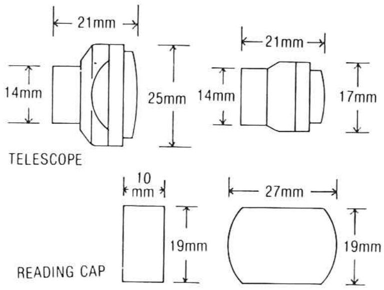
When binocular telescopes are prescribed, the reading cap is used only monocularly, since the telescopes will not be aligned for the near working distance. The cap is generally placed over the eye with the better acuity, or, in the case of equal acuities, over the dominant eye.

Although any frame can be used when fitting the patient with a monocular Bioptic Telescope, it must be of sturdy construction, and have adjustable nosepads so the telescope can be accurately aligned in front of the patient's eye. The Yeoman 6 is the frame of choice to meet these needs. It has adjustable pads, an all-aluminum front, and spring temples for a snug fit against the head. For binocular Bioptic Telescopes, it is essential that **only** the Yeoman 6 frame be used.

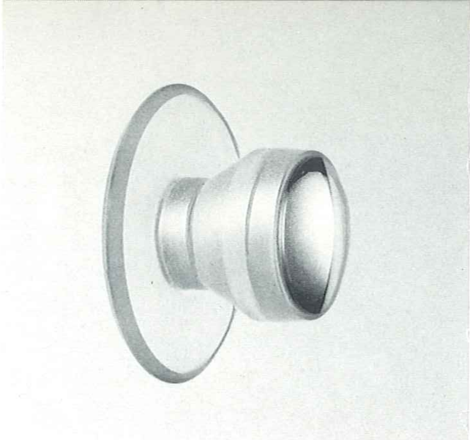
POWERS AVAILABLE

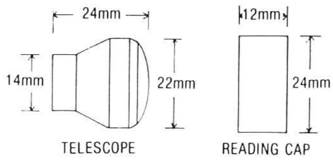
Model I: 2.2, 3.0, 4.0X
Model II: 2.2X
Wide Angle: 2.2, 3.0X



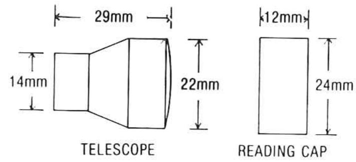


2.2X Bioptic Telescope—
Model I

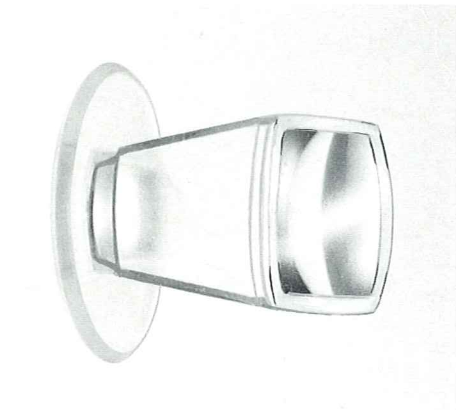


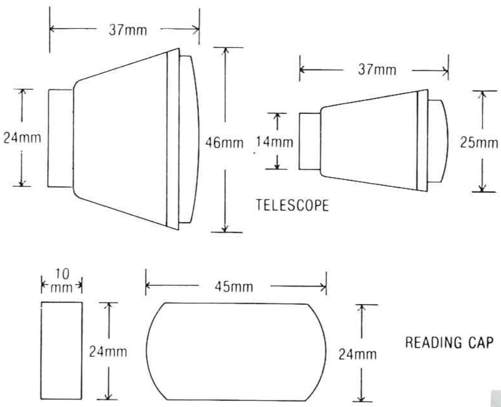


3.0X Bioptic Telescope

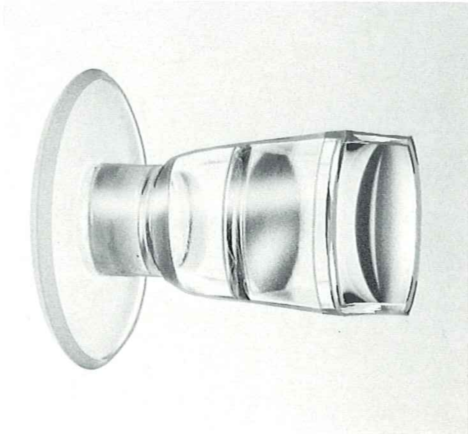


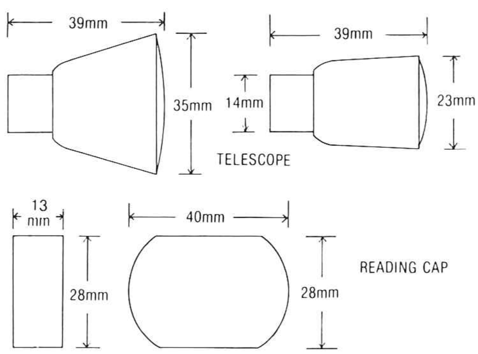
4.0X Bioptic Telescope



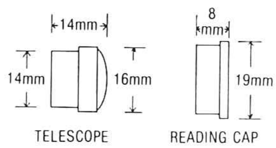


2.2X Wide Angle Bioptic
Telescope





3.0X Wide Angle Bioptic
Telescope



2.2X Bioptic Telescope—
Model II

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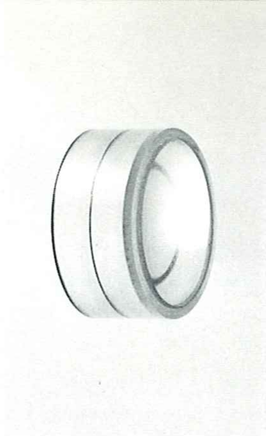
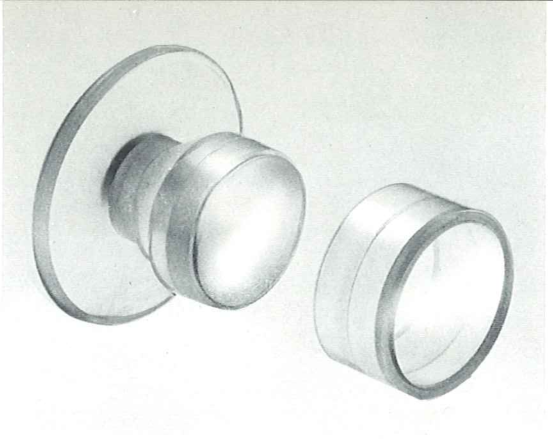
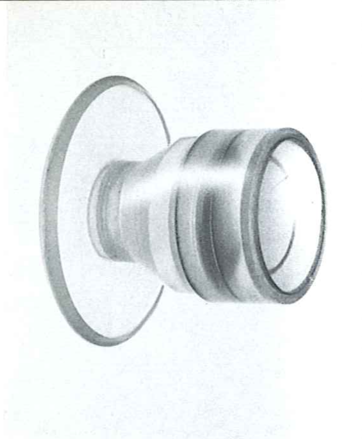


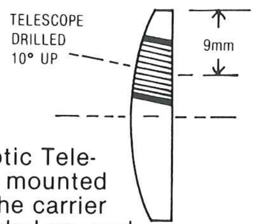
Reading Cap for 3.0X Bioptic Telescope



Reading Cap and 3.0X Bioptic Telescope



Reading Cap on 3.0X Bioptic Telescope



The Bioptic Telescope is mounted high in the carrier lens, angled up, and the optic center of the ocular lens is positioned 9 mm below the top of the carrier lens

Binocular 3.0X Bioptic Telescopes with clear housings, mounted in the Yeoman 6 frame

Reading Cap for 2.2X Bioptic Telescope—Model II

Reading Cap on 2.2X Bioptic Telescope—Model II

Binocular 2.2X Bioptic Telescopes—Model II with black housings, mounted in the Yeoman 6 frame

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FULL DIAMETER TELESCOPES

GENERAL

Full Diameter Telescopes (Galilean Telescopes) are designed for distance tasks that are to be performed while the patient is stationary. Mobility is not practical, since walking with Full Diameter Telescopes would be analagous to walking while looking through a pair of binoculars. These telescopes are especially suited for such distance tasks as watching T.V., going to the Theatre, sporting events, or spotting distance stock market quotations—anything that can be done while the patient is stationary.

Constructed of glass lenses mounted in a plastic housing, the telescope itself is mounted in a plastic carrier lens, making the whole system light-weight and easily worn. The Full Diameter Telescope is available in either the standard design, or in a wide angle design. The standard design is available in powers of 1.7X, 2.2X, 3.0X, and 4.0X. The wide angle design is available in powers of 2.2X and 3.0X.

While the Full Diameter Telescope is generally used for distance tasks, it may be converted into an aid with increased versatility by applying a reading cap over the front end of the telescope. The reading cap will focus the telescope for any desired working distance (intermediate or near), based on the power (focal length) of the cap. Since the cap is easily attached to and removed from the telescope, the patient can do this himself, thus achieving greater flexibility in the use of this system. Since patients will often want to perform visual tasks at different working distances, more than one reading cap will often have to be prescribed to satisfy all of the patient's needs.

The patient's distance prescription may be incorporated into the telescopic system itself. It is usually desirable to do this to achieve the best performance possible with the system. The carrier lens usually does not contain the patient's prescription.

The telescopic units can be supplied with either a clear or black housing. For patients with a glare or light sensitivity problem, a tint can be incorporated into both the telescope and/or the carrier lens, as well as the reading cap. Drilled Sunfilters are also available.

FITTING

Full Diameter Telescopes are mounted in the vertical center of the carrier lens, and decentered to the patient's interpupillary distance (p.d.). Any position within the physical limits of the carrier lens, however, can be specially requested. When mounted, the telescopes are aligned in the "straight-ahead" position. Telescopes can be ordered in either "clear" or "black" housings—this must be specified on the order blank.

Although any frame can be used when fitting the patient with a monocular Full Diameter Telescope, it must be of sturdy construction, and have adjustable nosepads so the telescope can be accurately aligned in front of the patient's eye. The Yeoman 6 is especially suited to meet these needs. This frame has adjustible pads, an all-aluminum front, and spring temples for a snug fit against the head. For binocular telescopes, it is essential that **only** the Yeoman 6 frame be used.

POWERS AVAILABLE

Standard: 1.7, 2.2, 3.0, 4.0X
Wide Angle: 2.2, 3.0X

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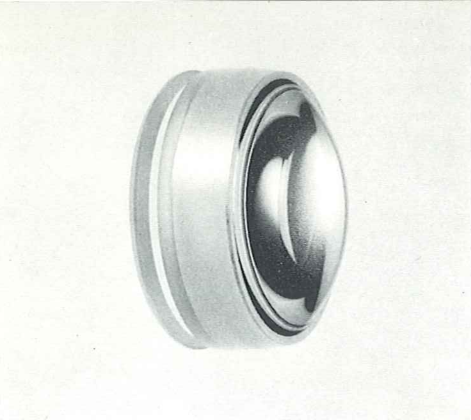
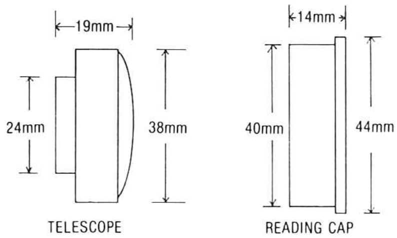
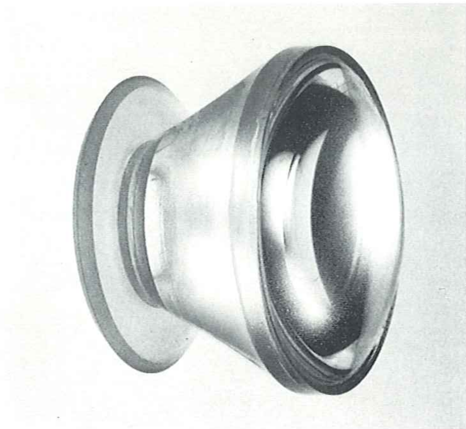
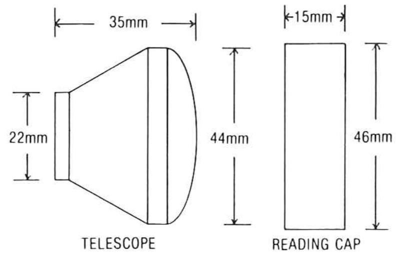


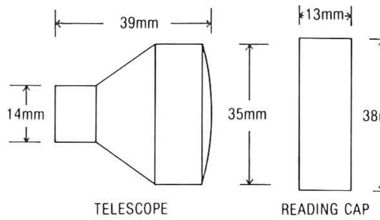


1.7X Full Diameter Telescope

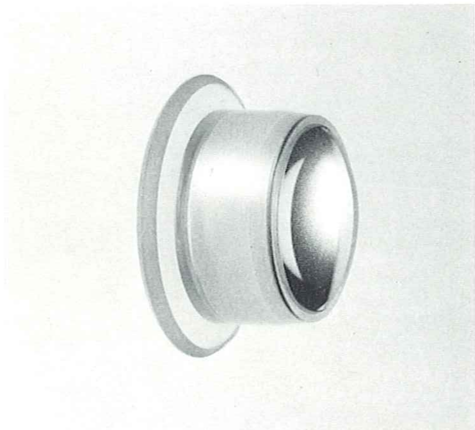


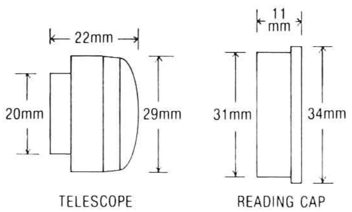


2.2X Wide Angle Full Diameter Telescope

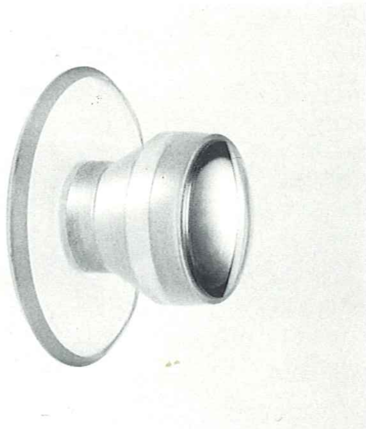


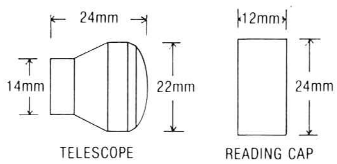
3.0X Wide Angle Full Diameter Telescope



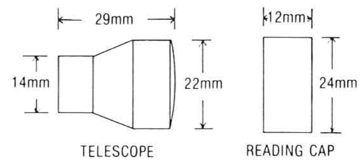


2.2X Full Diameter Telescope





3.0X Full Diameter Telescope



4.0X Full Diameter Telescope

FULL DIAMETER TELESCOPES

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READING TELESCOPES

GENERAL

Reading Telescopes are telescopic systems designed for occupation and reading distances. They allow an increased working distance from that which is found with a comparably-powered microscope (reading lens), while still maintaining an adequate magnification level. Secretaries, students, and electricians are just a few examples of the types of people who would benefit from this type of aid. The usefulness of these units, however, should not be considered to be limited to low vision patients. Anyone whose "seeing" requires more than normal visual acuity would benefit from these aids. It might be noted that different names have been used for Reading Telescopes. They have variously been called telemicroscopic loupes, telescopic loupes, telemicroscopes, and surgical glasses.

Reading Telescopes are composed of either the standard Bioptic Telescope (Model I), or the Expanded Field Prism Telescope (non-spiral). Based on the same principle as an afocal telescope combined with a reading cap, the extra power needed for close viewing is included in the lens system of the Reading Telescope. Mounted low in the carrier lens, and angled down and in for proper alignment with the eyes in their normal reading position, the telescope is "out of the way" for general seeing, but is available for reading whenever it is needed. It functions in the same manner as a standard bifocal segment. It is also possible to have the Reading Telescope mounted in an Executive bifocal carrier lens. This allows the patient to have his normal near vision available through the bifocal (for general close work), and also be able to move into the telescope as needed.

The patient's spectacle correction can be incorporated into the Reading Telescope, as well as a tint (in both the carrier lens and/or the Reading Telescope) for light sensitive patients. The Reading Telescope is available in only a black housing.

FITTING

Two types of Reading Telescopes are available: The Galilean design (in powers of 2.5, 3.5, and 4.5X) and the Expanded Field Prism design (in powers of 3.5, 4.5, 6.0, and 8.0X). The 2.5X has a rectangular objective—all the others are round. All of the telescopes can be ordered to be focused at **any** working distance.

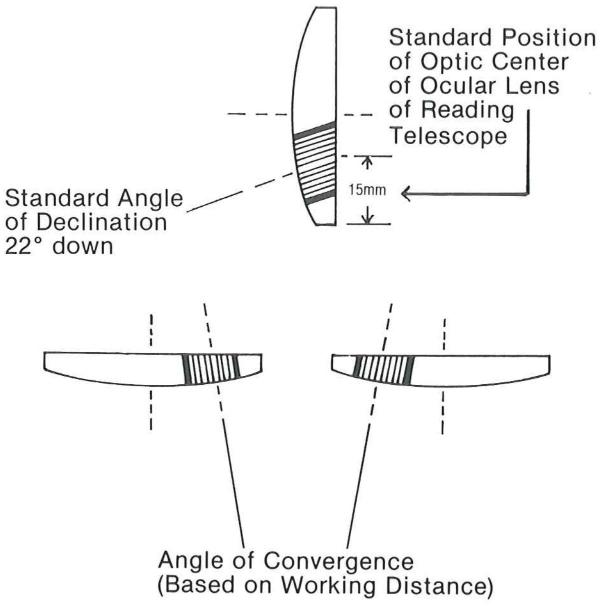
The telescopes are mounted low in the carrier lens, with the standard position of the optic center of the ocular lens 15 mm above the bottom of the carrier lens for the Galilean design, and 17 mm for the Expanded Field Prism design. The standard drilling angle of declination (below the horizontal plane) is 22° for the Galilean design, and 12° for the Expanded Field Prism design. The telescopes are converged for the prescribed working distance (which must be accurately measured from the spectacle plane), and are set at the patient's functional near P.D. The practioner is cautioned to measure this functional near P.D. in the manner described elsewhere in this Manual. The method used is the Engelmann method, utilizing complementary colored anaglyphics (red celluloid strips on the frame and a red card with a centered green square held at the proper working distance). The functional near P.D., taken by this method, may be quite different from the P.D. taken in the customary fashion (millimeter ruler).

If the patient desires to have the Reading Telescopes mounted in a bifocal carrier lens, it is a good idea to have the bifocal segments focus at the same distance as the Reading Telescopes. It is not essential that this be done, but it will allow the patient to switch back and forth between the bifocal and the Reading Telescope without having to change his convergence or accommodation each time he changes his fixation. The Executive bifocal can be set at any seg height (standard height is 7mm above the geometric center of the frame), and this style of bifocal is recommended to allow the patient an adequate bifocal segment area when he looks to the side of the telescopic unit.

The frame of choice for fitting Reading Telescopes is the Yeoman 6, and it is required for all Binocular Reading Telescopes. Also available is the Yeoman ½ Eye frame.

POWERS AVAILABLE

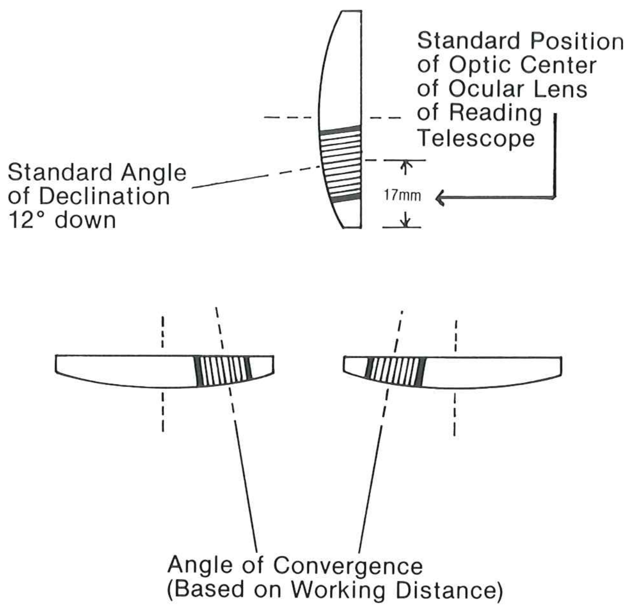
Galilean Design: 2.5, 3.5, 4.5X
Expanded Field Prism Design: 3.5, 4.5, 6.0, 8.0X



Reading Telescope—
Galilean Design

2.5X (Rectangular Objective)
3.5X (Round Objective)
4.5X (Round Objective)

Binocular 3.5X Galilean Reading Telescopes with black housings, mounted in an all aluminum frame.



Reading Telescope—
Expanded Field Prism Design

3.5X (Round Objective)
4.5X (Round Objective)
6.0X (Round Objective)
8.0X (Round Objective)

Binocular 6.0X Expanded Field Prism Telescopes with black housings, mounted in an all aluminum frame.

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