2nd Semester project - Hole punch

Group XII

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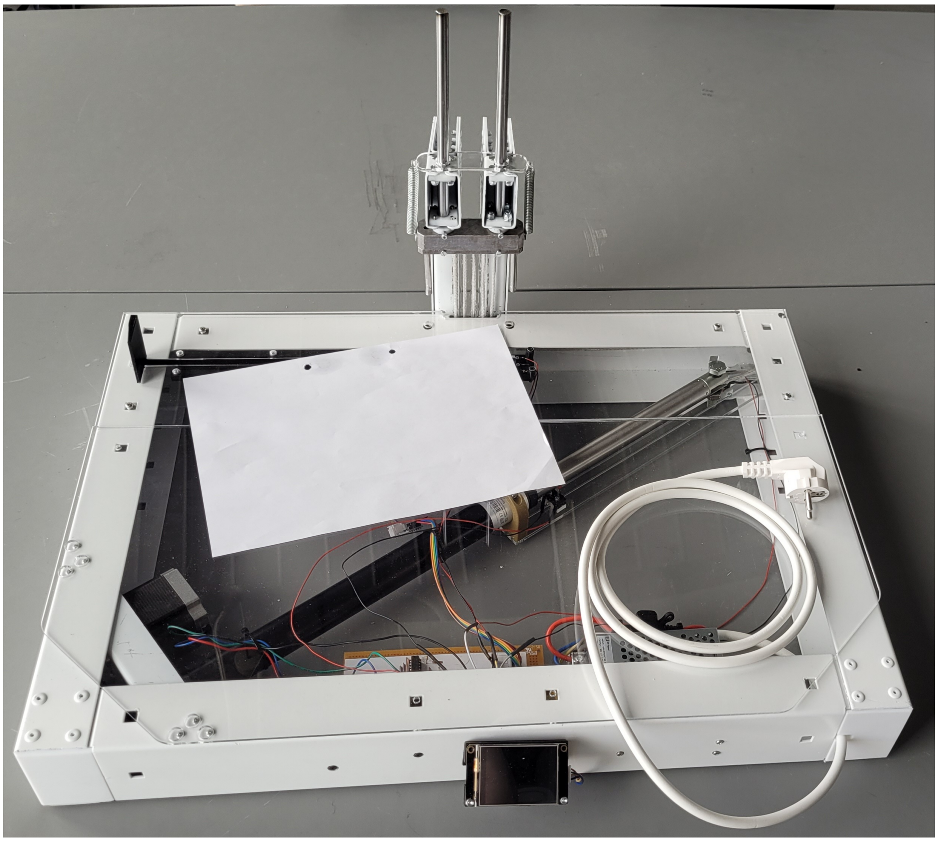


Contents

1 Introduction

This report covers the development of an automated hole punch, with adjustable paper sizing as a part of Semester project 2. The Overall Structure of the report is as follows: Following the introduction there will be an elaboration on chapter 2. Which covers the project formulations, background, problem statement, our required and secondary goals plus a delimitation and a walkthrough of the risk assessment. Chapter 3 gives an overview of the design ideas using morphology analysis. Here each selected step from the morphology analysis will be explained, as well as the idea behind the selection of the individual parts that would be making the hole punch. Chapter 4 will be about the mechanical development of the hole punch along with the paper size adjustment mechanism and the calculations included in this. It also includes calculations that were in order, to find the suitable motors for this. Chapter 5 & 6 covers both the electronics and software development, which is followed by a chapter 7, 8 and 9 which covers the manufacturing process of the mechanical, electronical and software engineering. Chapter 10 covers the testing done on the final product. Chapter **??** includes examination of all the tests, and how well the requirements were met, compared to the actual results. This is all followed by a conclusion, which among other things reflects upon what could have been done differently to achieve results closer to the initial goal of the project.

2 Project formulation

2.1 Background

The modern office environment has changed in recent years following a wave of digitization. As communication between employees, file storage, and whiteboards all been reduced to digital solutions, the variety in needed office appliances and furniture has followed accordingly. In our perception, the final area of the modern office workflow that has yet to transition to digital solutions is long term archiving of physical backups to critical data. Although they may seem slow and cumbersome, that is usually their best safety feature. In the case of some files, a company is required by law to store paper versions of official documentation[1]. Many organizations are transitioning to the digital age, evidenced by initiatives such as Europe's Digital Decade[2], that presents a set of ambitious goals for 2030. Documented by the ECS 2019 management questionnaire[3] only a minority of establishments across industries have achieved high level of digitalisation.

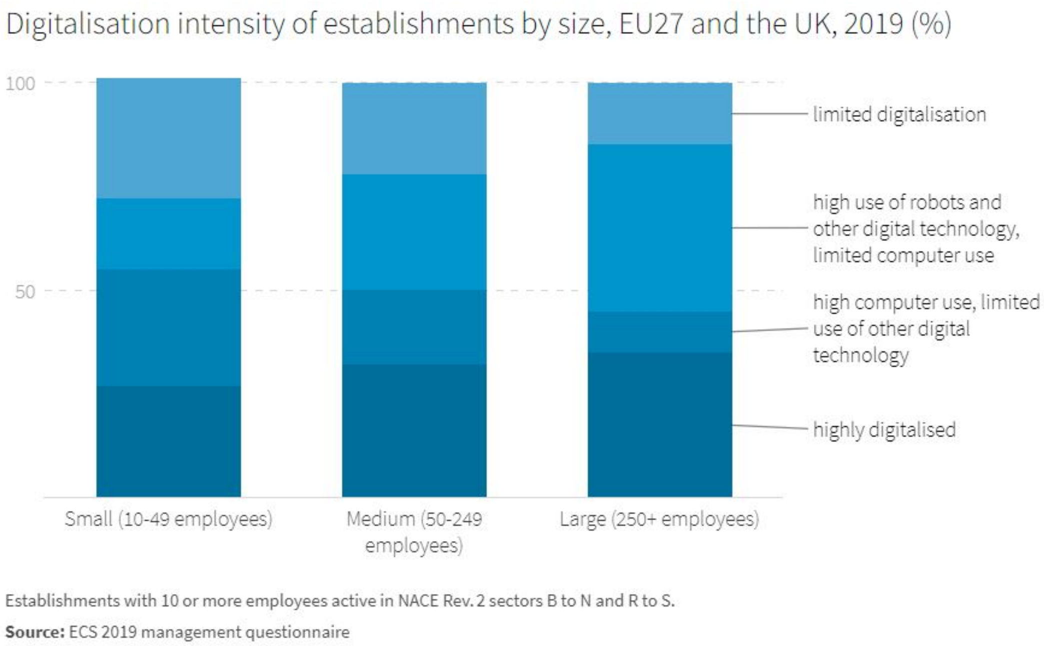


Figure 1: Digitalisation Intensity[3].

2.2 Problem statement

Our project aims to solve or assist in the process of adding new files to an archive. When assessed among other office tasks, paper handling is a comparatively manual process. To specify the problem further, we aim to decrease the human strain associated with making holes in stacks of paper and address accompanying inefficiencies Our product is to be compared with existing hole-in-paper-making solutions. For our project to be a success, existing manual and automated versions must be inferior to our solution. These criteria include to reduce the noise output to better suit the office environment. Many current solutions utilize a drill in their product, which has associated noise. Furthermore, to speed up the process our product shall make all the necessary holes in one action. This action should be highly automated and cause little to no mental and/or physical strain to the user. To reduce mental effort, the interface with the product shall be an intuitive graphical user interface on a touch display. It should be possible to input the size of the paper, to have the holes in their perfect position.

2.3 Requirements & Research question

The above-mentioned considerations have led us to the following question:
Can development of a smart hole punch be achieved within our given and self-imposed constraints?

2.3.1 Requirements (Primary goals)

- Integration of LINAK LA27 actuator as main component.
- Stay within a 2000kr budget for the entire development.
- Configurable via Nextion display.
- Able to punch through 500 pieces of 80g/m2 A4 paper, in 30 seconds or less.
- ISO838 Standard.

2.3.2 Secondary goals

- Electronic paper size adjustment, along A4.
- Good interaction-design (90% of users can operate product without introduction)
- Motor is providing constant force, possibly adjustable.

2.4 Delimitation

In the process of putting paper into a binder-based filing system, the following steps will be outside the scope of our project. Before making holes, it is commonplace to ensure the alignment of the pages with each other and placement of the tool. The correct tool-placement is decided by the user on a case-by-case basis. Selection of the right side to put the holes is a task of automation we will not be undertaking.
Post precision paper penetration, our product will not be designed to remove the stack from the tool, nor the slugs. Slugs may be directed to a container, which the user is expected to empty at regular intervals. Furthermore, binding the back into a pamphlet, placing pages in a binder, or in any way constraining the sheets to each other, is also outside to scope of our project.
The expected environment of operation is indoor, on a flat surface, around waist height e.g., on a pre-existing table.
Operation is guaranteed at mean sea level, in the ICAO standard atmosphere[4].

2.5 Risk Assessment

Table 1: Possible risks in project

ID	Risk	Likelihood	Consequence
A	Paper cuts (skin lacerations)	5	5
B	Running out of money	3	4
C	Supply constraints means that we can't get components	2	4
D	Breaking the supplied actuator	1	4
E	Lack of manufacturing skills	2	3
F	Lack of engineering skills	1	3
G	Not able to finish within timeframe	2	2
H	Running out of paper to test on	1	1

Table 2: Risk asssesment visualization

		Likelihood				
		Rare: 1	Unlikely: 2	Possible: 3	Likely: 4	Almost certain: 5
Consequences	Catastrophic: 5					**A**
	Major: 4	**D**	**C**	**B**		
	Moderate: 3	**F**	**E**			
	Minor: 2		**G**			
	Negligible: 1	**H**				

Table 3: Mitigation of risks table

ID	Mitigation
A	Wear gloves while handling paper.
B	Budget planning, with a safety margin for unforeseen costs e.g., need to build a second version of product
C	Ordering before the given deadline, and design with common components.
D	Try to source a replacement or borrow from another group. Design with the possibility of replacing the actuator, e.g., don't glue it shut inside.
E	We consult our design with third parties to reduce required skill level. We get the experts in the workshop to produce it for us.
F	We accept the risk.
G	Time planning, with buffers.
H	We accept the risk.

3 Product design

The main method of figuring out the hole punch design, was by use of a morphology analysis. This included selecting the main components of creating a hole punch machine and then expanding ideas for those categories. A full overview of our complete morphology analysis can be found in appendix 5. After making a table of all the ideas for the different categories, 3 possible solutions were selected, referring to appendix 5, the blue color being the final design solution. Each one of the solutions had a different working method, in terms of incorporating the actuator into the design, however all of the 3 solutions had identical components for: "Motor control electronics", "Nextion placement", "User interface components", "Paper size adjustment" and "Force sensing" and would therefore differ in: "Hole creation method", "Actuator placement", "Kinematics" and "Frame construction method". The following sections will go into depth on why we choose the specific components for the blue colored design solution in our morphology analysis. Hence also giving a reason for why the blue design solution was chosen over the other two.

3.1 Hole creation method

For creating holes in the paper, which is the primary focus of the project, we had 3 major methods of accomplishing it. The 3 methods were: drilling through the paper, punching directly down, or punching it in a scissor mechanism. The selected option was punching directly down, as drilling could be expensive, and the scissor mechanism seemed impractical.

3.2 Actuator placement

For the actuator placement we had 3 options, one being underneath the worksurface, one with the actuator behind the work surface and a third option with the actuator above the worksurface, actuating downwards. The option we ended up choosing was the one underneath the worksurface, since the other options would make the assembly extremely tall and hard to make rigid. A placement underneath the worksurface also complemented the selected hole creation method.

3.3 Kinematics

If the hole creation method was a drilling method, a directly driven actuator would work well to lower the drill. The kinematics of the scissor punch would obviously have been the scissor mechanism. In this project however, we would have a punch above the worksurface with the actuator placed underneath, a wire operated cam would therefore be a good option. (It would later be changed to a pulley system)

3.4 Frame construction method

To construct the frame a total of 7 ideas was presented, however only a few of them would actually be practical, since the frame would in any case have to be very rigid, to withstand the forces that could potentially be exerted on it. If a drilling method had been chosen to make holes, the aluminum extrusion could have been a good option, since the frame most likely would have been a larger tower construction. Although since the actuator would be mounted flat underneath the worksurface, sheet metal seemed more versatile in this case.

3.5 Motor control electronics

Controlling the motor for the actuator would require some kind of circuitry. Here there was 4 options to consider and for all the 3 potential solutions a H-bridge was chosen. The reason for choosing a H-bridge design over relays and stepper drivers was the components being cheaper. (A dual H-bridge stepper driver would later be chosen, because of the switch to a stepper motor)

3.6 Nextion placement

The Nextion display had 4 mounting options, one of them being in the worksurface, this could prove difficult to interact with. Another one being externally attached by cable, which could prove impractical. The selected option ended up being a side mount.

3.7 User interface components

User interface on the Nextion display had 4 options, however most of these incorporated mostly the same menu elements, so a combination of two options was chosen.

3.8 Paper size adjustment

Options that were considered included linear translation with leadscrews or belt drives using a linear rail, although these ideas were discarded in favor of a rack and pinion gear design. The reasoning behind this design decision was mainly linear rail being costly and together with belts or leadscrews would lead to a higher complexity in assembly. A rack and pinion gear setup would also have the advantage of being entirely 3D-printable, and therefore inexpensive.

3.9 Force sensing

Force sensing had several options, however most of them required a load sensor, which would result in it being very expensive. An option that didn't require a load sensor, was current measuring. Seeing as a dc motor would draw a larger current when approaching a higher load, it was a moderately easy option, while being extremely inexpensive, compared to the other options. (Force sensing was later discarded, as we switched to a stepper motor)

3.10 Assumptions

Since no other attempts at making a hole punch using hollow cutter tubes could be found, and a timeframe that limited the number of tests and prototypes that could be build, a set of assumptions was made to justify the decision:

- Pointy tip geometry will introduce a weakness in the paper sheet, from which sheer can occur across the plane of the paper instead of normal to it.
- We assume a single sheet and a stack of paper to be anisotropic, with fibers primarily in the plane of the sheet, and that it will be easier to sheer in an off-normal direction.
- Symmetric designs will see no lateral loading and cut straighter, and limit the moment applied to the tube.
- Using a pipe to evacuate cut paper though the top will reduce the force required.
- The force required is decided by surface friction on the inside, friction on the outside of the pipe and the number of sheets the cutting edge "sees". With the internal surface friction being constant, as during normal use the pipe is full of paper slugs
- The cutting force on the edge is constant after the initial bury
- The surface friction on the outside of the pipe increases near linearly with the depth of the tool in the paper stack.
- The upper portion of the paper stack will help guide the tool straight for cutting the bottom sheets accurately and the paper stack is clamped so it does not slide around.

So far, we do not know the force of any of these three sources. We will attempt to measure the force exerted on the cutting edge, by use of a standard office paper punch.

Figure 2: Testing setup for measuring required force to punch paper

We modified a broken holepunch, by sawing it in half and removing the springs, and lever-pin. This allowed us to almost directly measure the force required to punch a single hole. This was good for a few sheets, but with more paper the forces became too large for the kitchen scale. For larger forces, we used weightlifting equipment instead. This is inherently less accurate, as we were unable to accurately adjust the weight/force being applied. Within the range of the kitchen scale, we used a lever on which we placed a weight. We then gradually slid the weight along the lever and read the scale between movements.
While using the gym equipment, our procedure changed to simply stacking dumbbells on top. Since the weights did not balance themselves, and we had to manually steady them along with large step in weights, these measurements are far less trustworthy.

Our experimentation yielded these results:

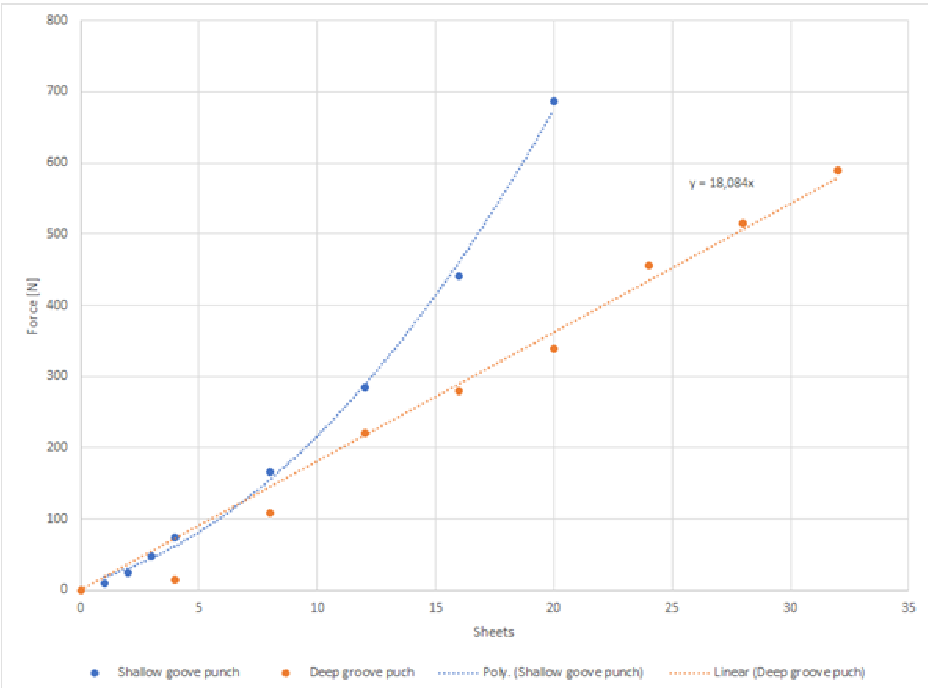


Figure 3: Graph showing measured data

After seeing the trend in blue with the modified punch, we decided to test another holepunch with a deeper notch in the cutter. Shallow is about 20-30 degrees from flat. While the new test specimen is around 40-50 degrees. The deep grooved holepunch cannot fit any more paper between the jaws than the cutter can engage at once. The groove is simply deep enough to fit it all at once. This way no sheets are ever sheared without first being punctured. They are then cut from this weakness. The orange line supports this theory, as the force becomes proportional to the amount of paper in contact with a cutting edge. The outlier at 4 sheets with very low cutting forces is an artifact of being measured in the gym with weights that cannot be fine adjusted. Furthermore, we attempted to measure the force required to compress the springs in the unmodified deep groove holepunch, and this value may be too large. It does become insignificant with thicker stacks of paper and higher loads.

The shallow groove paper punch can fit more paper between the jaws than the cutter can see at once. This means, as the slugs are not evacuated, and the bottom sheet has yet to touch the cutter, its entire edge is sheared at once, which requires a lot more force than cutting from a weak point.

The trend is mostly linear up to 8 sheets, but then is takes off as more and more sheets are not cut but punched. The bottom sheet of paper sees a punch made of a paper slug from above, this does not concentrate the stress as well as a metal punch. And the die below becomes ineffective, thereby we see loads diverge.

From this experimentation we can conclude that paper must be met by a cutter edge to be efficiently cut. Evacuation of the slugs is the limiting factor to the number of sheets a traditional paper punch can process in a cycle.

Our testing methodology has not contributed to knowledge of what loads a cutter deep in paper will see when the slugs are evacuated. We cannot say if the orange trendline will continue, flatten off or diverge to infinity. Simulation may be an option, but it is outside our area of expertise. This leaves only one option, to test the force with our unique cutter geometry in our prototype. Thus, we must design our prototype to be as strong, but no stronger than the actuator. All other components are subject to change.

4 Mechanical Development

After outlining the mechanical design in the morphology analysis, design begun. As there was a lot of uncertainty around the method of punching holes, it was decided that the design should allow for using the maximum force of the actuator, if needed. This meant that all components should allow for the actuator to pull with a force of 4 kN.

4.1 Hole making mechanism

In the morphology analysis it was decided to use a set of hollow tubes actuated by a cam to create holes in the paper. In the early stages of designing the cam mechanism, a simpler solution was found, in using a pulley system, seeing as the plan already was to transfer motion from the actuator to the cam by use of a wire. The complete hole making mechanism can be seen in figure 4.

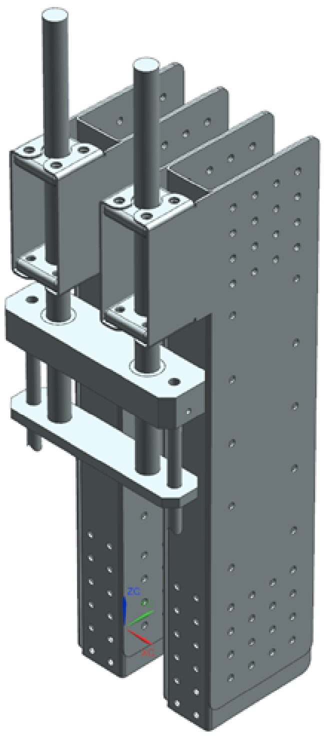


Figure 4: The two towers holding up the cutter mechanism.

4.1.1 Pulley system

To maximize the force transferred from the actuator to the pulleys, as much of the actuators stroke as possible should be utilized. To this end, since a pulley system is simply a gearing, the following calculation was made to figure out how many pulleys the rope should thread between. The actuator has a stroke of roughly 300 mm, and the specified stack of 500 sheets of paper is 50 mm thick, thus:

$$\frac{(300mm)}{50mm} = 6$$

Since 6 pulleys would not leave any space to spare in the actuation, it was decided to use 5, which means the cutters will have a maximum stroke of:

$$\frac{(300mm)}{5} = 60mm$$

This was deemed fitting as it left some space, e.g., for grinding tip geometry on the cutters.

4.1.2 Cutter head thickness

The cutter head is the block that interfaces the wire pulleys with the cutters. Here is a free body diagram with the forces acting on the cutter head:

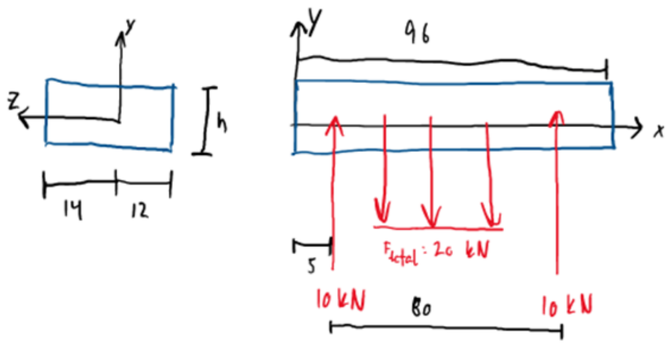


Figure 5: Free body diagram of the cutter head

The forces acting upon the cutter head is the “distributed” force around the center of the piece from the pulleys:

Since this is the only force pulling the block down, there must arise an equal and opposite force from the cutters (of 10 kN of magnitude each). These are placed symmetrically around the center of the block with a center distance of 80 mm, in accordance with ISO838.
This free body diagram is then simplified in order to calculate the thickness of the block. The new freebody diagram is set up as a worst-case scenario, where an object is lodged under one end of the block:

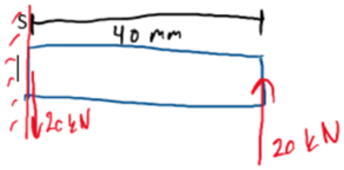


Figure 6: Simplified free body diagram

In this simplified scenario, the head can be seen as a cantilever beam, with the concentrated force of the pulleys at 40 mm from the mounting point. Thus, the formula for deflection of a cantilever beam [5] can be used:

$$\delta\left(max\right) = \frac{FL^3}{3EI}$$

In order to calculate the thickness, the centroidal moment of inertia is needed. The formula for cross sectional moment of inertia is[6]:

$$I_{cx} = \frac{bh^3}{12}$$

The cutter head cross section can be seen in figure 5.
Eq. (I_{cx}) into eq. $\delta(max)$, gives, whereafter the height is isolated:

$$\delta\left(max\right) = \frac{FL^3}{\left(3E \cdot \frac{b \cdot h^3}{12}\right)} \Leftrightarrow h = \sqrt[3]{\frac{\left(12FL^3\right)}{3Eb\delta\left(max\right)}}$$

The part will be made from steel which has a Young’s modulus of E=200 GPa [7]. A design decision is made that the max deflection can be $\delta(max) = 0.5mm$. Thus, the minimum thickness of the block is:

$$h = \sqrt[3]{\frac{\left(12 \cdot 20 \cdot 10^3 \cdot \left(40 \cdot 10^{-3}\right)^3\right)}{3 \cdot 200 \cdot 10^9 \cdot 26 \cdot 10^{-3} \cdot 0.5 \cdot 10^{-3}}} = 12.5mm$$

Therefore, the block is dimensioned at a thickness of 15mm.

4.1.3 Cutter tube attachment in cutter head

In order to transfer force from the cutter head to the cutter tubes, the tubes are mounted in counter-bored holes, the size of the lip, figure 7, needs to be calculated. The max load on the tube is 20 kN, in the situation that there is only an obstruction below one of the two tubes.

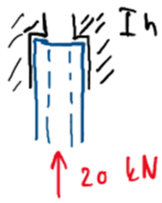


Figure 7: Cross section of counter bored hole with the end of one of the tubes.

This mounting arrangement loads the lip in shear. The area of the shear plane is the "outside" area of the cylinder the lip forms:

$$A = d\pi \cdot h$$

Shear is defined as:

$$\tau = \frac{F}{A} = \frac{F}{d\pi h}$$

Isolating h:

$$h = \frac{F}{d\pi\tau}$$

The shear yield strength can be estimated to be 58% of the yield strength[8]. Yield strength of steel is[7]:

$$\sigma_y = 350MPa$$

Thus τ_y is roughly:

$$\tau_y = 58\% \cdot 350 \cdot 10^{6\approx} 200MPa$$

Therefore, the lip must have a height of at least:

$$h = \frac{20 \cdot 10^3}{6 \cdot 10^{-3} \cdot \pi \cdot 200 \cdot 10^6} = 5mm$$

4.1.4 Guide rods

For the guide rods, that the cutter head rides on, Bosch Rexroth precision steel shafts made of heat treated Cf53 steel[9]. In order to calculate the diameter of the rods, the forces acting upon the rods must be known:

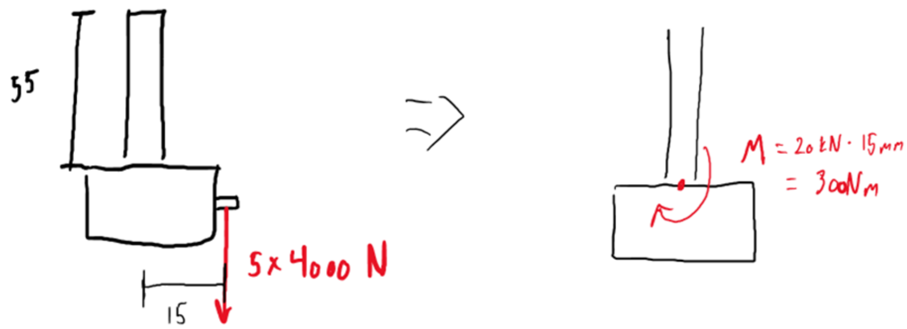


Figure 8: Moment acting on the rod at the maximum extension of the cutter head.

To calculate the rod diameter as a function of the deflection of the rod, the formula for deflection of a cylindrical cantilever beam subjected to an end moment can be used [5]:

$$\delta_{max} = \frac{M_0 L^2}{\left(2E \cdot \frac{\pi r^4}{4}\right)} \Leftrightarrow r = \sqrt[4]{\frac{(2M_0L^2)}{\pi E \delta_{max}}}$$

Youngs modulus of Cf53 is $E = 200GPa$[10], and at a 0.5 mm maximum deflection the minimum radius is:

$$r = \sqrt[4]{\frac{(2 \cdot 150 \cdot 0.055^2)}{\pi \cdot 200 \cdot 10^9 \cdot 0.0005}} \approx 7mm$$

Since the paper is expected to help guide the rods, a 10mm diameter is selected, since a larger diameter would enlarge the cutter head, and in turn increase the torque acting upon the end of the rod. This calculation is also made for unhardened Cf53, whereas the rods is surface hardened.

4.2 Actuator & Gearing assembly

The actuator, stepper and gearing were all mounted on a bracket, that attaches to the frame (see figure 9).

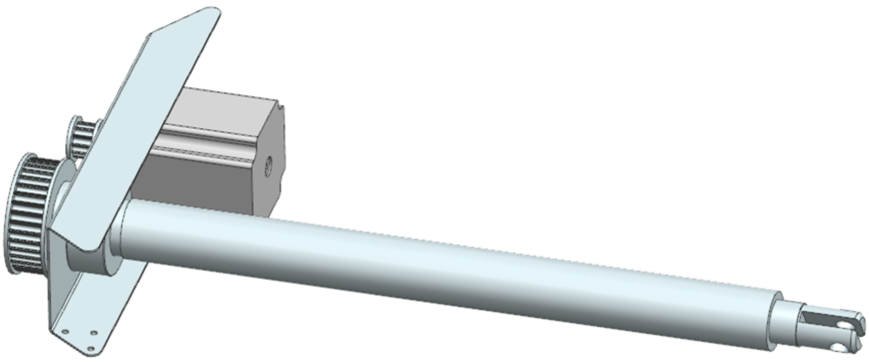


Figure 9: Actuator and gearing assembly in NX

The actuator is mounted, by means of a threaded adapter, see cross-section in figure 10

Figure 10: Actuator adapter design in NX, side view

The actuator has been drilled out and threaded in the end, where the pulley is then screwed on.

4.3 Frame

The frame is constructed from 4 pieces of bent sheet metal profiles (see profile in figure 11),

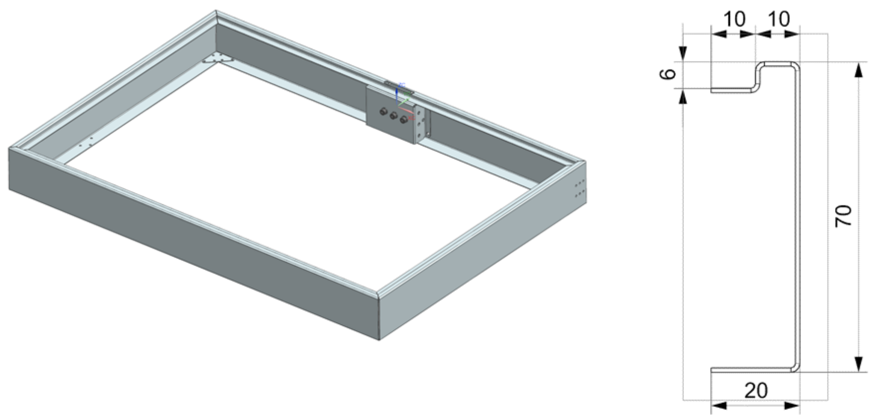


Figure 11: Frame in NX

4.4 Motor selection

4.4.1 Torque needed to pull 4kN

The moment of force is given by:

$$M_0 = d \cdot F \ \ (1)$$

Isolating the force F to get the work of moment:

$$F = \frac{M_0}{d} \Rightarrow \int F\, ds = \int \frac{M_0}{d}\, ds \ \ (2)$$

It is already known that the formula $S = d\theta$ where S represents the arc length, and $S = d\theta$ as a hole, represents the central angle in radians and d is the length of the radius and $\theta =$ angle in radians.

$$s = d \cdot \theta$$

By differentiation, the equation gives that:

$$s^{'} = d^{'} \cdot \theta^{'} \rightarrow ds = d \cdot d\theta \ \ (3)$$

This formula says that the change in length is equal to the change in angle. If formula (3) is taken into formula (2) it will then give the work of moment:

$$\int \frac{M_0}{d} \cdot d \ \ d\theta$$

"d" cancels out and the following equation is given:

$$\int M_0\, d\theta \ \ (4)$$

If it is assumed that the energy loss from a linear work to rotational a work is 0. Then it must be true that the work of the linear is equal to the rotational work. By rewriting equation (2) and adding the newly found values, the following equation can be deducted:

$$\int_{S_0}^{S_1} F\, ds = \int_{\theta_0}^{\theta_1} M_0\, d\theta$$

Inserting the force $F = 4000$:

$$\int_{0}^{S_1} 4000\, ds = \int_{\theta_0}^{\theta_1} M_0\, d\theta \ \ (5)$$

Now integrating with respect to S we get:

$$[4000S]_0^{S_1}\ [M_0\theta]_{\theta_0}^{\theta_1} \Rightarrow 4000S_1 = M_0 \cdot \theta_1 \ \ (6)$$

Now by measuring, it is given that one rotation of the end gear, moves the actuator 4mm. Thereby it can be concluded that one full rotation, leads to a 4mm change in position:

$$\Delta\theta = 2\pi \Rightarrow \Delta s = 4mm \ \ (7)$$

In order to calculate the amount of torque needed to pull 4kN we substitute eq. (7) into eq. (6) replacing the value of S_1 and the change in angle θ:

$$4000 \cdot 0.004 = M_0 \cdot 2\pi$$

Now isolating the work of moment:

$$M_0 = \frac{10}{2\pi} = 2.55Nm$$

In conclusion we need a torque of 2.55Nm to pull the required 4kN if there is no loss of energy in the system.

4.4.2 Required RPM to do a full cycle in 30s

The angular velocity is given by:

$$\omega = \frac{d\theta}{dt}$$

And this equation describes the relation between rotation and the linear motion:

$$\frac{ds}{d\theta} = \frac{0.004}{2\pi}$$

By isolating for the change in rotation following can be said:

$$d\theta = ds \cdot \frac{0.004}{2\pi}$$

Now taking eq. (2) into eq. (1) and moving the constant out of the fraction we get:

$$\omega = \frac{2\pi}{0.004} \cdot \frac{ds}{dt}$$

By replacing ds/dt with the constant V, which is the linear velocity, the equations given is:

$$\omega = \frac{2\pi}{0.004} \cdot V$$

Now in order to find the needed linear velocity, a full cycle of the actuator in 30 seconds which is 0.6m is needed. In order to achieve the above, the actuator needs to move:

$$\frac{0.6}{30} = 0.02\frac{m}{s}$$

Now inserting the linear velocity of 0.02 on V's place, the following equation is given.

$$\omega = \frac{2\pi}{0.004} \cdot 0.02$$

This gives the amount of rad/s:

$$\omega = 31.416\frac{rad}{s}$$

Since one radian per second is equal to 9.549297 revolutions per minute, the needed rpm must be:

$$31.416\frac{rad}{s} \cdot 9.549297 = 360RPM$$

Thereby it is proven that 360 rotations per minutes is needed to do a full cycle of the actuator in 30 seconds

4.4.3 Selection of stepper motor

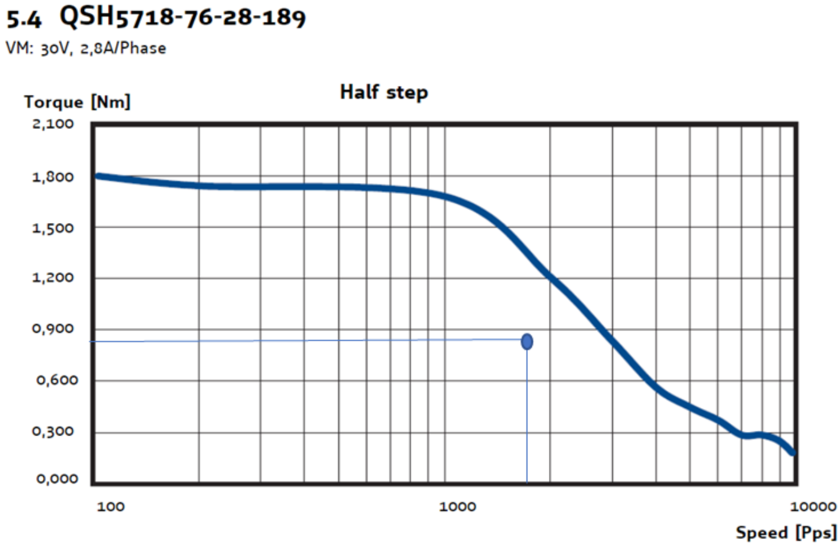


Figure 12: Torque vs. speed graph[11], for large stepper motor

The Ratio between the two gears is:

$$\frac{36}{12} = 3$$

That means the motor will have to rotate by

$$360 \cdot 3 = 1080RPM$$

To move the actuator a full cycle. Since the ratio is one to three the torque needed to rotate the gear is given by the amount of newton meters needed divided by three, hence:

$$\frac{2.55}{3} = 0.85Nm$$

Thereby, by arguing looking at the graph, it can be concluded that the stepper motor chosen for the job is able to handle our demands.

4.5 Paper size adjustment

To increase the functionality of our hole punch project, it was decided that a paper size adjustment function would be incorporated into the design.
Since the actuator would be placed diagonally in our mechanical design, the frame would already be a bit larger than the A2 paper size, therefore it was decided that it should be able to adjust from A4 to A2.
Since the paper size adjustment would not be the primary focus in our project, we needed the design to be inexpensive and relatively straightforward to manufacture.
To engage the linear translation of the rack gear, the system would obviously need a motor of some kind, to provide the necessary force. The motor would also need to be high precision, for the paper size adjustment to make any kind of sense. Therefore, the right motor for this application would be a small stepper motor and not a regular dc motor, since a stepper motor can achieve very accurate positioning.
During this initial design process, a rather inexpensive option for a stepper motor had already come to mind - precisely the 28BYJ-48 stepper motor. Though calculations were necessary to determine if it would have enough torque to move the rack gear and ample rotational speed for the desired velocity of our rack gear. Thus, the following segment explains the calculations necessary to determine if the stepper motor would suffice for this application.

4.5.1 Torque calculations

To determine the torque required to move the rack gear, a preliminary setup of the solution, had to be envisioned first. The idea that came to mind was that the rack gear would be mounted on two plastic rails with the pinion gear underneath. Therefore, determining the minimum torque required, was simply a matter of figuring out the rack gears friction on the plastic rails.
Static friction is defined as follows:

$$F = F_n \cdot \mu_s \Rightarrow F = mg \cdot \mu_s$$

This simple formula requires the mass of the object, in this case the mass is assumed to be around 100 grams. The static friction coefficient for plastic-plastic is 0,35[12].

$$F = 0.1kg \cdot 9.82\frac{m}{s^2} \cdot 0.35 = 0.344N$$

This gives the minimum force required to set the rack gear in motion, the minimum torque required from the stepper motor is then:

$$M = d \cdot F$$

Where d is the distance from the center of the pinion gear to the profile line of the rack gear. In this case it's the same as the radius of the pinion gear. Here the pinion gear is assumed to have a profile diameter of 30mm, just to give an estimate.
The torque is determined:

$$M = \frac{0.030m}{2} \cdot 0.344N = 5.16mNm$$

The small stepper motor therefore has an estimated minimum torque requirement of 5.16 mNm.

4.5.2 Velocity calculations

For the paper adjustment, a desired speed of 2 cm/s was decided, this meant that the small stepper motor should be capable of specific rotational speed. To determine that speed we utilized the following formula[13]:

$$n = \frac{V_{max} \cdot 60}{\pi \cdot d_{pinion}}$$

d_p being the pinion profile diameter, n being the rotational speed and V_{max} the linear speed of the rack gear. Inserting the desired speed of 2 cm/s and again giving the pinion gear a pitch diameter of 3cm, we get:

$$n = \frac{0.02\frac{m}{s} \cdot 60}{(\pi \cdot 0.03m)} \approx 12.732RPM$$

To make sure the speed of 12.732 rotations per minute was achievable, some preliminary testing of the small stepper motor was done. In this preliminary testing it was found that the small stepper motor has 2048 steps per revolution and a minimum of 2 milliseconds between each step. This gives a requirement of 4096 milliseconds per revolution, dividing that into the number of milliseconds in a minute:

$$\frac{60000}{4096} = 14.648RPM$$

With this, it's known that the pinion gear has max potential speed of 14.6 RPM, which is above the required 12.7 RPM of the pinion gear.

4.5.3 Torque at required velocity

Since the 28BYJ-48 datasheet[14] doesn't provide a torque - speed graph, a dependence on a forum post[15] is done. Reffering to figure 13, at 400 PPS the speed is around 12,5 RPM which gives a maximum torque of about 500 gram-force centimeters, which equates to about 49 mNm.

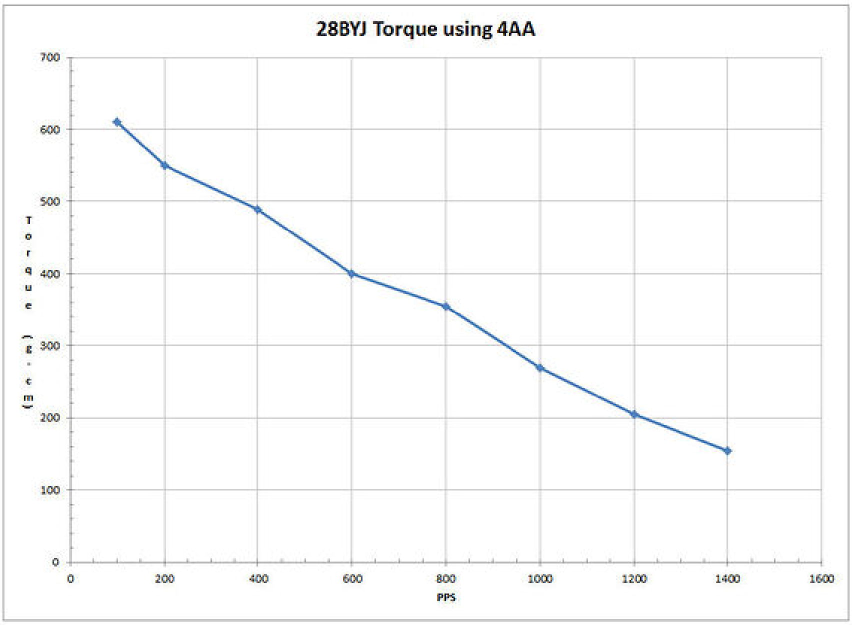


Figure 13: Torque vs. speed graph[15] for small stepper motor

49 mNm at 12.5 RPM is largely above the required 5.16 mNm at 12.7 RPM and the small stepper motor should therefore be more than adequate for the paper adjustment mechanism.

4.5.4 Paper adjustment assembly

The initial design sketch for the paper adjustment mechanism can be seen on figure 14, where the rack and pinion gear are sketched. The idea is to have the hole punch at the top center and then have the mechanism to the left of that.
To enable adjusting between A4 and A2, a distance of at least 148.5mm is needed on the rack gear, as seen on the sketch.

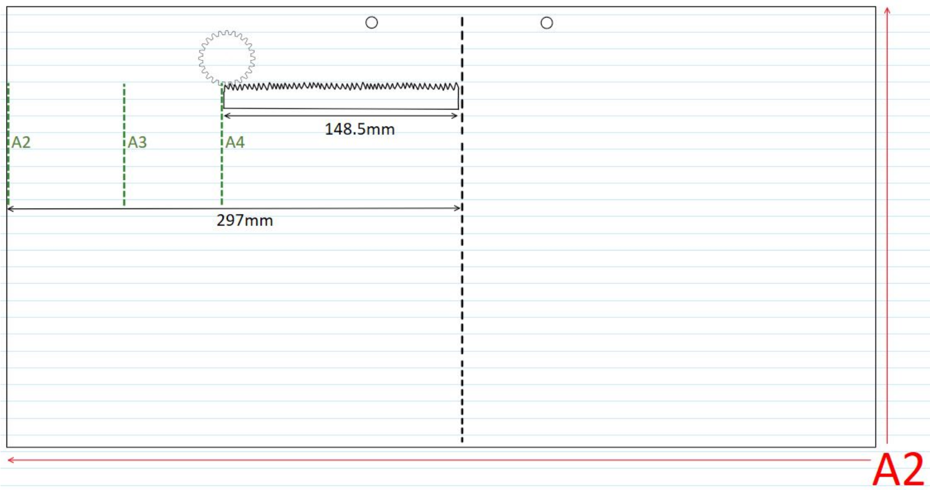


Figure 14: Sketch of paper size adjustment

Moving on to CAD design in Siemens NX, as seen on figure 15. For the profile diameter of the pinion gear, 30mm is used since that size worked in the torque calculations earlier. A module of 2 is chosen, which makes it possible to dimension the rack gear. For the rack and pinion gear to interface properly they need the same module value.

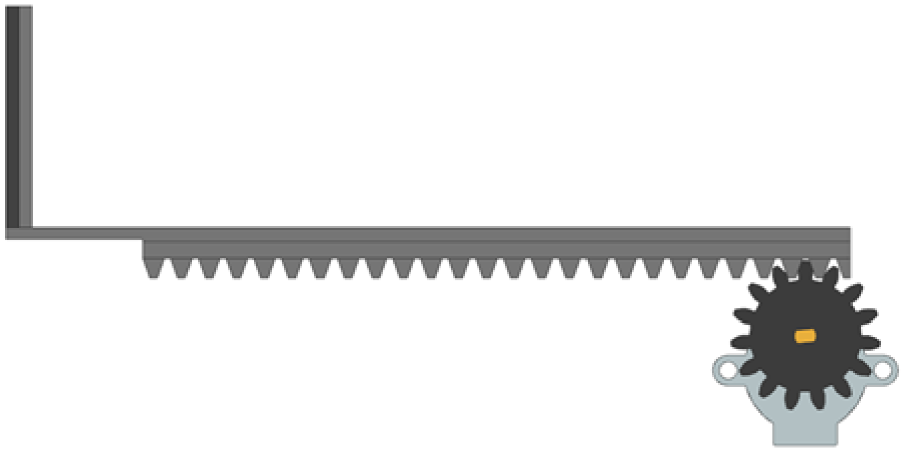


Figure 15: Side view of rack and pinion gear design (Siemens NX)

The pinion gear is placed underneath the rack gear at an exact distance, this distance is determined by the fact that the gears interface at the profile diameter of the pinion and profile line of the rack gear. The distance from the center of the pinion to the bottom of the rack gear is then:

$$\frac{d_{pinion}}{2} + m_{rack} + m_{rack} \cdot 0,25$$

The correct distance between the gears is then determined by inserting the known values into the expression:

$$\frac{30}{2} + 2 + 2 \cdot 0.25 = 17.5$$

The length of the rack gear needed to be a minimum of 148.5mm, as mentioned earlier in the design sketch, however it was made around 160mm, so the rack gear would stay connected with the pinion, even when being fully extended towards A2.
Referring to figure 15 again, the slight ledge at the end of the rack gear without any teeth is there to make sure it goes over the metal frame. This is designed according to our “new” frame design, discussed in chapter XX.

The finalized design of the paper size adjustment mechanism can be seen on figure 16. This includes the rails mount for the rack gear along with the mount for our endstop. The rails also include a mounting position for the small stepper motor controller the positioning.

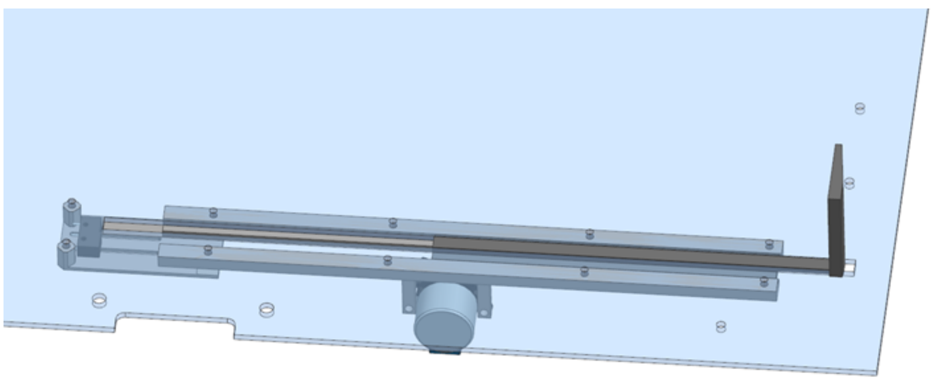


Figure 16: Finalized paper adjustment assembly (Siemens NX)

All of the mechanism is mounted to the underside of the acrylic top plate, using countersunk screws to avoid interfering with the paper placed on top.

4.6 Summary of mechanical assembly

The complete mechanical assembly can be seen in figure 17 below and the NX assembly can be found in appendix 8.

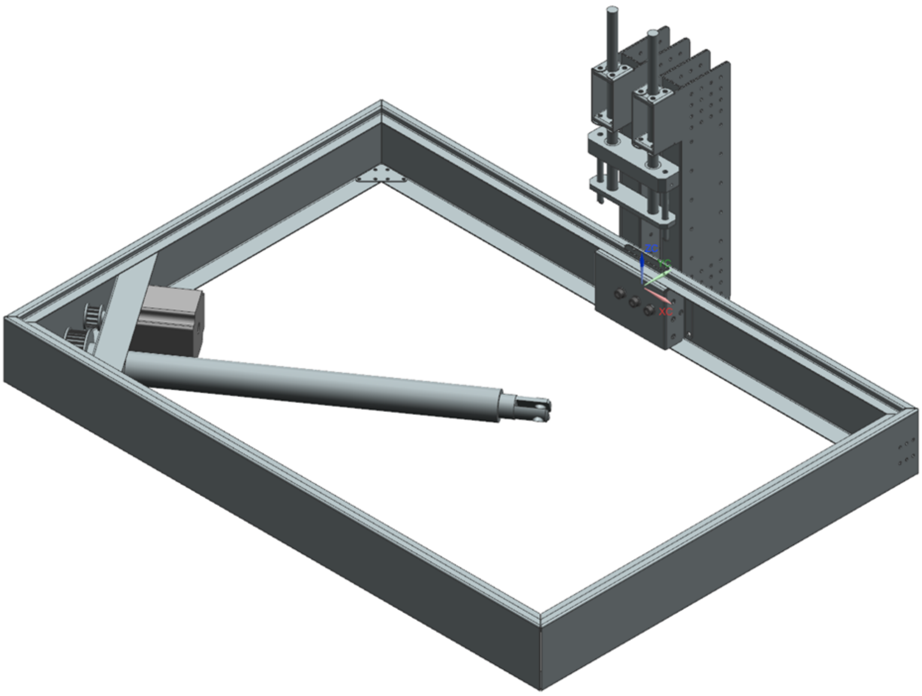


Figure 17: Mechanical Assembly

5 Electronics Development

Seeing as a stepper was going into the project, the initial idea from the morphology analysis to use a H-bridge with current sensing to measure force, was out of the equation, so a new circuit design was needed. Since the stepper has two coils, that have to be energized in both directions, H-bridges is still a good solution, thus the choice ended up on doing a stepper driver with dual H-bridges.

According to the stepper motors manual[11] the optimum driver supply voltage is $4 \cdot U_{COIL_NOM} \leq V \leq 22 \cdot U_{COIL_NOM}$. Since the voltage regulators in the 78xx series, that will be used to create a 12V and 5V rail, has a maximum input voltage of 35V[16], the driver supply voltage was set at 34V, which means:

$$U_{COIL_NOM} = 3.2V$$

$$\frac{34V}{3.2V} = 10.6$$

That the driver supply voltage is approximately 11 times the nominal coil voltage, right in the middle of the recommended span. This however creates another challenge, because if 34V is applied to the coil continuously, the coil would overheat, since the rated RMS current of the coil is only 2.8A, and with a phase resistance of 1.13Ω the current at 34V would be:

$$\frac{34}{1.13} \approx 30A$$

Therefore, a current limiter is required. A current limiting resistor would be a bad solution, both because a lot of power would be dissipated in it, but also because it would lower the voltage across the coil, which would make a change of direction of the current flowing through slower. Instead, a constant current circuit that rapidly switches the MOSFETs on and off, in order to attain a certain RMS current, is a better solution.
All of these design considerations have led to the design seen in figure 18 of one of the two identical H-bridges. The following sections will dive deeper into the selection and dimensioning of components. The full circuit can be found in appendix 7

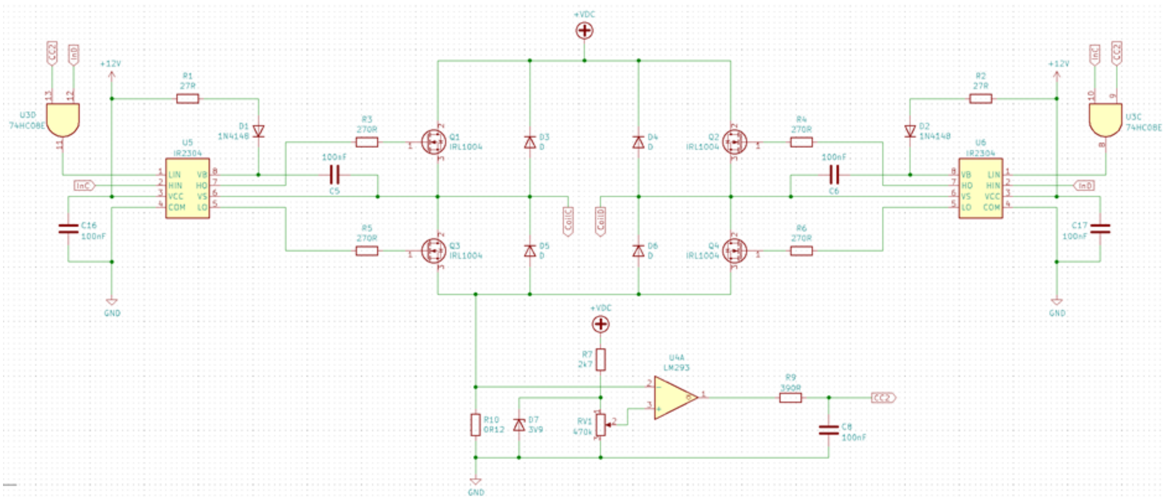


Figure 18: One of the H-bridges, with MOSFET drivers and constant current control circuitry.

5.1 Half bridge driver

In order to control the MOSFETs easier, a MOSFET driver was included in the circuit. In this case an IR2304 half bridge driver is used, which uses a floating channel to drive a half bridge consisting of two N-channel power MOSFETs, it also has an internal dead-time, to avoid shoot-through.
Since the driver will be switching the MOSFETS rapidly, in order to limit the current, it has been decided, that the driver should be able to switch the MOSFETS at least at an order of magnitude

faster than what will be needed to drive the stepper. Driving the stepper at a 1080 RPM will require the following pulses per second:

$$\frac{(1080)}{60} \cdot 200 = 3600pps$$

Since the stepper has 200 steps per revolution[11].
The switching speed of the driver can be calculated to be[17]:

$$\frac{1s}{t_{on} + t_r + t_{off} + t_f} = \frac{1}{((220 + 200 + 220 + 100) \cdot 10^{-9})} \approx 10^6 pps$$

Thus, the driver is plenty fast for this application.

5.1.1 High side floating supply

Another advantage of this driver is that no voltage rails is needed to switch the high side MOSFET on and off, which would usually a requirement, since the voltage drop across the H-bridge is larger than the maximum gate-to-source voltage of most MOSFETs.
To circumvent this need, the driver enables the use of a N-channel MOSFET for the high side, by either tying the HO pin to VS (The high side MOSFETs source) or to VB, which is approximately VS + VCC[17].

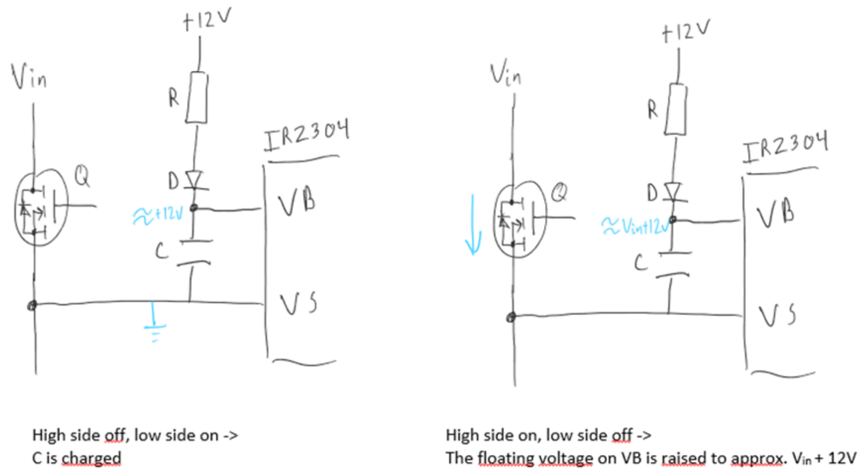


Figure 19: How the floating voltage on VB is generated.

The reverse voltage of the diode should be at least:

$$34 + 12 = 46V$$

Thus, the 1n4148 is a suitable diode with a reverse voltage of 75 V.
The 1N4148 has a maximum repetitive peak forward current of 500 mA, which is why a current limiting resistor R is introduced into the circuit (To not strain the component at the edge of its envelope a current of 400 mA max is chosen):

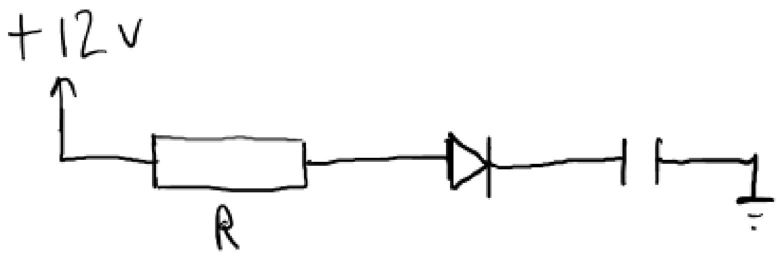


Figure 20: Floating supply charge curcuit

Circuit is modelled as the equivalent circuit of the diode modelled as a simple piecewise equivalent in the forward-bias region (The cap is omitted as we are only interested in limiting the max current, which appears when the voltage across the capacitor is equal to 0):

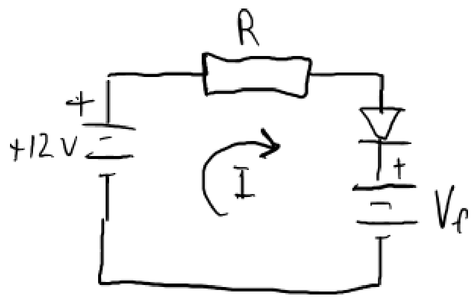


Figure 21: Floating supply charge curcuit, with diode modeled as a simple piecewise equivalent, in the forward-bias region.

KVL gives us:

$$0 = 12 - R \cdot I - V_f$$

From the 1N4148 datasheet:

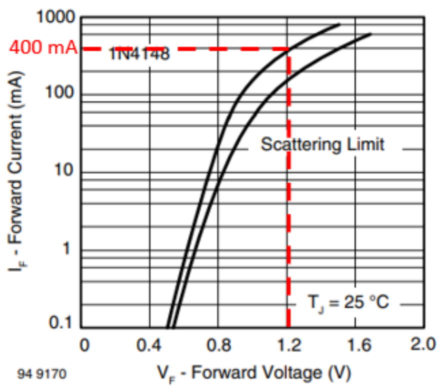


Figure 22: Forward current vs. forward voltage, with the initial state of the floating supply charge circuit marked[18]

The forward voltage $V_f = 1.2V$ can be found.
Thus

$$R = \frac{12 - V_f}{I}$$

$$R = \frac{12 - 1.2}{400 \cdot 10^{-3}} = 27\Omega$$

5.2 Constant current circuitry

The constant current circuitry works by comparing the voltage drop across a power resistor, with a static reference voltage. By use of a comparator this gives a binary signal that can be used to control the H-bridge.

The static reference voltage is generated by use of a Zener diode. According to the datasheet [19], the maximum power dissipation of the diode is 500 mW, in order to not strain the diode, a target power dissipation is set to 50 mW. Therefore, a current limiting resistor is needed. The current passing through the diode is:

$$P = VI \Leftrightarrow I = \frac{P}{V} = \frac{50 \cdot 10^{-3}}{3.9} \approx 13mA$$

Thus, the current limiting resistor must have a resistance of:

$$V = RI \Leftrightarrow R = \frac{V}{I} = \frac{34 - 3.9}{(13 \cdot 10^{-3})} \approx 2300\Omega$$

The closest resistor in the E12 series is 2700Ω, so this value is used.

5.3 Voltage regulators & power dissipation

Different components in our circuit require different voltages, consequently voltage regulators are needed in the circuit to make it work. As seen in appendix 2, a 7812 voltage regulator is used for 12V and a 7805 is used for 5V. For general stability, $1\mu F$ capacitors are added at both sides of the voltage regulators.
Since the power supply delivers 34VDC, the voltage regulators have quite a large voltage drop across them, especially the 5V regulator. The 5V regulator also has quite a few components connected, potentially drawing a large amount of current, hence calculations are necessary to determine if the voltage regulators require heatsinks to keep cool at their maximum power dissipation.
Starting with the 12V rail, according to the circuit schematic, it will have a total of 4 MOSFET drivers connected along with the Arduino Nano. The MOSFET drivers are expected to consume 100mA[17] and the Arduino 25mA[20], which totals 125mA. This gives the following:

$$P_{12V} = (34V - 12V) \cdot 125mA = 2,75W$$

Using the junction-to-ambient thermal resistance (θ_{JA}) for the TO-220 package of 65 °C/W from ON Semiconductor datasheet[16] and an ambient temperature of 25 degrees, the junction temperature of the 12V regulator without a heatsink will be:

$$T_J = \theta_{JA} P_{12V} + T_A$$

$$T_J = 65\frac{°C}{W} \cdot 2,75W + 25°C = 203,75°C$$

For the 5V regulator, it will be connected to the comparator (1mA)[21], AND-gate (50mA)[20], Nextion display (500mA)[22] and the small stepper motor (200mA)[14], totaling 751mA, which results in the following power dissipation:

$$P_{5V} = (34V - 5V) \cdot 751mA = 21,779W$$

Using the same junction-to-ambient thermal resistance and ambient temperature, the junction temperature of the 5V regulator without a heatsink will be:

$$T_J = 65\frac{°C}{W} \cdot 21,779W = 1415,635°C$$

Seeing as both voltage regulators would heat way above the thermal shutdown, especially the 5V regulator, a heat dissipation solution was essential. This would be done by mounting all our TO-220 housed components along one edge of our circuit board, electrically isolating them and attaching them to an aluminum plate, that would then be attached to our metal frame for further cooling of all the components.
Normally when using an off the shelf heatsink, it'll have a datasheet containing information about its thermal resistance. This value together with junction-to-case thermal resistance (θ_{JC}) can be used to estimate the voltage regulator junction temperature, with that exact heatsink attached.
As a consequence of the chosen heat dissipation solution, there is no known thermal resistance value. An estimation of the worst-case temperature with the heatsink solution is therefore not possible, instead a best-case scenario is looked at. The best-case scenario being if the heatsink solution has a thermal resistance of 0. To calculate the junction temperature with a heatsink a similar formula to before is used[23]:

$$T_J = (\theta_{JA_{Heatsink}} + \theta_{JC}) P + T_A$$

$\theta_{JA_{Heatsink}} = 0$ and $\theta_{JC} = 5\frac{°C}{W}$[16]:

$$T_{J_{12V}} = 2,75W \cdot 5,0\frac{°C}{W} + 25°C = 38,75°C$$

$$T_{J_{5V}} = 21,779W \cdot 5,0\frac{°C}{W} + 25°C = 133,895°C$$

With the worst-case current draw and the best-case heat dissipation solution, the 5V voltage regulator will still be incredibly warm, although now under the thermal shutdown of 150 degrees[16], showing that a heatsink definitely will alleviate the problem. The absolute maximum power dissipation in the 5V regulator without overheating can be determined with the following expression[23]:

$$P_{DMAX} = \frac{(T_{JMAX} - T_A)}{\theta_{JA}} = \frac{(T_{JMAX} - T_A)}{(\theta_{JA_{Heatsink}} + \theta_{JC})}$$

With an ideal heatsink where the thermal resistance is 0 and a maximum junction temperature of 150 °C:

$$P_{DMAX} = \frac{(150°C - 25°C)}{5\frac{°C}{W}} = 25W$$

This means that the voltage regulators with an ideal heatsink could dissipate upwards of 25W. So, if the 5V rail in the circuit was theoretically being taxed to absolute maximum, we would be dangerously close to the thermal shutdown of the component. Fortunately, the 5V voltage regulator will never draw 751mA continuously, so an ideal heatsink is not necessary.

5.4 MOSFET gate resistor

Choosing the MOSFET gate resistors highlighted on figure 23, can depend on many factors [24]. However, in this project the only focus is on getting the resistance value as low as possible, since that allows for faster switching speeds[25], while still limiting our gate current to protect our driver.

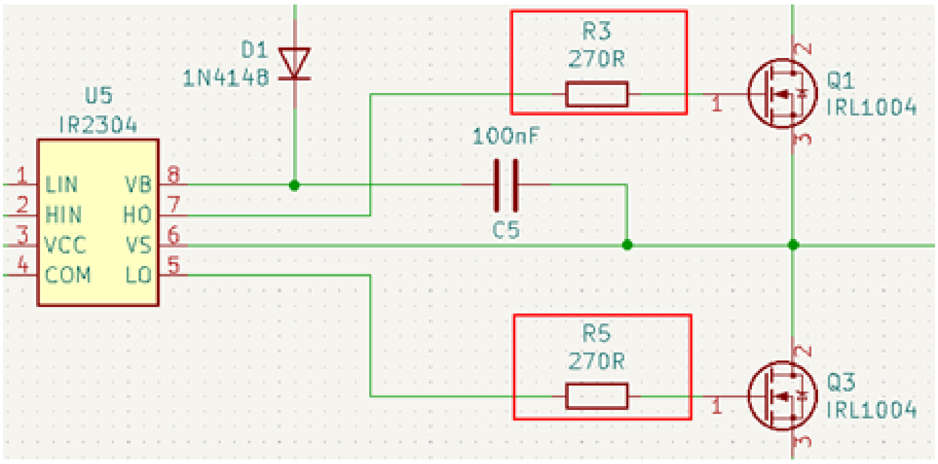


Figure 23: MOSFET gate resistors

According to the driver datasheet[17], the I_{O+} value determines that the driver can at least handle a current of 60mA. To be on the safe side, its dimensioned with 50mA.
From the schematic in appendix 7, it's known that the voltage is 12V and its simply a matter of using ohms law:

$$R_{gate} = \frac{V}{I} = \frac{12V}{50mA} = 240\Omega \approx 270\Omega$$

Because a 240-ohm resistor is unavailable, a 270-ohm resistor is used instead.

5.5 Choosing of MOSFETs

MOSFETs with appropriate ratings and characteristics are required to be selected, so that they follow our desired applications in which they will be used.

One of the most important parameters that should be looked at first is the continuous Drain current (I_D). The continuous Drain current is measured in amps. There are two Drain currents and that is because the drain Current will change based on the operating temperature of the MOSFET. Hence, we pick the MOSFET that can handle the higher temperature, since that is the more realistic drain current value. The drain current is important because this is the current going to the motor so this current needs to match and exceed the current rating of the motor.

The current flowing to the stepper motor is found by taking the voltage 34V over the coil resistance 1.13Ohm, which gives a value of 30 amps. Hence the MOSFETs must be able to handle a drain current of at least 30 amps.

Another important parameter is the Gate-source voltage (V_{GS}) that needs to be matched to the voltage coming from the gate drivers. The conditions governing V_{GS} are also important factors for the selection of MOSFETs. The amount of current that MOSFETs can handle is limited by the value of V_{GS}, which in this case is set to 12V. MOSFETs turn on when the gate-source voltage VGS exceeds their threshold voltage V_{th}. It is therefore necessary to choose a value for V_{GS} that is sufficiently higher than Vth.

The Drain-source breakdown voltage ($V_{(BR)DSS}$) shown is also one of the parameters we need to be considered of, when selecting the proper MOSFET for the H-bridge. If the breakdown voltage is exceeded the MOSFET may blow. So, a voltage much high then the supply voltage is needed for the MOSFETs protection as exceeding V_{DSS} might result in the destruction of a MOSFET. V_{DSS} in the electronical circuit is given by the voltage 34V divided by 2, hence a V_{DSS} of 17V is required in order to make sure not to exceed the breakdown voltage.

Furthermore, when a power MOSFET switches at a high frequency, its switching loss accounts for a significant portion of total loss. To reduce total loss for high frequency switching applications, high speed power MOSFETs should be used. Hence, MOSFETs that allows for fast switching to reduce the total loss are required.

Based on the requirements needed, the chosen type of MOSFETs for our electrical circuit is IRL1004. In appendix 3 the datasheet for the chosen MOSFET and all its specifications will be stationed.

6 Software development

6.1 State diagram

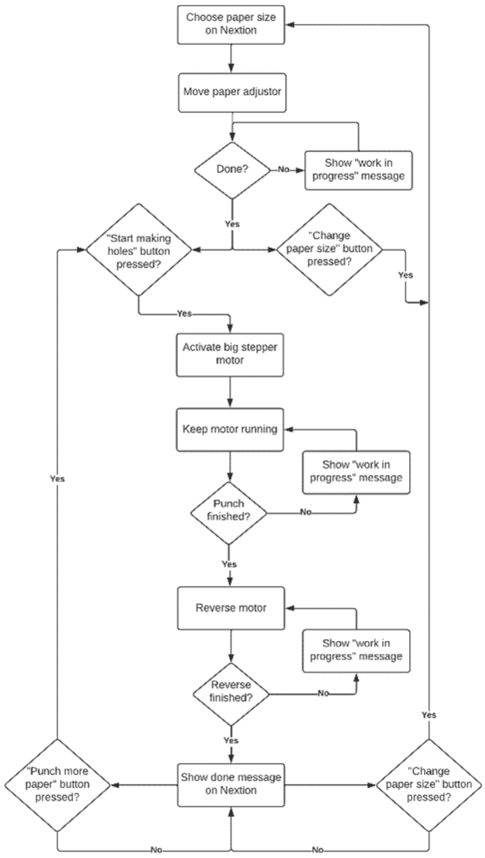


Figure 24: State diagram, describing software flow

The state diagram, figure 24, is made to define what process is going to take place. It is linked to the screens on the Nextion display to get a better view of what is going on during each state see Appendix 1.

The program starts by letting the user choose which paper size will be punched. Right after, the unipolar stepper motor is activated which moves the pinion at the paper adjustment. Since a stepper motor is used, the distance between each paper size can be set by calculating the steps it takes to move the certain distance. When it is set to go to A4 paper size, the motor will run until it reaches the end-stop which will stop it. When the motor is running it will display a "work in progress" message on the Nextion display so the user knows a process is taking place and doesn't interact with the paper punch in an unintended way.

After the paper adjustment is done, the user has two options, changing again the paper size just in case something else was pressed by mistake, or pressing the button "start making holes" which will activate the bipolar stepper motor. While the motor is running, the "work in progress" message is displayed. When the end-stop is triggered, then the motor runs in reverse until the other end-stop is reached.

Now that the process has finished, the user can either punch more papers or change the paper size.

6.2 Nextion display

The use of Nextion display was one of the requirements for this project.

It is a color Resistive Touch Panel (RTP), with a 320 by 240 resolution. It is used to send and receive information from the microcontroller so that the user has an easy interaction with the hole punch.

The model being used is the NX3224T024.[26]

6.3 Endstops

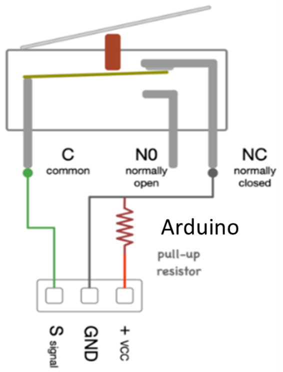


Figure 25: Endstop schematic

A way to stop or change the direction of the motors is needed, so the implementation of end-stops will take care of this task. By using end-tops, when the actuator or paper adjustor reach a certain distance will trigger their corresponding end-stop. By doing so, the end stop will go into open circuit, seen on figure 25 so the microcontroller will lose the signal from the end-stop so by implementation of code another action can take place. [27]

6.4 Arduino Nano

To control all the processes happening a microcontroller is needed. An Arduino nano will be the chosen microcontroller, since it is a cheap option, and it has all the ports needed to control all the actuators and sensors. (Appendix 4, Arduino nano)
An Arduino nano has a total of thirty-six pins. Fourteen of the pins are digital pins, which can be used either as output or input and will be used to receive input from the sensors and send signals to the actuators. This pins work with a maximum voltage of 5V and 40mA. They also have pull-up resistances form 20-50k ohms.
The RX and TX pins are used for TTL serial data communication. In this project are used to make the communication between the Arduino and the Nextion display. The RX pin is the one that receives the data and the TX the one that sends it.
The Vin pin is used to power the Arduino, it requires 5 volts to power it.
Most of the pins have other ways of being used, but in this project will not be used, like digital pins 6, 8, 9, 12, 13 and 14 are also PWM (Pulse Width Modulation) pins, but as no DC motors are being used, only stepper motors, there is no reason to use them as PWM pins.
Pins 5 and 6 can be used to trigger interrupts externally but will only be used as digital pins since there is no need to use external interrupts.
The analog pins are mainly used with analog sensors and considering non are used, these pins will neither be used.

6.5 Stepper motors

For this project, stepper motors are being used.
Stepper motors are DC motors that move in steps. They have multiple coils that are organised in phases. When giving energy to each phase in the required sequence, the motor will rotate in one direction step by step.

6.5.1 Paper adjustor (unipolar)

Figure 26: Unipolar stepper motor

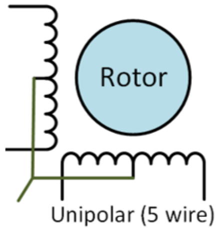


Figure 27: Unipolar motor wiring

Unipolar stepper motors always energize the coils the same way, the common lead, will always be negative and the other lead always positive.
This motors are inverted by reversing the sequence by which the coils are getting power.
Their disadvantage is that there is less torque available because only half of the coils can be energized at the same time.
The motor used, figure 26, is a 5 -wire steeper motor, figure 27, meaning that the common wires from each coil are tied together internally into one wire.

6.5.2 Linear actuator (bipolar stepper)

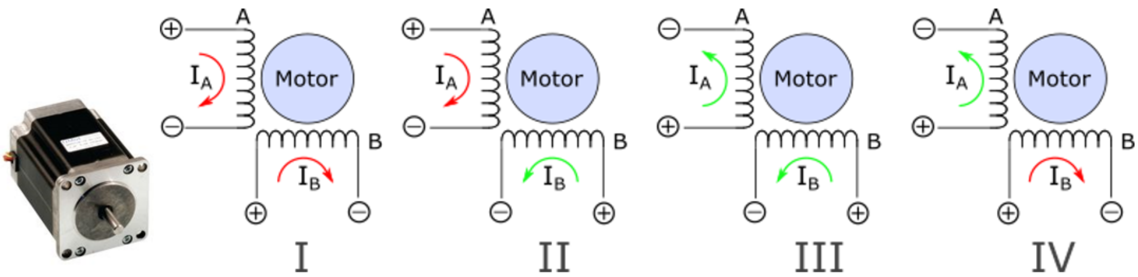


Figure 28: Bipolar stepper motor and its steps

For moving the linear actuator, a bipolar stepper motor is employed, figure 28.
This motor was chosen because bipolar steppers can give more torque than unipolar stepper motors and DC motors with the required torque were too expensive to afford. To drive these motors a H-bridge is needed since the current on the coils must be reversed for the stepper to rotate, as seen on figure 28.
These motors run by a four-step sequence, figure 28, that change the current on the coils. To reverse them, the four-step sequence must be run in reverse, same as with the unipolar stepper. [28]

7 Manufacturing of the mechanical assembly

When time came to manufacture the prototype, it turned out, some of the materials needed were impossible to get a hold of. Due to a lack of tools for working with sheet metal, manufacturing some of the component, especially the frame would be challenging. Therefore, a last-minute rework of the design was needed. We managed to get a hold of an old metal table leg, that when lightly modified, fell within acceptable tolerances for the frame. The modified assembly can be seen in figure 29 below and the NX assembly can be found in appendix 9.

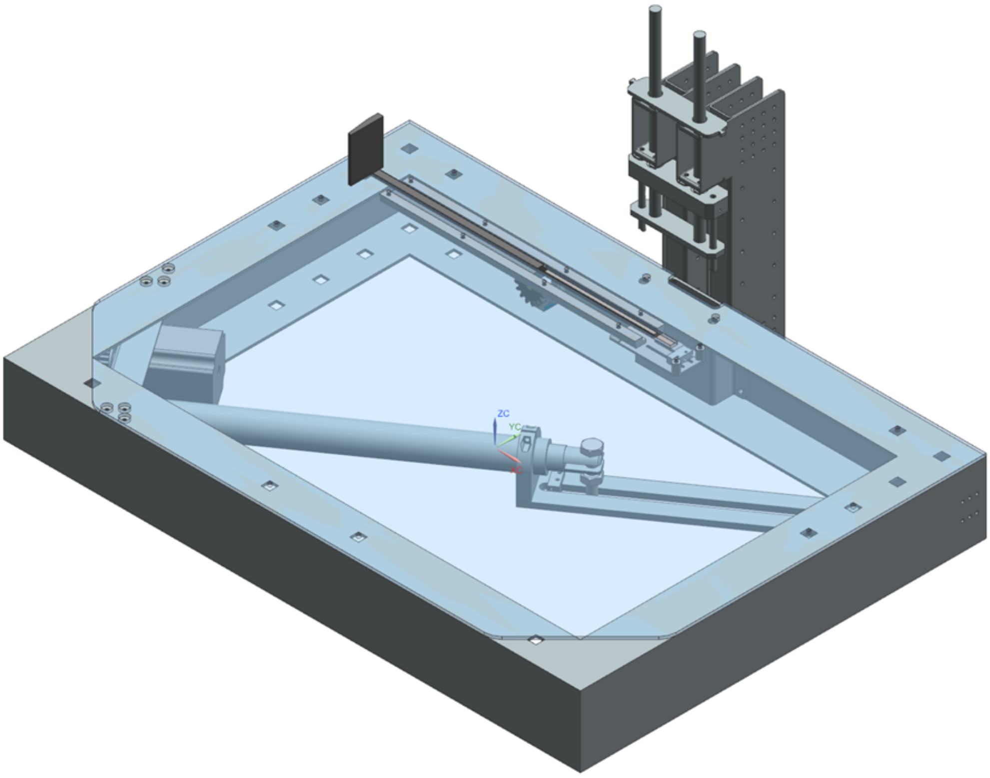


Figure 29: Mechanical Assembly

During the rework process, which included a recalculation of the height of the two towers, the height was unfortunately mis-calculated, as the thickness of the top plate, was forgotten in the equation.

7.1 Modification after destructive failure

During one of the first tests trying to punch through paper, one of the bolts holding a pulley bent, see figure 30. This happened because a reinforcement plate, that were in the original design, didn't get transferred to the modified design, when the plate thickness changed.

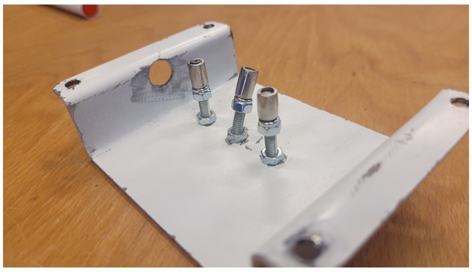


Figure 30: Mechanical failure - bent bolt

Assuming that the unmarked bolt probably is of property class 4.6 (cheapest standard M4 screw), the yield strength is 240 MPa[29](Table 3.1) , with this information the force upon the pulley can be estimated using the formula for maximum bending stress[5]:

$$\sigma_b\,(max) = \frac{M}{S}$$

Where S is the section modulus. In this case the section modulus of a cylinder with the minor diameter of the bolt threads, is used[6]:

$$S = \frac{\pi d^3}{32}$$

The minor thread diameter of a M4 bolt is 3 mm[30] giving the following equation, when the moment is defined as the force at a distance of x m:

$$\sigma_b\,(max) = \frac{F \cdot x}{\frac{\pi d^3}{32}} \Leftrightarrow F = \frac{\sigma_b\,(max) \cdot \pi d^3}{32x}$$

Inserting the known values in order to calculate the force required to bend the bolt in the initial configuration:

$$F = \frac{240 \cdot 10^6 \cdot \pi \cdot \left(3 \cdot 10^{-3}\right)^3}{32 \cdot 2 \cdot 10^{-3}} = 25N$$

Far from the 8 kN that is the maximum possible force that can act on the bolt, but also seems too low, in comparison with what it looked like.
Anyways, the structure had to be strengthened, and to do that an extra bracket much like the one in the original design was added, see figure 31. for the modified support bracket.

Figure 31: Picture of the modified and strengthed bracket

7.2 Cutter tubes bending

During the last test, the pressure applied made the cutter tubes bend. Upon further inspection this was because of the entire cutter head tilting in relation to the guide rails, thus imparting a moment on the tubes, which they are not designed to withstand. The suspected cause for the cutter head tilting, is the fact that the bushings it interfaces to the rails through is only made from 100% infill PLA 3D prints, which most likely is too soft when subjected to the forces acting upon the cutter head. A picture of the failure can be seen in figure 32. Unfortunately, this test was conducted rather close to the hand in of this project, and therefore, the conclusion was that there was not enough time, to try and source a suitable bushing material (e.g. POM) and fabricate and fit a new set of bushings and tubes.

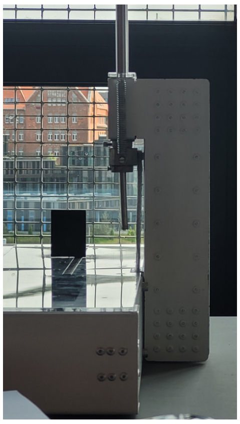


Figure 32: Picture of bent cutter tube

8 Manufacturing of the electronics

During manufacturing of the electronics quite a few minor challenges arose but in the end the circuit ended up functioning - although with a couple minor modifications, as can be seen on figure 33, depicting the final version of the board.

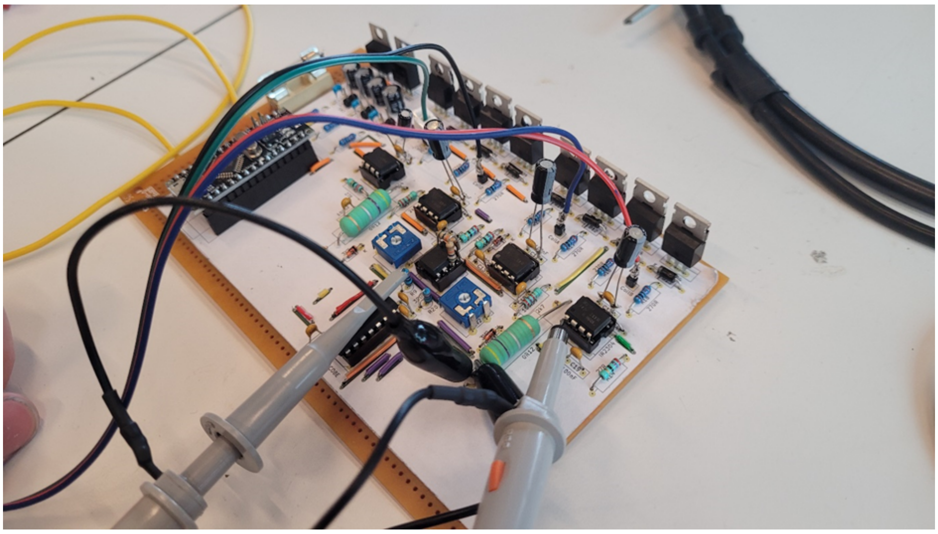


Figure 33: Finished electronics board

8.1 Comparator output not working

During the first test of the board, the comparator output never changed - no matter the setting. After a quick glance at the datasheet, it turned out to be a small misunderstanding of how the output worked. At first it was assumed that the comparator would output a binary voltage signal as output - this is not the case, instead it sinks current to ground whenever the inverting input exceeds the value at the non-inverting input. To fix this issue a pull-up resistor was needed at the output.

9 Manufacturing of the software

9.1 Nextion display

he first thing that was implemented on code was the Nextion display, since it did not need other actuators or sensors to be tested with.
The display was coded containing 4 screens, which change to each other by the code in the Nextion if no response is needed from the Arduino. Otherwise, if a response is needed from the Arduino, for example when changing screens after the motors have completed their task, the page is changed by sending the command from the Arduino to the Nextion.

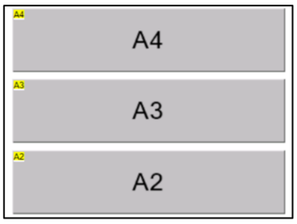


Figure 34: Page 0, Paper_size_pg

Figure 35: Page 1, work_ip_pg

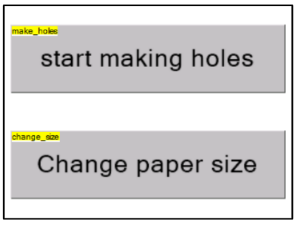


Figure 36: Page 2, make_holes_pg

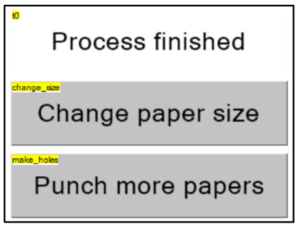


Figure 37: Page 3, done_pg

When pressing either button on the paper_size_pg, figure 34, the component ID from that button is sent to the Arduino, and afterwards, by these "page work_ip_pg" Nextion command, the page is changed to the work_ip_page, figure 35.
Now the stepper motor for the paper adjustment is running, and when its work is done, the Arduino will send this command "printf("page 2%c%c%c",255,255,255);" to the Nextion via the TX pin. Then the Nextion will read it and change to page 2, figure 36.
On this page, the user can press the change_size button which by "page paper_size_pg" command will go back to page 0. If pressing the make_holes button, the Arduino will receive the component ID from this button and will send the command "printf("page 1%c%c%c",255,255,255);" which the Nextion will receive and go to paper_size_pg. Then the Arduino will run the bipolar stepper motor and the Nextion will wait until the command "printf("page 3%c%c%c",255,255,255);" is sent from the Arduino once the motor has finished its process.
The Nextion changes to page 3, figure 37, the user can either change the paper size and go over all steps again by pressing the change_size button or punch more papers without changing the paper size by pressing the make_holes button.
For receiving the component ID from the buttons, the Arduino scans the RX port when a component ID is expected, by using this command "scanf("%c", &buffer[i]);" where "i" is a number from 0 to 6 depending on which number from the component ID the Arduino needs.
The component ID sent from the Nextion is different for each button and it is a 14 digit hexadecimal number that the Arduino reads by groups of 2. For example, when pressing the A3 button, the component ID is 65 00 02 00 FF FF FF. For the Arduino to know that it was this button, it needs to scan buffer 0, 1 and 2. Buffer 0 tells what type of action sent the component ID, 65 is a Touch event. Buffer 1 is to know the page number, in this case 00 stands for page 0. Buffer 2 is the number of that component, in this case 02. Buffer 3 tells if it was a touch or release action which is irrelevant for this project and the last 3 buffers send that the message is terminated.

9.2 Endstops

```
void punch(){
    PIND = 0b00000100; // enable pull up
    while (!(PIND&4)){ // pin D2
    //code that makes the motor run
    }
    retrive_punch();
}
```

Figure 38: Punch function

```
void retrive_punch(){
    PIND = 0b00001000; // enable pull up
    while (!(PIND&8)){ // pin D3
    //code that makes the motor run in reverse
    }
    PORTD = 0x00; //disable pull ups
    stop_punch();
}
```

Figure 39: Retrieve punch function

```
void run_motor_to_A4 (){
    PINB = 0b00010000; // enable pull up
    while (!(PINB == 0b00010000)){ //pin D12
    //code that makes the motor run
    }
    PORTB = 0x00; // DISABLE pull up
    stop_motor();
}
```

Figure 40: Run motor to A4 paper size function

In case of the one at the paper adjustment system, figure 40, when it is triggered, it breaks the loop that makes the motor run, and calls the void that makes the motor stop. In case of the ones at the linear actuator, one of them makes the motor run in reverse, figure 38 and the other one makes the motor stop, figure 39.
The end stops are in closed circuit, so when they are triggered, they go into open circuit. That is what the code checks for. When the signal on the pin is lost, the while loops are broken, and the code continues.
For the end stops to work only being connected to ground and the digital pin, the internal pullup resistor from the Arduino must be enabled. That is done by energizing the digital pin the end stop is connected to.

9.3 Delay function

To run the stepper motors, a delay is needed between each step to regulate the time it needs to wait until the next step.
Only one delay function has been created, having in mind the motor that drives the linear actuator and then for the other motor, the function is repeated more times to suite the desired delay.
Since the motor needs to go 1080 RPM, the following calculations have been made to get the delay needed between each step:

$$\frac{300^\circ}{1.8^\circ stideangle} = 200 step/rotation$$

$$1080RPM \cdot \frac{200steps}{1rotation} \cdot \frac{1minute}{60000ms} = 3.6\ step/ms$$

$$\frac{1}{\frac{3.6step}{ms}} = 0.27778\ ms/step\ \approx\ 0.28\ ms/step$$

Knowing the delay between each step is 0.28 milliseconds, the value needed to reach this time can be calculated by a simple equation:

$$OCR0A = \left[\left((clock\ speed)/prescalar\right) \cdot \text{time}_{(in\ seconds\ )}\right] - 1$$

$$OCR0A = \left[\left(\frac{16000000}{64}\right) \cdot 0.28 \cdot 10^{-3}\right] - 1 = \ 69\ \ =\ 45\ in\ hexadecimal$$

```
void delay_0_28ms(unsigned int loops){
    int counter = 0;//set counter to 0
    do {
        // Set the Timer Mode to CTC
        TCCR0A |= (1 << WGM01);
        // Set the value that you want to count to
        OCR0A = 0x45;
        // start the timer
        TCCR0B |= (1 << CS01) | (1 << CS00); // set prescaler to 64 and start the timer
        while ( (TIFR0 & (1 << OCF0A) ) == 0)  // wait for the overflow event
        {

        }
        // reset the overflow flag
        TIFR0 = (1 << OCF0A);
        counter ++;
    } while (counter < loops); //do while counter hasn't reached the loops
}
```

Figure 41: 0.28ms delay function.

Now a timer of 0.28 ms can be implemented between each step, figure 41.

9.4 Stepper motors

9.4.1 Paper adjustor (unipolar)

Since the motor should run at 12.7 RPM the next calculation is done to find out the delay between each step:

$$\frac{300°}{11.25°\ stide\ angle} \cdot 64\ gear\ reductio = 200\ step/rotation$$

$$12.7RPM \cdot \frac{2048steps}{1rotation} \cdot \frac{1minute}{60000ms} = 0.433\ step/ms$$

$$\frac{1}{\frac{0.433steps}{ms}} = 2.3068\ ms/step$$

$$2.3068\frac{ms}{step} \cdot \frac{1\ timer\ cycle}{0.28ms} = 8.238\ \approx 8\ timer\ cycles\ /step$$

This means the timer needs to run 8 times to achieve the desired delay. An alternative could have been made another delay function that had a delay of 2.31ms, but since the paper adjustment system is a secondary goal, this works good enough and simplicities the code.
To calculate the steps needed to do to change from one paper size to another the next calculations are done:

$$2048\frac{steps}{rotation} \cdot \frac{1rotation}{2 \cdot P\ I * 1.5\ cm} \cdot \frac{7.425cm}{distance\ from\ A4\ to\ A3\ \&\ A3\ to\ A2} = 1613.44\ \approx 1613steps/distance$$

$2 \cdot \pi \cdot 1.5$ is the perimeter of the pinion, or the distance the rack moves every rotation of the motor.
1613 steps are needed to change from a paper size to the next one or previous one, but when moving from A4 to A2 double this distance is needed, so two definitions are made: DISTANCE 1613 and DOUBLE_DISTANCE 3227
When calling the functions, these values are sent so the paper adjustment moves the required distance.

```
#define S_BLUE     0b10000000 //pin blue cable is connected
#define S_GREEN    0b01000000 // green cable
#define S_YELLOW   0b00100000 // yellow
#define S_ORANGE   0b00010000 // orange cable
#define S_DELAY 8  //S_DELAY * 0.28ms = delay between each step
```

Figure 42: PORTD pin definition related to cable connected on the unipolar motor, small motor.

```
void run_motor_forwards(int steps){
    for (int i = 0; i < steps ; i = i + 4){
       PORTD = S_BLUE;
       delay_0_28ms(S_DELAY);
       PORTD = S_GREEN;
       delay_0_28ms(S_DELAY);
       PORTD = S_YELLOW;
       delay_0_28ms(S_DELAY);
       PORTD = S_ORANGE;
       delay_0_28ms(S_DELAY);
    }
    stop_motor();
}
```

```
void run_motor_backwards(int steps){
    for (int i = 0; i < steps; i = i + 4){
        PORTD = S_ORANGE;
        delay_0_28ms(S_DELAY);
        PORTD = S_YELLOW;
        delay_0_28ms(S_DELAY);
        PORTD = S_GREEN;
        delay_0_28ms(S_DELAY);
        PORTD = S_BLUE;
        delay_0_28ms(S_DELAY);
    }
    stop_motor();
}
```

Figure 43: Run unipolar motor forwards and backwards functions

```
void run_motor_to_A4 (){
    PINB = 0b00010000; // enable pull up
    while (!(PINB == 0b00010000)){ //pin D12
       PORTD = S_BLUE; //pin blue cable from motor is connected
       delay_0_28ms(S_DELAY);//delay between each step
       PORTD = S_GREEN; //green cable
       delay_0_28ms(S_DELAY);
       PORTD = S_YELLOW; //yellow cable
       delay_0_28ms(S_DELAY);
       PORTD = S_ORANGE; //pin orange
       delay_0_28ms(S_DELAY);
    }
    PORTB = 0x00; // DISABLE pull up
    stop_motor(); //call the loop that stops the motor
}
```

```
void stop_motor(){
        PORTD = 0x00;
}
```

Figure 44: Run unipolar motor to A4 and stop motor functions

To make the motor rotate, each coil must be energized in order, from the first to the fourth coil, and to make it go the other way from the fourth to the first coil. The motor is connected in order with the coil cables from digital pin 4 to 7, which corresponds to PORTD, figure 42.
By setting a 1 on the corresponding pin from PORTD and setting the other pins to 0, only the corresponding coil is energized, and the next step only the next coil is energized and so on, figure 43. By doing so, the motor rotates. When the needed steps have been done, the stop_motor function is called, figure 44, which sets all PORTD pins to 0, so none of the pins connected to the motor are energized, making the motor stop.
As seen in figures (43 and 44), between each step, a delay of value 8 is sent (S_DELAY), this means the timer will do 8 cycles every time is called using the S_DELAY value.
There are 3 different functions to run the motor, one that runs it to A4, figure 44 and the other 2, figure 43, run the motor either forwards or backwards a certain distance that is calculated by steps.

```
if (buffer[2] == 0x01){ //if A4 button pressed on nextion
    run_motor_to_A4(); //call run_motor_to_A4 function so motor stops when reaching end-stop
    change_page();
    paper_size = 4; //save A4 as the new paper size
}

if (buffer[2] == 0x02){ //if A3 button pressed on nextion
    if (paper_size == 4){ //A4 previous paper size
        run_motor_backwards(DISTANCE); //run motor backwards to reach A3
    }
    if (paper_size == 2){ //A2 previous paper size
        run_motor_forwards(DISTANCE); //run motor forwards to reach A3
    }
    change_page();
    paper_size = 3; //save A3 as the new paper size
}


if (buffer[2] == 0x03){ //if A2  button pressed on nextion
    if (paper_size == 4){ //A4 previous paper size
        run_motor_backwards(DOUBLE_DISTANCE); //run motor backwards twice the distance to reach A2
    }
    if (paper_size == 3){ //A3 previous paper size
        run_motor_backwards(DISTANCE); //run motor backwards to reach A3
    }
    change_page();
    paper_size = 2; //save A2 as the new paper size
}
```

Figure 45: Code logic to call the right motor function

The voids are called when the button A4, A3 or A2 are pressed on the Nextion, figure 45. To ensure the motor only moves when a different paper size is being pressed, every time a function is called to change the paper size, the variable "paper_size" stores the value corresponding to the paper size. The value is afterwards used to call the corresponding function and send a distance if required. If the variable is the same as the button pressed, then the program does not call the void and prints the next screen on the Nextion. Since when paper size is A4 the motor will stop when the end-stop is triggered, when pressed the A4 button, the function to send the motor to A4 is called, and if it is already there, the end stop will be triggered, and the motor will not run.

Initially an EEPROM memory was implemented on the code, so that each time the paper adjustment changed, the value "paper_size", figure 45, at which paper it was changed to was stored in the EEPROM memory. But after some thought it was changed so that the paper adjustment system when starting the Arduino moved to the A4 size adjustment. This was implemented so that if the microcontroller lost power while moving the paper adjustment system, in the EEPROM would be stored a value that is not right, because the adjustor would be between two paper sizes and all the next changes to the adjustment system would be wrong. So, by moving the adjustor to A4 paper size, it is ensured that the paper adjustor will move until it touches the end-stop, and then all the next changes will be right.

9.4.2 Linear actuator (bipolar stepper)

The bipolar stepper is programmed similar to the unipolar one, but this one needs to activate more than one coil at a time for it to move, and to drive it in reverse, it is not as easy as reversing the order of the steps.

```
#define ZERO    0b00001001 //pins energized at step 0
#define ONE     0b00000101 //step 1
#define TWO     0b00000110 //step 2
#define THREE   0b00001010 //step 3

#define B_DELAY 5 //cycles the timer will run
```

```
#define PP 50 //number to accelerate for punch
#define RR 50 //number to accelerate for retrieve punch
int p = PP; //variable to accelerate the motor
int r = RR; //variable to accelerate for retrieve punch
```

Figure 46: Code logic to call the right motor function

```
void punch(){
    PIND = 0b00000100; // enable pull up
    while (!(PIND&4)){ // pin D2
        PORTB = (ZERO); //3 0
        delay_0_28ms(B_DELAY + p);
        PORTB = (ONE); //2 0
        delay_0_28ms(B_DELAY + p);
        PORTB = (TWO);//2 1
        delay_0_28ms(B_DELAY + p);
        PORTB = (THREE);//3 1
        delay_0_28ms(B_DELAY + p);
        if (p>0) p--; /*decrease p value until 0 so the
        motor accelerates until the needed value to rotate
        at the desired RPM*/
    }
    stop_punch();//stop motor before reversing it
    p = PP;// reset p value
    PORTD = 0x00; //disable pullups
    delay_0_28ms(1000); //delay before reversing the motor
    retrive_punch();
}
```

```
void retrive_punch(){
    PIND = 0b00001000; // enable pull up
    while (!(PIND&8)){ // pin D3
        PORTB = (THREE);// 3 1
        delay_0_28ms(B_DELAY + r);
        PORTB = (TWO);// 3 2
        delay_0_28ms(B_DELAY + r);
        PORTB = (ONE);// 2 0
        delay_0_28ms(B_DELAY + r);
        PORTB = (ZERO);// 3 0
        delay_0_28ms(B_DELAY + r);
        if (r>0) r--; /*decrease r value
        until 0 so the motor accelerates
        until the needed value to rotate
        at the desired RPM*/
    }
    r  = RR; //reset r value
    PORTD = 0x00; //disable pull ups
    stop_punch();
}
```

```
void stop_punch(){
    PORTB = 0x00;
}
```

Figure 47: Punch, retrieve punch and stop punch functions

This driver is connected to digital pins 8 to 11, but since the motor only has 2 coils, one end of the fist coil is connected to pin 8 and the other one at pin 9. Subsequently, the other coil is connected to pins 10 and 11. These pins correspond to PORTB.
As seen when the steps are declared, figure 46, in every step, two ports are energized, and the two ports are never energizing the same coil. What this means is that for the motor to run, both coils must be energized every step.
To energize 2 pins at the same time, the same as with the unipolar stepper is done, but now 2 pins must be set with a 1 instead of only one and the rest of the pins must be at 0.
Apart from this, the bipolar stepper is programmed as the unipolar one, the only addition made to the code is added a variable, "p" or "r", depending if punching or reversing, in the delay between each motor step, figure 47. What this variable does is make a bigger delay between steps that decreases gradually until the desired delay to run the motor at the optimal speed is reached. This is done so the motor does not start at full speed, avoiding things to break. Moreover, when the punch is finished, the motor is stopped instead of going directly to reverse for the same reason, avoiding breaking things and making the motor run smoothly.
When the end stops have been hit, "p" and "r" are reset to their original value so the next time a punch is made, the motor also accelerates.
In this case, since the pins correspond to PORTB and not PORTD, the function that makes the motor stop, sets all digits on PORTB at 0.

One important thing to mention is that the motor was not able to run at the desired speed, so by testing it by increasing the delay between each step, it started rotating consistently when the delay between each step was 5 times the one calculated. For that reason, between each step the delay is done 5 times, the value B_DELAY. This can be a result of many things, either the voltage given to the moor was not high enough or the H-bridge was not able to handle that many switches in a short time.

10 Testing

10.1 Primary Goals

10.1.1 Ability to punch through paper

- Able to punch through 500 pieces of 80g/m2 A4 paper.
In our final testing after reinforcing the bolt with a second plate holder, the puncher was finally cable of punching through 3 pieces of paper and the product was deemed finished. This was no way near the initial goal, but as lot of unforeseen results can take place, during too many factors working different in practice from what might have been conducted theoretically, either because of minor calculation mistakes, or that something might have been unnoticed at first hand, and therefore not considered. Roughly the overall idea of the hole punch worked, and everything went seemingly as it was supposed to, only not quite reaching our initial goals of punching through 500 pieces of paper. Refer to figure 48 for picture of test.

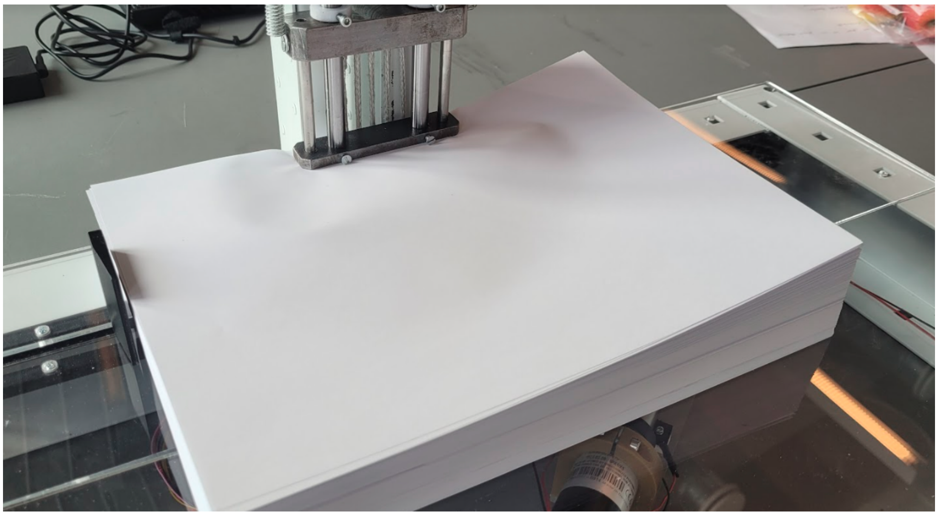


Figure 48: Punch test on around 400 papers that managed to punch the top 3

10.1.2 Goals for speed

- Goal for speed(s) depending on paper thickness and so
The initial cycle time of the of the actuator was also not uphold in the end, which lead to a cycle speed of 3min, and not the required 30 seconds that was set to be the goal. This mean that the actuator did not perform at a speed of Speed of 0.02m/s as intended.

10.1.3 Budget of 2000 DKK

The cost of materials to do the project summed up to 1813.2 DKK which is within the 2000 kr. budget. The bill of materials can be found in appendix 6.

10.1.4 Precision (ISO838 Standard)

The precision of the holes was measured with callipers to see how well they would fit the ISO838 standard on the three pieces of paper, that the hole punch was able to punch through. By measuring the diameter of each hole, distance from the nearest edge, and the distance from one center of the hole to the other, and taking the average the following results was acquired:

- Center to center79.61mm
- Location from edge: 11.4mm
- Diameter of the hole:6.14mm

Though the measurements did very from paper to paper, the average where within ISO838 standard in both, diameter, length from the nearest edge and distance between the center of the holes. Overall, this requirement was well succeeded.

10.2 Secondary goals

10.2.1 Ability to adjust paper size

The ability to adjust paper size trough the Nextion display with help of a rack and pinion gear setup was achieved quite well. And through the Nextion, both the adjustment of A4, A3 & A2 was achieved. To test the speed accuracy of the paper size adjustment, a video was recorded of it moving, the number of frames in the video was then measured and converted to an exact number of seconds. Knowing that the phone was recording at 30frames/s. we measured a total of 217 frames using VirtualDub, from when it started moving until it stopped.

$$\frac{(217 frames)}{30\frac{frames}{s}} = 7.233s$$

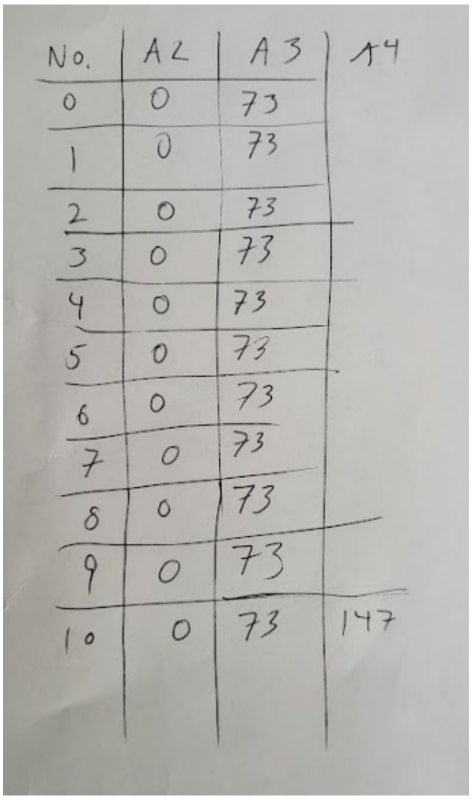
It moved from A4 to A2:

$$148.5mm = 0.1485m$$

The average speed is determined:

$$\frac{0.1485m}{7.233s} = 0.02053\frac{m}{s} = 2.05\frac{cm}{s}$$

We get a speed of 2.05cm/s which is very close to being exactly goal. The precision of the adjustments was also measured, and during our tests it did not deviate at all, although it was off by 1mm the entire test. Test results can be seen on figure 49.



No.	A2	A3	A4
0	0	73	
1	0	73	
2	0	73	
3	0	73	
4	0	73	
5	0	73	
6	0	73	
7	0	73	
8	0	73	
9	0	73	
10	0	73	147

Figure 49: Paper size adjustment precision test results

10.2.2 Nextion interface

Good interaction-design (90% of users can operate product without introduction) As only one person from the group preformed the design of the Nextion display and its user interface, and each of us where able to use the display as required; The user-friendliness of the display was granted a 100%.

10.2.3 Adjustable force (Force sensing)

As was seen in the morphology analysis, the plan was to measure the force, by current sensing on the current flow through the motor. But that only works when using a DC motor (Naturally, seeing as we are using a constant current limiting circuit to drive the stepper), and thus sensing force would have required some other form of sensing when using a stepper. Some ideas for this was briefly considered, e.g. a load cell or maybe even some kind of spring pushing on the rope paired with some kind of position sensor, but due to the increase in both cost and complexity these ideas was deemed non-viable for the project.

10.3 Requirements check

Requirement	**Pass/Fail**	**Goal**	**Acquired**
Integration of LINAK LA27 actuator as main component.	Pass		
Stay within budget	Pass	2000 DKK	1813 DKK
Configurable via Nextion display.	Pass		
Able to punch through 500 sheets of 80g/m2 A4 paper.	Fail	500 sheets of 80g/m2 A4 paper	3 sheets of 80g/m2 A4 paper
Cycle speed	Fail	Full cycle in 30s	Full cycle in 180s
Comply with ISO838	Pass		
Electronic paper size adjustment, along A4.	Pass		
Good interaction-design, 90% of users can operate product without introduction	Pass		
Adjustable force	Fail		

Table 4: Sum up of requirements

11 Conclusion & Reflections

Overall, the bar and requirements for the hole punch were set quite high as we originally were supposed to be a six-man group and the challenge therefore seemed fitting. However, we ended up as a four-man group, which made everything a bit more complicated and challenging. The complexity of the design, including a stepper motor was certainly a tough challenge, and considering the actuator had to be able to pull with 4kN, the mechanical assembly had to be able to resist a lot of force. Since it was not possible to find anyone who had already made a paper punch using hollow cutters before, it was hard to find any help online from other sources. These were all hard challenges, and a lot of thought and calculations had to be taken into consideration. One of the harder task's assembly wise, was making some sort of mechanical construction that would be able to fit as an adaptor for the actuator gear. Furthermore, along the way the whole mechanical assembly had to be redesigned as the required material was not acquirable, and instead had to settle with a big metal table leg as a frame. This change among other lead to the destructive failure of one of the bolts holding the pulley in place, as a reinforcement plate, that were in the original design, didn't get transferred to the modified design, when the plate thickness changed because of the missing sheet metal.

Factors that could have helped improve the outcome could have been the capability of being able to calculate how much force was required to punch through a piece of paper with our specific cutter tubes. Since this was not an option, it was necessary to draw less precise conclusion, of how much force was needed to cut through the paper. The group shrinking to a four-man group also put a lot more work on our other members and gave a way tighter time plan. Furthermore, having all the needed materials would have made the job easier, providing us more time, as a change in design would not have been needed, which also would have not let to the destructive failure of one of the bolts. If one reflects on the design period, it unfortunately took place rather late, ending up costing a lot of valuable time. In the future for next semester project, being early out, and starting the design phase as soon as possible would make up for a great improvement, as there will then be time for more testing and improvements. Otherwise, a higher budget would have made it capable to use a dc motor and avoid having to use a stepper motor, which added a great amount of complexity to the electronic design. The higher budget would also have made it capable to build two prototypes, without exceeding the required budget. Hence a great number of improvements would have been able to take place.

Although it didn't end up succeeding at all the requirements, it still proved the concept, and the overall functionality were there. with more time and development, a second prototype might have been able to succeed.

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