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Benchmaker - An easy-to-use test bench and machine building system

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Abstract

Human-Computer Interaction (HCI) is a field in computer science that focuses on the interfaces between humans and technology. In HCI research, many things have to be tested, and most of the time, there is not a working test bench available, so researchers have to build a bespoke one just for the project currently being carried out. Most researchers, however, do not have experience in building test benches and have to learn how to do so from scratch. These test benches might not be very well built and therefore unreliable. In the end, building a bespoke test bench is time consuming and stressful and not a good use of the researcher's effort. The Benchmaker will address personal fabrication issues and will aid researchers in testing their prototypes and products. It should also facilitate and accelerate testing procedures, and as an open source project, a wide range of researchers and fabrication labs will be enabled and encouraged to build and use it. This thesis proposes a hardware solution that will energize software engineering which will ultimately revolutionize testing processes in Human-Computer Interaction.

Überblick

In der Maker Community sind open-source Prüfstände und modulare Maschinenbausätze noch nicht sehr weit verbreitet, jedoch könnten diese die Forschung im Bereich Mensch-Maschine-Interaktion nachhaltig beeinflussen und vereinfachen. 2017 ist mit der Docktorarbeit von Nadya Peek am MIT ein wichtiger Grundstein gelegt worden, um Prüfstände und Maschinen schnell, einfach und kostengünstig auf der ganzen Welt zu bauen. Diese Prüfstände könnten zum Beispiel sehr wichtig in der Forschung von neuartigen Touchoberflächen und mit Sensoren ausgestatteten Textilien werden, da sie über eine lange Zeit zuverlässig die gleichen Sensoren an bestimmten Punkten mit gleichbleibendem Druck auslösen können.

Ziel dieser Arbeit ist es ein einfach erweiterbares, robustes und modulares Bauteil zu entwickeln, um den bau von Prüfständen und unterschiedlichsten Maschinen selbst für unerfahrene Forscher und Bastler zu ermöglichen. Ein einfacher Aufbau soll Forschern ermöglichen sich mehr auf die Entwicklung ihres Projektes zu konzentrieren und möglichst wenig Zeit in den Aufbau und Design einer für sie nebensächlichen Maschine zu verschwenden. Das Benchmaker projekt soll somit langristig dafür sorgen, dass Prüfstände für Forscher zur Nebensache werden und sie es als hochwertiges simples Werkzeug nutzen können.

Diese Arbeit liefert den Grundstein für weitere Entwicklung und setzt bei Problemen und Ideen an, die bei ähnlichen Projekten, wie dem von Nadya Peek gefunden wurden. Hauptaugenmerk liegt darauf eine zuverlässige Hardwarelösung zu finden, die allen erdenklichen Anforderungen entspricht und eine gute Grundlage für detailierte Softwareentwicklung schafft. Durch den Einsatz von Lichtschranken konnte ein zuverlässiger kostengünstiger Encoder realisiert werden, der dafür sorgt, dass Positionen Hardware basiert bestimmt werden. Dies merzt eine bekannte Fehlerquelle aus und sorgt dafür, dass Schrittmotoren in solchen Maschinen obsolet werden könnten.

Conventions

Throughout this thesis we use the following conventions.

Text conventions

Definitions of technical terms or short excursus are set off in coloured boxes.

EXCURSUS:
Excursus are detailed discussions of a particular point in a book, usually in an appendix, or digressions in a written text.

Definition: *Excursus*

Source code and implementation symbols are written in typewriter-style text.

`myClass`

The whole thesis is written in American English.

Download links are set off in coloured boxes.

File: myFile[a]

[a]https://github.com/srieseb/Benchmaker/tree/masterfolder/file_number.file

Chapter 1

Introduction

" Our opportunity, as designers, is to learn how to handle the complexity, rather than shy away from it, and to realize that the big art of design is to make complicated things simple. "

— Tim Parsey, former SVP of User Experience Design at Yahoo

Human-Computer Interaction (HCI) is a field in computer science that focuses on the interfaces between humans and technology. Research topics include usability and design of technology, interaction techniques, interactive textiles, and everyday things. Personal fabrication is also a topic of HCI, and in the last couple of years, interest has grown in it due to a decrease in price and an increase in the availability of tools such as 3D printers and the user-friendly micro-controllers, e.g. Arduino [Borchers [2013]]. The Benchmaker projct will address personal fabrication issues and will aid researchers in testing their prototypes and products. It should also facilitate and accelerate testing procedures, and as an open source project, a wide range of researchers and fabrication labs will be enabled and encouraged to build and use it. This thesis proposes a hardware solution that will energize software engineering which will ultimately revolutionize testing processes in Human-Computer Interaction.

In HCI research, many things have to be tested, and most

of the time, there is not a working test bench available, so researchers have to build a bespoke one just for the project currently being carried out. Furthermore, most researchers do not have experience in building test benches and have to learn how to do so from scratch. As a result, simple test benches are constructed that may not allow testing devices with multiple moving parts or with a large degree of movement. It goes without saying that these test benches might not be very well built and therefore unreliable. In the end, building a bespoke test bench is time consuming and stressful and not a good use of the researcher's effort.
This thesis will also provide instructions on how to build a ready to use axis that can be quickly and easily assembled and thereby enabling thousands of different machines and tests. Research was influenced by the different approaches undertaken by Fab Lab Aachen. There, they have used LEGO, 3D printers, and various parts of other devices to build a working machine, but alas, most of their endeavors did not fully meet their expectations or ended much more time consuming than planed. One such example is their attempt at testing a touch surface. The machine was supposed to place a tangible at a certain position and move many times while turning it. This task needed four degrees of movement in order to test every part of the surface. It was realized with an modified RepRap. Despite it flaws, Pearce's work is a role model in designing the Benchmaker. Another influence was Nadya Peek who in her PhD thesis at Massachusetts Institute of Technology (MIT) dealt [Pearce [2014b]] with an issue similar to that of Fab Lab Aachen. In her work, Peek introduced a cardboard machine construction kit which has a modular system that allows quick assembly. She proposed the use of axes of differing lengths that could be arranged as needed [Peek [2016]]. The Benchmaker combines the knowledge gained from these previous approaches and aims to be a reliable and robust modular system that will improve testing procedures.

1.1 Overview

This section gives an overview of the chapters and their contents.

- Chapter 2 “Related Work” discusses previous endeavors and analyzes them.
- Chapter 3 “Own Work” lists the Benchmaker project's requirements and presents prototypes with accompanying discussion.
- Chapter 4 “Instructions” provides directions on how to build an axis.
- Chapter 5 “Evaluation” assesses whether requirements listed in Chapter 3 have been met.
- Chapter 6 “Summary and future work” summarizes thesis and presents ideas for future work.

Chapter 2

Related work

3D printers, CNC-Routers, and laser cutters have three degrees of movement and meet some of the requirements of a test bench. They serve as a good starting point for further research and have been used by Fab Lab Aachen in the past. Many people have tried to build the aforementioned tools on their own because they are still quite expensive to purchase from a professional fabricator. This has led to a variety of do-it-yourself kits that employ different approaches. This chapter will review a few test benches and will show how the past projects of Media Computing Group Aachen and Nadya Peek's Cardboard Machine Construction Kit inspired the design and choice of material used in the Benchmaker project.

2.1 3D printer, Laser Cutter & CNC-Router

3D printers, CNC-Routers, and laser cutters are similar to a test bench in many respects. During research, websites where people could go to get information on how to use these items to complete a homemade project (e.g. `www.instructables.com`) was scanned for potential ideas. Such a website allows individuals to pool ideas, discuss best practice, debate requirements and expectations, and rectify errors. Most projects use step motors because they allow the ability to count steps digitally, which reduces effort, and are adequate enough for small machines and applications like 3D printing. As machine size increases, however, complaints about execution speed rise. For example, it can take several days to complete a large laser cutter job using a step motor, so for the Benchmaker, a regular DC motor is used instead. Detailed explanations of decisions can be found in chapter .

2.2 LEGO

Tangibles are haptic input devices, which enable haptic feedback on different touch sensitive surfaces.

Media Computing Group Aachen needed a low cost, modifiable, and easy to build test machine for moving tangibles* on a touch surface. The researchers wanted a machine on which a tangible could be placed in a position on a touch surface, and the machine should rotate the tangible for 5 degree each iteration. It was also necessary to collect information about the tangible's and motor's positions in order to evaluate them. The main problem that arose was that every tangible had to start in the exact same position as the others in order to get a reliable reading. At first the researchers used a laser cutter and 3D printers to build a test bench. They did not have much experience in building machines since most of the research they conducted dealt with software, so they struggled with designing and assembling laser cut parts. At some point, they decided to switch to aluminum profiles because of better usability and quicker assembly.
The researchers, however, still had to figure out the control and the adjustment of the hardware parts, such as motors, and what microcontroller to use. They became so frustrated that they stopped the construction of an aluminum test bench. After being advised to give LEGO Mindstorms a try, they attempted once more to build their test bench. Figure 2.1 shows the machine that met their needs. It consists of a large motor that moves a threaded rod which in turn moves the tangible and the other attached motors up and down. The motor in the middle rotates the tangible. The so called EV3 brick provides control of this machine

using a network and setup is done using the buttons. The left button is for initialization, and the one on the right is an emergency stop button that prevents the machine from moving components too far up [Krämer [2017]].
LEGO prototyping is easy and does not need much building experience in order to construct a working machine; nevertheless, it has its limits. The motors used in this particular LEGO machine are not really strong and cannot be used in larger applications. Moreover, because LEGO uses the push together system, machines can be quite large, and complex connections might have to be made. To save time, prefabricated pieces from LEGO, which come in a variety of shapes, sizes, and functions, can be used, but this does not afford much freedom in design when compared to a 3D printer.
LEGO Mindstorms is an uncommon, but fast prototyping tool. It can be quickly assembled, and it consists of fairly robust material. LEGO Mindstorms' logic unit allows the control of several moveable parts, and this leads to the construction of a wide array of prototypes. No tools are needed to build a functioning LEGO prototype, and it is not only easier to detect errors using a LEGO prototype but also even more complex prototypes can be based on it.
Some of the requirements of Media Computing Group Aachen's LEGO project have been incorporated into the Benchmaker. Additional demands were identified during interviews with researchers. One such demand is modularity. This allows the construction of multipurpose machines. If a machine is modular, it will be easy to build many different machines using the same basic structure. The LEGO project also confirmed that it is very important to have a reliable position control for every motor in order to determine an exact position. It is not possible to use the same exact position for every new tangible tested without using extra sensors. Furthermore, by analyzing the limits of the LEGO prototype, it became clear that the Benchmaker has to be scalable and that its complexity should not increase even if the machine were large.

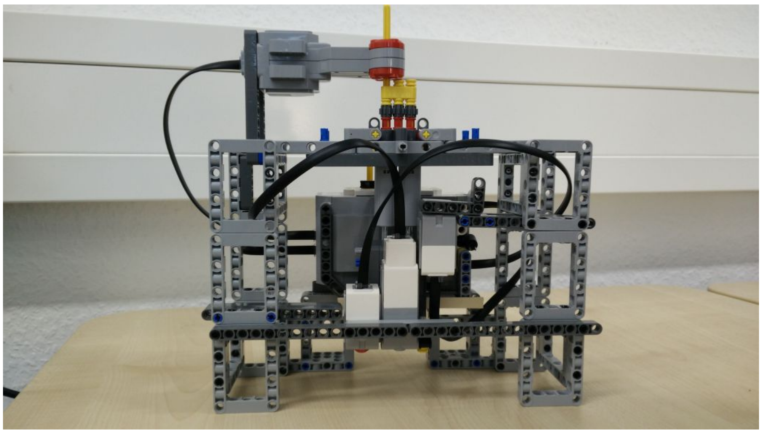

Figure 2.1: Finished LEGO Test Bench [Aaron Krämer]

2.3 RepRap

RepRap is short for *Rep*licating *Rap*id-prototyper. It is not only a 3D printer but also a self-replicating machine. It can print most of the parts needed to construct it. The other parts are standard engineering parts that are inexpensive and can be easily found [Rhys Jones [2010]].Therefore the RepRap project introduced the first low cost 3D printer. Today it is one of the most widely-used 3D printers [Pearce [2014a]].

Fab Lab Aachen used RepRap as a test bench to move a probe tip between two exact points and press them with a defined pushing force. This test bench was primarily used for a multi-touchpad textile. Fab Lab Aachen's test was to simulate a finger's pressing action. The basic test setup was easy to achieve with the RepRap, since the movement should be the same as a printer. Additionally some parts which are needed for 3D printing, for example the complex extruder, are not needed. The different pushing force was simulated by attaching weights of various sizes onto the tip of the probe. Figure 2.2 shows the modified RepRap, and it displays the testing of the pushing force. This test was conducted to determine if construction was feasible.

RepRap, however, does not provide position feedback for the motors, and if there is no feedback given for actual movements, steps may get lost during execution. This steps

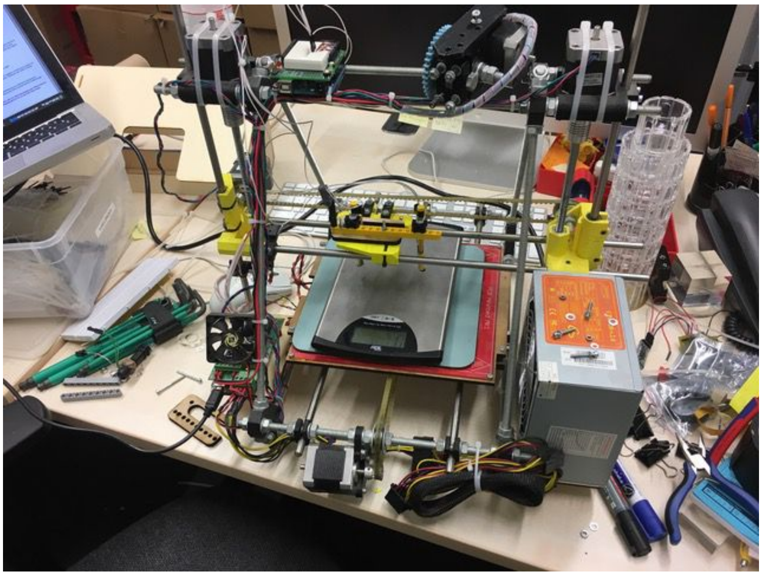

Figure 2.2: Test of Pushing Force with Modified RepRap [Jan Thar]

sum up to a great error. Therefore it is impossible to know if the estimated position of the motors is correct. The Benchmaker project rectifies this by providing a precise position recognition and feedback system. And like RepRap, being an open-source project will aid in the development and acceptance of the Benchmaker. Open-source adds availability and usability to the list of requirements.

2.4 Cardboard Machine Construction Kit

> *" How can we make it easy to extend machines mechanically? How can we build up a machine tool out of individual degrees of freedom? "*
>
> *— Peek [2016]*

Peek raised these two interesting questions in her PhD thesis at MIT. Her solution was the cardboard machine construction kit. This kit is completely modular and can be adjusted in size through the use of modular pieces that are common and come in different sizes. She used cardboard because it was low-cost and readily available [Peek [2016]]. Peek devised a modular system that consists of independent axes that when combined forms a functioning machine. Each axis is designed separately. The cardboard machine construction kit is an open source hardware project and in order to make sure that it was available to all, Peek designed it to be reorderable, replaceable, and reusable [Peek [2016]].

Each cardboard axis consists of two metal rods, a step motor with an integrated lead screw, and many pieces of laser cut cardboard. The bearings on the metal rods are made out of plastic. The material needed is shown in Figure 2.3. To ensure modularity, each axis has its own control circuit attached which allows the free arrangement of the axes without too much worry about the control. The use of cardboard makes every axis very light weight, and as a result, each step motor is capable of moving multiple axes. See Figure 2.4 for assembled cardboard axes.

Peek tested these cardboard axes in many workshops, and people from around the world built machines using her cardboard machine construction kit. Participants had just one day to build a machine. Peek received much positive feedback from many fabrication labs, and the sheer number of various machines built showed not only her kit's usability but also its versatility. Although satisfied with the results of her study, Peek was somewhat surprised to find that many users did not like the use of cardboard, for they found it not very aesthetic [Peek [2016]]. Another flaw of cardboard was discovered by the Fab Lab Aachen because it is not robust enough. During the tests the machine started to destroy itself. Other machines were built using plywood instead of cardboard to make it more robust. After longer testing, plywood was ruled out, as it bends if used in a long time application.

Even though Peek's cardboard machine construction kit has shown promise, it is not without its faults, and therefore can still be improved upon. It is part of a foundation on which the Benchmaker is based and by subjecting Peek's project to different scenarios, flaws have been discovered. Fab Lab Aachen, for example, has also tried Peek's cardboard machine construction kit as a test bench, and they found that the individual controlling circuit for each axis

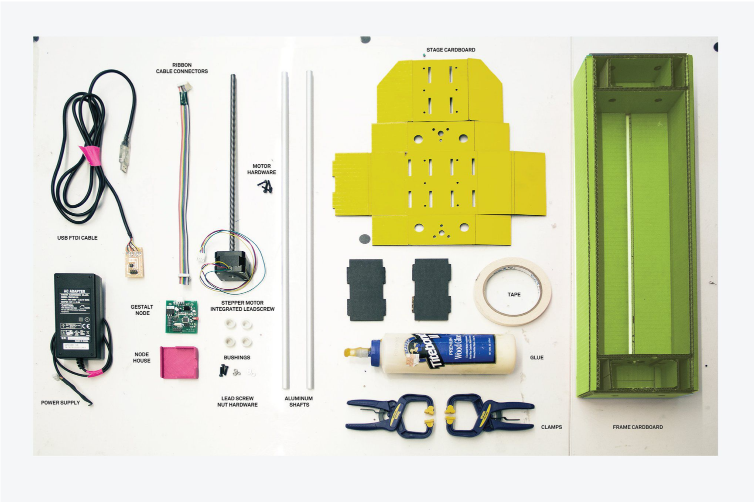

Figure 2.3: Material to Build One Cardboard Axis [Nadya Peek]

was problematic due to usability. The circuits provided no information about the processes to control each axis, and that made it difficult to modify. The circuits were connected to each other, and they retrieved information about their movements, but this connection made it very difficult to control the whole machine with only one code.

The Benchmaker uses aluminum profiles which should be robust and available in different sizes and easy to handle. Aluminum profiles are also lighter than metal parts and offer good stability. The difference in weight and thickness has to be taken into account and thus the motor has to be stronger. Step motors are usually weaker, heavier, larger and more expensive than DC motors of the same power usage. And, this is the reason why the Benchmaker utilizes DC motors so that it achieves better performance.

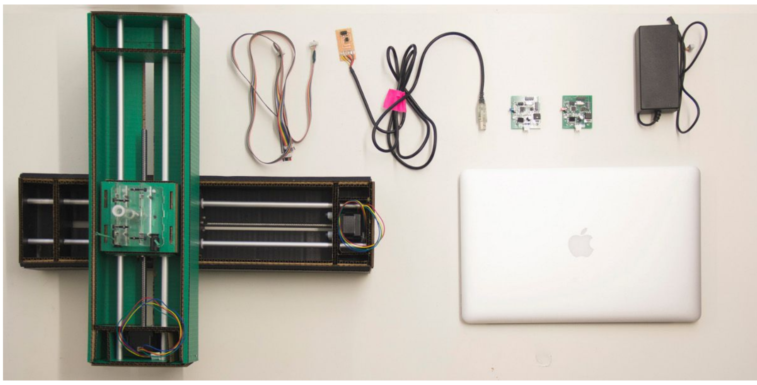

Figure 2.4: Two Connected Cardboard Axis and Controlling Parts [Nadya Peek]

Chapter 3

Own work

3.1 Requirements

The presented machines in 2 “Related work” result in a list of requirements for this project.

3.1.1 Modularity and Scalabilty

The Benchmaker consists of modularly assembled axes that should operate independently (only if the control of multiple axes is not influenced). This modularity extends to the use of axes of various sizes. Each axis has to be scalable so that it can fit almost any project size and purpose.

3.1.2 Durability and Aesthetics

The material used for the Benchmaker project has to be robust, resistant to force, and capable of carrying heavy loads for extended periods without breaking, bending, or malfunctioning. An aesthetic issue was raised in Peek’s research, and this will be taken into account; however, functionality is the main focus.

3.1.3 Open-source/ Do-It-Yourself project

The Benchmaker is an open-source, user-friendly project. Parts have to be accessible and inexpensive. Every design decision had this in mind.

3.1.4 Position Feedback

The Benchmaker's motor has to receive precise and correct position feedback at all times. This feedback should be based on real life events and not digital function calls. The Benchmaker has to be able to start at the exact same position where it left off at every iteration of different movements.

3.1.5 Stressful and Fast Movement

The axis design has to support stressful and fast movements. Since, the Benchmaker will be a scalable machine, each axis has to arrive at a position quickly. Moreover, the use of robust material might add to the axes' weight; nevertheless, the motor has to move them quickly and reliably.

3.2 Hardware

In this section the Design Implement Analyze cycle [Borchers [2001]] was used to develop a final hardware prototype. Each prototype was tested for material and design properties and was evaluated for lessons learned so that subsequent prototypes could be improved

3.2.1 First Prototype

The goal of the first prototype was to create a movement mechanism with a simple but strong and reliable driveshaft. A threaded rod was used and tests were done with M3, M5, and M8 rods. The initial challenge was to connect the platform with the rod in such a way that the platform would not turn with the rod but instead move the rod up and down. First, a few nuts were glued to a piece of wood and then mounted onto a platform. Next, two simple tests were carried out to see what would be the better way to keep the platform from turning but enabling its movement. One was to keep the nuts from turning, and the other was to prevent the platform from turning. See Figure 3.1 for a better understanding.

The former was quite easy to do using a rail of the same size and width around the nuts. This prevented the nuts from turning and allowed the platform to move up and down as long as the nuts stayed inside the rail. Thus, the length of the rail limits the length of the axis. In this setup, the connection between the nuts and the platform was not very strong, so a second platform under the rail was necessary in order to strengthen it.

The second setup was somewhat harder to test. The easiest way to do so was to simply fix the platform on a table by using some small blocks placed on both sides of the rod. For this setup, metal rods should be used to prevent the platform from turning. In both cases, a normal drill was used as a motor.

Discussion

Tests showed that a threaded rod was suitable in both scenarios. Smaller rods were more likely to bend and were unsuitable for a long axis, and they could even break during installation or during usage on small setups. Smaller rods will also have to turn more often to match the distance of a longer rod. And, although higher speeds can lead to inaccuracies, no significant discrepancies were found when using the M8 rod. Lastly, the movement on the z-axis can be done by a smaller rod since the axis is not very long nor does it have to bear heavy weight. The comparison of the two setups revealed that a suitable motion system was needed.

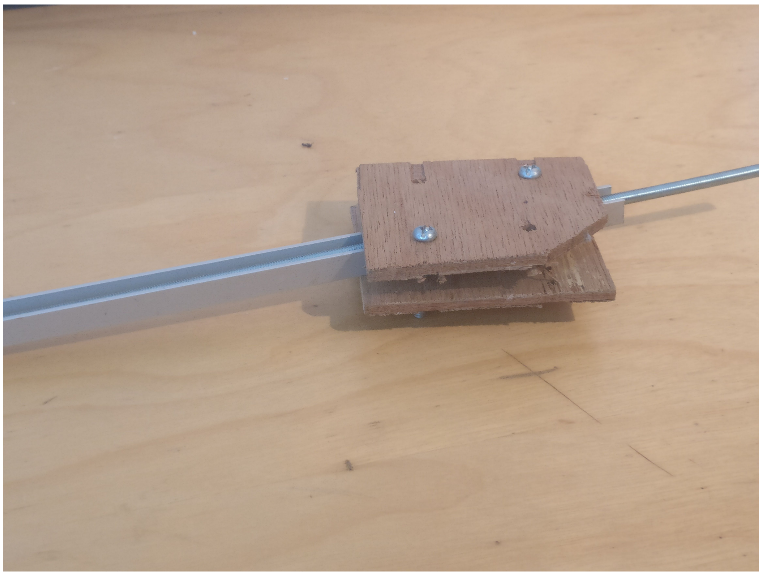

Figure 3.1: First Solution: Fix the nuts to enable Movement

Motion Systems

The test bench has similar requirements to the earlier introduced projects especially for the motion system. All these projects have three movable axis which have to move independently and have to be controlled with a program that can easily pre-define a movement for every run. Although drawer slides are robust and can handle heavy loads, they are not appropriate for the Benchmaker because they have limited movement not only in desired direction but also in orthogonal direction. Plus, they cannot easily be adjusted in size and most slides cannot be cut without breaking them.

Drawer Slides

Likewise, skate bearings are not suitable. They have little friction and can transport things with a relatively low need of moving force, but skate bearings need a guiding system which makes them difficult to assemble when compared to other prefabricated rail systems. Skate bearings are not robust in all directions and could jam under extreme weight.

Skate Bearings

There are different kinds of rail systems, linear bearings and profile systems. The round linear systems use a simple

Rail Systems

rod and a linear bearing to smoothen the friction. The profile linear systems are mostly professional build and therefore expensive and not easily accessible.
A linear bearing system was chosen because, compared to a profile rail system, it is less expensive and is not so difficult to find. Moreover, profile rail systems need a special glider and a profile to run properly. A linear bearing system uses a simple rod as a "rail", and these rods are easy to cut and adjust in size.

3.2.2 Second Prototype

The second prototype included the motion system and was created to determine what type of frame and motor could be used. For the frame, wood and aluminum profiles were tested. A linear bearing motion system, with a metal rod on both sides of the threaded rod, was used. Each side had two linear bearings and the wooden platform was connected to the threaded rod using a 3d printed piece. The linear bearings were connected by laser cut pieces of wood which connected them to the platform. The motor was on the outside of the aluminum profile not only for additional space but also to keep the electronics away from any moving parts. Lastly, a hole, no bigger than the threaded rod, was drilled into the aluminum profile. This limited the size of the threaded rod.
The next step was to figure out the best way to connect the motor to the threaded rod. A step motor and a direct current (DC) motor were considered. For this prototype, it was fine to just glue the motor to the threaded rod. To test the motors, a technique similar to Kumar's, was used [K.S Ravi Kumar [2015]]. Kumar used a micro controller, an Analog-to-Digital converter (ADC), a driver circuit, the motor and an appropriate generator. He also configured two keys ("up" and "down") to adjust motor speed.
By allowing the possibility of a solution using a serial port, the Arduino made controlling the motor's speed much easier. Each motor had a different driver circuit. The step motor had a driver with six input PINS from the Arduino–one for each speed and direction, one to enable and disable the motor to prevent electrical flow, and three for special con-

These H-shaped circuit consists of four transistors which protects the microcontroller from current overload and helps control current flow to the motor [Abhishek Khanna [2015]].

figurations. The DC motor, however, could be controlled by an H-bridge*, for example the IC L293D, which incidentally, was used by Kumar. The L293D from Texas Instruments has build in diodes, so it is well suited for DC motors. DC motors create a great voltage peak if turned off. The diodes prevent the integrated transistors from breaking from this voltage peak. One L293D IC is able to control the speed and direction of two DC motors[Instruments [2016]]. Both drivers were inexpensive and could be easily obtained, but for testing purposes, the H-bridge IC was not necessary. Finally, to get the DC motor to operate in both directions, the wires were switched.

Discussion

When compared to DC motors, step motors provide better position control. This can be done by counting steps. It was determined later through consultation with more experienced personal fabrication builders that simply counting steps sent to the motor is not very reliable because some steps might get lost during the transmission of data or during the execution of the motor. Thus, each motor needed a mechanism that could calculate or measure an exact position. One could use a professionally built encoder, but they are expensive. The Benchmaker utilizes two photo sensors and a gear to count steps made by the threaded rod. This eliminates the possibility of losing steps during the transmission process.

Hot glue was found to be insufficient to create a durable bond between motor and rod. Furthermore, it appeared that a DC motor fit the Benchmaker better. When compared to step motors, DC motors are lighter and smaller and can deliver the same amount of force as step motors. Plus, step motors' speed is limited by the size of one step, and the time the controller needs to switch between a high and low current output. This is not the case with DC motors since they will turn as long as the current is flowing, which makes them faster. Finally, with pulse-width modulation, it is also possible to adjust speed at will. Pulse-width modulation allows the possibility to accelerate and brake the motor whenever necessary so as to reduce the risk of

Sources with PWM produce a signal which rapidly changes between supply and ground (GND). By changing the speed the average current flow is controlled. The transmitted power increases by decreasing the time of GND-phases in the signal [Renann G. Baldovino [2013]]

abrasion. Therefore the Benchmaker project uses DC motors.
With photo sensors, it is only possible to make a relative or incremental encoder. This means that the position is lost if the machine is turned off. This problem can be remedied by doing a calibration run at each start of the test bench. This is also useful in checking to see if everything is in working order. This relative encoder with photo sensors consisted of two different parts. One is a circuit that connected the photo sensors to the Arduino; the other is a perforated disc that turned at the same speed as the motor. In this project, forked photo sensors were used. The circuit was connected to the Arduino using wires–one for each output of the sensor and the other two for the power supply. A step was regarded as a change in the photo sensors' status. To properly implement and test the code, a perforated disc was needed. The perforated disc's teeth had to activate both sensors simultaneously as well as to prevent both sensors' activation. The gap and the teeth can be the same size and should be the size of the combined length of the sensors. The sensors' size limited the accuracy of the position control, so they were positioned side by side to reduce their combined length. Using two photo sensors result in four possible states which have to be coded (Let PS1 and PS2 be the two photo sensors and PS1 is on the left). A sensor was interrupted if one tooth of the disk was between the fork and blocked the light; otherwise it was open. The states were as follows:

1. $PS1$ and $PS2$ interrupted
2. $PS1$ open and $PS2$ interrupted
3. $PS1$ and $PS2$ open
4. $PS1$ interrupted and $PS2$ open

These states occurred in the order 1-2-3-4-1-2, and so on, if the motor was turning left or 4-3-2-1-4-3, and so on, if the motor was turning right.

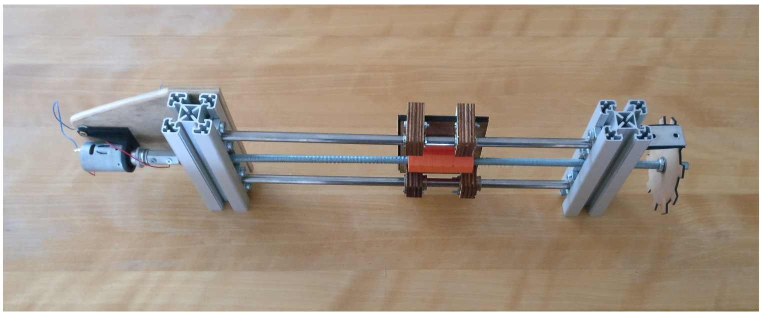

Figure 3.2: First Hardware Attempt of an Axis

3.2.3 Third Prototype

The DC motor was connected to the threaded rod using a conical piece and a nut. To keep the motor from loosening the nut, a hole was drilled through the nut and into the rod. A screw was used to fix the connection. A wooden plate was used to connect the motor to the aluminum profile. The two metal rods and the platform were put together as shown in figure 3.2. For the position control, the disc was connected to the rod using two nuts to keep it in place, and the circuits were glued in the corner of the axis. This setup was tested by connecting the motor and photo sensors to the Arduino. A program had to be written to test them both together and separately.

Discussion

The axis was robust, and excessive force, on the edges as well as on the rods, appeared to have no impact. The first test showed that if a weight is connected to the platform, the rods will bend and that if the platform happens to be at an end position, the motor might not run smoothly or will stop altogether. This was especially the case if the platform was not balanced. Therefore, the aluminum profiles were connected to each other using another aluminum profile in order to restrict movement and to support the structure. Additionally, the threaded rod could not bear any weigh;

otherwise, it did not turn freely, and the motor stopped. The next prototype will include two bearings, one on each aluminum profile, in order to keep the threaded rod balanced and to reduce friction. The motor, however, still seemed to be a little bit too weak and too fast, so for axes that had to move weight, a motor with a transmission was used. This added enough torque to move heavy weight.
To test the photo sensors, a program was written that counted and displayed steps using the serial port of the Arduino. Since two photo sensors were used, direction was taken into account by increasing or decreasing the step counter. The step counter failed after connecting the motor at maximum speed, and when tested at a lower speed, the photo sensors were prone to make errors because of different light conditions. This will be corrected in the next prototype by using a box to block foreign light. Furthermore, many steps were lost due to the Arduino's inability to handle fast inputs of new information from the sensors. This problem will be solved too in the next prototype by writing better code; swapping out hardware; or using a faster logic chip.

Fixed Position Control

The first attempt at improving the position control was done by increasing the clock speed, so Texas Instruments Launchpad was used instead of the Arduino. It was easy to program due to its use of a similar api. Although the Texas Instruments Launchpad correctly detected more steps than the Arduino, it still missed a few.
The next approach was to clean up the code. After consulting more experienced members of the lab, it became clear that interrupts should be used to detect steps. Arduino IDE has an interrupt library, and a few interrupt pins which are faster at detecting. Arduino IDE prevents steps from being lost while operations are being done. If the logic unit is busy, interrupts are queued. Furthermore, interrupts do not block calculating resources because the main loop does not need to constantly check the state of the sensors. Though the Texas Instruments Launchpad can achieve the

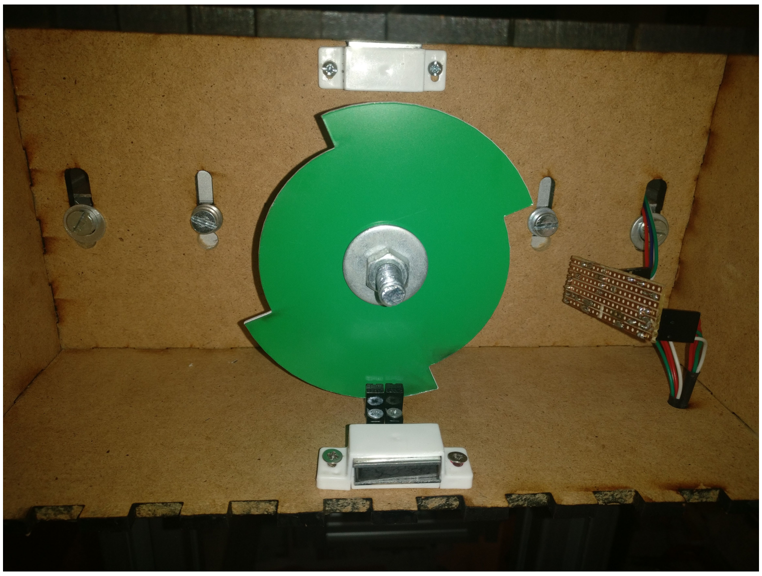

Figure 3.3: A two toothed disc is sufficient for the Benchmaker project. Magnets on two sides of the box are helping to open the box.

same if not better performance, the Arduino IDE is preferred since it is well known and is probably found in most labs. To prevent interrupts from blocking the logic unit, which would in turn prevent the main loop from executing, the amount of interrupts had to be reduced. This was done by modifying the disc. Because the disc had too few teeth and a large diameter, the photo sensors were slow to react, so there was a decrease in the position control's precision. The new disc has two teeth which results in four steps every 360 degrees. The resulting error can be calculated by $\frac{\text{gradient of thread}}{\text{steps per cycle}}$. In this project, the maximum error of 0.3125 mm $\frac{1.25mm}{4} = 0.3125\ mm$ is acceptable. The position control is shown in 3.3.

3.2.4 Final Hardware Prototype

The final hardware prototype included a box that had elliptic holes for height adjustment, the photo sensors, and for easy installation of the position control, which was now

connected to the axis. The box also blocked foreign light. A bearing was attached at the top and bottom ends of the threaded rod—one placed in a hole on the side near the motor, and the other one attached to the box. At each end of the axis, a button was installed denoting the beginning and ending of the axis.
The motor was exchanged for a stronger one with a 2.5:1 transmission, and this should help the system run smoother and deliver enough power. The new motor was connected to the threaded rod differently (setscrews, two nuts, and a longnut). See figure 3.4. The nuts had to be tight in order to lock movement in both directions. The motor driver IC L293D is changed to a stronger one,because it can only handle one ampere of current output [Instruments [2016]]. The L6203 has a peak of five ampere which is enough for this project. Additionally the L6505 MOSFET is suggested for the motor controller [STMicroelectronics [2016]].
The 3d printed part and the platform were switched to enable the threaded rod to move freely. A slot in the wooden platform was added, and the 3d printed part was modified to fit into it. See figure 3.5. The platform's entire weight rests on the bearing holder, and the printed part just pushes or tows the platform with the slot's aid. Additionally, the platform's screws were loosened. They should connect the parts to move in a horizontal direction but should allow free movement in a vertical direction.

Discussion

The third and final prototype solved most hardware issues. The position control worked perfectly, and with the two end stops, it was possible to get exact position feedback in relation to them. The box blocked all foreign light, and there were no changes in the photo sensors' perception.
The stronger motor with a transmission helped the axis to run slower but more powerful. The movement was smoother, and the motor did not fail so easily. The slot in the platform supported this, and if heavy weight were put on the axis, the motor would run just fine.

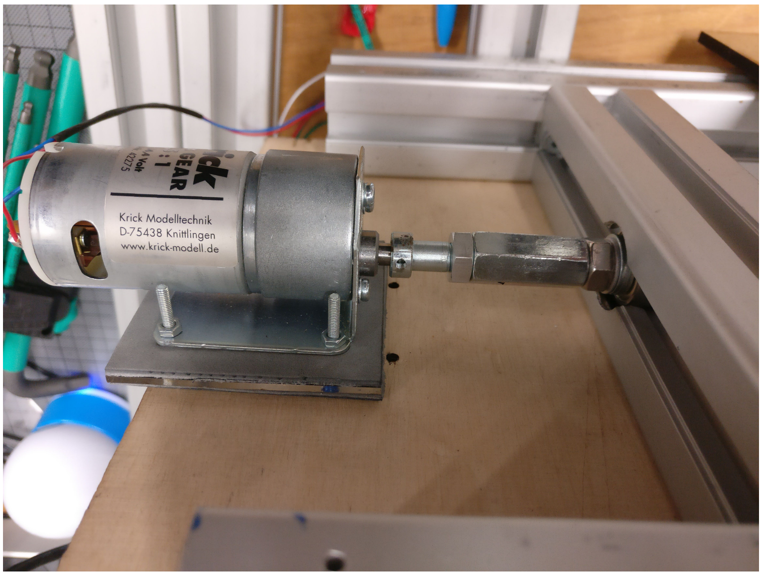

Figure 3.4: Connection of the Motor to the threaded rod

Figure 3.5: The extra material on top of the part will push the wooden platform in the wished direction

Chapter 4

Building Instructions

4.1 Instructions

The following chapter explains how to build *one* ready to use axis. If more than one axis is needed it has to be repeated. The final assembly of different axes rely mostly on the purpose. One example of a finished project is explained in 4.2 “Example”.

Material

The necessary files for this Instructions can be found on GitHub. The list of materials is as following.

Here you find all Files for Laser Cutting and 3d printing[a]

[a]https://github.com/srieseb/Benchmaker/tree/masterfolder/DesignFiles

1. 2 18 cm and 2 60cm aluminum profiles
2. 4 M8 Nut
3. 2 M8 Longnut
4. 2 M8 wide washers
5. 2 M2.5x8 screws (Motor attachment)

6. 9 M3x25 screws
7. 4 M3x8 wood screws
8. 13 M3 Nuts
9. 9 M3 Washers
10. 6 M6x30 screws
11. 6 M6x16 screws
12. 20 M6 slot nuts
13. 2 Metal rods
14. 1 Threaded rod
15. 3 Linear bearing (14 cm outer diameter)
16. 2 Bearing (21 cm diameter)
17. 8 Metal aluminum profile connector plates (following called ”Metal Holder”)
18. Motor (Krick MAX GEAR 2.5:1, 12V)
19. Motor bracket (Matching to motor)
20. Motor adapter (Matching to fit M8)
21. 2 Forked photo sensors
22. 2 Buttons with big lever
23. 2 220 Ω resistor
24. 2 10k Ω resistor
25. 3 different colored wire
26. shrinking tube
27. circuit board
28. glue
29. wooden glue
30. magnets
31. 5 mm MDF board

Printing

Machines: 3D printer
Material: one M8 long nut
Files: thread.stl

1. print file
2. insert long nut into printed part

See figure 3.5

Linear Bearing holder

Machines: Laser Cutter
Material: 5 mm MDF board, three linear bearings, nine M3x25 screws with nuts and washers
Files: platform.dxf, bearingholder.dxf

1. use files to cut MDF board (cut bearingholder.dxf 12 times)
2. insert linear bearings into 4 bearingholder parts each
3. fix bearingholders with the screws

See figure 4.1 for an example.

Prepare the Aluminum Profiles

Machines: Drill
Material: two 18 cm aluminum profiles, four metal holders, 8 slot nuts with matching screws, metal rod
Files: -

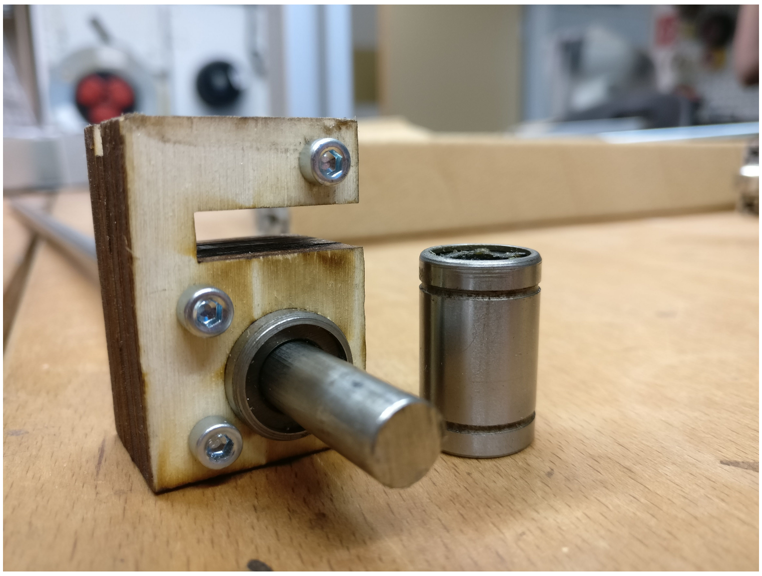

Figure 4.1: An example assembly of the bearing holder with attached linear bearing.

1. Drill an 8mm hole in the center of each aluminum profile.

2. If possible: drill a big slot for the bearing (not all the way through the aluminum profile) alternative solution: file bearing.dxf offers a way to mount the bearing to the aluminum profile without drilling

3. Widen the middle hole of metal holders to fit on the metal rod

4. Attach a metal holder to each end of the aluminum profile using a screw and a nut in the top and bottom holes of each metal holder. Do this for all metal holders. Make sure the holes align perfectly. The metal holder have to be on the opposite site as the bearing hole.

See figure 4.2 for a visual representation of the metal holders. See figure 4.3 for the bearing hole.

Figure 4.2: Aluminum profile with attached metal holders.

Alternative bearing attachment

Machines: Laser Cutter
Material: 5 mm MDF board, bearing, aluminum profile, two slot nuts with matching screws
Files: slotbearing.dxf

1. use file to cut MDF
2. insert bearing
3. fix and position part on the profile. The slots enable different positions. Be careful to lift the threaded rod to a centered position in the hole.

See figure 4.4

Figure 4.3: Centred hole widened to fit a bearing

Assembly of the core Axis

Machines: -
Material: M8 threaded rod, two metal rods, bearing, prepared aluminum profiles, printed part, laser cut parts from 4.1 “Printing”
Files: -

1. Insert bearing in aluminum profile

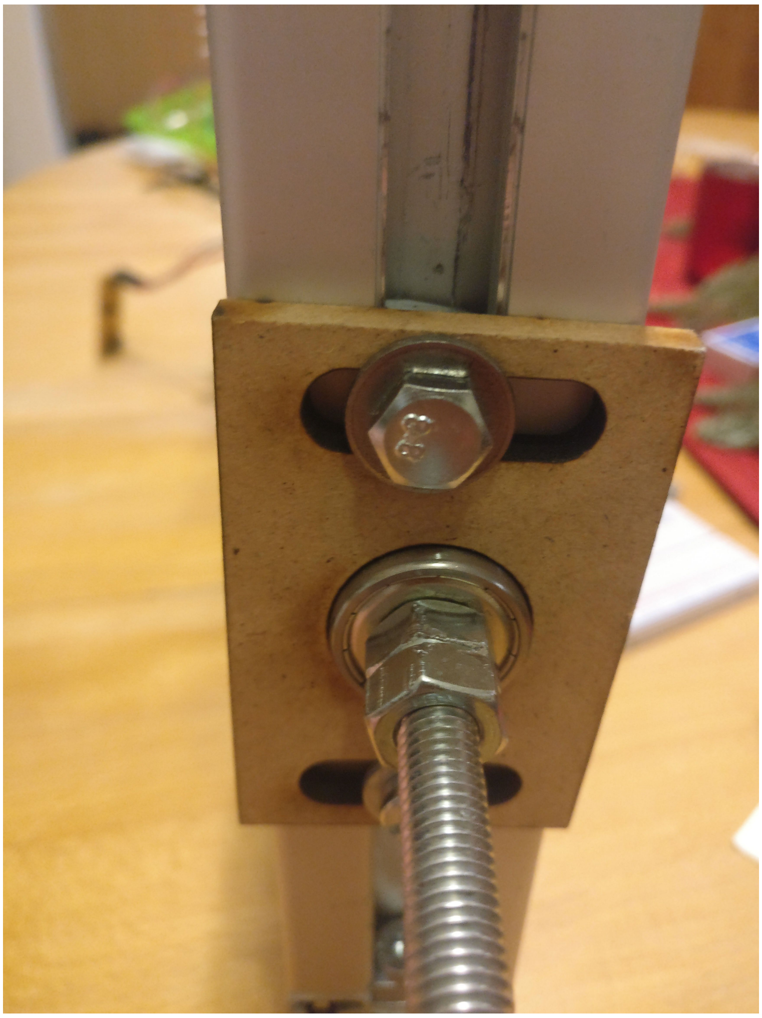

Figure 4.4: Attachment of a bearing on the rod.

2. Slide threaded rod through one bearing and one profile
3. Screw printed part on the rod (not facing the bearing)
4. Slide threaded rod through second profile. The metal holders should now face each other
5. put bearingholders on the metal rods. Two on one rod and the other one on the other rod.
6. Insert metal rods in the metal holder.

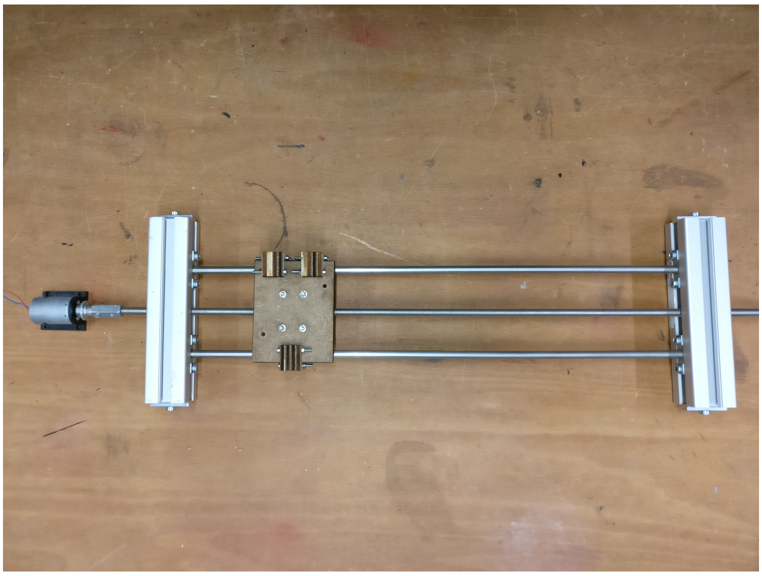

Figure 4.5: Previous version of axis assembly. The platform has no slot and the motor is smaller.

7. Place platform into the slots of bearingholders and printed part

See 4.5 or a view of the axis without the new designed platform.

Frame

Machines: -
Material: previous assembled part, 60 cm aluminum profiles, four metal holders, four M6x30 screws, eight slot nuts with screws
Files: -

1. Attach metal holder to each end of short aluminum profile using middle hole and the M6x30 screws
2. Attach long profiles to the shorter ones using the slot nuts

Motor preparation

Machines: -
Material: Motor, Motor bracket, motor adapter, long nut, two M8 nuts, two M2.5x8 screws
Files: -

1. Attach motor bracket to the motor with the M2.5 screws
2. Attach motor adapter to motor
3. Screw one M8 nut and long nut on threaded rod (half of long nut should be filled by threaded rod)
4. Screw the other M8 nut on the adapter
5. connect motor adapter to the threaded rod by screwing it on the threaded rod
6. tighten all nuts to each other to fix the position
7. see figure 3.4 in the beginning of this paper for a overview

Prepare Electronics

Machines: soldering iron
Material: two photo sensors [VISHAY [2017]], two buttons, shrinking tube, wires (pref. 3 different colors: red, white, green)
Files: -

1. Attach wires to the PINs of photo sensor (red to ″+″, green to ″D″, white to ″E″)
2. Every connections is secured with a shrinking tube
3. Group all wires with a shrinking tube
4. Repeat steps for the buttons (choose green as the ″data″ wire)

Box for Position Control

Machines: Laser Cutter
Material: 5 mm MDF board, wood glue, glue, magnets
Files: case.svg, 4holesbearing.dxf

1. use files to cut MDF board
2. insert photo sensors in one case plate
3. glue magnets on one end of the photo sensor and on one end of the elliptic holes board. Glue the matching magnets to the other two large boards of the box (same size as this plates but without holes)
4. glue photo sensor board to the board with elliptic holes (elliptic holes should be closer to the photo sensor side)
5. glue the two small sides of the box to the previous glued part

See figure 4.6 for the bearing attachment.

Position Control

Machines: -
Material: glued box, laser cut holesbearing, assembled aluminum part, bearing, four M6x16 screws, two M6x30 screws, four wood screws M3x8, two M8 nuts, 2 big washer, laser cut disc
Files: -

1. Insert slot nuts in the short profile which is not connected to the motor.
2. Attach box to the profile with the M6x16 screws and slot nuts.

Figure 4.6: Material for attaching a bearing to the box.

3. Drill M6x30 screws into each end of the longer aluminum profiles to give the box more stability.
4. Assemble bearing and the cut part
5. Attach bearing to the box with the wood screws. Be careful to lift the threaded rod with the bearing until it is centered and runs smoothly.
6. Add one nut and one washer to the threaded rod
7. slide disc on the threaded rod
8. fix disc with nut and second washer. The disc should be fixed in a position it activates the photo sensors.

Figure 3.3 shows the attached box.

Circuit Soldering

Machines: soldering iron
Material: two 220 Ω resistors, two 10k Ω resistors, PINs

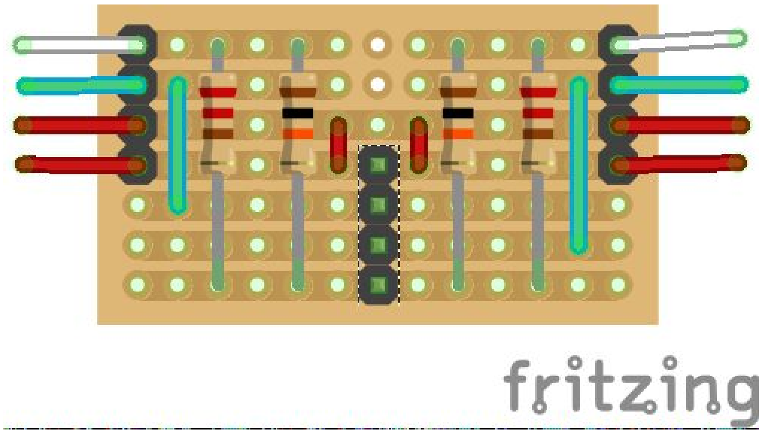

Figure 4.7: Schematics of photo sensor circuit [fritzing]

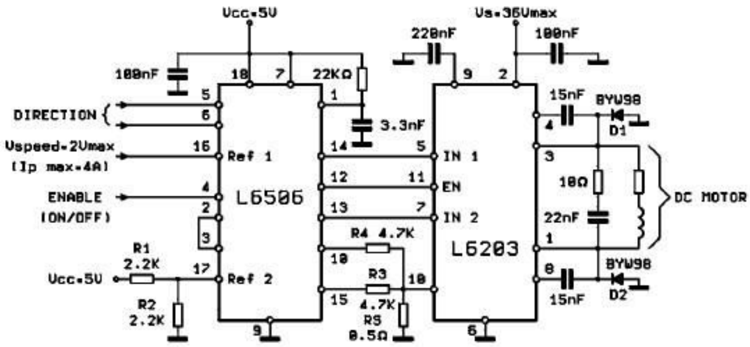

Figure 4.8: Motor Controller [STMicroelectronics [2016]]

Files: -

1. Solder a circuit as presented in 4.7
2. Solder a circuit as presented in 4.8

Wire connection

Machines: -
Material: circuits, wires

Files:

1. Place photo sensor circuit inside the box
2. connect wires of photo sensor to circuit
3. connect Arduino and circuit with wires. The wires should go outside of the box
4. place the motor controller circuit in the near of motor
5. connect all wires to the circuit and connect it to the Arduino

Attach endstops

Machines: Laser Cutter
Material: buttons, two slot nuts, two matching screws, 5 mm MDF board
Files: button.dxf

1. Use file to cut MDF board
2. Attach buttons to cut part (use glue or screws)
3. place buttons on the long aluminum profiles with the slot nuts ans screws. This buttons mark the start and end of the axis. Be careful that the platform hits the button at the right time.

Connecting Axis

Machines: Laser cutter
Material: four M6x16 screws + slot nuts, four M3x25 screws, 5mm MDF board, two axes which should be connected
Files: wideaxis.dxf or longaxis.dxf

1. Use file to cut MDF board
2. Connect cut file to the carrying axis by using the M3 screws
3. Connect axes with the slot nuts and M6 screws in the aluminum profile

4.2 Example

This section provides an example of three connecting axes. This is an attempt to determine if the Benchmaker is an adequate solution for a large test bench.

4.2.1 Construction

First, two 60 cm long axes were built. These axes formed the x and z axes and were held in place by an aluminum frame. The z axis was at a 90° angle to the x axis which allowed more space for movement. To show two possibilities the y axis is mounted on the z axis in a different way. Since the probe tip did not have to travel much in the y direction, the axis was smaller. The position control for the y axis was redesigned so that the probe tip had a better fit. The position control and motor were on the same side of the box. See Figure 4.9.
The Arduino was placed on top of the motor plate of the x axis. This was the best place to put it because the wires did not restrict movement. Wires were grouped by function and the slots in the aluminum profiles made for easy hiding and protection. See Figure 4.10 for assembled machine.
The size of the machine led to increased weight which required extra metal rods and bearings to evenly distribute that weight so that the axes did not tilt and impair motor function.

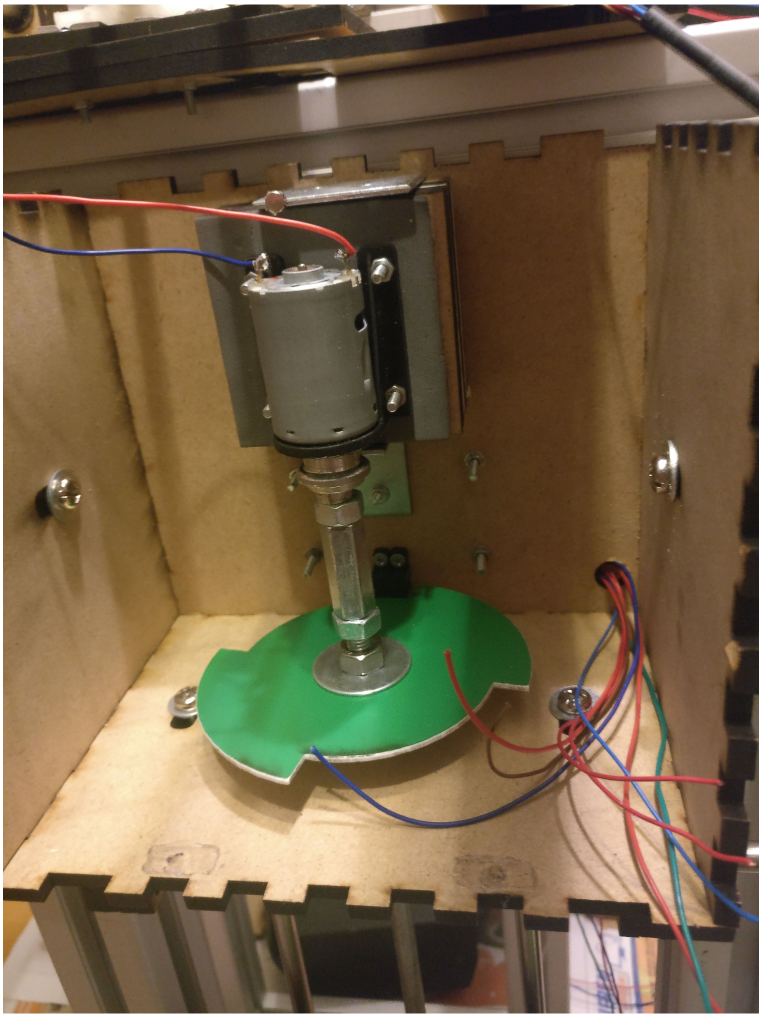

Figure 4.9: Motor and position control setting for y axis of example

4.2.2 Things to improve

It was not possible to move all axes simultaneously with the same program and with the same microcontroller. This software development remains for future work. However, each axis performed fine individually. Even at extreme positions, the motor suffered no problems in operation. Furthermore, the motor could move the heaviest axis at a low speed. All hardware tests met expectations but failed when

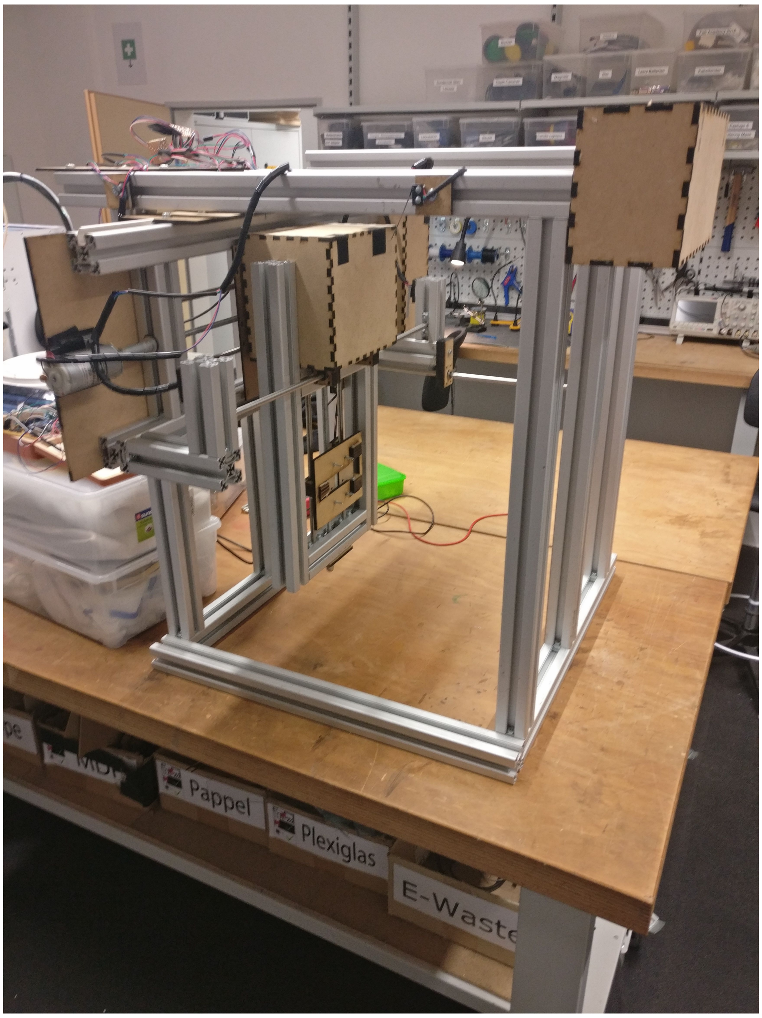

Figure 4.10: Assembled example machine

used in conjunction with software. This thesis offers basic programs to test all functions of one axis. The included programs and the design of the electronics build a good basis for future software engineering and individual test bench design.

Chapter 5

Evaluation

5.1

This section discusses whether and to what degree the requirements from 3.1 “Requirements” are met.

5.1.1 Modularity and Scaleability

Aluminum profiles, metal and threaded rods are available in a wide range of sizes and can be easily cut into different lengths. DC motors can be found in different strengths and pose no problem when upscaling a project. Large projects, however, will most likely require a DC motor with a transmission for smooth operation. Tests showed that there are some limits in terms of size.Therefore while first testing to build a test bench it is recommended to approximate the slack of each axis. Axes with a longer slack than 50 cm should use additional metal rods to cancel weight related problems. This value needs to be adjusted when we have additional data from construction test benches.

5.1.2 Durability and Aesthetics

The use of aluminum profiles led to a robust machine and after adding the frame, the axis became more resistant. Moreover, the rods provide protection too, and it is unlikely that the aluminum profiles will break from external forces. Additionally, the threaded rod cannot bear any weight; otherwise, it will not turn freely, and the motor will stop. Thus, bearings were installed which keeps the threaded rod balanced and reduces friction.

5.1.3 Position Feedback

After adjusting the disc, the Benchmaker gives reliable position information, but this information is lost if the system is shut down. However, at each end of the axis, a button was installed denoting the beginning and ending of the axis, and every other position can be restored in relation to these points. Position feedback is based on real life events and not digital function calls.

5.1.4 Stressful and Fast Movement

The DC motor with transmission provides fast movement of each axis. The machine vibrates and is noisy when operating at top speed but, nevertheless, runs smoothly. PWM allows individual adjustment of speed, but the motor gets weaker if the PWM value is decreased. Finally, the potential speed and strength of the 2.5:1 transmission in this project should be sufficient for most projects. If the project demands more power, the motor has to be exchanged. In this case a powerful motor with additional transmission system is needed.

5.1.5 Open-source/ Do-It-Yourself project

The Benchmaker is an open source, user-friendly project, and every component is assessible. The Arduino is a well-known, affordable microcontroller that offers a vast library with much information and many tutorials. 3D printers and laser cutters are also not difficult to find nor too expensive.

Chapter 6

Summary and future work

In the previous chapters the idea and the development process of the Benchmaker project as an easy-to-use test bench and machine building system were presented. At last, this chapter will give a summary of the most important aspects and possible insights into the next steps in future.

6.1 Summary and contributions

In this work, an open-source, modular, user-friendly test bench was created. Previous projects from Fab Lab Aachen and the maker community were analyzed to determine needs. Nadya Peek's Cardboard Construction Kit was a good basis to start development. After analyzing Peek's kit, it became clear that deficiencies were present and a basis hardware setup has to be developed. With several prototyping and analyzing stages a convincing hardware solution was found and will now deal as a starting point for further research. This thesis contribution to the community is a first approach on a robust and modular test bench and machine building system which offers several advantages in durability, speed, strength and position control.

6.2 Future work

During this project, a number of issues arose that required adjustments to prototypes so that a functional machine could be built. Going forward, additional research should be done in the areas below to further improve the Benchmaker so that it will truly be a first-class test bench.

6.2.1 Weight

Previous failures led to concern about durability. Prototypes showed that heavy material caused stress on the threaded rod and in turn caused the motor to malfunction. As a result, additional linear bearings were added as well as extra rods to strengthen the design. This raises the issue that if the machine is too large, the weight of the material will no doubt cause problems. Research could be done to see if there is other material that might be more suitable for these large projects.

6.2.2 Transmission

During this project, a number of issues arose that required adjustments to prototypes so that a functional machine could be built. Going forward, additional research should be done in the areas below to further improve the Benchmaker so that it will be truly a first-class test bench.

6.2.3 Software

The included programs are not designed to build a fully functioning machine but instead to test if hardware parts are operating as intended. Future research should look into software that can not only test hardware parts but also run the entire machine. Other important software issues include a better interrupt service routine and a fast but reliable calibration run for all axes. A modular software development environment which enables a modular programming of the Benchmaker would ensure a truly user friendly test bench.

6.2.4 Position Control

The position control is precise, but at full speed, the motor tends to turn too much. Future research should look into whether or not a braking system with a dynamic adjustment of motor speed can prevent this overshooting. Furthermore, it might be possible to reduce the position control's size.

Appendix A

Additional Pictureset

Not all pictures fit in the thesis itself, but might be helpful to rebuild and understand the whole process of the instructions better. This appendix is a collection of project related pictures with a short description.
The example assembly offered a nice opportunity to see the Benchmaker project at work. Here is a link to a short example video. The axis are moving in a fast but smooth manner. Additionally it is good to see how the the button as an endstop stops the movement.

Video of Example[a]

[a] https://github.com/srieseb/Benchmaker/tree/masterfolder/video

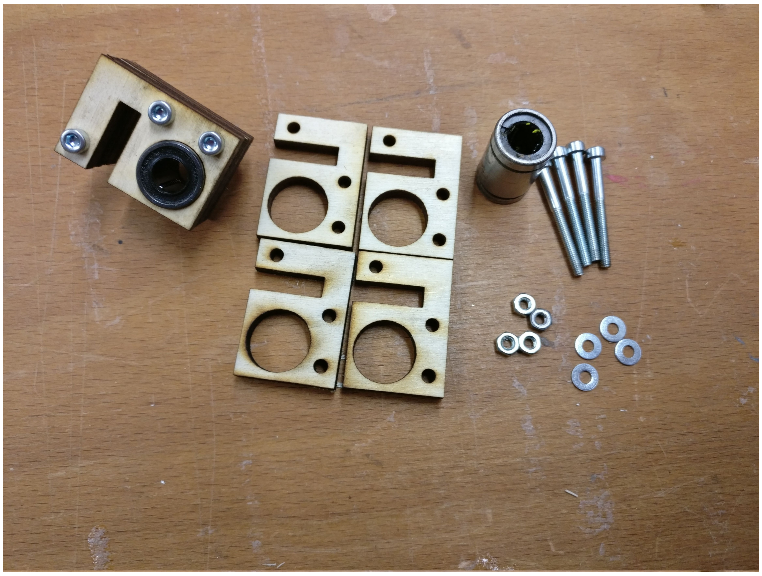

Figure A.1: Parts to build a linear bearing holder

Figure A.2: Linear bearing holder for the support structure in 4.2 "Example"

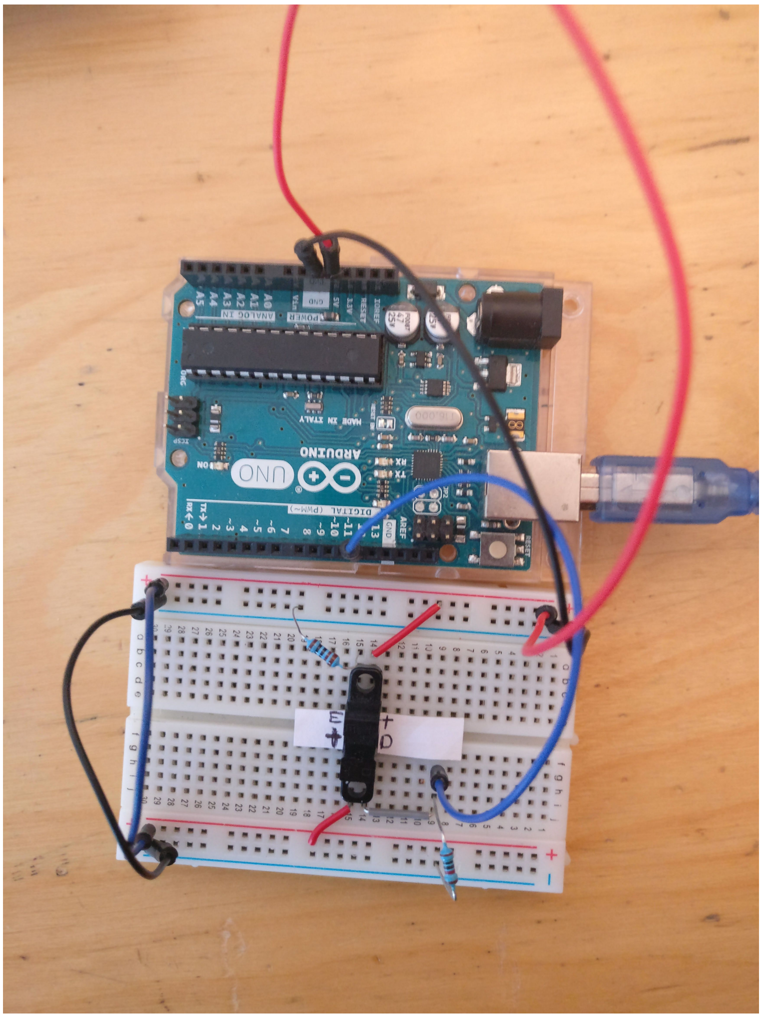

Figure A.3: Test assembly for photosensor with Arduino

Figure A.4: Smallaxis withouth threaded rod, but attached bearing and bearingholder for platform.

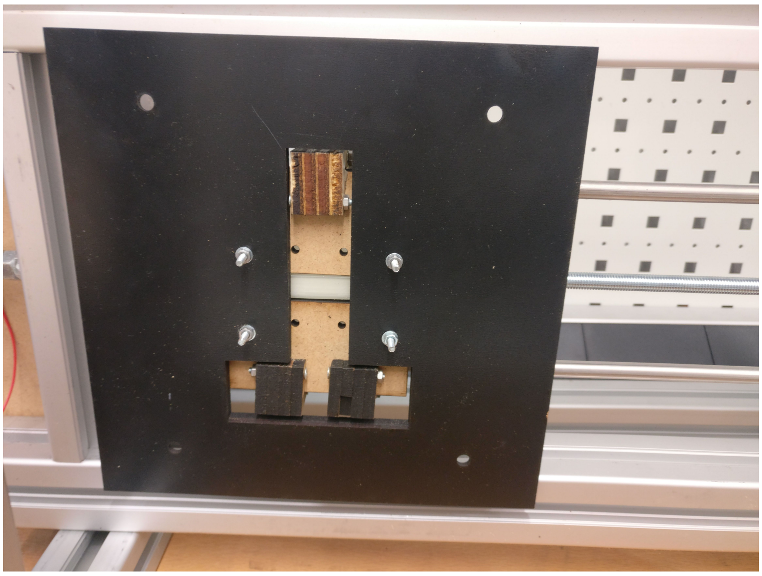

Figure A.5: Piece to easily connect two axis

Figure A.6: Piece to easily connect two axis (saves space, but less robust due to less connecting points)

Figure A.7: Example for drilling a slot for the bearing into the aluminum profile

Appendix B

Arduino Programs

Here you find all Files for Arduino Programming[a]

[a] https://github.com/srieseb/Benchmaker/tree/masterfolder/programs

B.1 DualMotor

This little script controls two different DC motors using one H-bridge IC. Both motors will increase speed in steps of 5 in 20 millisecond intervals. Both rotation directions are displayed. This test helps to check whether the motor speed is suitable and the motor works fine with the H-bridge.

B.2 Motortest

Similiar test as DualMotor. This tie only one motor is tested, this helps to check every axis and circuit after the assembly idividually.

B.3 SerialMotorControl

This script enables to freely adjust speed and direction of a DC motor connected with an H-bridge to the Arduino. Values between -255 and 255 can be entered through the serial console. The rotation direction changes with positive/negative integers. The suggestet minimum speed is in both directions 50.

B.4 testPhotosensors

This script displays the state of each photo sensor on the serial console. It is perfect to check if the wires are properly connected to both photo sensors and if the photo sensors are working properly. It also helps to search potential errors in an assembled machine. If the disc does not slide thorugh the sensors properly this script can help to detect it.

B.5 testphotocounter

This script counts steps in the main loop and will display the amount every once in a while on the serial console. This method was used to determine how fast the motor is allowed to turn without missing steps. Interruptphoto offers a interrupt based solution which can detect steps much faster and more reliable. Nevertheless this script might help in a few developing situations and is therefore still subject of this thesis.

B.6 Interruptphoto

Interruptphoto is a position control solution, which relies on hardware interrupts. This script counts and displays steps for every state change in the photo sensors. This script does not differentiate between directions, but is a good way to check if the connections and interrupts are working properly.

B.7 Motor_photo

After testing both, photo sensors and DC motors, this script can be used to test both functions at once. It lets the user decide the speed of the motor and then displays the amount of steps taken.

Bibliography

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