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TALLINN UNIVERSITY OF TECHNOLOGY

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Rulluisu laagrite pesumasin

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Department of Mechatronics

Chair of Mechanosystem components

MHE70LT

Lauri Leemet

Roller skate bearings cleaning machine

Master's Thesis

The author applies for

the academic degree

Master of Science in Engineering

Tallinn

2016

AUTHOR'S DECLARATION

I declare that I have written this graduation thesis independently. These materials have not been submitted for any academic degree. All the works of other authors used in this thesis have been referenced.

The thesis was completed under PhD Alina Sivitski supervision

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Author

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The thesis complies with the requirements for graduation theses.

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Supervisor

.... signature

Accepted for defence.

.... chairman of the defence committee´

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.... signature

TUT Department of Mechatronics
Chair of Mechanosystem components

MASTER'S THESIS TASK

Year 2016 Springsemester

Student: Lauri Leemet 143763MAHM (name, student code)

Study programme:MAHM-MechatronicsMAHM02/13

Spetsiality: Mechatronics

Supervisor: PhD, Teaching Assistant Alina Sivitski (position, name)

Consultants: ……………………………………….(name, position, phone)

MASTER'S THESIS TOPIC:

(in English)Roller skate bearings cleaning machine

(in Estonian) Rulluisu laagrite pesumasin

Assignments to be completed and the schedule for their completion:

Nr	Description ofthe assignment	Completion date
1.	Overview of the roller skate bearing cleaning devices available in the market.Formulating requirements to the roller skate bearing cleaning machine. Making first concept.Definition of technical parameters of roller skate bearing cleaning machine being designed.	**01.02.2016**
2.	Construction modeling and strength calculations. Selection of mechanics components and materials.Construction optimization. Choosing of the motor, power supply, sensors and control systems.	**01.03.2016**
3.	Technical drawings. Cost calculation of developed construction.	**30.04.2016**
4.	Printing and binding of Master's thesis.	**15.05.2016**

Engineering and economic problems to be solved: In this Master's thesis the roller skate bearing cleaning device should be developed. The automated roller skate bearing cleaner should cut the time of roller skate bearing maintenance and to make the process of cleaning much easier.
Project cost calculations should be done.

Additional comments and requirements:…………………………….........................

Language of the thesis: English

Deadline for submission of the application for defence 16.05.2016

Deadline for submitting thetheses16.05.2016

StudentLauri Leemet/signature/ ……….............date 09.02.2016

Supervisor Alina Sivitski /signature/ ………............... date 09.02.2016

Confidentiality requirements and other corporate terms and conditions shall be set out on the reverse side.

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EESSÕNA

Magistritöö teema on valitud koostöös ettevõttega HOOG SISSE OÜ. Magistritöö on kirjutatud TTÜ Robotiklubis. Ettevõttepoolsete konsultatsioonide ja lähteandmetega aitas Olle Kitsing, HOOG SISSE OÜ asutaja. Magistritöö on kirjutatud PhD Alina Sivitski juhendamisel. Magistritöö autor tänab Olle Kitsingut ja Alina Sivitskit.

FOREWORD

The topic of master's thesis was selected on a company HOOG SISSE OÜ initiative. The thesis was written in TTÜ Robotiklubi. With data and consultations helped Olle Kitsing, HOOG SISSE OÜ cofounder. The thesis was written under supervision of PhD Alina Sivitski. The author of the thesis wishes to thank Olle Kitsing and Alina Sivitski.

1 INTRODUCTION

The topic of master's thesis was defined by a company specialized in maintenance of roller skates [1]. The company is interested in speeding up maintenance work and improving work conditions by decreasing employee contact time with toxic fluids. The aim of roller skate bearings cleaning machine is to wash and dry one set of roller skate bearings in one washing cycle.

Current manual workflow is built up as follows:

1. Skates are brought into maintenance by user.
2. The skates are disassembled, bearings extracted from the wheels.
3. The dust caps of the bearings are removed.
4. Bearings are soaked in the solvent number 1.
5. The container of fluid is closed and shake for 10 seconds.
6. Bearings are drained from solvent number 1.
7. Steps number 4 to 6 are repeated with solvents number 2 and 3.
8. Bearings are dried with compressed air.
9. Bearings are greased.
10. Dust caps are reinstalled.
11. Skate wheels are put in the order by the diameter.
12. Skates are assembled and returned to the owner.

Preferred solution should include all washing and drying steps (steps 4 - 8). As solvents are highly flammable and toxic, there are special safety requirements for the machine that have to be taken into consideration. Machine has to be sealed correctly to avoid any toxic vapours in the working environment. Toxic vapours can be harmful if inhaled. [2]

Standards ISO 11014:2009 [3] and ISO/TS 15029-2:2012 [4] include some safety information about flammable and toxic chemical products. These standards should be considered while producing a machine that works with flammable liquids.

There are several solutions available to wash roller skate bearings, but commercially available products are unable to cover the needs and requirements of HOOG SISSE OÜ. Most of products for roller skate bearing cleaning are for private use and consist of bottle of liquid with bearings holder [5]. The bottle is intended to be used for single pair of roller skates and then disposed (Figure 1.1).

Figure 1.1. Bones® Bearings Cleaning Unit [6]

The company that ordered bearings washing machine had its clear vision how to clean roller skate bearings and how to use smallest amount of cleaning liquid in the process.

In collaboration with the company machine definition and technical requirements were composed as follows:

- Flammable solvents are used: brushed motors and hot surfaces are prohibited.
- The maximum area on the table for the machine is 500 mm wide and 500 mm deep.
- Mains voltage 230V AC is used.
- Standard compressed air fittings and 40 mm vacuum cleaner fitting.
- The bearings have to be attached to a removable holder- holders can be replaced.
- Machine has inspection window to observe the process.
- Machine has semi- automatic solvent replacement system.

Current thesis describes the development of the roller skate bearings cleaning machine and gives an overview of the problems raised and solutions found during the development process of the machine.

There are four main chapters in the thesis:

1. Mechanics chapter describes the 3D model of the machine and explains different mechanical design solutions used. This chapter includes choosing drive mechanism and strength calculations.
2. Electronics chapter describes the principles of motor selection. The chapter also includes calculations and comparison of different types of motors. The comparison of motor drivers is done and PCB (Printed Circuit Board) is designed for machine control box.
3. The chapter of programming consists of driver software written for the machine and software design choices made in the project.
4. Future modifications are discussed in the fourth part of the thesis.

The roller skate bearings washing machine was constructed from readily available and affordable components. An Atmel 8-bit microcontroller was used [7] and mounted on the PCB with Pisi-XBee 4 [8] board which enabled the use of SMD (surface mount devices) on a CNC milled PCB.

3D models and technical drawings were made in SolidWorks [9] program. Schematics and PCB were designed in the Altium Designer [10] software. The programming language C and Atmel Studio [11] software were used to write the program for the machine. The program was uploaded to the microcontroller over USB interface.

Safety requirements for the machine were introduced to the company. Small amount of testing was done in the prototyping phase during the time thesis was compiled. The prototype is not finalized in the thesis and extensive testing is conducted in the future if the prototype fits the company's needs as expected.

Large amount of work was done in TTÜ Robotiklubi [12], where 3D printer and other tools were used to complete this machine. The PCB was made in Mektory [13].

2 MECHANICS

2.1 Model

A 3D assembly of the machine was designed in the SolidWorks [9] program. The assembly contains all produced parts of the machine. Most of the electronics and mechanical parts are included on the model. Wiring and some fasteners are missing due to complexity of designing and mostly redesigning the parts that were changed during prototyping process. (Figure 2.1)

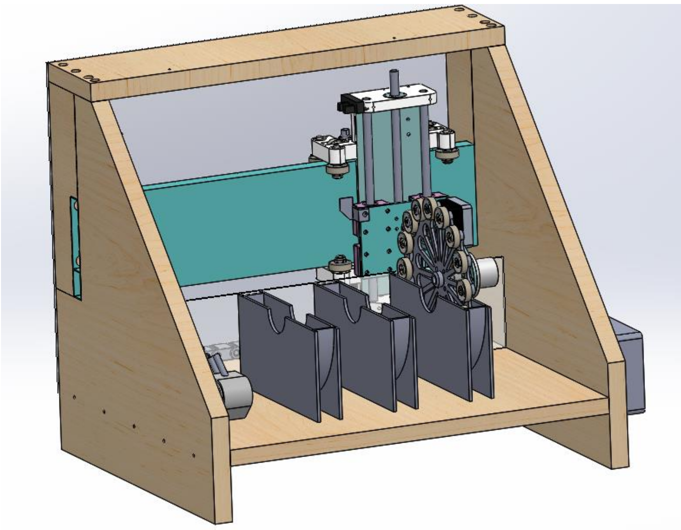

Figure 2.1. 3D model

2.1.1 Enclosure

The model of the enclosure was constructed and most of drawings were done by the time the machine frame was assembled. The purpose of the frame is to make a sturdy fixture for the X-axis beam and enclose everything in there. The enclosure has a cover which is connected to the bottom frame with hinges and has a window to see the progress of the washing process in the machine. (Figure 2.2)

Figure 2.2. Enclosure

The enclosure is made from MDF (medium density fibreboard) which is easy to machine and clean. The choice of material was made considering the fact that modifications could be easily made during the prototyping phase. After the prototyping phase the material of the enclosure will be changed due to the high safety requirements for the machine.

2.1.2 Z-axis assembly

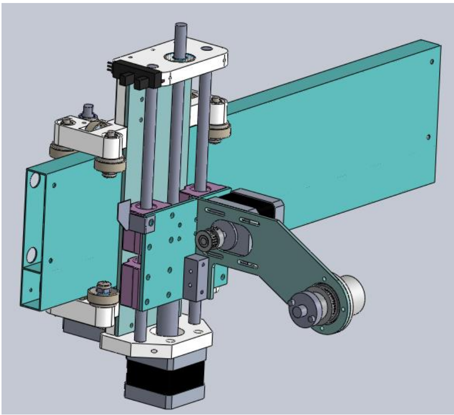

Figure 2.3. Z-axis assembly

The assembly of Z-axis linear rails and X- axis rollers with motors is the most complicated part of the machine. Several revisions of 3D models for Z-axis assembly were made to fit all components in the small space. Final solution of the Z-axis assembly accommodates all three motors, two linear rails, four bearing blocks and X-axis bearings (Figure 2.3). Both upper and lower components that hold bearings for X-axis are symmetrical and identical (Figure 2.4).

Bearings are fastened to the frame with M5 bolts and there is an eccentric bushing between the bolt and the bearing, which gives 2 mm movement for the bearings on both sides of the rail (Figure 2.4).

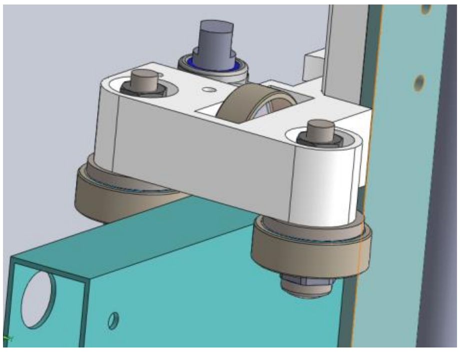

Figure 2.4. X-axis slider bearings

The Z-axis linear motion is accomplished with two 8 mm chromed precision rods. SC8UU linear bearing blocks [14] slide on the rods and provide precise movement for the Z-axis. In the middle of bearing blocks there is a leadscrew that is driven by the motor from the bottom end and top part of the leadscrew is fastened to the support with bearing (Figure 2.5). There is a 3D printed support block for leadscrew nut [15] that is also fastened to the carriage. This block is fastened with 3 mm Plastofast screws [16].

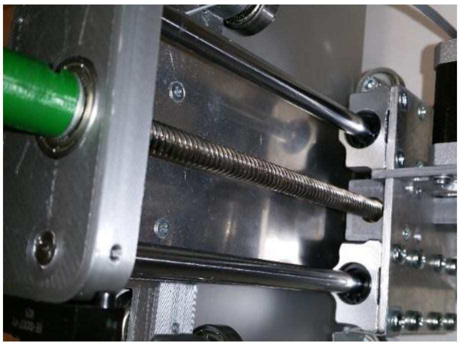

Figure 2.5. Leadscrew

2.1.3 X-axis

The horizontal movement is accomplished with roller skate bearings on the aluminium rail. Aluminium rail is actually a straight edge construction tool [17] from Tööriistamarket [18]. It is used as it is available, affordable and rigid building material. The structure of the aluminium profile makes it perfect for this kind of rail material. It is a square tube with 1mm wall thickness and one strengthening rib in the tube. This tube is connected to the machine enclosure sides with four screws. The slider is rolling on the rail with 12 bearings- 6 on the bottom and 6 on the top part.

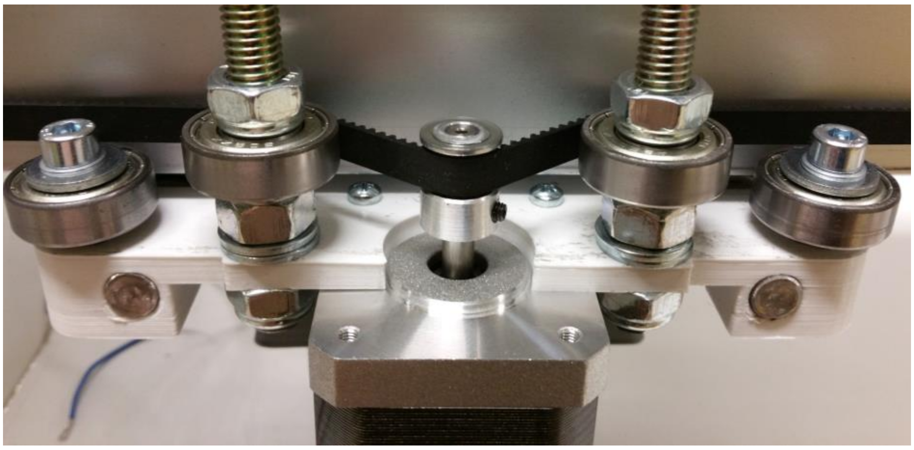

Figure 2.6. X-axis belt drive

Horizontal drive mechanism is constructed of NEMA17 [19] stepper motor with pulley and GT2 timing belt [20]. Belt is driven around two bearings to make contact surface with pulley longer (Figure 2.6). The ends of the belt are running through aluminium extrusion and ends fastened with M2,5 screws (Figure 2.7). The Belt can be tensioned by adding wedges in the aluminium rail between the belt and the screw. If the screw is tensioned the wedges are also fixed with the screw tip.

Figure 2.7. X- axis belt fixture

X-axis must be constructed before the aluminium rail is fastened to the machine enclosure sides. If Z-axis assembly is needed to be removed the best way is to release the aluminium rail from the enclosure, remove belt and pulley from the motor and then aluminium rail can be slid out from Z-axis assembly.

2.1.4 A-axis

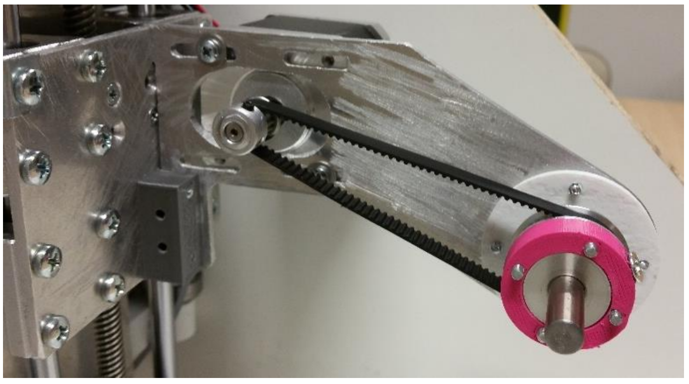

Figure 2.8. A-axis assembly

A-axis is the most moving part in the machine. This assembly (Figure 2.2) consists of:

- A-axis holder that is fastened to the Z assembly's aluminium plate with mechanical joint and a bracket that is 3D printed from PLA (Polylactic acid). A-axis holder is milled out from 3mm sheet on a drill press and cut out with jigsaw.

- A-axis bearing block is fastened on the holder with screws. The bearing block is also 3D printed.

- A-axis motor with pulley and belt. NEMA 17 [19] stepper motor is mounted with screws.

The calculations for A-axis holder:

Table 2.1. Mass properties of components

Component	Mass m/g
Stepper motor NEMA 17 size with pulley (m_1)	300
Bearing holder with pulley and bearings (m_2)	500

There are two potential places for failure on the A-axis holder (Figure 2.9):

1. L1 – there is cross section area $10 \cdot 3 = 30\ mm^2$
2. L2 – there is cross section area 43 – 23 – 3 – 3 = 14 mm by 3mm. $14 \cdot 3 = 42\ mm^2$

The L1 is has less material and the distance between forces and L1 is longer.

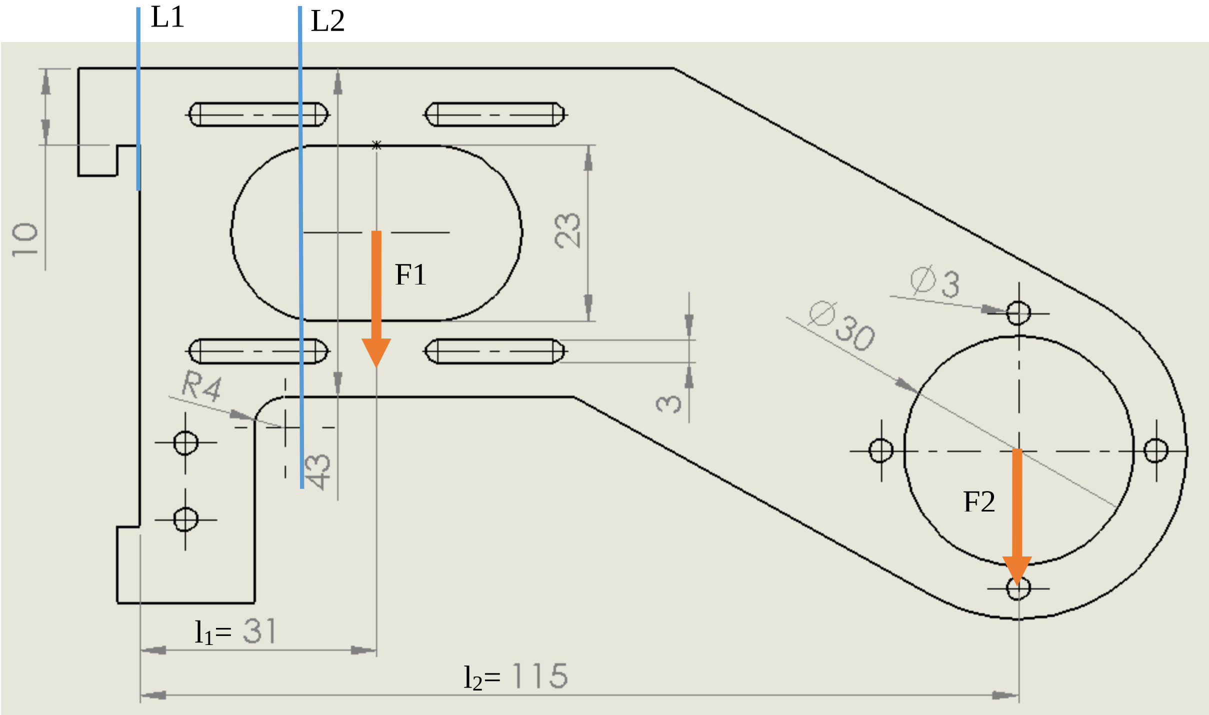

Figure 2.9. A-axis holder

The calculation is done to be sure that 3mm aluminium sheet fits the needs of the machine.

First, the bending moment M of the cross- section L1 is calculated. For that forces are calculated:

$$F = m \cdot g \qquad [21, p. 13] (2.1)$$

$F -$ force (N),
$m -$ mass of the component (kg),
$g -$ standard acceleration due to gravity [22, p. 34] $g = 9{,}81\ m/s^2$.

$$F1 = m_1 \cdot g = 0{,}3 \cdot 9{,}81 = 2{,}943\ N$$

$$F2 = m_2 \cdot g = 0{,}5 \cdot 9{,}81 = 4{,}905\ N$$

$$M = F1 \cdot l_1 + F2 \cdot l_2 \qquad [23, p. 5] (2.2)$$

$M -$ bending moment of the cross- section (N·m),
$F -$ force (N),
$l -$ distance between force and calculation point (m).

$$M = 2{,}943 \cdot 0{,}031 + 4{,}905 \cdot 0{,}115 = 0{,}655308 \approx 0{,}66\ N \cdot m$$

Bending stress σ is calculated in the L1 cross section and compared to the aluminium properties.

$$W = \frac{h^2 \cdot b}{6} \qquad [23, p. 13] (2.3)$$

$W -$ cross-sectional moment resistance (mm^3),

$h -$ cross section height (mm),

$b -$cross section width (mm).

$$W = \frac{10^2 \cdot 3}{6} = 50\ mm^3$$

$$\sigma = \frac{M}{W} \leq [\sigma] \qquad \text{[23, p. 12] (2.4)}$$

$\sigma -$ bending stress (MPa),

$M -$ bending moment of the cross- section (N·m · 10^{-3}),

$W -$ cross-sectional moment resistance (mm^3),

$[\sigma] -$ allowed stress (MPa).

$$\sigma = \frac{0{,}66}{50 \cdot 10^{-9}} = 13{,}2\ MPa \leq [\sigma]$$

$$[\sigma] = \frac{\sigma_y, Al}{[S]} \qquad \text{[23] (2.5)}$$

$[\sigma] -$ allowed stress (MPa),

$\sigma_y, Al -$ yield strength of aluminium 55 MPa [24, p. 94],

$[S] -$ Safety factor, [S] = 2.

$$[\sigma] = \frac{55}{2} = 27{,}5\ MPa$$

Criteria $\sigma \leq [\sigma]$ is fulfilled:

$$13{,}2\ MPa \leq 27{,}5\ MPa$$

The shaft of the A-axis is supported by two bearings. A 3D printed bearing block holds bearings (Figure 2.10). One end of the shaft is held by locking ring and on the other side a 40 tooth timing belt pulley is tightened on the shaft. Between the pulley and the bearing is a washer to keep pulley away from the edge of the bearing and bearing block. The motor is fastened to the aluminium plate with 4 screws and it has slots to tension the belt. A 232 tooth 6 mm GT2 timing belt [25] is used.

To fasten the roller skate bearings holder to the axis a 3D printed ring is added around the pulley. The ring is fastened with two 4 mm bolts to the pulley and the ring has four 3 mm bolt ends extruding out from it for keeping the bearings holder in place. This way there is a minimum possibility to slip on the shaft as the ring is directly connected to the pulley and the shaft does not work on torque. There are only belt tension and the mass of bearings on the shaft.

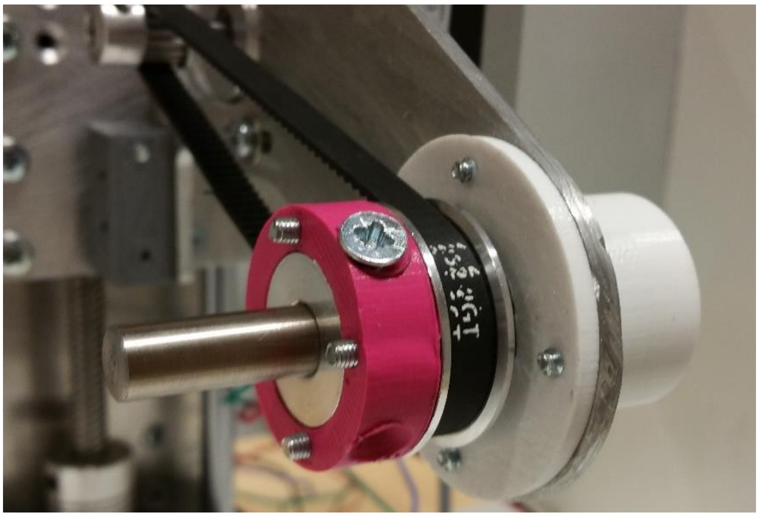

Figure 2.10. 3D printed ring on pulley

The bearings holder is held on the shaft with neodymium [26] magnet which keeps the bearings holder from falling off the pins that are driving it. The magnet is a disk with larger diameter than shaft and is placed on the shaft end after installing roller skate bearings holder.

2.2 Liquid management

The liquids management is important part of roller skate bearings cleaning machine as minimal amount of liquid has to be used. Standards ISO 11014:2009 [3] and ISO/TS 15029-2:2012 [4] have to be applied. There are three half round washing bins (Figure 2.11), each of which has its own inflow and a drain reservoir. The inflow is restricted with valve and uses gravity to flow in the container. In the first place these valves are implemented as manually driven automotive solenoid valves or manual valves for petrol.

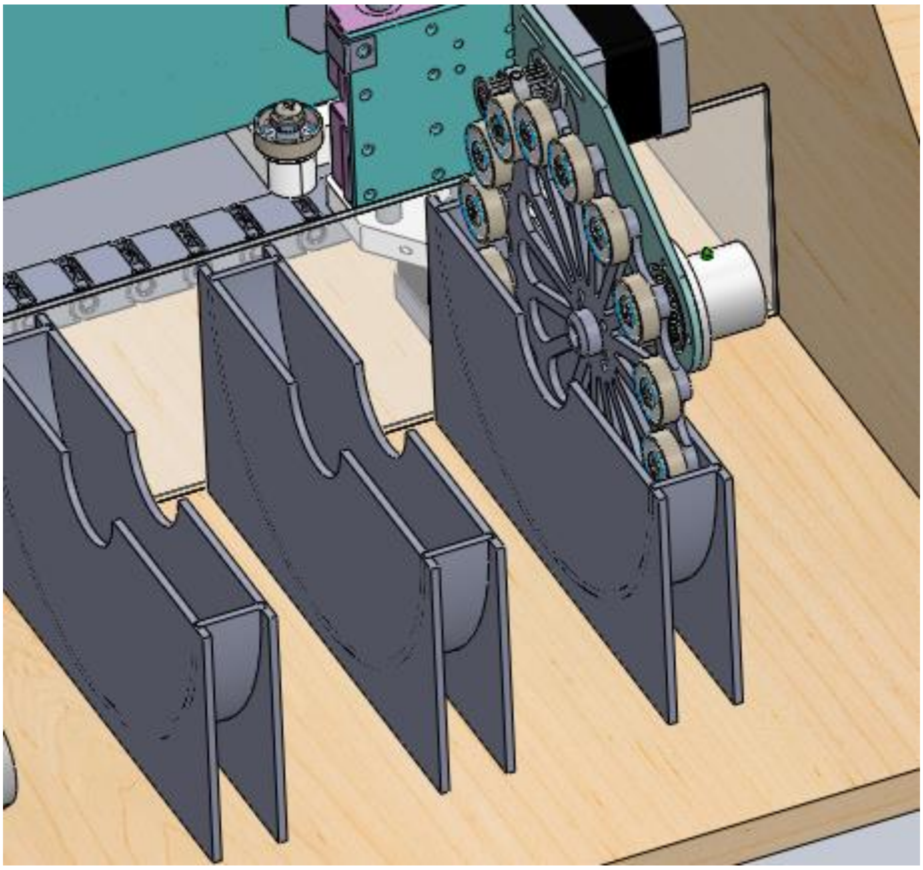

Figure 2.11. Washing liquid containers

The drain part has to have a minimal volume, which means the bottom of the bin and the draining valve must be as close as possible to avoid liquid filling the hose between them. Developing best solution for liquid control is the next step after machine mechanics are ready.

2.3 Dryer assembly

Next step after washing cycle is drying. The dryer has two main components- a compressed air side and a vacuum side. Both of the components are connected on the dryer frame. This frame is 3D printed from PLA (Polylactic acid) and is made to be an easily configurable and interchangeable piece.

Compressed air is used to dry the bearings and to blow contamination away from the bearings. At the start of the development process it was requested that the bearings spin at high speeds to create centrifugal forces which would help to get rid of debris. Research has shown that bearing manufacturers have a different view of bearing maintenance. Main bearing manufacturers describe that bearings should be washed and dried with compressed air, but never should spin freely as bearing is not lubricated and could be easily damaged [27, p. 5] [28, p. 49].

Author’s solution for the problem is to use some felt or rubber between bearings and the dryer assembly to keep bearings from spinning. This kind of solution gives an opportunity to compare washing results with both: spinning bearings and stationary bearings.

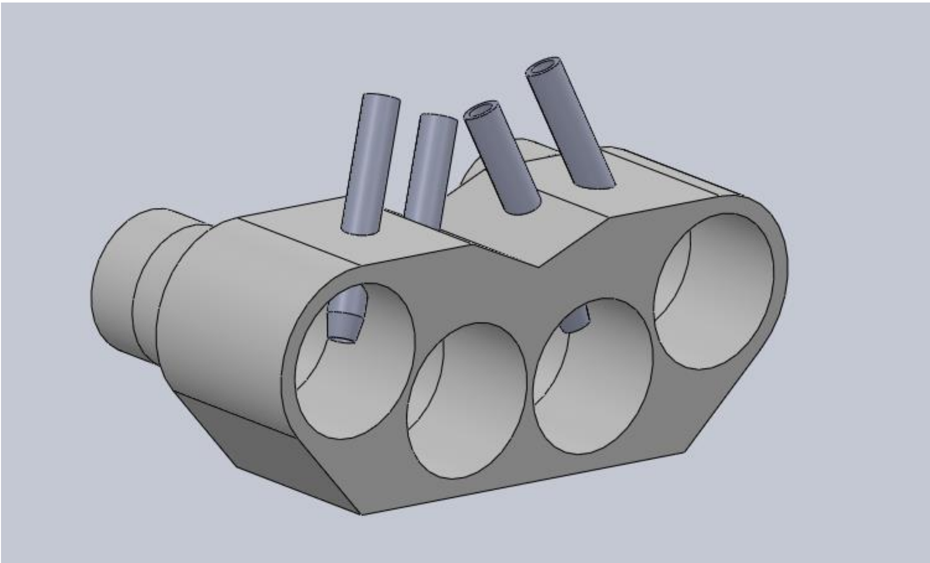

Figure 2.12. Dryer assembly

Air is supplied from the air compressor from another room and a standard air inlet is used for convenience. The regulator on the air line is set to the 4,5 bar. The air is divided between four nozzles as four bearings are dried simultaneously. There are four separate solenoid valves for the air supply (Figure 2.13). The microcontroller can switch every nozzle separately. This gives an opportunity to use more pressure on one bearing and then switch to a next bearing. As the prototype is still in development, changes in cycles and in overall program can be made as well as changing nozzle sizes and shape. Nozzles are made from brass or steel bar and drilled to the suitable size.

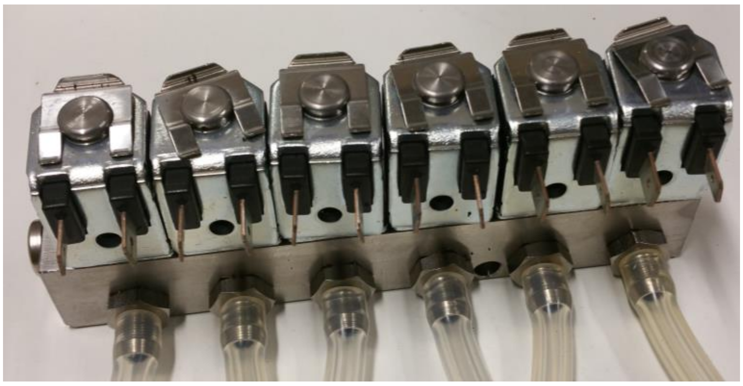

Figure 2.13. Solenoids

Due to air being pumped in the housing, there has to be a way for the air to leave. As one of the needed features were cleaner air in the workshop, there has to be a ventilation connected to the machine. This ventilation is basically a vacuum cleaner connected to 4 drying hoses and the fumes are pumped out from the workshop. This kind of flammable fume extractor has to be explosion-proof.

The solvents used for conducting the thesis were not flammable and were oil or water based. This thesis consists of mechanical and electronical part of the machine and some safety concerns, but this prototype will be used only with safe liquids. If this kind of washing is possible and profitable, a new machine with all safety considerations taken into account will be prototyped. The author of this thesis has given instructions to the users and company to use this prototype safely.

2.4 Holder for the bearings

The holder for the bearings is designed to be interchangeable and users can have multiple holders to make workflow more linear. It also gives an opportunity to wash different bearings after redesigning only the holder. The first prototype of the holder is 3D printed. This holder has time consuming fastening method – all of the bearings have to be fastened separately with M5 bolts. (Figure 2.14)

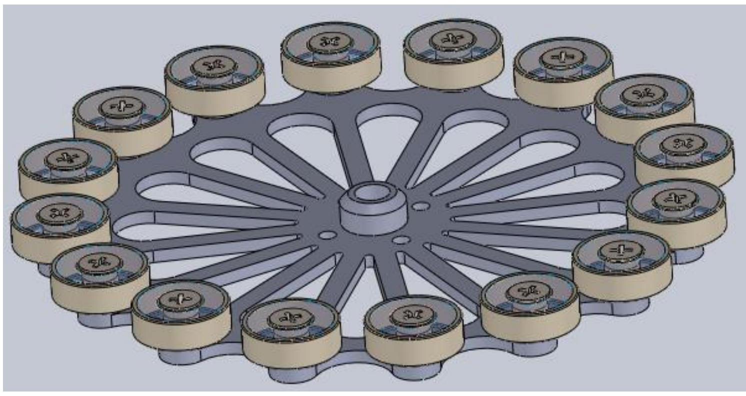

Figure 2.14. Bearings holder

If the holder for the prototype is working correctly a new holder, which will have quick fastening bearing holding pins (Figure 2.15), will be produced from aluminium sheet.

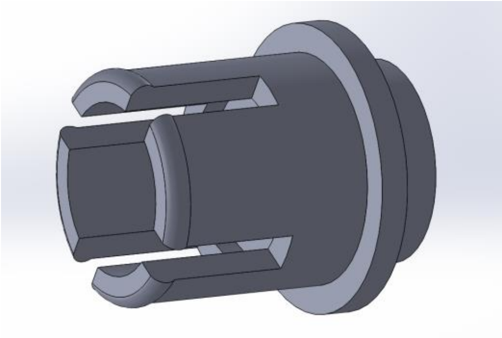

Figure 2.15. Proposed solution for bearing fastening

3 ELECTRONICS

3.1 Motors

The roller skate bearings washing machine has three motors. Several criteria have to be considered when choosing a motor. Designing same type and size of motors for every application in this machine provides opportunity to engineer the electronics in the most efficient way.

Any exposed contacts in the working environment are prohibited due to the explosion hazard, which means brushed DC motors are out of the range of choice. There are three kinds of brushless motors available that could fill the requirements.

1. AC (alternating current) motor.

   - Advantages: Special explosion proof motors available. [29]
   - Disadvantages: A specific speed controller is required. Position control could be added with external encoder. Relatively expensive solution. Difficult to obtain in small size. [30]

2. Brushless DC (direct current) motor.

   - Advantages: Preferred option for fast moving and lightweight solutions. Motors with integrated encoders are available. [31]
   - Disadvantages: Requires complicated driver circuit and software for precision speed and position control. [32]

3. Stepper motor.

   - Advantages: Brushless. Simple drive circuit. Do not require external components for position control. Micro stepping capabilities. [33]
   - Disadvantages: Low speed. In order to maintain position, motor coils need to be energized. Overheating. [7]

Considering motor availability and the ease of position control, stepper motors were chosen to be used in the roller skate bearings cleaning machine.

3.1.1 Bipolar or unipolar stepper motors

Stepper motors are separated based on windings type. Only two phase stepper motors are compared. Stepper motors with higher phase count exist but these are more expensive and not so common in CNC (computer numerical control) machine building. [34]

Two kind of stepper motors are:

1. Unipolar stepper motors have one winding with centre tap per phase. This gives an opportunity to drive steppers with a really simple circuit. These motors have usually 5 wires. Centre tap wires are connected internally. In order to drive motor different parts of windings are energized to reverse magnetic pole. [35]

    - Disadvantages: Doubled windings add mass.
    - Advantages: Only 4 transistors are needed to drive that kind of motor. Can be wired in bipolar configuration. [35]

2. Bipolar stepper motors have one winding per phase. In order to reverse magnetic pole in the windings the current flow through the windings has to be reversed. [35]

    - Disadvantages: Usually H- bridge driver is used [35]. Driver is complicated.
    - Advantages: Special stepper driver modules enable Micro stepping and simplify motor driving. Bipolar stepper motors have better power to mass ratio than unipolar stepper motors. [36]

Bipolar stepper motors were chosen for roller skate bearings washing machine.

3.1.2 X-axis motor (horizontal belt drive) calculations

For horizontal drive a stepper motor in size NEMA 17 [19] is used. In order to calculate sufficient motor torque [21], the mass of components was measured.

Table 3.1. Mass of X-axis components

Component	Mass m/g
Z-axis assembly	1300
Motor NEMA 17	290
Cable chain	26
Bearing holder with bearings	386

Measureable total mass for X-axis to move is 1300 + 290 · 3 + 25 + 386 = 2581 g. (Table 3.1)

Components that could not be measured and will be added later are considered to be 119 g. The total mass for motor selection is 2700 g = 2,7 kg.

Known parameters:

Total moving mass $m = 2{,}7\ kg$

Diameter of the pulley $D = 0{,}01\ m$

Mass of the pulley $m_1 = 0{,}003\ kg$

Friction coefficient of work guide: $\mu = 0{,}04$

Efficiency of belt and pulley: $\eta=0{,}9$

Movement for once: x = 0,25 m

Positioning time: $t_0 = 2\ s$

Acceleration and deceleration time: $t_1 = 0.25\ s$

Carriage (Z-axis assembly) has to move the distance of 250 mm in 2 seconds.

Safety factor $K = 2$

Stepper motor resolution $\theta_s = 1{,}8°$

Required torque calculations based on motor manufacturer recommended method [21]:

The travel length of the carriage is calculated.

$$\Delta l = \frac{\pi \cdot D \cdot \theta_s}{360} \qquad [21, p. 7]\ (3.1)$$

$\Delta l -$ position increment per 1 pulse (m),

$D -$ diameter of the pulley (m),

$\theta_s -$ stepper motor resolution (°).

$$\Delta l = \frac{3{,}14\ \cdot 0{,}01\ \cdot 1{,}8}{360} = 0{,}000157\ m$$

The number of stepper motor steps needed for 250 mm travel of the carriage.

$$N_{pulse} = \frac{x}{\Delta l} \qquad [21, p. 7]\ (3.2)$$

$N_{pulse} -$ the number of pulses needed for movement in full step mode,

$x -$ linear distance to move (m),

$\Delta l -$ position increment per 1 pulse (m).

$$N_{pulse} = \frac{0{,}25}{0{,}000157} = 1592{,}4 \approx 1592$$

Calculation for maximum frequency of step pulses required. Maximum frequency is reached if there is no acceleration or deceleration.

$$f_2 = \frac{N_{pulse}}{t_0 - t_1}$$ [21, p. 14] (3.3)

f_2 – steady pulse frequency (Hz),

N_{pulse} – the number of pulses needed for movement,

t_0 – total time for movement (s),

t_1 – acceleration and deceleration time (s).

$$f_2 = \frac{1592}{2 - 0{,}25} = 909{,}7 \approx 910\ Hz$$

The moment of inertia of the pulley:

$$J_{Pulley} = \frac{1}{8} \cdot m_1 \cdot D^2$$ [21, p. 13] (3.4)

J_{Pulley} – moment of inertia of the pulley (kg·m^2),

m_1 – mass of the pulley (kg),

D – diameter of the pulley (m).

$$J_{Pulley} = \frac{1}{8} \cdot 0{,}003 \cdot 0{,}01^2 = 3{,}75 \cdot 10^{-8}\ kg \cdot m^2$$

The moment of inertia of the carriage:

$$J_{Carriage} = m \cdot \left(\frac{D}{2}\right)^2$$ [21, p. 13] (3.5)

$J_{Carriage}$ – moment of inertia of the carriage (kg·m^2),

m – total moving mass (kg),

D – diameter of the pulley (m).

$$J_{Carriage} = 2{,}7 \cdot \left(\frac{0{,}01}{2}\right)^2 = 0{,}0000675\ kg \cdot m^2$$

Total moment of inertia:

$$J_{Total} = J_{Pulley} + J_{Carrige} \qquad [21, p. 13]\ (3.6)$$

J_{Total} – total moment of inertia (kg·m^2),
J_{Pulley} – moment of inertia of the pulley (kg·m^2),
$J_{Carriage}$ – moment of inertia of the carriage (kg·m^2).

$$J_{Total} = 0{,}0000000375 + 0{,}0000675 = 0{,}00006754\ kg \cdot m^2$$

Torque calculations:

Linear load:

$$F = \mu \cdot m \cdot g \qquad [21, p. 13]\ (3.7)$$

F – force needed to move linear load (N),
μ – friction coefficient [22, p. 41] μ = 0,04,
g – standard acceleration due to gravity [22, p. 34] $g = 9{,}81\ m/s^2$.

$$F = 0{,}04 \cdot 2{,}7 \cdot 9{,}81 = 1{,}05948 \approx 1{,}06\ N$$

Carriage friction torque:

$$T_F = \frac{F \cdot D}{2 \cdot \eta} \qquad [21, p. 13]\ (3.8)$$

T_F – torque from the carriage friction (N·m),
F – force needed to move linear load (N),

$D -$ diameter of the pulley (m),

$\eta -$ efficiency of the belt and the pulley [21, p. 13] $\eta = 0{,}9$.

$$T_F = \frac{1{,}06 \cdot 0{,}01}{2 \cdot 0.9} = 0{,}0059\ N\ \cdot m$$

Acceleration torque calculation:

$$T_A = (J_0 + J_{Total}) \cdot \frac{\pi \cdot \theta_s}{180} \cdot \frac{f_2}{t_1}$$ [21, p. 15] (3.9)

$T_A -$ acceleration torque (N·m),

$J_0 -$ motor rotor moment of inertia (kg·m^2),

$J_{Total} -$ total moment of inertia (kg·m^2),

$\theta_s -$ stepper motor resolution (°),

$f_2 -$ steady pulse frequency (Hz),

$t_1 -$ acceleration / deceleration time (s).

$$T_A = (J_0 + 0{,}00006754) \cdot \frac{3{,}14 \cdot 1{,}8}{180} \cdot \frac{910}{0{,}25} \approx\ 114{,}3\, J_0 + 0{,}0077\ N \cdot m$$

Operating torque calculation:

$$T_M = (T_F + T_A) \cdot K$$ [21, p. 15] (3.10)

$T_M -$ operating torque (N·m),

$T_F -$ torque from the carriage friction (N·m),

$T_A -$ acceleration torque (N·m),

$K -$ safety factor.

$$T_M = (0{,}0059 +\ 114{,}3\, J_0 + 0{,}0077) \cdot 2 = 228{,}6 \cdot J_0 + 0{,}0272\ \ N \cdot m$$

The parameters of stepper motor were collected from PCB Linear motors catalogue [37]. Intention was to acquire motors from eBay [38] but the product information is not sufficient for calculations. Similar product from PCB Linear catalogue was chosen.

The moment of inertia of the motor:

$$J_0 = 57\ g \cdot cm^2 = 0{,}0000057\ kg \cdot m^2$$ [37]

$$T_M = 228{,}6 \cdot 0{,}0000057 + 0{,}0272 = 0{,}029\ N \cdot m$$ [37]

$T_M -$ required operating torque (N·m).

The motor rated torque is $0{,}48\ N \cdot m$ which is greater than required.

$$0{,}48\ N \cdot m > 0{,}029\ N \cdot m$$

Stepper motor output torque also depends on the speed and voltage. In the roller skate bearings cleaning machine stepper motors supply voltage is 24 V and maximum step frequency is 910 Hz. According to the datasheet [37] the maximum torque on these parameters is $0{,}3\ N \cdot m$. This still covers required torque:

$$0{,}3\ N \cdot m > 0{,}029\ N \cdot m$$

The motor chosen despite of that there is 10 times more torque than required. Extra torque could be used to speed up washing process.

3.1.3 Z-axis leadscrew drive motor calculations

There is a steel leadscrew with bronze nut to drive Z-axis up and down. Motor chosen for Z-axis is also bipolar stepper motor. Similar motor to X-axis motor is used in Z-axis. Calculations are based on a textbook of machine design [39].

Table 3.2. Mass of Z-axis components

Component	Mass m/g
Moving part of the Z-axis assembly	300
Stepper motor size NEMA 17	290
Bearing holder with bearings	386

The load that Z-axis has to move is the sum of components in Table 3.2. Mass of Z-axis components 300 + 290 + 386 = 976 g. There will be cables and sensor added later. Mass for motor selection is considered to be 1000 g = 1 kg.

Known parameters:

Mass for motor selection m_z = 1 kg

$W_z = m_z \cdot g$

$g = 9{,}81\ \frac{m}{s^2}$

$W_Z = 1 \cdot 9{,}81 = 9{,}81\ N$

Major diameter of the leadscrew $d_0 = 8\ mm$

Thread pitch $p = 2\ mm$

Lead = 8 mm

The coefficient of friction $\mu = tan\varphi = 0.15$ [39, p. 637]

$\mu_1 = 0.20$

Mean diameter of the leadscrew is required for tangential force calculations.

$$d = d_0 - \frac{p}{2}$$ [39, p. 637] (3.11)

$d -$ mean diameter of the leadscrew (mm),

$d_0 -$ major diameter of the leadscrew (mm),

$p -$ thread pitch (mm).

$$d = 8 - \frac{2}{2} = 7\ mm$$

Calculating tangent of the helix angle:

$$tan\alpha = \frac{Lead}{\pi \cdot d} \qquad [39, p. 637] (3.12)$$

$tan\alpha -$ helix angle tangent,

$Lead -$ screw lead (mm),

$d -$ mean diameter (mm).

$$tan\alpha = \frac{8}{3,14 \cdot 7} = 0,364$$

Tangential force calculation:

$$P = W_Z \cdot \tan(\alpha + \varphi) = W_Z \left(\frac{\tan\alpha + tan\varphi}{1 - tan\alpha \cdot tan\varphi} \right) \qquad [39, p. 637] (3.13)$$

$P -$ tangential force (N),

$W_Z -$ mass to be moved (N),

$tan\alpha -$ the tangent of helix angle,

$tan\varphi -$ the coefficient of friction.

$$P = 9,81 \cdot \left(\frac{0,364 + 0,15}{1 - 0,364 \cdot 0,15} \right) = 5,33\ N$$

Required torque calculation:

$$T = P \cdot \frac{d}{2} \qquad [39, p. 637] (3.14)$$

$T -$ torque needed (N·m),

$P -$ tangential force (N),

$d -$ mean diameter (mm).

$T = 5{,}33 \cdot \frac{7}{2} = 18{,}66\ N \cdot mm = 0{,}019\ N \cdot m$

According to calculations the required torque is 0,0019 N·m. Motor is chosen from PCB Linear catalogue and is rated for torque 0,3 $N \cdot m$ at voltage 24 V. [37]

The Z-axis motor is over dimensioned more than hundred times. A motor with less torque should be considered. For prototyping NEMA 17 motor is used. If prototype fits company's needs new holder and a motor in smaller size will be considered.

3.1.4 A-axis continues rotation motor sizing calculations

The axis A is a rotating axis for bearings holder. Holder is rotated continuously in the liquid containers and at the end of washing process the holder is required to align with dryer. Same motor type and model was chosen for the A axis as it was chosen for X and Z axis. The motor is connected with timing belt. There are different sized pulleys used to increase torque and resolution. To simplify calculations, bearings holder is considered to be one part and the bearings are cylindrical objects including screw. (Figure 3.1)

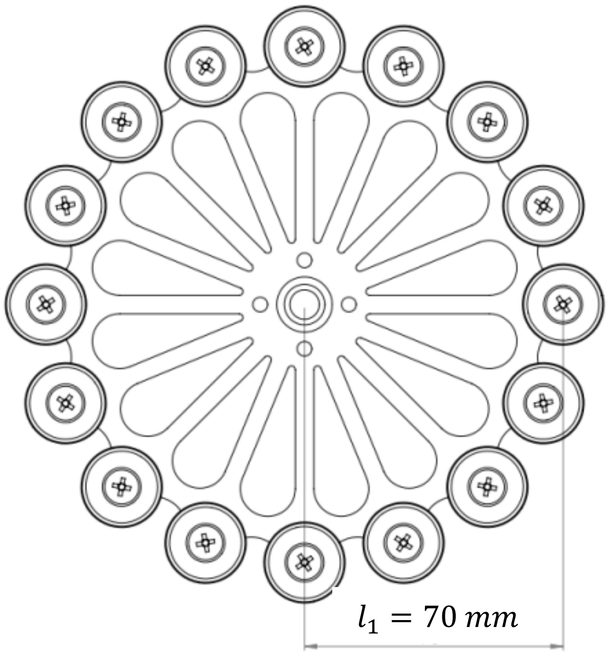

Figure 3.1. Bearings holder

As given below:

The mass of a roller skate bearing with bolt for fixing $m_B = 15\ g = 0{,}015\ kg$

Diameter of the roller skate bearing $D_B = 22\ mm = 0{,}022\ m$

Bearings with holding bolt is considered to be a cylindrical detail.

Bearing distance from the centre $l_1 = 70\ mm = 0{,}070\ m$

The number of bearings $N_B = 16$

Number of teeth on motor pulley $N_m = 16$

Number of teeth on bearings holder pulley $N_h = 40$

Stepper motor resolution $\theta_s = 1{,}8°$

Safety factor $K = 2$

Acceleration and deceleration time $t_1 = 0{,}25\ s$

Positioning time for one turn $t_0 = 1\ s$

One revolution- angle for calculations $\alpha = 360°$

Friction load $T_L = 0$

The calculation of gearing ratio:

$$i = \frac{N_h}{N_m}$$ [21, p. 13] (3.15)

$i -$ gearing ratio,

$N_h -$ number of teeth on bearing holder pulley,

$N_m -$ number of teeth on motor pulley.

$$i = \frac{40}{16} = 2.5$$

Step resolution with gearing:

$$\theta_g = \frac{\theta_s}{i}$$ [21, p. 14] (3.16)

θ_g − resolution after gearing (°),

θ_s − stepper motor resolution (°),

i − gearing ratio.

$$\theta_g = \frac{1{,}8}{2.5} = 0{,}72°$$

Number of pulses needed:

$$N_{pulse} = \frac{\alpha}{\theta_g}$$ [21, p. 14] (3.17)

N_{pulse} − number of pulses needed,

α − angle to rotate (°),

θ_g − stepper motor resolution (°).

$$N_{pulse} = \frac{360}{0{,}72} = 500$$

Operating pulse frequency:

$$f_2 = \frac{N_{pulse}}{t_0 - t_1}$$ [21, p. 14] (3.18)

f_2 − steady pulse frequency (Hz),

N_{pulse} − the number of pulses needed for movement,

t_0 − total time for movement (s),

t_1 − acceleration/ deceleration time (s).

$$f_2 = \frac{500}{1 - 0{,}25} = 666{,}7\ Hz$$

Calculations for acceleration torque:

Holder plate inertia is calculated in the SolidWorks program:

$J_P = 102295{,}35\ g \cdot mm^2 = 0{,}00010229535\ kg \cdot m^2$

Inertia of the bearing on the holder:

$$J_B = \frac{1}{8} \cdot m_B \cdot D_1^2 \qquad [21, p. 3]\ (3.19)$$

J_B − inertia of one bearing on the holder (kg·m^2),

m_B − mass of one bearing (kg),

D_1 − diameter of bearing (m).

$$J_B = \frac{1}{8} \cdot 0{,}015 \cdot 0{,}022^2 = 0{,}0000009075\ kg \cdot m^2$$

Inertia of 16 bearings on holder:

$$J_W = n \cdot (J_B + m_B \cdot l_1^2) \qquad [21, p. 14]\ (3.20)$$

J_W − inertia of wheel of bearings (kg·m^2),

m_B − mass of bearing (kg),

n − number of bearing,

l_1 − distance from the centre of the wheel (m).

$$J_W = 16\ (0{,}0000009075 + 0{,}015 \cdot 0{,}070^2) = 0{,}00119052\ kg \cdot m^2$$

Whole load inertia:

$$J_L = J_W + J_P \qquad [21, p. 14]\ (3.21)$$

J_L − inertia of wheel of bearings with holder (kg·m^2),

J_W − inertia of wheel of bearings (kg·m^2),

J_P − inertia of holder (kg·m^2).

$$J_L = 0{,}00119052 + 0{,}00010229535 = 0{,}00129281535 \; kg \cdot m^2$$

Acceleration torque calculation

$$T_A = (J_0 + i^2 + J_L) \cdot \frac{\pi \cdot \theta_s}{180} \cdot \frac{f_2 - f_1}{t_1} \quad [21, p. 15] (3.22)$$

T_A − acceleration torque (N·m),

J_0 − motor rotor moment of inertia (kg·m^2),

J_{Total} − total moment of inertia (kg·m^2),

θ_s − stepper motor resolution (°),

f_2 − steady pulse frequency (Hz),

t_1 − acceleration / deceleration time (s).

$$T_A = (J_0 \cdot 2{,}5^2 + 0{,}00129) \cdot \frac{3{,}14 \cdot 0{,}72}{180} \cdot \frac{666{,}7 - 0}{0{,}25} = 209{,}3 \cdot J_0 + 0{,}043 \; N \cdot m$$

Required torque:

$$T_M = (T_F + T_A) \cdot K \quad [21, p. 15] (3.23)$$

T_M − operating torque (N·m),

T_F − torque from the carriage friction (N·m),

T_A − acceleration torque (N·m),

K − safety factor.

$$T_M = (0 + 209{,}3438 \, J_0 + 0{,}04320856032) \cdot 2 = 418{,}688 \, J_0 + 0{,}086 \; N \cdot m$$

Choosing stepper motor from PCB Linear catalogue [37]:

$$J_0 = 0{,}0000057\ kg \cdot m^2$$

$$T_M = 418{,}688 \cdot 0{,}0000057 + 0{,}086 = 0{,}088\ N \cdot m$$

Same motor, as it was for two other axes, is chosen. The motor has operating torque of $0{,}3\ N \cdot m$ [37].

$$0{,}3\ N \cdot m > 0{,}088\ N \cdot m$$

The NEMA 17 motor chosen for other axes fits the requirements on the A-axis also. This motor has to have some extra torque for unexpected situations. The required torque in the liquid is not known as the bearings that are washed have to roll on the bottom of the tank.

3.2 Sensors

There is a requirement for positioning every motor on the roller skate bearings washing machine. Starting position is set with limit switches. There are some different kind of limit switches which are common in CNC (computer numerical control) machines:

- Inductive proximity sensors [29] are used often but Inductive sensors are for industrial use and there is a bulky protective casing.
- Photo interrupters are more compact and easier to acquire [30].

There was a test done by Bertho Boman in 2007 to measure the repeatability of a photo interrupter [31] which resulted in a really good repeatability. In the light of this information, photo interrupters were chosen for this project.

Roller skate bearings cleaning machine needs three switches. One for horizontal movement start position, one for vertical movement and one for positioning rotational movement position. In the mechanical design process one of the switches was removed and one switch will serve the purpose of two switches (Figure 3.2). One photo interrupter is used as a limit switch for both X and Z axis. The photo interrupter has a wider slot so both axis position flags can fit through it.

Figure 3.2. X and Z-axis sensor

There is a wide variety of sensors available to recognize the position of A-axis. The A-axis is driven with stepper motor. The use of stepper motor means that only one position is actually needed and every other position can be found using stepper motor steps. Considered sensors are following:

- On-axis magnetic rotary position sensor [40] – This sensor is precise, it outputs up to 14bit absolute angle measurement. Difficult to use- too much position information.
- Switch and a bump on the shaft. Simple solution. Wear between shaft and switch shortens system lifetime.
- Optical switch and an off centred hole or notch on the shaft.
- Photo interrupter could be used if there is a slotted disk added on the shaft.

The simplest solution- optical switch- was implemented. Basically it is a photo interrupter cut in half and fastened to the opposite sides of the shaft. One half is an infrared LED (Light Emitting Diode) and the other half is a phototransistor or a photodiode [41]. On Figure 3.3 the main idea of the sensor is shown. Sensor is located between two bearings. There is only one position of the shaft when the infrared light can reach through the shaft to the sensor. If the shaft is every time rotated in one direction, then the light reaches to the sensor exactly on the same angle of the axis and home position can be recorded.

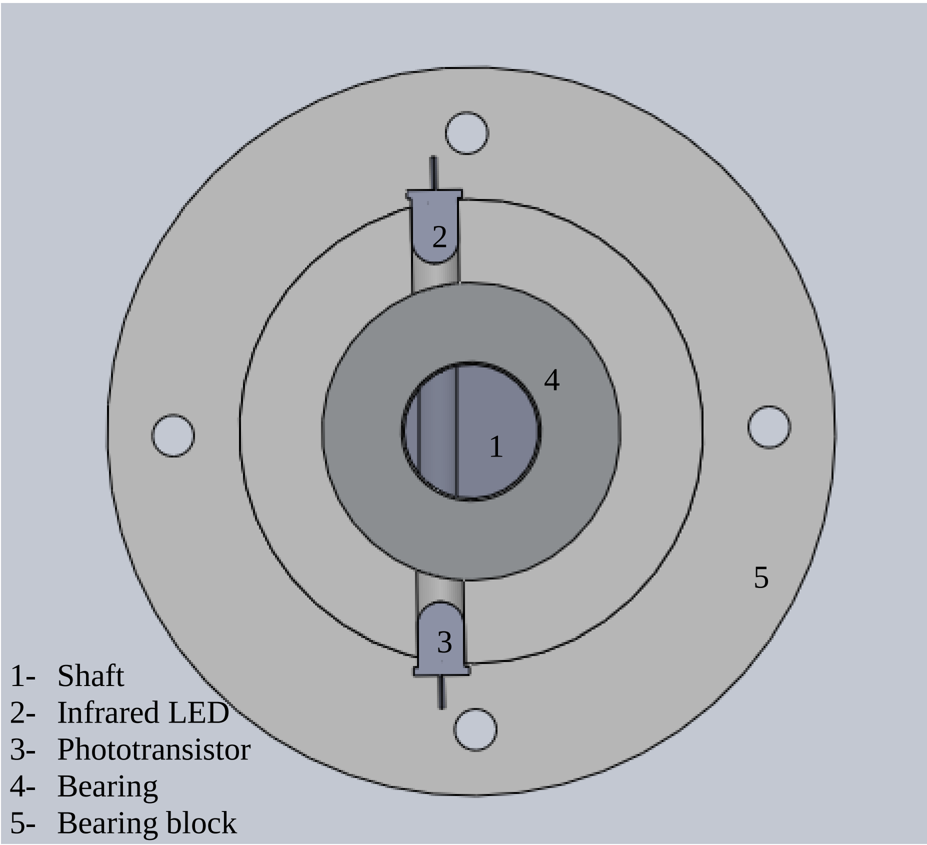

Figure 3.3. A-axis sensor layout section view

3.3 Power supply

The power supply is chosen according to the maximum current rating of the stepper motors. The stepper motor drivers can supply up to 1,5 A per phase without additional cooling. We will run the stepper driver on 50% of maximum current or less to reduce heating of the motor. Stepper motors are energized all the time when the machine is running, which means there is a lot of heat radiated. 3 · 1,5 A = 4,5 A and around 500 mA for microcontroller. All of solenoids and other periphery consume less power than stepper motors and are operated separately. A power supply with 5 A rating at 24 V DC is selected. There is a possibility to upgrade the power supply in the future as the plug used on the machine is universal. To reduce costs and make prototyping faster a power supply from an old coffee machine is used (Figure 3.4).

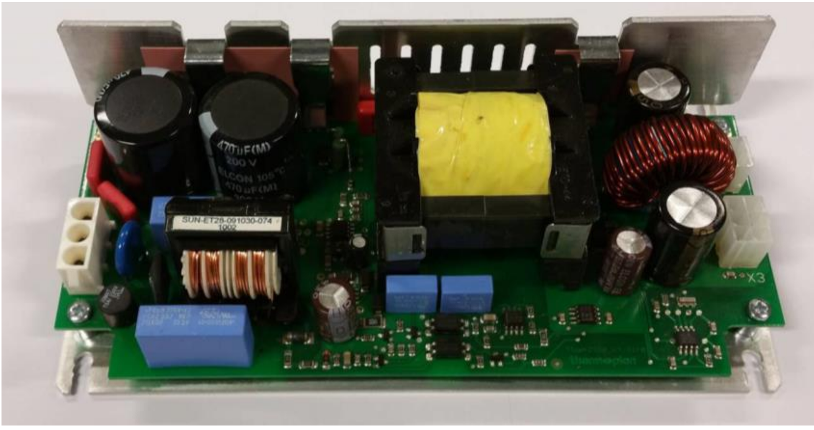

Figure 3.4. Power supply

It is fitted in a plastic box and has a fuse and a power switch. There is a universal socket for Mains voltage mounted to the box. There is a cord with plug for roller skate bearings washing machine.

3.4 Drivers for stepper motors

There are many different stepper motor driving integrated circuits. The roller skate bearings washing machine requires reliable drivers that are reasonably priced. A research in online shops and retailer websites showed many possible options: All of compared products are Stepper driver modules. Module consists of driver, PCB and passive components for driver. There is no need to design full stepper driver circuit on PCB and these modules are made for simple replacement:

1. A4988 DMOS Micro Stepping Driver with Translator and Overcurrent Protection [42] is sophisticated IC for stepper motor driving. Suits for bipolar stepper motors up to 2 A.

2. ULN2003 [43] based motor driver boards are actually just amplifiers and do not have any micro stepping or overcurrent protection features. Can be used in controlled environment with small motors.

3. A3967 Micro Stepping Driver with Translator [44] is sophisticated IC for stepper motor driving. Suits for bipolar stepper motors up to 750 mA [45].

4. L298 Dual Full Bridge Driver - Driver from ST Microelectronics, capable driving up to 4 A motors [46] [47]

5. Texas instruments DRV8825 stepper motor controller IC [48] max 2.5 A current. Affordable and widely used.

For motor drivers DRV8825 chip based module [49] is chosen because it fits the needs of current and affordability.

3.5 Driver for solenoid valves

There is a need to drive several solenoid valves to operate the inflow, drain of the washing liquids and compressed air for dryer. There is a possibility to use MOSFET (metal–oxide–semiconductor field-effect transistor) [50] or transistor to drive solenoids. Solenoid is an inductive load. Circuit protection is necessary on every channel. More sophisticated solution is to use one integrated circuit from ULN200x series. The ULN200x has internal protection diodes for every channel and it is designed to drive inductive loads like stepper motors and solenoids [51].

ULN200x Integrated Circuit is best choice for this application. ULN2003 is chosen as it can be driven with TTL 5 V logic [51]. It is possible to wire ULN2003 channels parallel to get more current per solenoid (Figure 3.5).

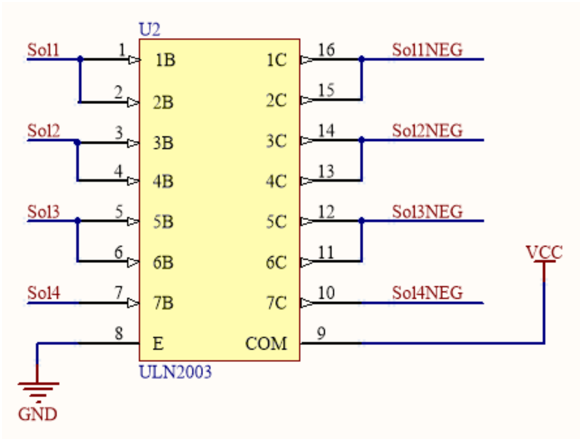

Figure 3.5. Solenoid driver circuit diagram

There are 4 separate solenoid outputs three of these are wired parallel for higher current, up to 1 A. Solenoid output number 4 is capable to drive up to 500 mA. Solenoids are connected to the P5 pin headers, VCC is always connected to the solenoid and GND is driven from microcontroller (Figure 3.6).

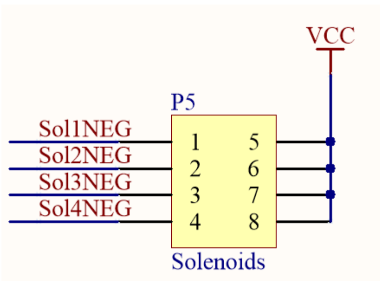

Figure 3.6. Solenoid pin headers

3.6 Microcontroller

The roller skate bearings cleaning machine needed some kind of controller. Author has had experience with different 8-bit and 32-bit microcontrollers. There are plenty of possible choices for microcontroller and even some kind of PLC (Programmable Logic Controller) could be used. Cheapest and most convenient choice was a Pisi-XBee 4 board from TTÜ Robotiklubi. It is a bit outdated in TTÜ Robotiklubi but it has a powerful microcontroller on board. [8]

There is an ATmega32U4 [7] microcontroller on the Pisi-XBee board. This microcontroller should be capable of driving all needed hardware. As stepper motors are going to be used one by one then there is no need for more complicated or faster microcontroller and two timers for motors are used. There is a XBee socket [52] also in the board to add Bluetooth connection if needed.

The Pisi-XBee 4 board is used as a break out board for microcontroller. It has up to 10 V input capability and all voltage regulators on the board. This microcontroller can be programmed with ISP (In System Programming) interface. Also there is possibility to use directly USB (Universal Serial Bus). For that TTÜ Robotiklubi has modified DFU (Device Firmware Upgrade) Bootloader [53] supplied by Atmel.

The programming software in the bearings cleaning machine project is FLIP Program [54] from Atmel which is used together Atmel Studio [11] editor to write program for the microcontroller.

3.7 User Interface

In the prototyping stadium there will be 1-2 buttons for operation and all configurations are done by reprogramming microcontroller. As there is no need for external programmer and only USB cable is needed then it is not complicated to reprogram the device. There are two possibilities to make a user interface for the machine. One possible way would be a small LCD screen and some buttons to navigate through menu. There are also some touchscreen modules that are easily configurable and do not take much processing power. Nextion module [55] is a LCD screen that can be programmed with graphic user interface. This module connects to the microcontroller over serial interface and includes most of user interface in itself, sending out only serial commands. Other possibility is to use Bluetooth and make an application for mobile phone or laptop. It would be best to have an application as configuring machine through serial terminal would be more difficult than programming.

3.8 PCB

The PCB (Printed Circuit Board) is designed with Altium Designer [10] software. This is professional PCB design tool to create multilayer PCB-s. As PCB required in this project is simple and do not include too many components, it is designed as one sided PCB and is produced in Mektory [56] with CNC mill.

This PCB is a link between motor controllers and other inputs and outputs. Pisi-XBee 4 connects to the PCB with pin headers. There is a socket for XBee on the Pisi-XBee PCB. There is enough room between the Pisi-XBee and PCB to accommodate XBee radio module. (Figure 3.7)

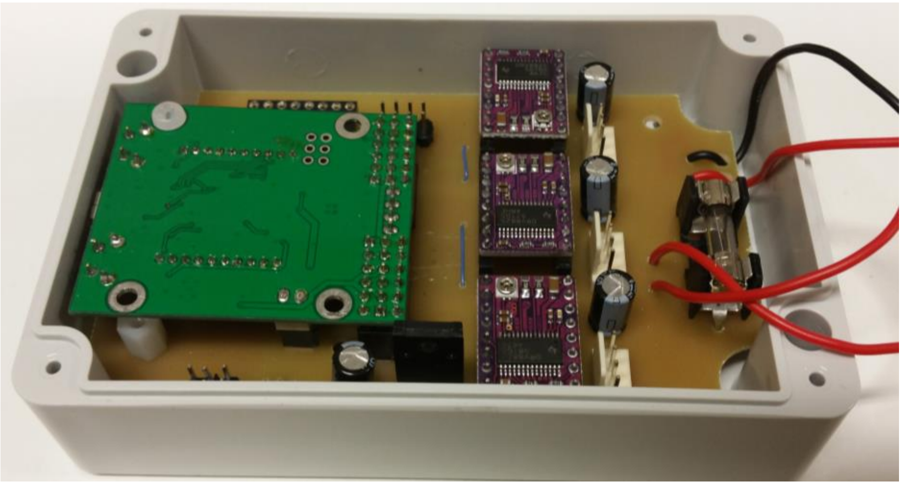

Figure 3.7. Assembled PCB

The Pisi-XBee has its own built in voltage regulator but it runs on voltages between 5,5 V and 10 V. There is U1 voltage regulator (Figure 3.8) on the PCB to make 24 V VCC suitable for Pisi-XBee. There are also places for filter capacitors. TracoPower TSR 1-2465 DC/DC Converter [57] has built in filter capacitors but there is a possibility to use some similar products that does not include filter capacitors.

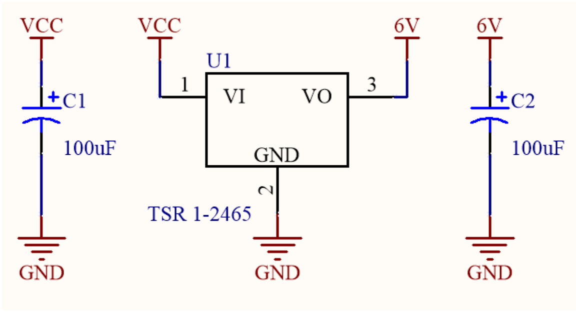

Figure 3.8. 6 V Power supply

Sensors are connected through pin header on the side of the PCB. Every sensor has 3-way connector and pin headers according to the connector. The middle pin is 5 V pin and one side is GND pin. One of the side pins is Pisi-XBee input pin. Sensor output signal is connected to the Pisi-XBee input pin. Sensors that are used does not have pull up resistors. These resistors are also added on the PCB (Figure 3.9).

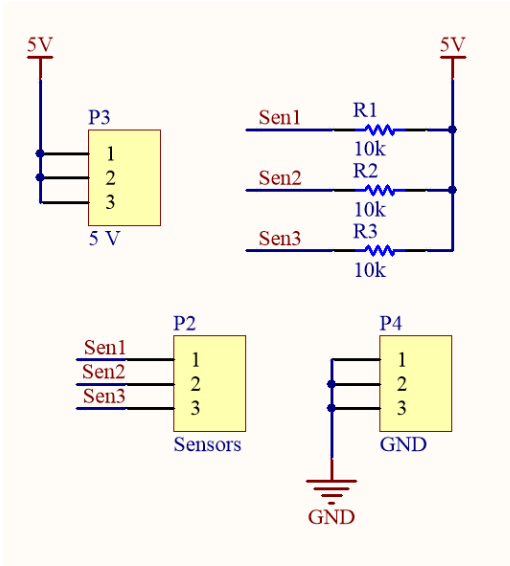

Figure 3.9. Sensor connectors

Pisi-XBee is placed on the PCB this way that buttons can be pressed outside of the box and an USB cable can be connected to upload a new program. Almost all of the input-output pins of the Pisi-XBee are used (Figure 3.10). Some of the sensor inputs and solenoid outputs are not in use on the first prototype but it is possible to add some features in the future without replacing PCB.

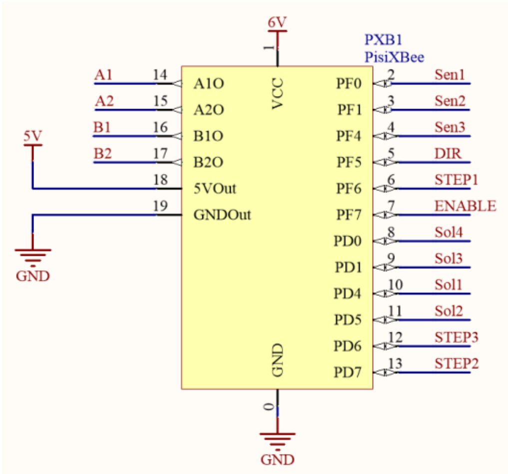

Figure 3.10. Pisi-XBee pin usage

There are three Stepper motor drivers placed on the PCB (Figure 3.11). Drivers are placed in the row to accommodate copper or aluminium bar under the drivers for cooling. This way all stepper motor drivers are sandwiched between cooling radiators and there is a thermal tape between the radiator and driver IC (Integrated Circuit) and also between stepper driver PCB and radiator. Also resistors R7 – R13 are designed on the PCB to choose stepper driver micro stepping configuration. These resistors are on PCB where the radiator should be. There are two options to make room for resistors- cut radiators or solder resistor on the bottom side of the PCB. There are three pin headers to connect motors- P7, P8 and P9. (Figure 3.11)

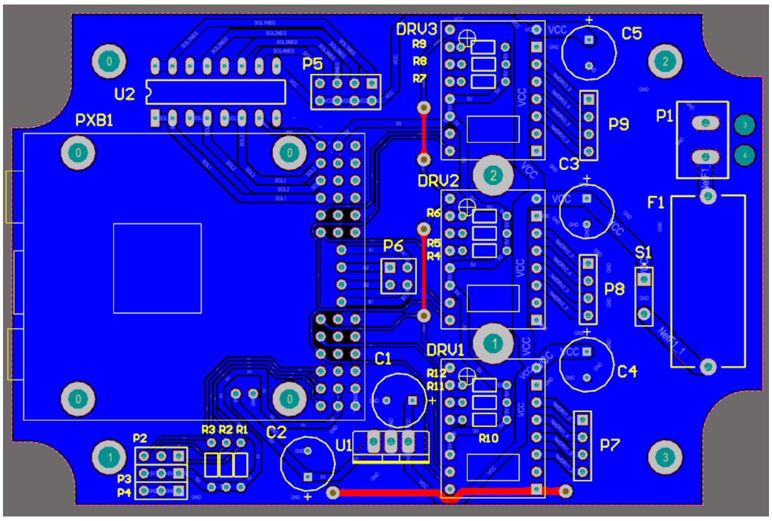

Figure 3.11. PCB Layout

The schematics of the three stepper drivers are similar. On the Figure 3.12 is shown one of stepper motor drivers. Driver is connected to the microcontroller with three signals: DIR, STEP and ENABLE.

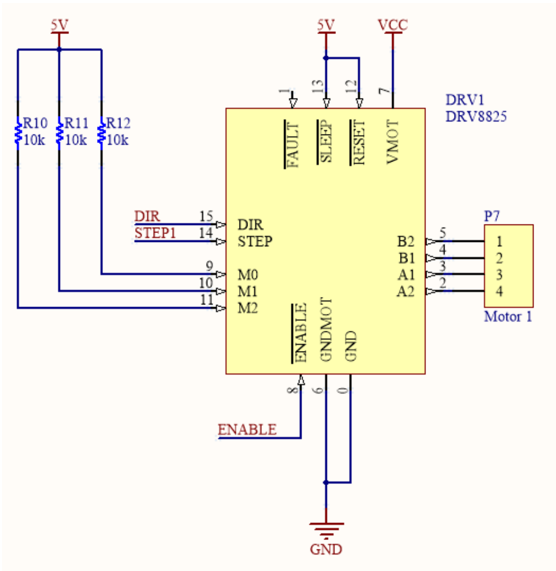

Figure 3.12. Stepper driver circuit diagram

Every stepper motor driver has a 100 nF decupling capacitor (Figure 3.13) as it is required in reference design in the DRV8825 datasheet [58]. This helps to curry enough current for the drivers if it is needed shortly.

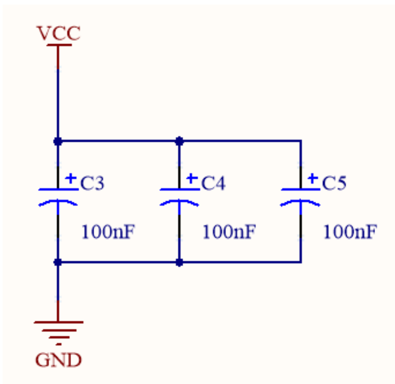

Figure 3.13. Stepper drivers decupling capacitors

A fuse and a power switch is included in the PCB Design. The amperage and characteristic of the fuse have to be tested when machine is running. Cable from 24 V supply is connected to the screw terminals. Ground is directly connected to the PCB GND and 24 V is routed through the fuse and switch (Figure 3.14). Switch is not soldered to the PCB, it is connected to the box and wired on the PCB.

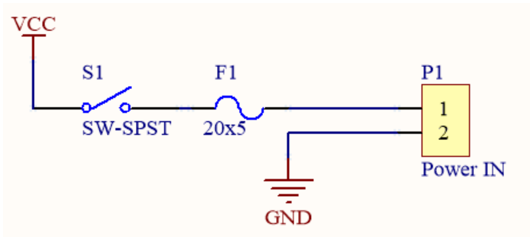

Figure 3.14. Fuse circuit diagram

There is a DC motor driver on the Pisi-XBee board. PCB brings out these headers (Figure 3.15). This driver can be used for solenoids also.

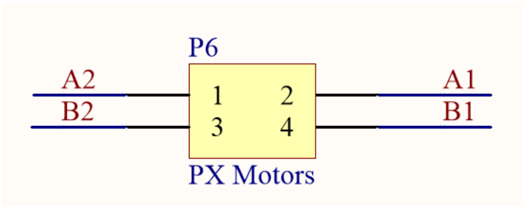

Figure 3.15. Pisi-XBee motor headers

4 PROGRAMMING

The programming of the machine is ongoing process. In this chapter some of the programming problems are discussed.

4.1 Stepper motor driver

There are two signals per every motor. The difficult work driving and micro stepping is done in DRV8825 motor driver, but this driver do not incorporate absolute position handling and acceleration and deceleration. This has to be handled in microcontroller software. Fortunately, the DRV8825 manufacturer has made an effort by supplying application note for DRV series stepper controllers [59]. There are even more theories on the subject of the stepper motor acceleration [60] one of the theories was chosen and implemented.

First implementation was created using two timers TIMER1 and TIMER0. Timer 0 is 8-bit timer and can count from zero until 255. This timer is started when STEP signal is driven high and TIMER0 runs for 0,064 milliseconds.

TIMER0 input signal is divided by 1024 (Table 4.1) and if microcontroller clock is set to 16 MHz then this gives timer clock frequency 16 MHz / 1024 = 15625 Hz. The TIMER0 runs for: 1 / 15625 Hz = 0,000064 s.

Program code to start timer 0:

```
…
//Turn on 8bit timer to clear STEP pin
        TCCR0A=(1<<WGM01);              //CTC mode
        TCCR0B|=(1<<CS00)|(1<<CS02); //Set clock clk /1024
        OCR0A=1;                    //set compare value Match A
        TIMSK0=(1<<OCIE0A);     // Match A interrupt enable
...
ISR(TIMER0_COMPA_vect)// 8bit timer 1 compare 1A match
{
        PORTD&=~(1<<STEP);              //Reset STEP signal
        TCCR0B=0;                       //Stop Timer0
        TCNT0=0;                        //Reset counter
}
```

Table 4.1. Clock selection table [7]

CS02	CS01	CS00	Description
0	0	0	No clock source (Timer/Counter stopped)
0	0	1	$clk_{I/O}$/(No prescaling)
0	1	0	$clk_{I/O}$/8 (From prescaler)
0	1	1	$clk_{I/O}$/64 (From prescaler)
1	0	0	$clk_{I/O}$/256 (From prescaler)
1	0	1	$clk_{I/O}$/1024 (From prescaler)
1	1	0	External clock source on T0 pin. Clock on falling edge.
1	1	1	External clock source on T0 pin. Clock on rising edge.

The second timer is used to generate required frequency. On every step of the motor the next step time is calculated and timer adjusted to run accordingly.

4.2 Home position

The home position has to be located every time there is a power off or any disturbance that makes a stepper to skip steps. Homing program is started first at every startup. There is one sensor for two axes – X and Z. Every time has to be considered that if program is started there can be 7 different situations:

- X and Z are in home position (cutting signal of the sensor).
- X and Z are in the middle of their axis.
- X and Z are at the end of the movement axis.
- X is in the home position and Z is in the middle or at the end of the axis.
- Z is in the home position and X is in the middle or at the end of the axis.

Best solution to find out which situation is present on start of the machine is to find out if sensor is activated, if it is then move one axis as much steps away of the sensor as it is maximally needed to clear the sensor from the very beginning of the axis. If this did not succeed to clear the sensor, then moving other axis definitely has to clear the sensor.

There is a possibility that this axis which is moved blindly is at the end of its travel and actually hits the wall of the machine enclosure. If this axis would be a leadscrew drive Z-axis this could be a problem because leadscrew could be pushed off from motor shaft. If the first driven axis is belt driven X-axis no harm is made. Stepper skips some steps only. Stepper drivers are tuned to be powerful enough to keep machine running in normal working conditions but not powerful enough to break something if any unknown obstacle is met.

4.3 Washing cycle

Washing cycle starts with filling liquid reservoirs. This is done manually in the first prototype. Then a button is pressed to indicate that machine is ready for washing cycle. Washing starts with first liquid and rotating wheel of bearings is submerged in the first washing liquid. Bearings are rotated in there both ways: clock ways and counter clock ways. This should not take longer than two minutes. After two minutes the wheel of bearings is submerged in the second liquid that is meant to soak loose most of debris. This step takes another two to three minutes and incudes rotating wheels oi different speeds and directions. After that bearings are rinsed in the last container of liquid. This should clean the last bits of dirt and also the soaking liquid itself from the last step.

Finally, the A-axis is indexed with sensor on the shaft to be sure that there is no error in positioning the bearings in the compressed air dryer. If the home position of the A-axis is found, the bearings are dried four by four in the dryer. After placing bearings in the right place, the compressed air is released in burst to the four bearings simultaneously.

5 FUTURE UPGRADES

In the scope of the thesis prototype was made and at this point some tests have been made. If further testing is done and the machine has shown possibilities to speed up maintenance process, there are certain parts that need upgrading. Most of machine's complicated parts are printed on 3D printer and some of them may wear due to harsh environment conditions. There are also some parts that can be designed different way for easier manufacturing.

The main frame and body of the machine which is made from MDF could be produced from aluminium or steel sheet. In the prototype stadium it is better to make parts from easily available materials and using available tools.

The bearing mounting wheel on A-axis should be made out of metal. PLA plastic wheel is not lasting well if bearing fastening screws have to be driven in and out several times a day. There will be a better solution for this mounting problem developed.

The carriage should be lighter and stiffer to save energy and gain better acceleration and more precise movement. This can be done by reducing bearings size as these bearings that support carriage on X-axis can be smaller. Also the linear bearing assembly on the Z-axis can be reduced by designing bearing holders in one piece.

The user interface could be more user friendly and allow some adjustments of running time and may be some more opportunities to start, stop and restart washing cycle.

The liquid management can be made more intelligent by using sensors to measure the level of the liquid in the both containers and even in the inflow or drain tank. Level measurement using ultrasonic sensors is one possible option. This gives also an opportunity to measure the density of liquid. [61]

5.1 Safety

The safety is most important in this kind of machinery. There are high risks of explosion and toxic liquids are used that can be harmful for human. Some of the safety risks and solutions are included in the thesis but this list is not final and further analysis of the risk factors will be done. The standards that apply to the roller skate bearings cleaning machine are: Human exposure to benzene is covered in the standard EH40/2005 [62]. Also standards ISO/TS 15029-2:2012 [4] and ISO 11014:2009 [3] should apply to the machine.

CONCLUSION

The roller skate bearings cleaning machine was ordered by a local company HOOG SISSE OÜ specialized in roller skate maintenance. The company provided main concept of the cleaning cycle. As the research in the Internet showed, there is no readymade solutions in the market. In cooperation with the author of the thesis the requirements of built machine were decided.

The thesis is divided into four main chapters that describe prototype building. The thesis is divided into mechanics, electronics and programming chapters and future upgrades chapter.

In the chapter of mechanics, the mechanical design is discussed. Entire machine is designed in the SolidWorks software. The machine consists of:

- Enclosure. The enclosure of the roller skate bearings washing machine is made of furniture grade MDF sheets.
- X-axis. The X-axis slides on an aluminium extrusion with roller skate bearings.
- Z-axis. Z and A- axis are constructed and calculations done for A-axis holder.
- Bearings dryer construction.
- Holder for the bearings that are cleaned.

In the electronics chapter all about motors, sensors and drivers are discussed. Stepper motor are chosen to be used and calculations for required torque are done.

In the Programming chapter some problems with home position finding and driving steppers with acceleration are discussed and solutions introduced.

In the last chapter some upgrades and required changes are brought out to find better solutions for problems that arise during prototyping and testing.

The roller skate bearings cleaning machine prototype was constructed during the thesis some tests were conducted and the author of the thesis concludes that the machine prototype is successful and basing on that some improvements will be made. The machine is planned to be tested in the 2016 and if extensive testing was successful roller skate bearings cleaning machine should be ready in Spring 2017.

SUMMARY

Magistritöö „Rulluisu laagrite pesumasin“ eesmärgiks oli valmistada ettevõttele HOOG SISSE OÜ rulluisu laagrite pesumasina prototüüp, kuna taolist seadet pole võimalik kaubandusvõrgust hankida. Koostöös ettevõttega koostati loodavale masinale esitatavad nõudmised:

- Tuleb kasutada harjadeta mootoreid ja vältida kõrget temperatuuri. Kasutusel on tuleohtlikud puhastusvedelikud.
- Masin peab lauale ära mahtuma ja toimima võrgupingel.
- Laagrihoidikud on vahetatavad.
- Masinal on vaateaken protsessi jälgimiseks.
- Masinal on poolautomaatne pesuvedelike vahetussüsteem.

Antud nõuetele vastava masina prototüübi valmistamiseks käsitleti magistritöös järgnevaid teemasid:

- Mehaanika joonised ja 3D mudelid.
- Tugevusarvutused.
- Mootori valik ja vajalikud arvutused.
- Elektroonika skeem ja trükkplaat.
- Programm mikrokontrollerile.
- Pesuprogrammi ja kuivati kirjeldused.
- Pesuvedelike kasutamine ja hoiustamine.
- Ohutusnõuded ja ettepanekud ohutuse parandamiseks.
- Ettepanekud masina komponentide parenduste tegemiseks.

Magistritöö autor on rahul töö tulemustega. Suur osa masinast valmis töö käigus ja ettevõte saab peagi alustada prototüübi testimist. Magistritöö andis hea võimaluse prototüübi valmistamisega seotu dokumenteerimiseks, mis saab olema masina valmistamise aluseks. Töö käigus oli raskusi masina komponentide hankimisega ja ohutusstandartite juurdepääsuga. Enamikele probleemidele leiti lahendused töö käigus. Magistritöö väliselt jätkub rulluisu laagrite pesumasina testimine ja arendamine.

SUMMARY IN ENGLISH

The purpose of the thesis, written on the topic "Roller skate bearings cleaning machine", was to develop a roller skate bearings cleaning machine prototype for a company HOOG SISSE OÜ. This kind of machine is not commercially available. In collaboration with the company machine requirements were composed:

- Brushless motors shall be used. Flammable liquids for cleaning are used.
- Machine has to fit on the table and use mains voltage.
- Bearing holders are replaceable.
- Inspection window is necessary.
- Semi- automatic solvent replacement system is required.

The development of the prototype of roller skate bearings cleaning machine is discussed in the thesis which consists of:

- Mechanical design of the machine.
- Calculations for the mechanics.
- Motor choice and calculations.
- Schematics and PCB for the control board.
- Program for the microcontroller.
- Washing cycle and dryer descriptions
- Liquid management descriptions.
- Safety notes and recommendations.
- Recommendations for next upgrades.

The author of the thesis is satisfied with the results of the thesis. There will be extensive testing done but most of the machine is ready and the thesis was a good opportunity to document the process of the development of the prototype. There were some difficulties with materials and standards acquiring. All of the difficulties have found solutions and this machine will be tested and developed further outside of the scope of the thesis.

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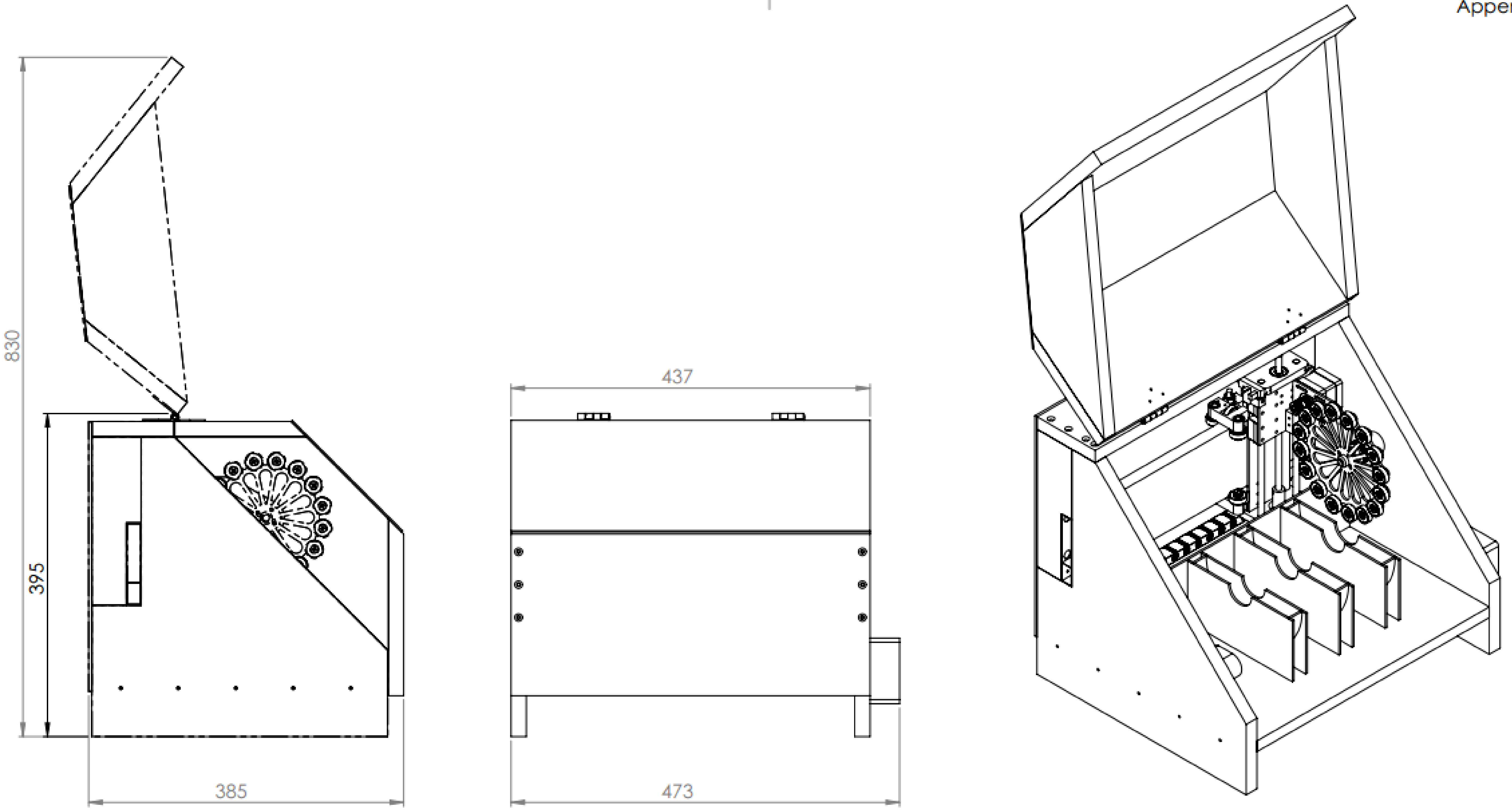
APPENDICES

1. Roller skate bearings cleaning machine assembly overall dimensions.

2. Roller skate bearings cleaning machine schematics.

Appendix 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Lauri Leemet		18.05.16
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

Roller skate bearings cleaning machine overall dimensions

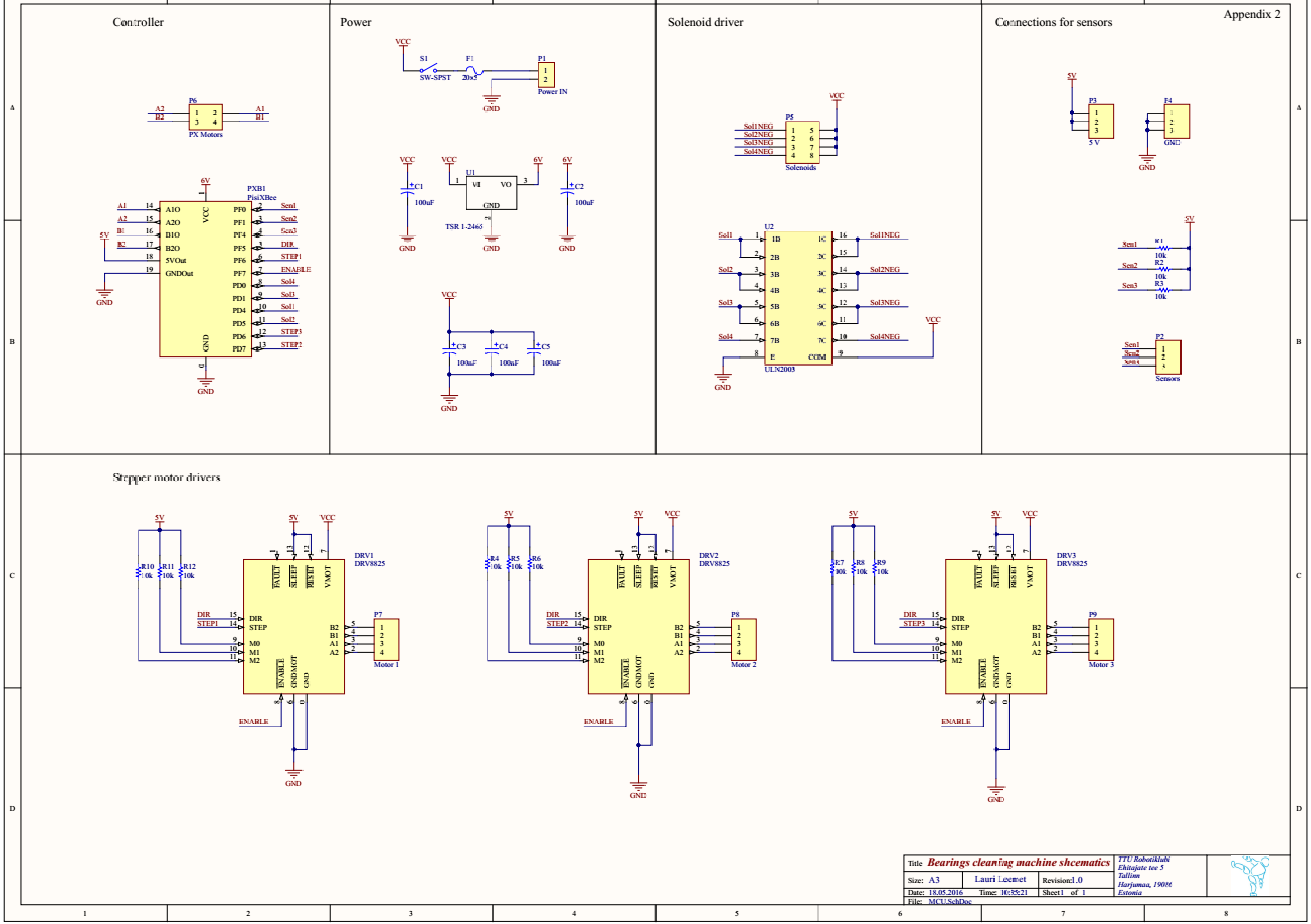
DWG NO. 1

A3

SCALE:1:5

SHEET 1 OF 1

Appendix 2



Controller
Power
Solenoid driver
Connections for sensors
Stepper motor drivers
PX Motors
PXB1
PisiXBee
TSR 1-2465
ULN2003
Solenoids
Power IN
Sensors
DRV1
DRV8825
DRV2
DRV8825
DRV3
DRV8825
Motor 1
Motor 2
Motor 3
Title Bearings cleaning machine shcematics
Size: A3
Lauri Leemet
Revision: 1.0
Date: 18.05.2016
Time: 10:35:21
Sheet 1 of 1
File: MCU.SchDoc
TTU Robotiklubi
Ehitajate tee 5
Tallinn
Harjumaa, 19086
Estonia