



# **Dust Maker a Volcanic Ash Dispersion Unit**

Eiður Örn Þórsson

Thesis of 30 ECTS credits

**Master of Science (M.Sc.) in Mechanical Engineering**

June 2015







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Thesis of 30 ECTS credits submitted to the School of Science and Engineering  
at Reykjavík University in partial fulfillment of  
the requirements for the degree of  
**Master of Science (M.Sc.) in Mechanical Engineering**

June 2015

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## **Abstract**

Ash clouds from volcanic eruptions can be the source of airspace being closed for some time, greatly affecting airtraffic. To predict and analyze the hazard, these conditions need to be simulated in a controlled environment. The primary objective of this thesis is to develop, produce and test a small prototype that is capable of dispersing fine particle volcanic ash in a controlled manner, suitable for use in a volcanic ash plume simulator. The ash sample used for testing came from the 2010 eruption in Eyjafjallajökull. In order to extend the time that the ash particles are suspended in the air, the sample was sifted to a sub 75  $\mu\text{m}$  particle size. The mean particle diameter within that sample is  $\approx 35 \mu\text{m}$ . Experiments were conducted on the sample to determine its angle of repose of  $69^\circ$  and density of  $1098 \text{ kg/m}^3$ . A prototype device was built and several experiments were performed with different feed rates and times, resulting in repeatability in ash output of  $\pm 10.1 \%$  from the nominal value with a confidence level of 99.7 %. This gives reason to investigate the device further and ultimately create a large scale ash plume of concentrations of interest. That ability would further aid the research into “Ash detectors mechanisms” for modern aviation and reduce closed airspace in the event of a similar eruption as in the case of Eyjafjallajökull in 2010.



# Dust Maker

Eiður Örn Þórsson

júní 2015

## Útdráttur

Öskuský frá eldfjöllum geta og hafa lokað loftrýmum sem hafa töluverð áhrif á flugumferð. Til að spá fyrir og rannsaka þessi áhrif er nauðsynlegt að geta endurskapað slíkar aðstæður undir eftirliti. Meginmarkmið verkefnisins er að hanna, smíða og prufa smækkaða frumgerð af apparati sem með stýranlegum hætti er fært um að mata út fínni eldfjallaösku, heppilegri til að herma öskuský. Öskusýnið sem notast er við kemur úr gosinu í Eyjafjallajökli 2010. Til að lengja tímann sem agnirnar hanga í loftinu var sýnið sigtað í kornastærðir minni en  $75\text{ }\mu\text{m}$  en meðalþvermál agna innan þess sýnis er u.þ.b  $\approx 35\text{ }\mu\text{m}$ . Tilraunir voru framkvæmdar á sýninu til þess að ákvarða hvíldarhorn þess,  $69^\circ$ , og eðlisþyngd,  $1098\text{ kg/m}^3$ . Frumgerðin var smíðuð og fjölmargar tilraunir framkvæmdar, bæði með mismunandi mótunarhraða og tíma. Niðurstöður leiddu í ljós endurtæktar mörk miðað við  $99.7\%$  öryggismörk og þrjú staðalfrávik, uppá  $\pm 10.1\%$  í öskuútmötun frá meðalgildi hvernar tilraunarlotu. Þessar niðurstöður gefa tilefni til að rannsaka apparatið enn frekar og að lokum að búa til stórt öskuský, með áhugaverðum öskupéttleika. Sú geta myndi stíðja frekari rannsóknir á öskuskynjurum fyrir flugsamgöngur sem gætu leitt til fækkunar í lokunum lofthelga líkt og þeim meðan gosið í Eyjafjallajökli 2010 stóð yfir.





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.....  
date

.....  
Eiður Örn Þórrson  
Master of Science



*I dedicate this thesis to my family, for their endless support on every level imaginable.*

**CHALLENGE COMPLETED**





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I would like to thank my thesis advisors, Dr. Joseph Timothy Foley and Dr. Þorgeir Pálsson for the challenging project. A big high five goes out to Hrannar Traustason for his mad skills in many fields, Gísli Freyr Þorsteinsson for idea bouncing and input on fabrication, Björgvin Þórhallsson for Dustloop information and Gylfi Árnason for extensive knowledge and help in setting up experiments with the DustMate. Would also like to thank, Amber Grace for keeping things in order in my absence, Guðmundur at Rafloft ehf. and Kristinn Jónsson at REKI ehf. for their insight and help in finding a suitable filter for the job.





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# Chapter 1

## Introduction

On April 14th 2010 a volcano erupted in Eyjafjallajökull Glacier in Southern Iceland. This eruption affected air traffic in Europe heavily for the next few weeks, due to ejected ash particles that could potentially damage jet engines on aircrafts. There are no international regulations regarding maximum ash concentration in the air for aircraft safety. Recommendations have been published by the European Air Safety Agency (EASA) in a Safety information bulletin [1]. There is a global network of nine Volcanic Ash Advisory Centers (VAAC), set up by the International Civil Aviation Organisation (ICAO). The VACC is responsible for gathering, processing and redistributing information on ash clouds that can endanger air traffic. They often incorporate computer simulation models in their ash cloud forecast called volcanic ash advisories (VAA). Studies were done on the distribution and concentration of the ash during that eruption, around Iceland and Germany [2], along with England [3] to name a few. However, ash dispersion forecasts depend on a lot of information [4] and can be improved because after all, they are only forecasts.

### 1.1 Background

Research into ash cloud detectors for aircraft has been under way for some time. EasyJet, Airbus, Nicarnica Aviation and Düsseldorf University did an experiment with the Airborne Volcanic Object Identifier and Detector (AVOID) system in 2013 [5][6]. There they successfully created an artificial ash cloud by releasing 1 t of volcanic ash from an Airbus A400M aircraft that flew in a spiral between 9000 *ft* and 11 000 *ft*. A second Airbus aircraft, fitted with the AVOID system, flew towards the ash cloud and measured it from 60 km away. A Diamond DA42 aircraft from Düsseldorf University equipped with state of the art laser based ash sensors flew directly into the ash cloud to take measurements which could then be compared to the ones made by the AVOID system. In a similar project called Volcanic Ash Detection and Awareness System (VADAS) there is a need to simulate an ash cloud but one where it is possible to control the concentration of ash in it.

### 1.2 Scope

It is this need that we intend to fulfill by making a dispenser mechanism that is capable of dispensing volcanic ash in a controllable manner. This dispenser should have the ability to disperse  $80\text{ }\mu\text{m} \pm 5\text{ }\mu\text{m}$  ash particles at a rate that equvalates ash concentration in a test volume of  $1000\text{ }\mu\text{g}/\text{m}^3 \pm 100\text{ }\mu\text{g}/\text{m}^3$ . Reykjavík University has access to a Piper Pawnee

crop duster airplane that is suitable for intermediate testing of such a device. Therefore it must also fit into that plane and not exceed a weight of  $25 \text{ kg} \pm 1 \text{ kg}$ .

It is also of great interest to have the ability to test, in a controlled environment, ash output by the dispenser with industry standard dust sensors and other non industry standard, and comparing the results from those sensors.



## Chapter 2

# Requirements Definitions Assumptions

### 2.1 Test volume parameters and ash dispensing rate

To be able to start the design process of a dispensing mechanism, parameters that would simulate the volcanic conditions it should be simulating needed to be established. As it is not clear at this point in time what shape or size of an artificial ash cloud is best suited for research. As the aircraft that is to be used has a weight capacity of 545 kg the volume was chosen so there would be some room for expanding it and increasing concentration levels without overshooting the 545 kg. The size of the test volume where a large scale test would be conducted should have the dimensions  $1000\text{ m} \times 100\text{ m} \times 300\text{ m}$  [LxWxH] for a total of  $3 \times 10^7\text{ m}^3$  [7] as depicted in Figure 2.1. Whether the test volume is a box or cylinder in shape is irrelevant as both the speed of the plane and dispensed ash output are constant.

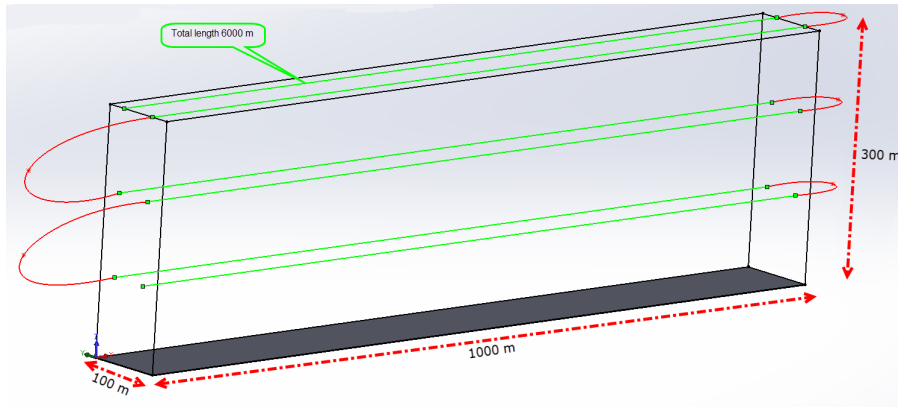


Figure 2.1: Dimensions of the test volume where the full scale test would be performed in with the plane. Green lines are where the dispenser mechanism is on, red lines where it is off. The red lines are not a realistic representation of a flight path

The plane will take off and fly to a given location, there it will fly according to the path shown in Figure 2.1. It will fly the length of the test volume, along the green line and the dispenser mechanism will be dispensing ash. Then make a U-turn where the dispenser will be off, shown as the red line. It will then fly back the full length, parallel the first pass, but at a distance of 50 m. This is because, as shown in Figure 2.2, the dispersion width of ash from the plane is 25 m in each direction, left and right of the plane body [7].

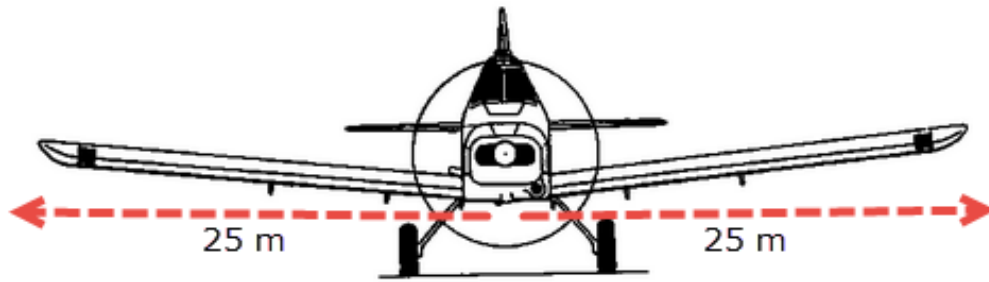


Figure 2.2: Ash dispersion from plane is 25 m in each direction

Once at the end of the parallel pass, the dispenser shuts off and the plane climbs 100 m while making another U-turn. This process is repeated three times to make up the test volume. Whether the 100 m is too much or too little in order to get an even ash concentration in the volume, is beyond the scope of this thesis. The total length of the defined flight path is 6000 m and the speed of the plane while the dispenser is on is 41.1 m/s. Therefore it takes 145.8 s or 2.4 min for the plane to cover it. As a starting point, the ash concentration in the test volume was set as  $1000 \mu\text{g}/\text{m}^3$  [7]. With these definitions, the total ash amount needed to fill the test volume is 30 kg and the dispenser mechanism will have to be able to dispense ash at a rate of 205.8 g/s. Detailed calculations are available in Appendix A.5.

## 2.2 Requirements

### 2.2.1 Dispenser requirements

For practical and financial reasons it is not the intention to build a full size version of the dispenser mechanism, but rather a scaled down model. The requirements for the full scale dispenser mechanism are:

- Ability to dispense volcanic ash with a sub  $80 \mu\text{m} \pm 5 \mu\text{m}$  particle size at a rate that equivalent ash concentration in a test volume of  $1000 \mu\text{g}/\text{m}^3 \pm 100 \mu\text{g}/\text{m}^3$ .
- Not weigh more than  $25 \text{ kg} \pm 1 \text{ kg}$ .
- Fit at the bottom of the hopper on board the Piper Pawnee airplane, not exceeding dimensions  $85 \text{ cm} \times 20 \text{ cm} \times 30 \text{ cm}$  [L x W x H].

### 2.2.2 Test environment requirements

The test environment needs to be something that can be used in an environment like Reykjavík University and therefore the requirements are:

- Must be usable in a classroom so ash must be contained.
- It should be mobile and fit through doors and into elevators at Reykjavík University or not exceed  $250 \text{ cm} \times 80 \text{ cm} \times 200 \text{ cm}$  [L x W x H].
- Setup time from storage to test ready should be  $30 \text{ min} \pm 10 \text{ min}$  for one person.

- It should have the ability to use the DustMate<sup>1</sup> dust detector from Turnkey Instruments Ltd for measuring ash concentration in the environment.

## 2.3 Duster Aircraft

The airplane that will be used for conducting a full scale test is a Piper Pawnee PA-25-235 [8] that is owned by Svifflugfélag Íslands. The Pawnee is seen in Figure 2.3 and is currently located in a hanger at Sandskeið airport just outside of Reykjavík. Based upon previous experience, the cruising speed during dispensing was decided to be 80 kn or 41.1 m/s [7].



Figure 2.3: The Piper Pawnee crop duster airplane is located in a hanger at Sandskeið airport.

The Piper Pawnee was designed as a crop duster and has a built in hopper capable of handling loads up to 545 kg [9]. The hopper has an opening at the bottom with inner dimensions of 82 cm × 20 cm [L x W]. A maintenance illustration of the hopper is available in Appendix A.8, where the opening is marked No.25. This opening is where the dispenser mechanism is to be placed and the height constraint of 30 cm is so that there is still room in the hopper for ash and other things.

---

<sup>1</sup><http://www.turnkey-instruments.com/environment.php?id=21>



# Chapter 3

## Design

### 3.1 Dispenser mechanisms

There were discussions in the beginning of this work on what type of a dispenser mechanism would be appropriate.

- Auger system

To get a feel for how an auger dispenser system would work and behave, an old meat grinder, seen in Figure 3.1 was purchased for 1500 ISK. at a the local thrift shop Góði hirðirinn.

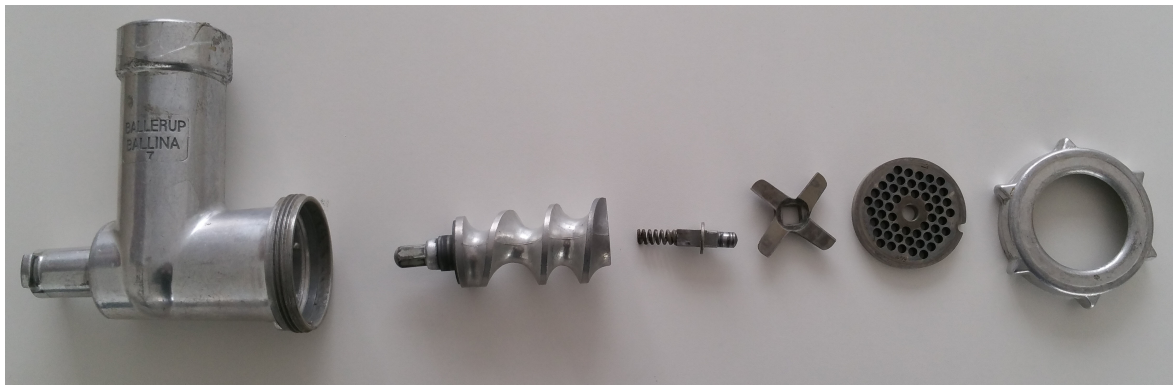


Figure 3.1: The meat grinder used for testing ash dispensing with an auger system

All auger experiments were carried out in the Energy lab at Reykjavík University on October 10th 2014, temperature was  $24^{\circ}\text{C} \pm 1^{\circ}\text{C}$  and humidity was  $52\% \pm 4\%$ . The grinder was placed in a vice and clamped down to a table as seen in Figure 3.2. A coupler that consisted of a 12 mm socket that connected to the grinders auger and a extension from it to a Makita *BHP451RFE* cordless drill. The drill was set to speed setting 1 of 3 and the trigger firmly squeezed all the way back. The speed was determined to be 1.9 revolutions per second (RPS) by the same methods described in (h) in Section 3.3. 150 g of ash was put into the grinder silo and the drill trigger pulled either until the grinder was empty or it jammed.



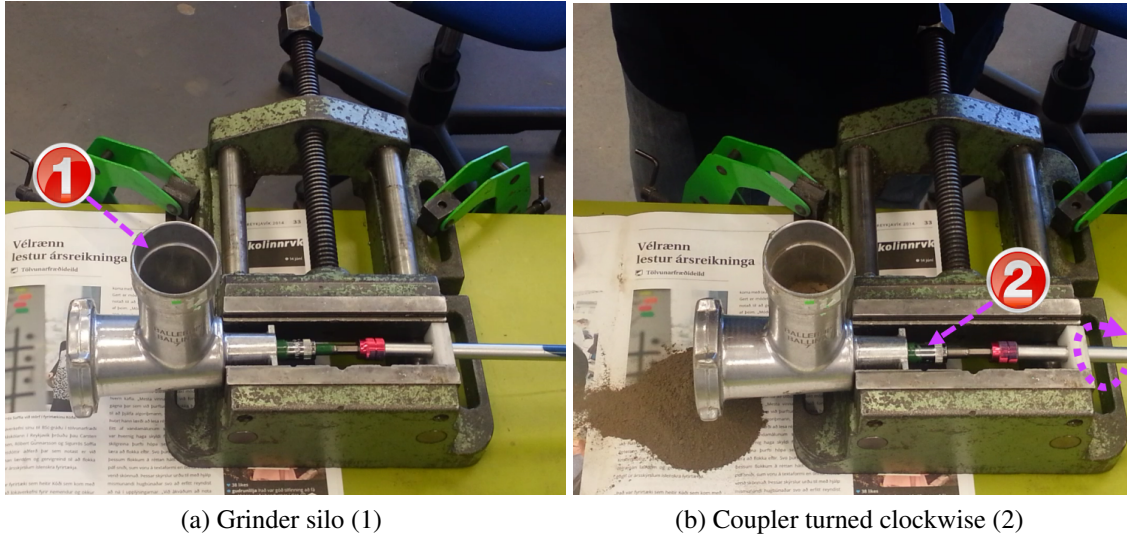


Figure 3.2: Auger system testing setup, ash was put in the silo of the grinder (1) and then the coupling turned clockwise at 1.9 RPS (2) until silo was empty.

A few different variations of grinder plates, seen in Figure 3.3 were tested both with and without the cutting blades installed to try to control the ash output.



Figure 3.3: Different grinder plates tested, cutting blades (1), locknut (2), custom grinding plates (3,4), original grinding plate (5).

Both of the custom plates (3) and (4) in Figure 3.3, jammed within 3 s. This was because the ash compacted to a solid clump behind the plates even with the cutting blades installed. As it was designed with the original grinder plate (5) in mind, the system was able to dispense all the ash put in it, but only with the cutting blades installed. If they were left out, the ash formed a clump like previously. It became apparent that this type of system would not work without redesigning it from the ground up. The wear and tear that the ash would cause to the inside of the grinder housing, the auger itself and the cutting blades was also a concern. That could all be addressed in a redesign, but was deemed non feasible for a few reasons. As we did not posses the

tools needed to fabricate an auger in the machine shop at Reykjavík University at the time, just the manufacturing cost would be much higher than something that we could make ourselves with the current equipment available. In addition, when the system is stopped and started again. A serious flaw with any auger design is that the airstream can draw additional ash even when the auger is not rotating.

- Gunpowder dispenser

People use store bought reloading gunpowder machines <sup>1</sup> as seen in Figure 3.4 to reload used shell casings or their own custom shell casings. It's composed of a silo where gunpowder is stored and some sort of adjustable bin underneath it. The idea is that you adjust the size of the bin to your needs for the casing type that you are going to load. You then pull a handle that spins the bin 180° and dumps the gunpowder into the shell casing. Once you pull the handle back up, the bin spins back to it's original position and gets filled back up with gunpowder, thereby closing the circle. This design never made it to testing due to concerns of getting it to output a steady stream of ash. It's likely going to feed one dash after the other with a gap in between, whether that gap can be reduced or if the gap does not matter at all, remains to be figured out.



Figure 3.4: The gunpowder dispenser considered [10]

- Roller system

A surprising source of inspiration for this design comes from the baking industry. A visit on October 20th 2014 to the local Myllan bakery proved very valuable. There they have processing lines that transport dough from point a to point b and need to keep the dough from sticking to the conveyor belts. A thin layer of flour is sprinkled on the conveyors from a small machine. A diagram is shown in Figure 3.5. It is mobile and can be placed from one side to the other anywhere on the length of the conveyor. An open silo on top contains the flour and guides it towards an opening at the bottom, where a roller turns slowly. The flour output is controlled by the size of the opening in the bottom of the silo.

---

<sup>1</sup><https://http://hlad.is/index.php/netverslun/endurhledsluvoerur/hledsluverkfaeri/vogir-and-skammtarar/lyman-no.-55-purskammtari>.

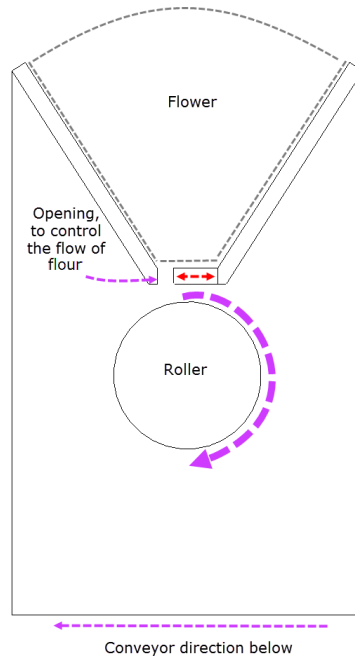


Figure 3.5: Diagram of flour dispenser at Myllan bakery.

Since it was possible to dispense flour with this design, there was a good chance it could be used for dispensing ash with minor changes. This design is what the current dispenser is based on.

### 3.1.1 Scaled down roller design

After some discussions in a project meeting on October 27th 2014, this concept was chosen due to its simplicity and similarity in its current application [11].

As stated before due to practical and financial reasons, it was already decided to make a scaled down version of the mechanism. The scale was determined by the width of the air intake on the test environment. The inner diameter of the tube, where the air enters the test environment and the dispenser mechanism was to be placed, was 56.0 mm. Reason being that the roller length would have to be across the length of the pipe to disperse the ash more and make better use of the airflow amongst other things.

The test environment was going to be made from plexiglass as it is transparent and as that material is nice to work with and can be cut with the laser in the workshop, it was decided to use that for the dispenser as well.

The roller itself is lathed from a 50 mm diameter aluminium 6060 rod. Shown in Figure 3.6 is the rollers total length 66 mm (1) and the length where ash is output 56 mm (2). The blue fuzzy material on each end is a 5 mm strip of carpet, used as an insulator to prevent ash from going between the roller and the side wall of the housing, causing it to jam. The roller was knurled to get an even, rough surface ensuring a good grip with the ash.



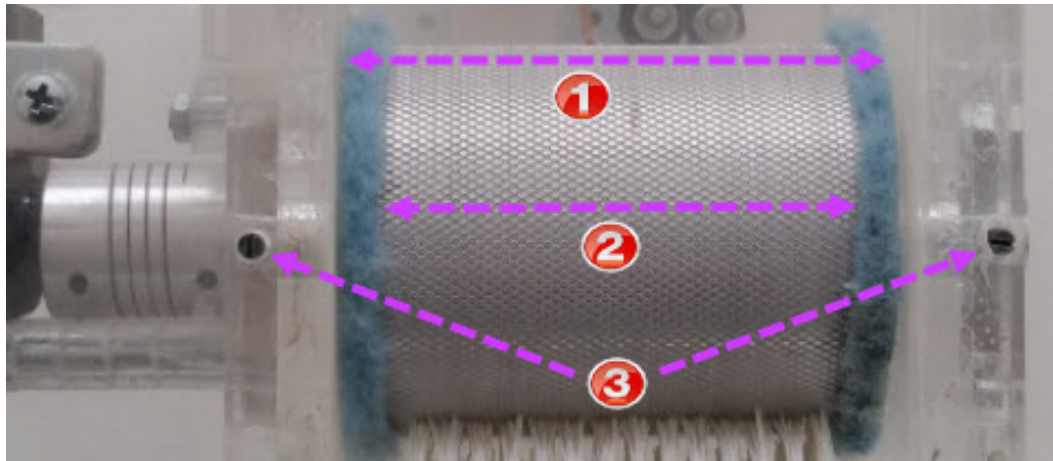


Figure 3.6: Roller dimensions, total length of roller (1), length of ash output (2), gap size adjustment screws (3)

To adjust the gap size (6) for ash output, shown in Figure 3.6 there are two flat head screws (3) on each side of the roller.

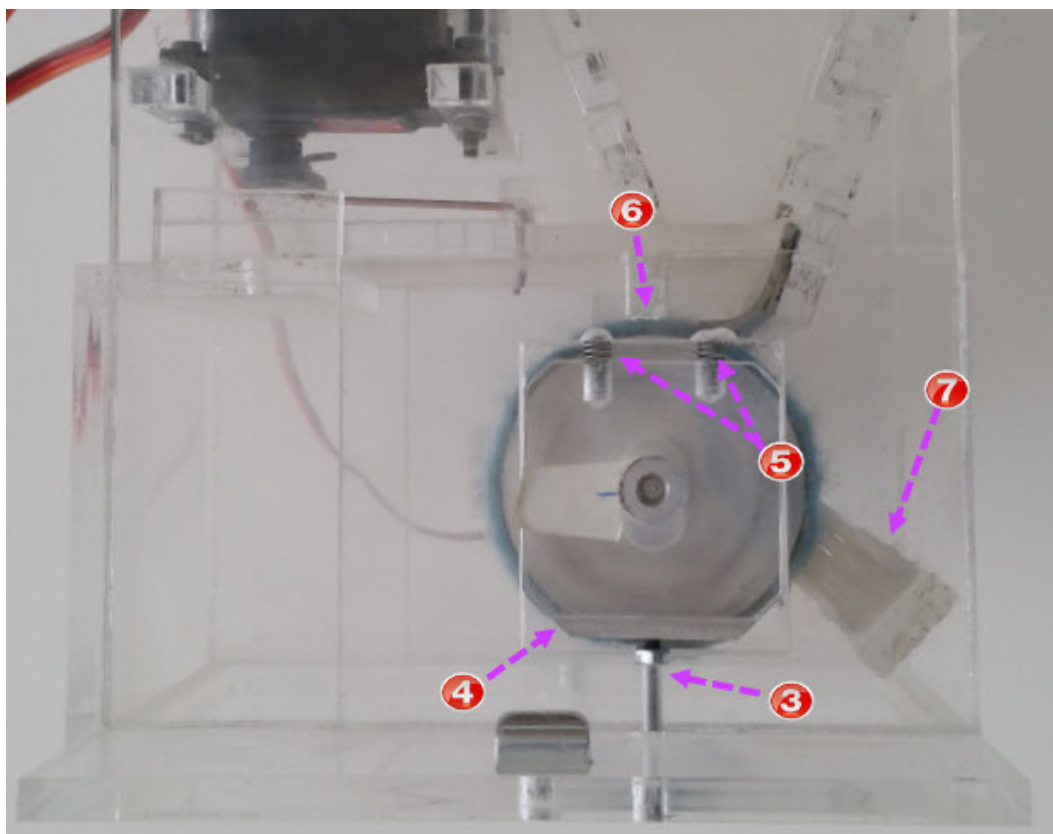


Figure 3.7: How the gap size adjustments work.

In Figure 3.7 is shown gap size width (6). If adjustment screws (3) are turned clockwise, the roller moves up and the gap size (6) decreases, counter clockwise and it increases. The roller is spring loaded (5) and sits on a piece of aluminium (4) on each side. This prevents any wobbling in the roller whether the gap size is set at it's minimum of 1 mm or it's maximum of 7 mm. A hard bristle brush (7) ensures that no ash sticks to the roller surface.

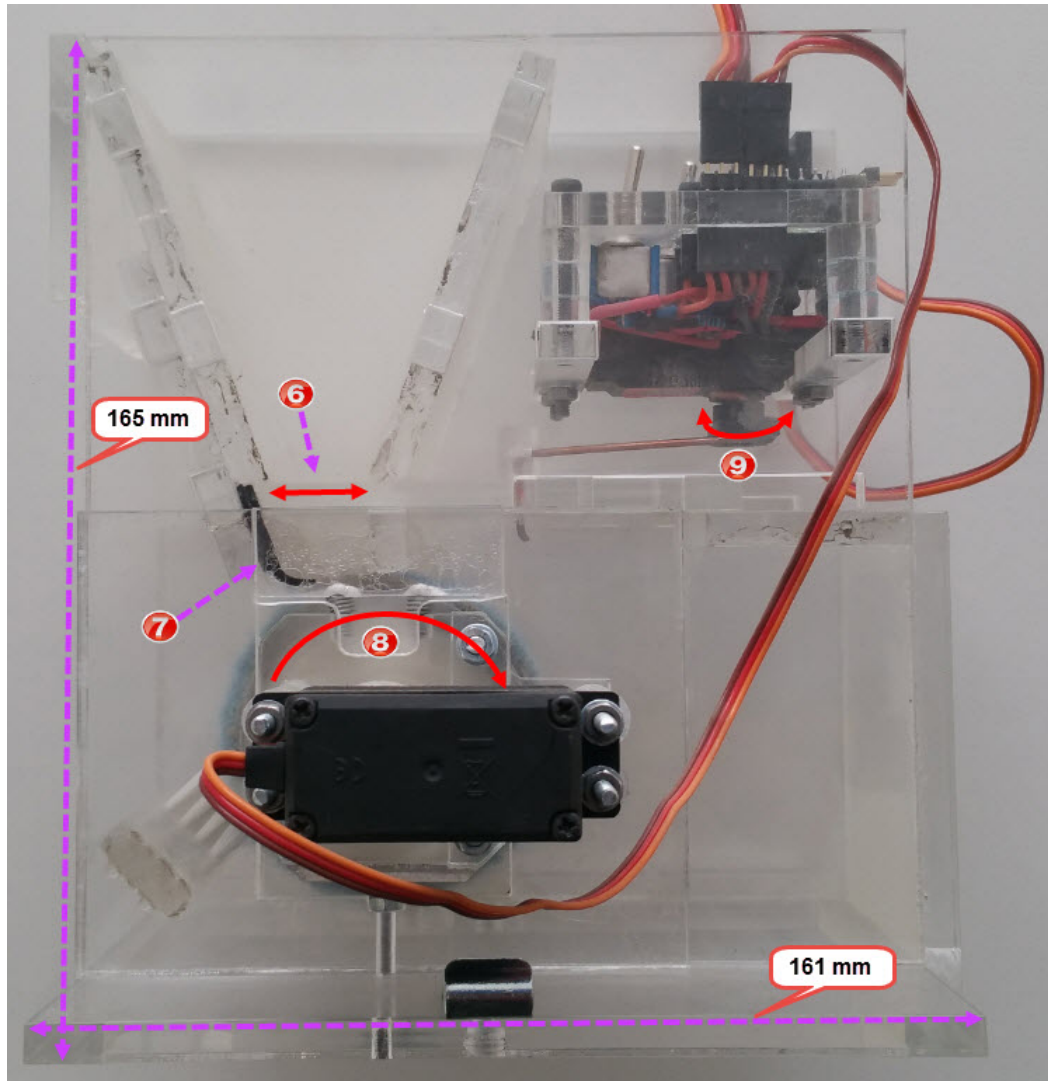


Figure 3.8: Dispenser dimensions and workings

Shown in Figure 3.8 are door (6) at bottom of silo that the servo (9) opens and closes, roller servo (8) and its direction of rotation. There is a rubber flap (7) that prevents the ash from going down the wrong side of the roller when it's on. Dispenser's dimensions are as shown 161 mm  $\times$  165 mm [L x H].

### 3.1.2 Roller control

An Arduino Pro Mini micro controller as seen in Figure 3.9 was used to control the roller mechanism. It was chosen for its small size of 18 mm  $\times$  33 mm, cheap cost of \$10<sup>2</sup>, ease of use and availability. This version of it is running the ATmega328P [12] chip at 5 V and 16 MHz. A detailed schematic of the Pro Mini can be found in Appendix A.12, there is also an easy to read pin-out figure at A.11 where you can see what each pin on the board is designated for with it as reference.

<sup>2</sup><https://www.sparkfun.com/products/11113>

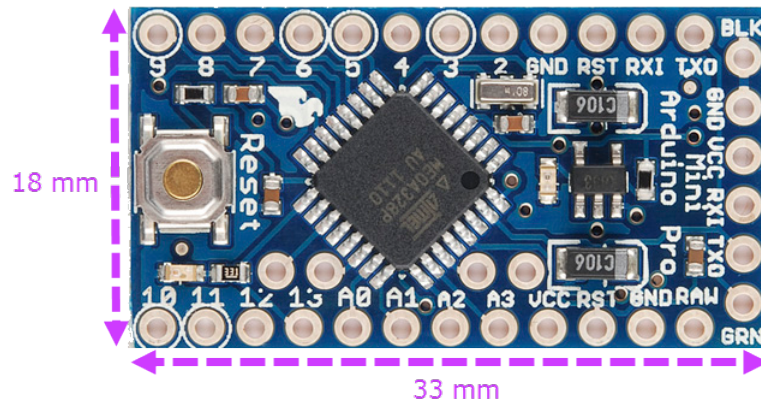


Figure 3.9: Arduino Pro Mini

The first choice was to use an EasyDriver V4.4 [13] stepper motor driver connected to the Arduino micro controller. It was then used to control the speed of the roller via a Mercury stepper motor. A connection diagram can be seen in Figure 3.10 and a schematic in Appendix A.13. The EasyDriver has an Allegro A3967 [14] micro stepping driver on board capable of full, half, quarter and eight step micro stepping. It can drive 4,6 or 8 wire stepper motors of any voltage, which made it a good choice in terms modularization. Precision where one revolution on the motor is split up into 200 steps or  $1.8^\circ \pm 5\%$  increments per step is achievable by having the roller driven by this \$15<sup>3</sup> stepper motor as can be seen in it's datasheet available in Appendix A.15 .

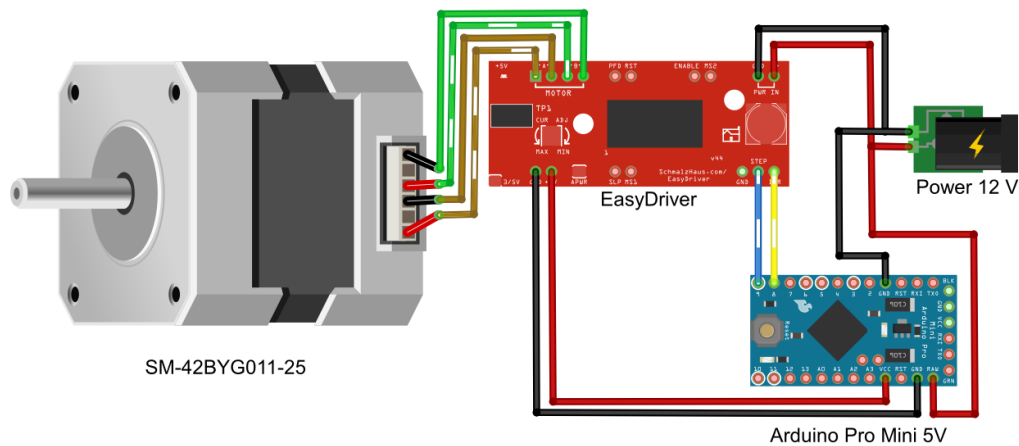


Figure 3.10: Connection diagram of roller control version 1, with the EasyDriver, Mercury stepper motor and Arduino Pro Mini.

This setup did however not work as the stepper motor did not have the necessary torque to turn the roller during preliminary testing of the unit. A larger stepper motor was acquired from Wantai, that was 1.7 A per phase and had a holding torque of 0.48 N m versus 0.33 A and 0.23 N m that of the smaller one. Details on this motor are available in Appendix A.16. A larger stepper driver was implemented as the EasyDriver could not supply the new motor with the needed current. The new driver, a breakout board from Pololu [15] carrying an Allegro A4988 [16] micro stepping driver, was connected to the circuit as shown in Figure 3.11. A schematic is located in Appendix A.14.

<sup>3</sup><https://www.sparkfun.com/products/9238>

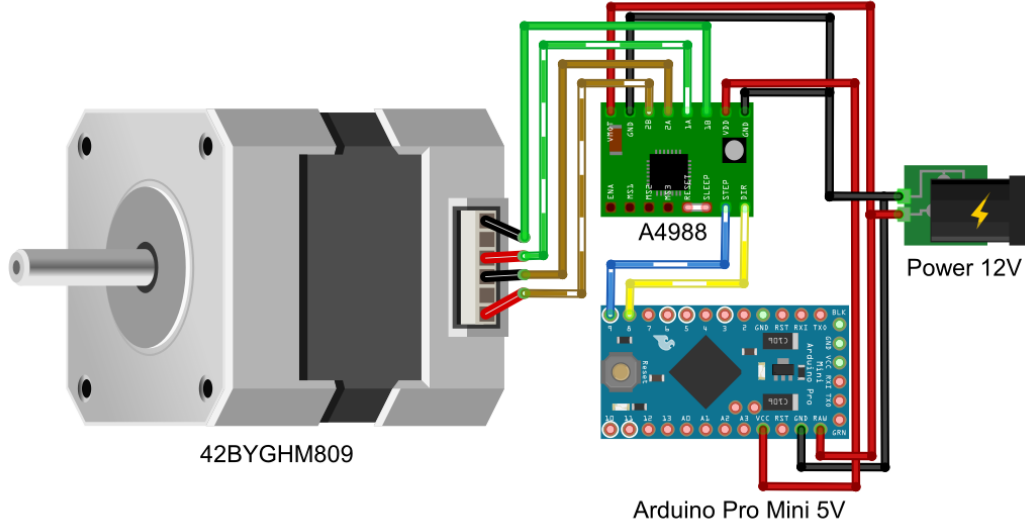


Figure 3.11: Connection diagram of roller control version 2, with the A4988 driver and Wantai stepper motor

In both cases, limiting the current that the stepper driver supplies the stepper motor was crucial to protect the motor. If neglected, the motor could potentially not receive the current it can handle and therefore not output its maximum torque or get too much current and burn itself out.

In order to ensure that the stepper driver supplied the maximum current that the stepper motor could handle a potentiometer (POT) on them had to be set in both cases. This was done before connecting the motor to the driver while it was powered by the 12 V power supply. The procedure was the same for both the EasyDriver and the A4988 stepper drivers, below is the description for the A4988 driver and Wantai motor setup.

It is recommended to limit the current to the motor to 70% or less of the manufacturer's current rating per coil [17]. According to the Wantai motor datasheet in Appendix A.16 then  $I_{max} = 1.7 \text{ A}$  per coil. The board was powered up and a digital multi meter (DMM) used to measure the voltage between reference voltage pin ( $V_{REF}$ ) and the ground connection (GND) as seen in Figure 3.12. By using Equation 3.1 the potentiometer was adjusted with a phillips screw driver until the desired value of  $V_{REF} = 0.476 \text{ V}$  was reached. Detailed calculation available in Appendix A.4.

$$I_{max} = \frac{V_{REF}}{8 R_{sx}} \quad (3.1)$$

Where  $I_{max}$  is the maximum current per coil in [A],  $V_{REF}$  is the reference voltage in [V] and  $R_{sx}$  is the resistance of the sense resistor in [ $\Omega$ ].



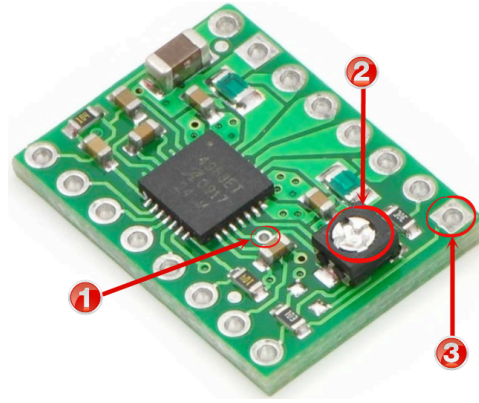


Figure 3.12: Measuring  $V_{REF}$  on the A4988 stepper driver: Place a DMM on pins  $V_{REF}$  (1) and GND (3). Adjust the POT (2) until satisfied

This setup proved unreliable during testing as the roller would turn one minute and then jam the next. The weight of the stepper motors was creating too much friction between the roller and the housing, even though the roller was spring loaded and a flex coupler was used between the motor and the roller. The smallest give in the plexi glass was enough to cause it to jam. In light of this result, it was opted to scrap this type of motor and use a continuous rotation radio controlled (RC) servo instead as they weigh less. As seen in Figure 3.13 there are two types of radio controlled (RC) servos in regards to movement, the more common RC servo which is capable of movement traditionally in the range of  $0^\circ$  -  $180^\circ$  and the continuous rotation RC servos that, can rotate indefinitely at set speed.



Figure 3.13: Standard RC servo (1) vs. Continuous rotation RC servo (2)

The continuous rotation servo (2) shown in Figure 3.13, was used to drive the roller. It was a Power HD  $360^\circ$  analog servo model number AR3606HB. It was run on 6 V where its datasheet, in Appendix A.17, reports holding torque of 0.67 N m at 900 mA. To open and close the door on the bottom of the silo, a Power HD  $180^\circ$  analog servo model number 1501MG (1) in Figure 3.13, was used. It was also running on 6 V and its datasheet, in Appendix A.18, states a stall torque of 1.7 N m at 2500 mA. They were connected as shown

in Figure 3.14. Both servos have proven reliable throughout the testing of the dispenser and have functioned without issues.

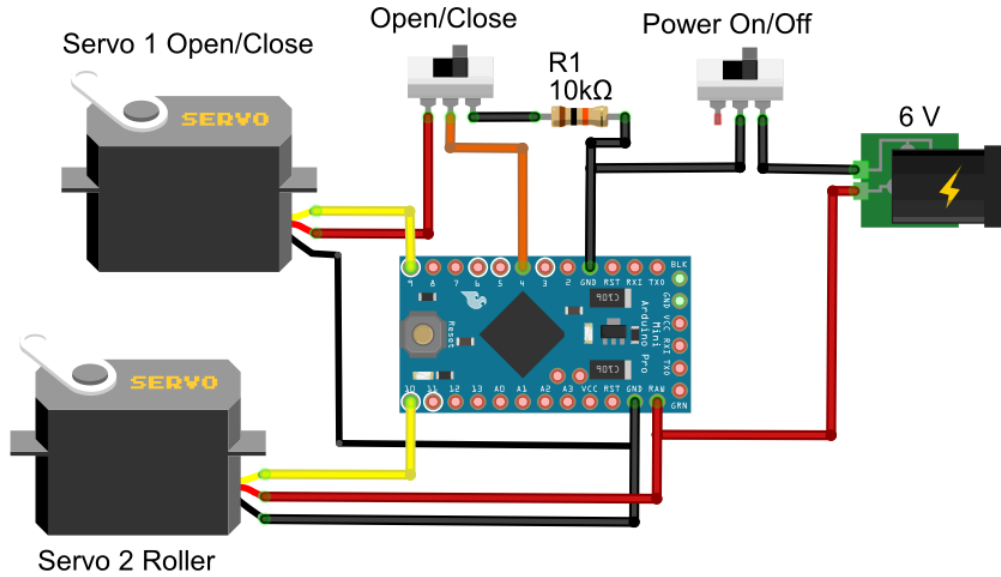


Figure 3.14: Connection diagram of roller control version 3, with the Power HD 360° and the Power HD 180° servos.

The open/close switch (2) shown in Figure 3.15 was there for initial test purposes. It has no function in the final Arduino code in Appendix A.10 where the process has been automated with internal timers in the Arduino Pro Mini micro controller. The control board shown in Figure 3.15 consists of direct current (DC) barrel jack (3) for 6 V in, an on/off switch (1) for the power, Arduino Pro Mini micro controller (4), servo connector (5) for open/close function and servo connector (6) for driving the roller. If for some reason the micro controller or servos need to be replaced, it can be done quickly by hand.

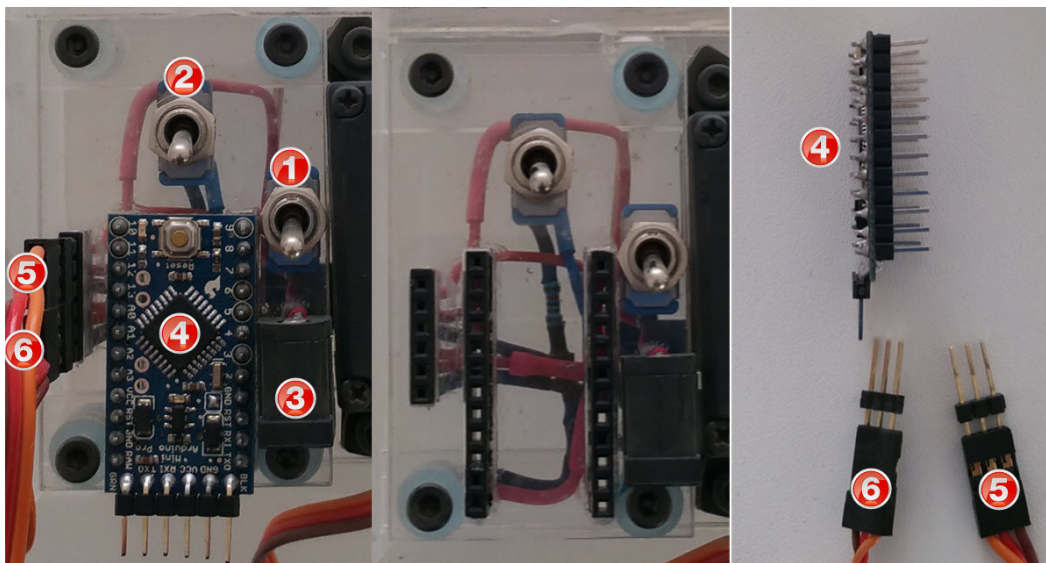


Figure 3.15: Roller control board layout, On/off (1), open/close (2) 6 V in (3), Arduino Pro Mini (4), servo 1 (5), servo 2 (6).

## 3.2 Characterizing the ash

In order to design some sort of ash dispensing mechanism, the ash needed to be examined. One pile of ash isn't the same as the next pile of ash. As stated before in chapter 1, volcanic eruptions of the same type as the Eyjafjallajökull eruption in 2010 are of great interest, mainly because of the potential threat that the ash plume poses to modern aviation. The ash used in the project came from the eruption at Eyjafjallajökull in 2010 which Reykjavík University had previously acquired for a similar project called Dustloop [18]. The total amount of ash on hand was weighed in at  $5.515 \text{ kg} \pm 0.027 \text{ kg}$ .

### 3.2.1 Sifting

Ash retrieved from Eyjafjallajökull contains particles of all shapes and sizes as one would expect. Different particle weights cause the larger ones to fall faster to the ground than the smaller ones. Our interests lie with creating an ash cloud replicating the eruption conditions and the particle ratio was recalibrated to match that of airborne ash as closely as possible. This served two purposes; the first was that the amount of ash needed to achieve the concentration of interest would be less as smaller particles stay in the air for longer than larger ones. This reduces the weight of the ash that would have to be loaded on to the aircraft for dispersion. Secondly, this increases repeatability from a dispenser mechanism by having the ash more homogeneous [19]. To identify the sizes and their proportion, the ash was separated using sieves.

Sifting was carried out on October 13th 2014 in the Civil engineering lab at Reykjavík University. Temperature was  $25^\circ\text{C} \pm 1^\circ\text{C}$  and humidity was  $53\% \pm 4\%$ . The sieves used were laboratory test sieves from the English manufacturer Endecotts LTD. They comply with the American Society for Testing and Materials (ASTM) standard ASTM E11:15 [20]. There were 9 sieves used with a diameter of 200 mm and mesh sizes ranging from 16 mm to  $75 \mu\text{m}$  as seen in Figure 3.16. A full list of the sieves used in the process can be seen in Table 3.1.

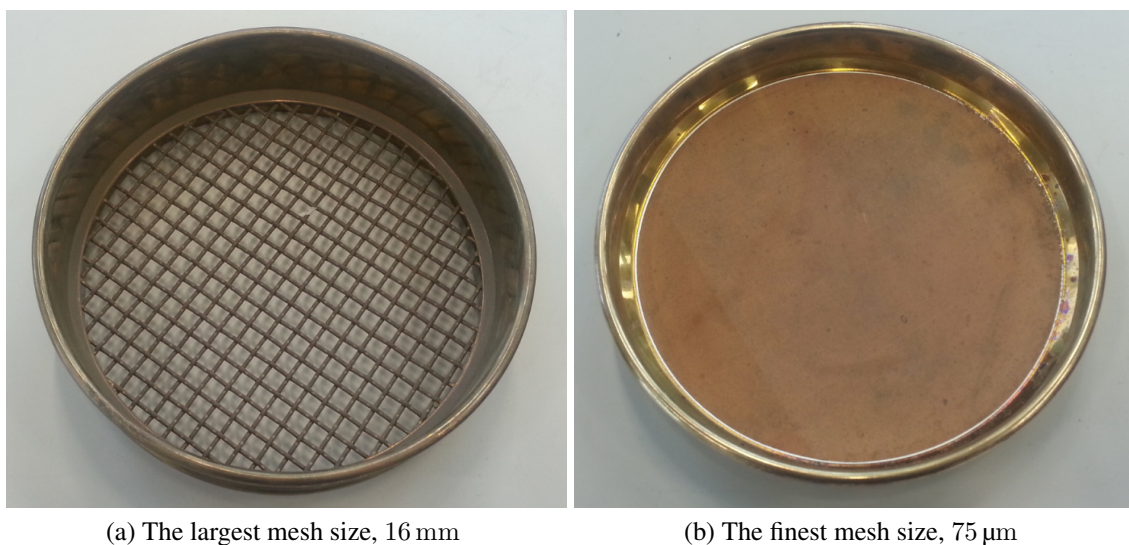


Figure 3.16: Difference in the largest and the smallest mesh sizes used to sift the ash



The sieves stack on top of each other as can be seen in Figure 3.17. The Largest mesh size is on top of the stack and the smallest on the bottom. Under it is a container that is shaped like the sieves and the particles smaller then  $75\ \mu\text{m}$  end up there.



Figure 3.17: The 9 stackable sieves used for sifting the ash, along with the bottom container where particles less than  $75\ \mu\text{m}$  end up.

Table 3.1: Aperture size, mesh and serial number of sieves used for sifting the ash.

<i>Aperture</i>	<i>Mesh no.</i>	<i>Serial no.</i>
16 mm	5/8	224 376
8 mm	5/16	237 768
4 mm	5	239 128
2 mm	10	240 804
1 mm	18	240 804
500 $\mu\text{m}$	35	240 804
250 $\mu\text{m}$	60	240 807
125 $\mu\text{m}$	120	240 807
75 $\mu\text{m}$	200	240 806

### 3.2.2 Sifting procedure

An empty 200 ml paper cup placed on a large digital scale and tared.  $100\ \text{g} \pm 5\ \text{g}$  of ash weighed and poured slowly into the top sieve. The whole stack is shaken for 1 min and the particles fall down the stack, thereby separating them into categories that correspond with



each mesh size that is in the stack. The stack is then disassembled and the ash in every sieve is put in a tray as seen in Figure 3.18. This process was repeated until all the ash had been sifted. Each tray was then weighed and recorded. Results can be seen in Table 3.2 and graphically in Figure 3.19.



Figure 3.18: Trays that the ash groups were put into

Table 3.2: Particle distribution in the ash sample used in the project

<i>Mesh size</i>	<i>Particle sizes</i>	<i>Weight (g)</i>	<i>% of total</i>
16 mm	>16 mm	125 ± 6	2.3
8 mm	8 mm to 16 mm	480 ± 24	8.7
4 mm	4 mm to 8 mm	515 ± 26	9.3
2 mm	2 mm to 4 mm	610 ± 31	11.1
1 mm	1 mm to 2 mm	780 ± 39	14.2
500 μm	0.5 mm to 1 mm	640 ± 32	11.6
250 μm	250 μm to 500 μm	535 ± 27	9.7
125 μm	125 μm to 250 μm	595 ± 30	10.8
75 μm	75 μm to 125 μm	535 ± 27	9.7
	<75 μm	695 ± 35	12.6
		5510 ± 276 <sup>a</sup>	100

<sup>a</sup> 5 g of ash got misplaced during sifting

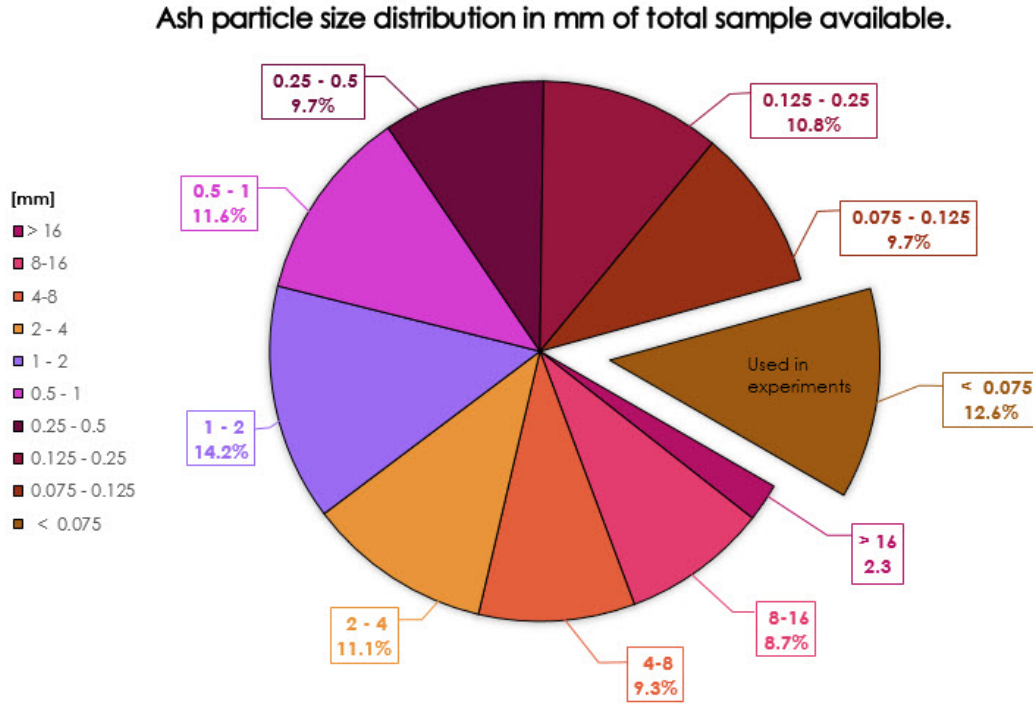


Figure 3.19: A graphical presentation of the size distribution within the  $5.515 \text{ kg} \pm 0.027 \text{ kg}$  of ash available for the project

As can be seen in Figure 3.19 roughly 12 % of the total ash available will be used in this project.

### 3.2.3 Angle of repose

Now that the ash had been sifted and everything larger than  $75 \mu\text{m}$  discarded, little was known about fine powderlike ash that was to be used in the dispenser mechanism. The angle of repose (AoR) measures the angle of inclination of a bulk solid pile, in this case an ash pile, to the horizontal plane on which it rests as seen in the schematic in Figure 3.20. This test is simple to perform and gives insight into some of the primary properties of the ash, like friction between particles [21]. It has also been used to characterize the flow behavior of powders [22]. The container that is on board the aircraft is shaped like a funnel at the bottom to avoid jamming [23]. The dispenser mechanism will also have inclined walls that will direct the ash from the container walls towards the center into the mechanism itself. If the inclination of these walls is not steep enough, that is the AoR is not large enough, the ash will not flow freely towards the center of the container. Especially when the amount is low. The AoR is given by:

$$\alpha := \arctan \left( \frac{H_{ash}}{0.5 D_{ash}} \right) \quad (3.2)$$

Where  $\alpha$  is the AoR in  $^\circ$ ,  $H_{ash}$  is the height of the ash pile in [mm] and  $D_{ash}$  is the diameter of the ash pile in [mm]. Detailed calculations can be found in Appendix A.1. The AoR is  $69^\circ \pm 1^\circ$ , so as long as the inclination of the container walls at the bottom of the hopper and the dispersion mechanism are  $>69^\circ \pm 1^\circ$ , the ash will freely flow down them towards the mechanism.

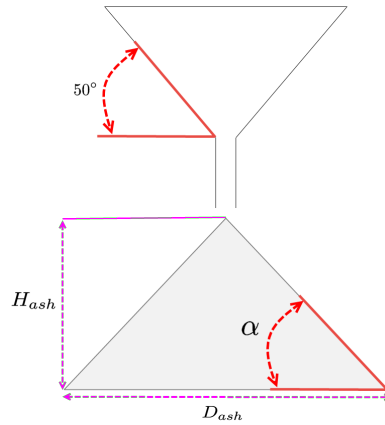
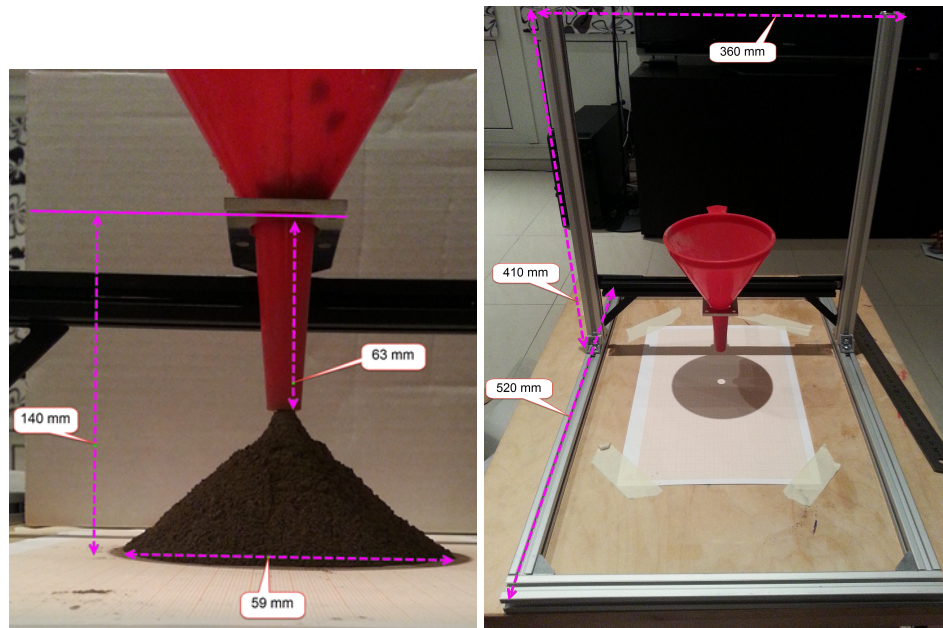


Figure 3.20: Angle of repose schematic

### 3.2.4 Angle of repose experiment procedure

A test rig was built out of 25 mm x 25 mm aluminium extrusion. Dimensions and setup of the rig are shown in Figure 3.21b. A piece of graphing paper was taped down as seen in Figure 3.21b and a small  $X$  marked in the middle of it. The rig was then positioned over the paper so that the funnel opening was over the  $X$ . This was to ensure that the pile of ash would fit within the dimensions of the graphing paper. The opening at the funnel bottom measured at  $10.00 \text{ mm} \pm 0.01 \text{ mm}$  and its walls formed an angle of  $50^\circ$  with the horizontal plane as seen in Figure 3.20. For consistency, a small household sifter with ash in was held in place just above the funnel with one hand. Then the sifter was tapped with the other hand, using one finger and having 1 s between taps. The experiment was stopped when the ash pile below was just about to reach the funnel exit as seen in Figure 3.21a. Once finished, the rig was carefully removed without disturbing the ash pile. A 0.3 mm pencil was used to draw a dotted outline of the pile and the ash was put back into a container. Then using a compass, a circle was drawn that represented the mean value radius of the ash pile after taking into account all the dotted lines on the paper as seen in Figure 3.22. The experiment was conducted at Heiðarlundur 19, Garðabær on November 23rd 2014 and repeated five times. The temperature was  $20^\circ\text{C} \pm 1^\circ\text{C}$  and humidity  $40\% \pm 4\%$ . Results are presented in Table 3.3.



(a) Angle of repose results example. (b) Angle of repose rig setup and dimensions.

Figure 3.21: Angle of repose experiment overview

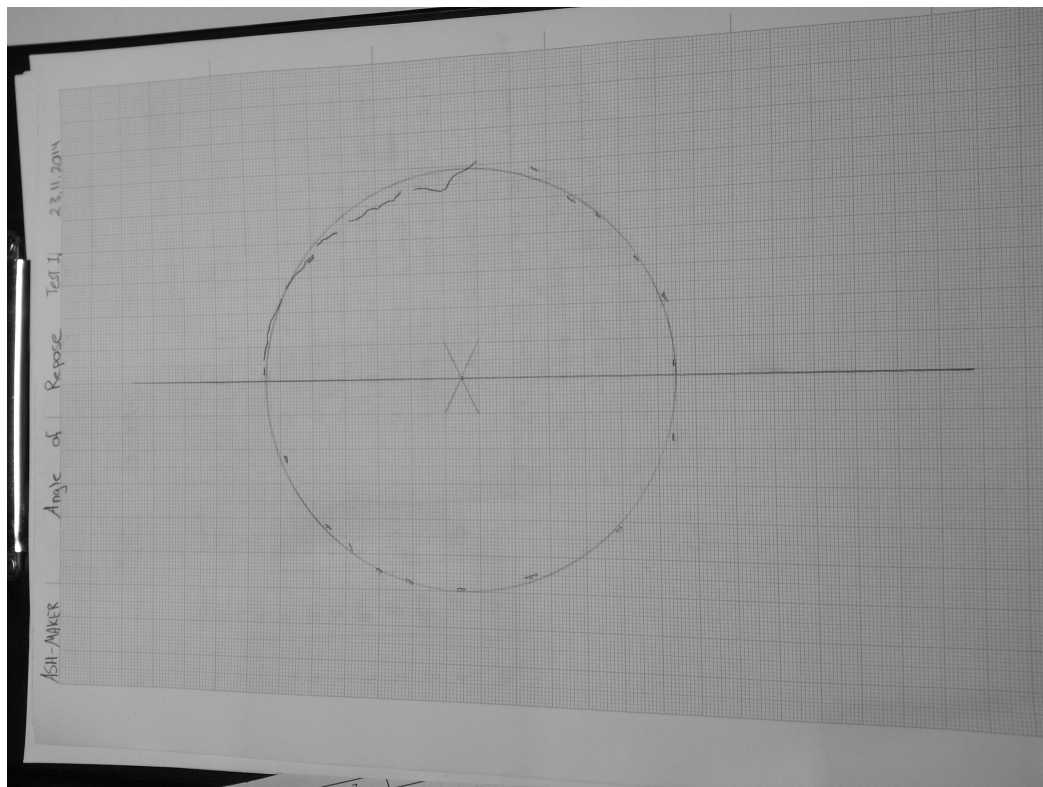


Figure 3.22: Example of the mean value radius of ash pile from AoR experiment.



Table 3.3: Measured diameter of ash piles from AoR experiments

Test #	Ash dia ( <i>mm</i> )
1	$59 \pm 2$
2	$60 \pm 2$
3	$61 \pm 2$
4	$57 \pm 2$
5	$59 \pm 2$
$\overline{59.2 \pm 2.0^a}$	

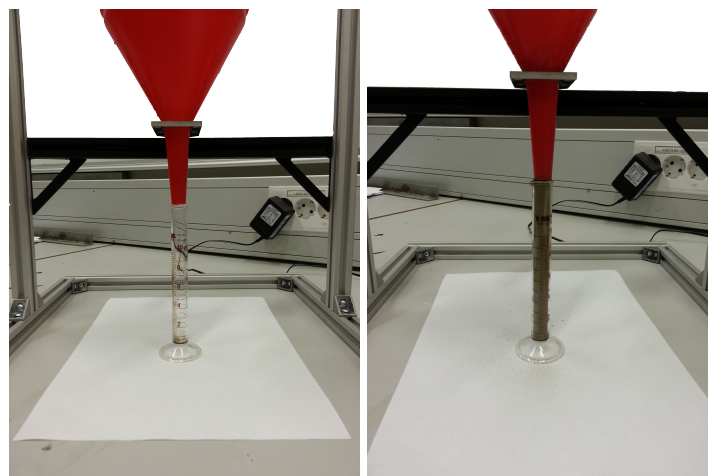
<sup>a</sup> Average of measurements taken

### 3.2.5 Ash density

As dispensers use volume rates for measuring quantity the density of the sifted ash was needed. During a weekly project meeting on November 11th 2014 [24]. A few ideas on how to achieve this were discussed. The simplest way was determined to weigh several times a known volume of ash, in two separate states representing the extremes. Compacted to a certain extent and then when naturally filled or unpacked as possible. Therefore getting each end of the spectrum and an average value from all the samples.

### 3.2.6 Ash density experiments procedure

The rig from Section 3.2.3 was also used for this experiment. It was carried out on December 1st 2014 in the Energy lab V-217 at Reykjavík University. The temperature was  $24^\circ\text{C} \pm 1^\circ\text{C}$  and humidity  $53\% \pm 4\%$ . The vertical bar holding the funnel was raised to  $202\text{ mm} \pm 1\text{ mm}$  so that a  $10.0\text{ ml} \pm 0.2\text{ ml}$  graduated cylinder (Gc) could be placed under it as seen in Figure 3.23 .



(a) Initial setup of unpacked experiment. (b) Gc filled with ash, then weighed.

Figure 3.23: Setup of ash density testing

For consistency, the same method used in the AoR experiment in Section 3.2.3 to deliver the ash into the funnel was done in the loose half of the experiment as seen in Figure 3.23b. The experiment was stopped when the ash had filled the Gc, the rig was removed and a flat wooden stick was dragged over the top of the Gc starting from the side without the spout and towards it. This resulted in an even, flat surface of ash in the Gc every time. It was then weighed and this was repeated ten times. When doing the compressed half of this experiment, the rig was not needed. Instead, the Gc was placed on a digital heavy duty scale and filled with ash.

A lathed piece of polyoxymethylene (POM) that was 0.1 mm less in diameter than the inner diameter of the Gc was then used to press down on the ash and compress it. The scale was tared with the Gc full of ash and the POM pressed until the scale read  $15.0 \text{ kg} \pm 0.8 \text{ kg}$ , the equivalent of  $147.0 \text{ N} \pm 7.3 \text{ N}$ . This was repeated until the Gc was full and then the flat wooden stick was used as in the loose half of the experiment and it weighed. The compressed experiment was also done ten times.

Results for both compressed and loose experiments are presented in Table 3.4. The Gc has a volume of  $14.1 \text{ ml} \pm 0.2 \text{ ml}$  where the average weight of the ash is  $15.50 \text{ g} \pm 0.03 \text{ g}$  with a standard deviation of  $2.50 \text{ g} \pm 0.03 \text{ g}$ . It is concluded that the density of the ash used is  $1098 \text{ kg/m}^3 \pm 0.018 \text{ kg/m}^3$ . Detailed calculations are available in Appendix A.2 and Appendix A.3.

It should be noted that even if these calculations are off by 50 %, the dispenser still outputs the same physical amount of ash as before, only the weight of it changes and therefore the concentration as well. That issue would be fixed by adjusting the gap size and/or speed of the dispenser mechanism accordingly.

### 3.2.7 Ash output testing procedure

1. Setup scale on table and center bubble on it, by adjusting each of the four legs up or down. Plug in and power on.
2. Place paper on scale, weight registered at 2 g, tare scale.
3. Place empty container on scale and tare.
4. Carefully pour, depending on the settings of the dispenser, 160 g to 200 g of ash into the container and keep for later use.
5. Place empty plexiglass container on scale, weight registered at 160.7 g, tare scale.
6. Lift dispenser assembly scale-overhang plexiglass structure and place over scale so that it looks as seen in Figure 3.24, take care to ensure that the container already on the scale does NOT touch the structure. There should be around 1 mm clearance on all sides as seen in Figure 3.25, this ensures that structure will not distort the scale reading during testing and keeps the mess down.

Table 3.4: Results from unpacked and packed ash experiments.

Weight (g)		
#	Unpacked	Packed
1	13.1	17.9
2	12.8	18.1
3	12.8	18.0
4	12.5	18.1
5	12.8	17.9
6	13.0	18.0
7	12.9	18.1
8	12.9	18.0
9	13.0	18.0
10	13.1	18.0
$\overline{12.9^a}$		$\overline{18.0^a}$
$\overline{15.5^b}$		

<sup>a</sup> Ave. of measurements

<sup>b</sup> Total average weight



Figure 3.24: Dispenser testing, only proceed with testing when the scale is stable and the corresponding circle lights up to indicate that (1).

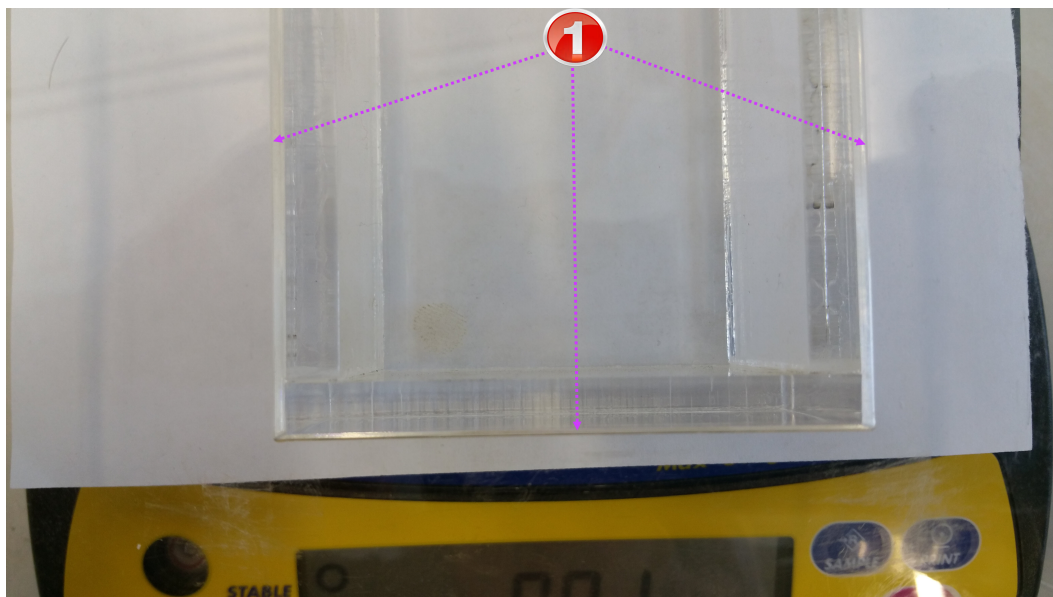
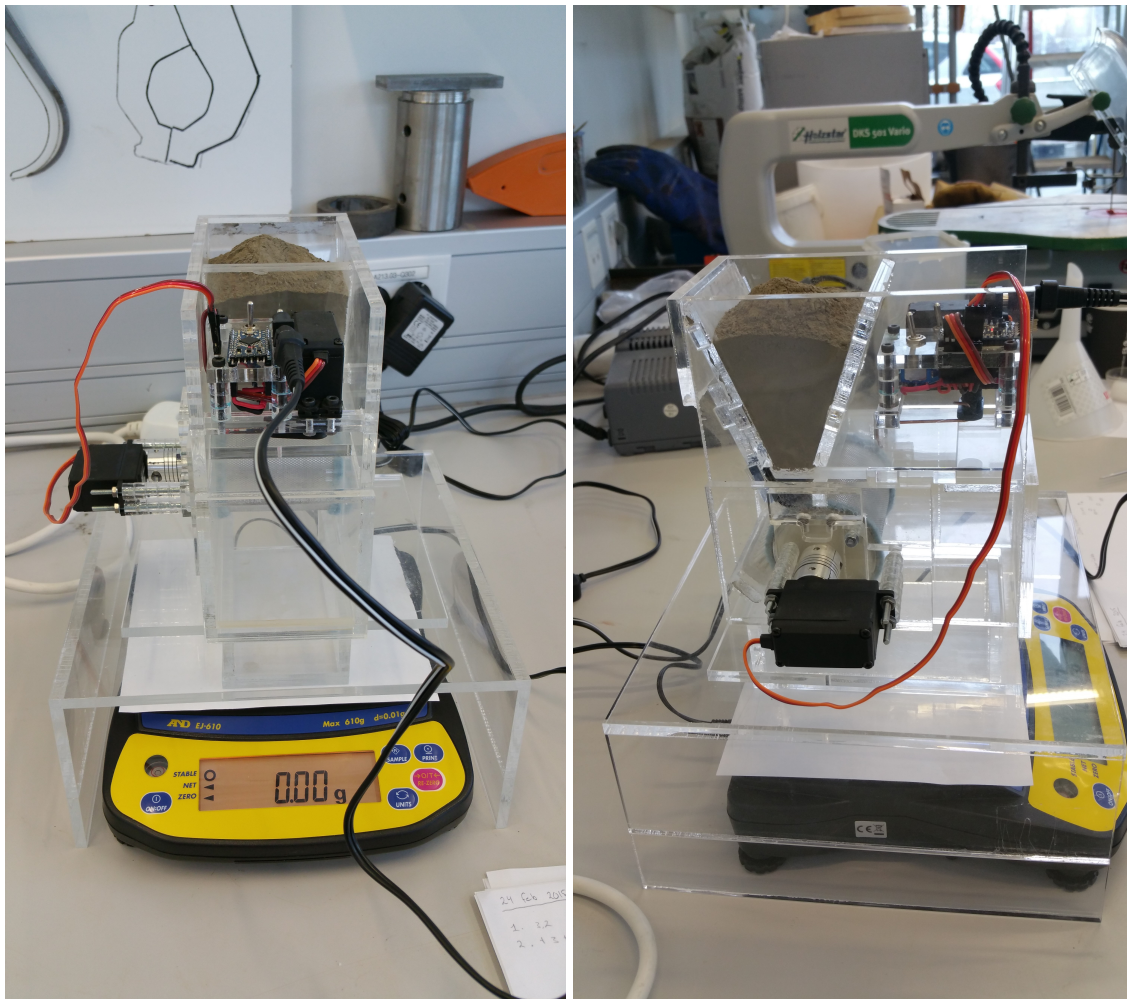


Figure 3.25: Ensure that there's a 1 mm gap around the container so that it is not touching the scale-overhang (1)

7. Carefully pour the earlier weight 160 g to 200 g of ash into the dispenser silo so that setup looks as seen in Figures 3.26a and 3.26b.



(a) Front view of test setup ready to go

(b) Side view of test setup ready to go

Figure 3.26: This is what the setup should look like before each test

8. Plug in the Dispenser assembly and flip on/off switch (1) shown in Figure 3.15 to power on, if scale is stable then flip the power switch on to start test procedure as described in the Arduino code in Appendix A.10. If scale is off by more than 0.5 g, check if support structure has moved and is touching the container underneath.
9. Once test procedure has finished and everything is stopped, flip switch two to reset procedure and carefully lift Dispenser assembly off the support structure. Clean it with pressurized air without oil, spray air everywhere possible until visual ash residue is not present. It is suggested that this procedure is done outside or at least in a well ventilated area as the fine ash particles will settle everywhere and make a mess. It is recommended to use suitable respiratory protection masks throughout the whole testing phase though especially in this step.
10. Remove dispenser assembly structure and take scale reading, then empty the ash container and clean with pressurized air as done with the Roller assembly.
11. Repeat procedure as necessary.



### 3.3 Engineering approximations of error and uncertainty in experiments

As with all experiments, there is error and uncertainty (E&A) when taking measurements. All instruments used in experiments are listed in Section 3.3.1 with their resolution, repeatability and accuracy where available. General procedures on video processing along with temperature and humidity measurements are located in Section 3.3.2. In Section 3.3.3 are all experiments listed with the E&U's involved in each one accompanied by how the result of the total E&U is combined. Where statistics are applied, the following functions are used, both in Microsoft Excel 2013 and PTC MathCAD Prime 3.0. It is assumed that samples follow a normal distribution curve.

- i) Average or mean value (AVERAGE).

Used to get an impression of the expectation  $\hat{\mu}$ , the average value of the sample, by dividing the sum of all samples by the number of samples as shown in Equation 3.3 below

$$\hat{\mu} = \bar{X} = \frac{\sum_{i=1}^{i=n} X_i}{n} \quad (3.3)$$

Where  $\hat{\mu}$  is the average value of the sample,  $n$  is the number of samples taken.

- ii) Standard deviation of the sample (STDEV.S).

Used to give an idea on how close all of the samples stray from the average sample found with Equation 3.3. As we are dealing with all the results from a particular experiment, but not all that could have been done, we use the standard deviation of a sample also known as  $n - 1$  method and not the standard deviation of a population.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{i=n} (X - \bar{X})^2}{(n - 1)}} \quad (3.4)$$

Where  $\sigma$  is the standard deviation of the sample,  $\bar{X}$  is the sample mean from Equation 3.3 and  $n$  is the total number of samples.

- iii) Standard deviation of the mean also known as standard error of the mean.

Is used to give an indication of the uncertainty involved in the standard deviation in Equation 3.4 with regards to the size of the sample. The relationship between sample standard deviation  $\sigma$  and the standard error of the mean  $\sigma_{\bar{X}}$  shown in Equation 3.5, has an important feature. As the sample size increases,  $\sigma_{\bar{X}}$  will decrease while change in  $\sigma$  will be less noticeable.

$$\sigma_{\bar{X}} = \frac{\sigma_X}{\sqrt{n}} \quad (3.5)$$

Where  $\sigma_{\bar{X}}$  is the standard error of the mean,  $\sigma$  is the standard deviation of the sample and  $n$  is the number of samples taken.

### 3.3.1 Instruments

The same instruments were used throughout the duration of the project in regards to taking measurements. When referring to a specific instrument in the remainder of the text the instruments corresponding letter is used. The instruments were:

a) Mitutoyo No (500-672) digital calipers

- Resolution 0.01 mm
- Repeatability 0.01 mm
- Accuracy  $\pm 0.02$  mm

b) A&D *EJ-610* digital scale, small

- Weight capacity 610 g
- Resolution 0.01 g
- Repeatability 0.01 g
- Accuracy  $\pm 0.03$  g

c) Electronic programmable charging scale *RCS-7040* digital scale, large

- Weight capacity 100 kg
- Resolution 0.005 kg
- Accuracy  $\pm 0.5\%$  of reading

d) Aluminium meter stick

- Length 1.000 mm
- Accuracy  $\pm 0.5$  mm

e) Endecotts laboratory test sieves

- Accuracy  $\pm 1\%$  of weighed sample

f) Graduated measuring cylinder 10 ml *E-MIL 244-074*

- $\pm 0.2$  ml

g) Anemometer, Extech model 45158

- Windspeed
  - Range 0.5 m/s to 28 m/s
  - Resolution 0.1 m/s
  - Accuracy  $\pm 3\%$  reading + 0.2 m/s
- Temperature
  - Range  $-18^{\circ}\text{C}$  to  $50^{\circ}\text{C}$
  - Resolution  $0.1^{\circ}\text{C}$
  - Accuracy  $\pm 1^{\circ}\text{C}$
- Relative humidity

- Range 10 % to 95 %
- Resolution 1 %
- Accuracy  $\pm 4$  %

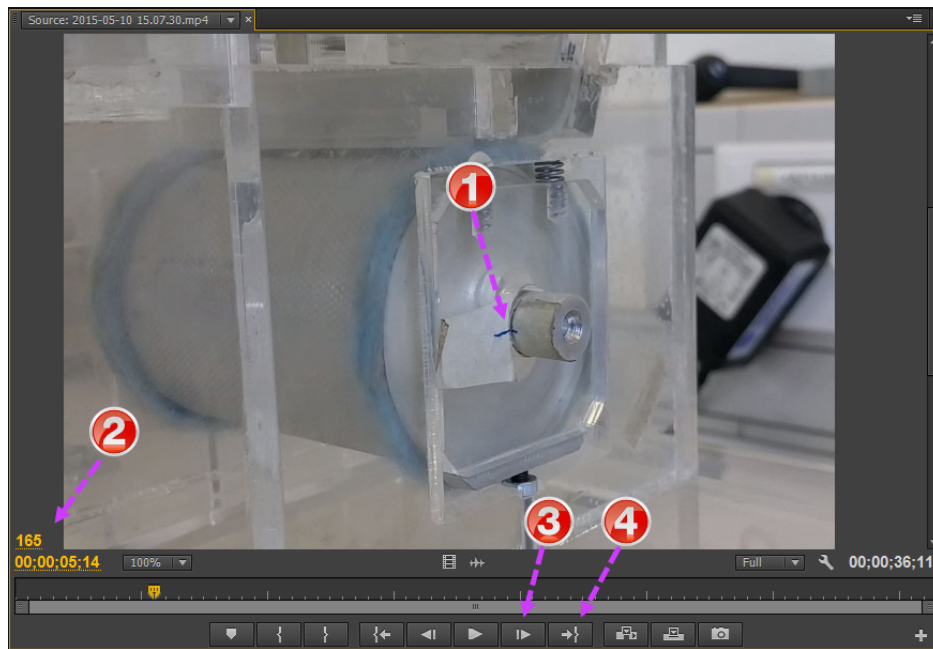
h) Video camera, Samsung Galaxy Note 4

- Resolution  $\pm 1/30$  s
- Accuracy  $\pm 1/30$  s

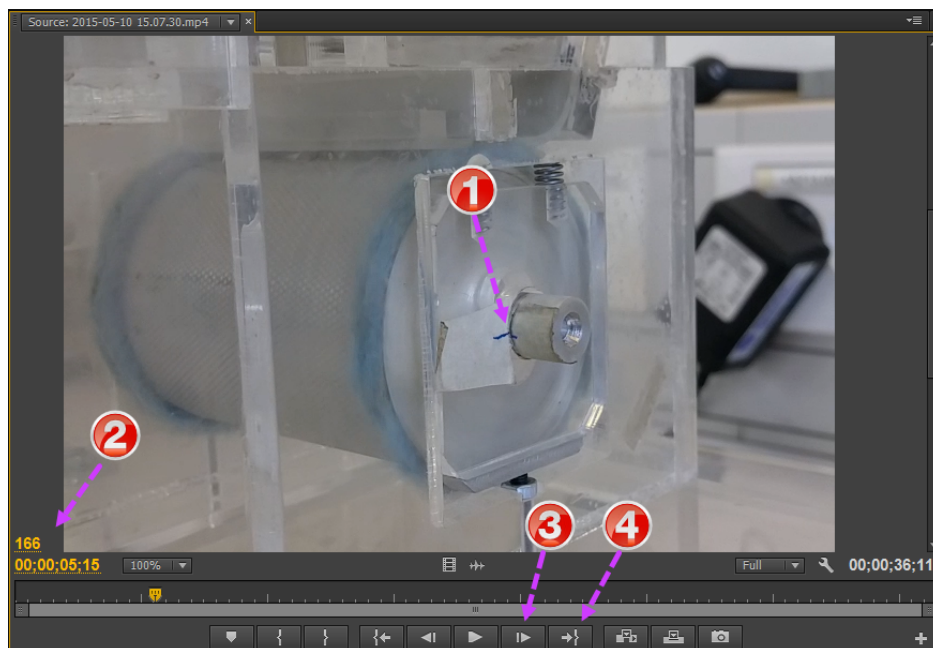
### **3.3.2 Video processing, temperature and humidity measurements description**

#### **3.3.2.1 Video processing of experiments**

All experiments in this project were filmed on a Samsung Galaxy Note 4 cellphone mounted on a tripod. Videos were shot in high definition (HD) at 30 frames per second (FPS). Video was then stored on a computer and reviewed in Adobe Premiere Pro CC 2014 (APP), where time stamps could be seen on a frame by frame basis as seen in Figure 3.27. In experiments where speed had to be determined, masking tape was placed on both the moving and resting item of interest before starting. A 0.1 mm blue marker was used to draw a line (1) seen in Figure 3.27a on the tape on both parts. When reviewing the video in APP this line could be lined up again and the frame number or time stamp (2) shown in Figure 3.27a was recorded in Excel as well as placing a marker (4) into the timeline in the program. The next frame button (3) in Figure 3.27a is then pressed several times until the blue lines on the masking tape line up again once a full revolution has been made. Process repeated as necessary, by placing markers in the time line in the program, one can jump back and forth between them and record the time stamps later on.



(a) Video processing, first frame



(b) Video processing, next frame

Figure 3.27: Video captured of one of the roller speed experiments. Marker on roller is aligned in video (1) and a marker made on the timeline in the program (4). Next frame is pressed (3) until the roller marker lines up again and time stamp (2) recorded in Excel

### 3.3.2.2 Temperature and humidity measurements

The Extech anemometer was placed next to the experiment being preformed 1 h before it was carried out. As the experiment was about to start the temperature and humidity were recorded. This was done in all experiments.

### 3.3.3 Error and uncertainty composition in experiments

#### 3.3.3.1 Ash sifting

What accounts for error and uncertainty (E&A) in the ash sifting procedure in Chapter 3.2.1 are

- Test sieves (e)
- Digital scale, large (c)

As the internal particle distribution within the ash sample is not of major importance in regards to this thesis, only the E&U from the scale will be used for the total E&U. That amounts to  $\pm 0.5\%$  of each reading taken, regardless of the weight.

#### 3.3.3.2 Angle of repose

What accounts for E&U in the AoR experiments in Chapter 3.2.3 are

- Pencil used to draw the outline of the ash pile 0.3 mm
- Led point in the compass used to draw the mean value circle 0.5 mm
- Graphing paper used to draw the above on 1 mm
- Digital calipers (a)

If the worst case E&U is  $\pm 2$  mm in the diameter of the ash and  $\pm 1$  mm in the height of the ash then the worst case min AoR is  $68.1^\circ$  and the worst max is  $69.9^\circ$ . As the average AoR is  $69^\circ$ , then the E&U is the difference between the worst case from the average or  $\approx \pm 1^\circ$ .

#### 3.3.3.3 Ash density

What makes up the E&U in the ash density experiments in Chapter 3.2.5 are

- Graduated cylinder (f)
- Digital scale (b) for loose part of experiment
- Digital scale, large (c) for packed part of experiment

As the packing force E&U of  $\pm 7.3$  N has minor effects on the results, the main source of E&U is the  $\pm 0.2$  ml in the volume of the Gc along with the  $\pm 0.03$  g accuracy in scale (b). The worst case scenario is  $-0.2$  ml in volume and  $+0.03$  g in weight, accounting for an E&U of  $\pm 0.018$  kg. Detailed calculations are available in Appendix A.3.

#### 3.3.3.4 Dispenser testing

What makes up the E&U in the dispenser experiments in Chapter 3.2.7

- Digital scale (b)
- Video processing (h)

The E&U from the video processing is minor and is excluded from the total. The  $\pm 0.03$  g accuracy in scale is the main source of E&U. However as this experiment was conducted more than 100 times in total, statistics will be used to estimate the E&U as described in Section 3.3.

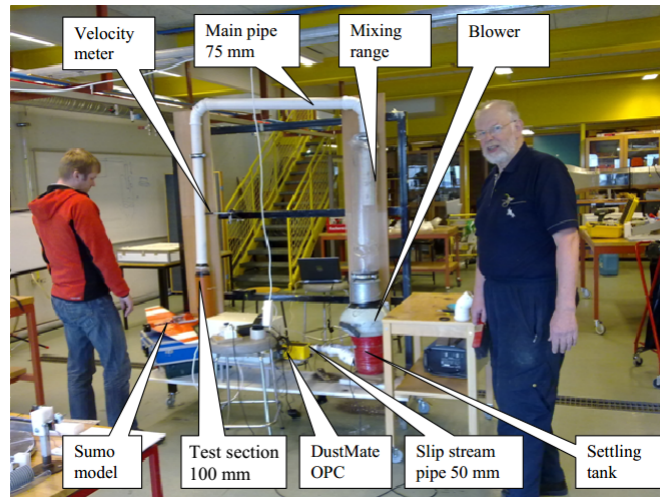
### 3.4 Test environment

A previous collaborative project between the University of Iceland and Reykjavík University called DustLoop was supposed to be used to measure the output from the dispenser mechanisms produced in this project. DustLoop version 1.0 [25] that can be seen in Figure 3.28a was made by Dr. Jonas Elíasson from the University of Iceland in 2012.

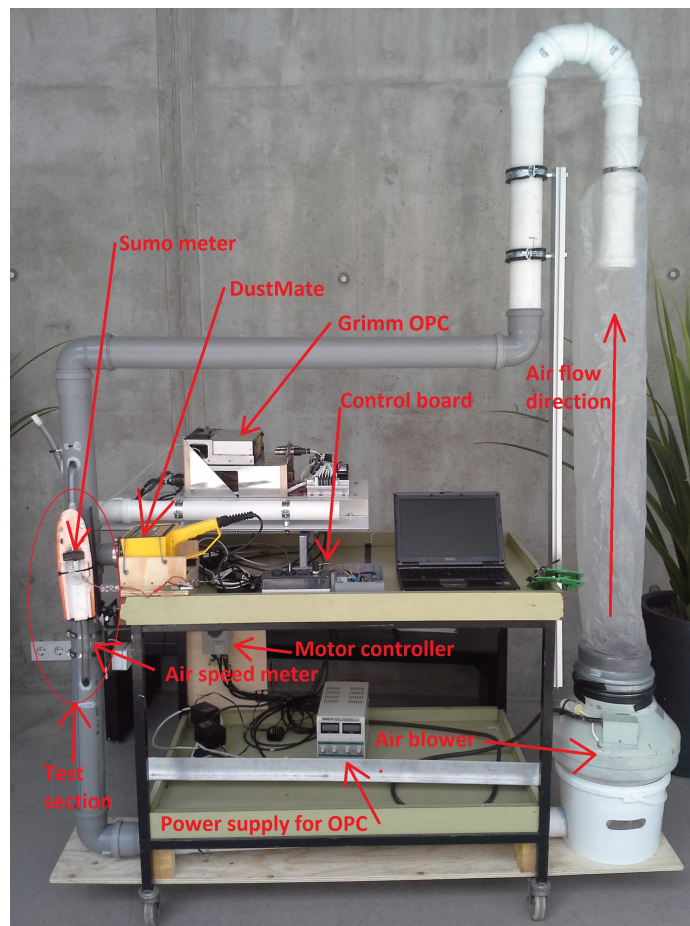
In 2014 DustLoop version 2.0 [18] as shown in Figure 3.28b was made by Björgvin Þórhallsson, a electrical engineering student at Reykjavík University, that was based on the previous version. DustLoop is a closed loop test bench for aerosol dust meters, where the goal was to be able to compare dust meters, confirm calibrations and calibrate cheap meters with more accurate expensive ones. Ash is put into the system and it circulates in the closed loop, readings from the different dust meters can then be compared and/or calibrated.

It became apparent that the DustLoop system would not give a consistent environment as were hoped for. Ash concentration changes over time, probably due to leaking issues. Two choices remained, the first was to modify the current DustLoop system and get it into such a state that it would be acceptable as a calibration bench for the different dispenser mechanisms produced in this project. The second choice was to start from scratch and tackle the problem from a different angle. The second option was deemed more feasible as more discussions took place.

It was decided to start designing a new test environment along with the dispenser mechanism.



(a) DustLoop version 1.0 [25]



(b) DustLoop version 2.0 [18]

Figure 3.28: DustLoop version 1.0 and 2.0

### 3.4.1 Test environment design

The test environment was constructed from 6 mm thick plexi glass for easy viewings and could be laser cut. Even though the ash would most likely scratch the insides of the environment with time, that can be fixed easily with a small butane torch by quickly heating the scratched sides up with the torch, leaving the plexi glass looking like new.



The shape of the environment was chosen because a box would be easiest to construct. There won't be homogeneous concentration of ash everywhere in the box, but there should be steady state conditions through the center line of it. The inner dimensions of the sampling area is  $500 \text{ mm} \times 500 \text{ mm} \times 500 \text{ mm}$  or a convenient  $1/8 \text{ m}^3$  where shown in Figure 3.29 the ash mixed air enters (1) gets sampled and goes through the filter (2) and clean air exits (7).

The ash gets caught by the filter and can be reused later so the vacuum cleaner that creates the airflow in the box also serves as a secondary filtering device for ash containment.

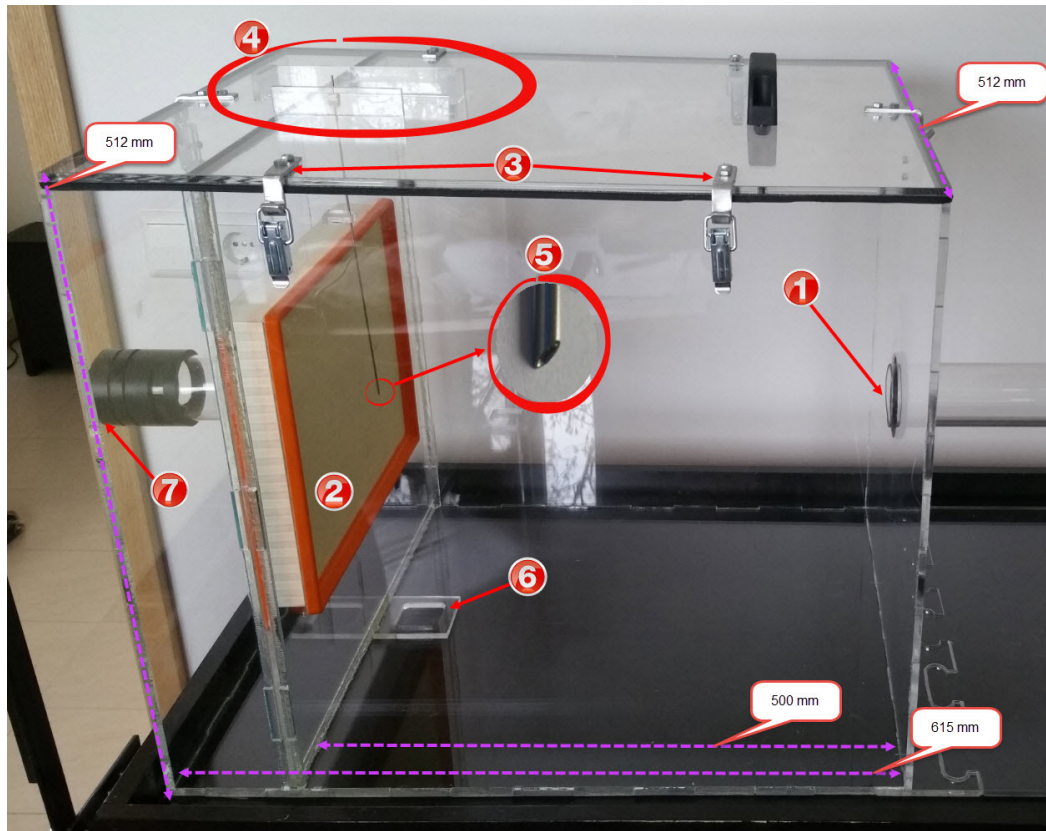


Figure 3.29: Test environment

Clamps (3) shown in Figure 3.29 create a seal around the environments outer edges and across the filter holder where the filter (2) is located effectively splitting the box in two parts. The sampling chamber as mentioned earlier and clearance chamber that was needed to shrink the surface area back down to a size suitable for a connection with a vacuum cleaner. The filter is tight fit in the filter holder and creates a seal of its own once the vacuum is turned on.

In the sampling chamber there is a cutout plexi glass fixture glued to the bottom referred to in the remainder of the text as the wind speed dock (6), the idea is to have the Extech anemometer screwed on the end of a threaded rod that is attached to another removable plexi glass fixture that the rod is fixed to and it fits tightly into the wind speed dock.

The lid on top of the chamber box is where the DustMate dock (4) is located, it has plexi glass guides around the sampling tube coming through the lid that ensures a proper connection to the DustMate. The sampling tube (5) draws its sample from the center line of the sampling chamber as close to the filter as possible and is cut at a  $45^\circ$  angle for optimal sampling results. By having docking stations for both sensors we can increase repeatability in measurements between experiments and compare results.



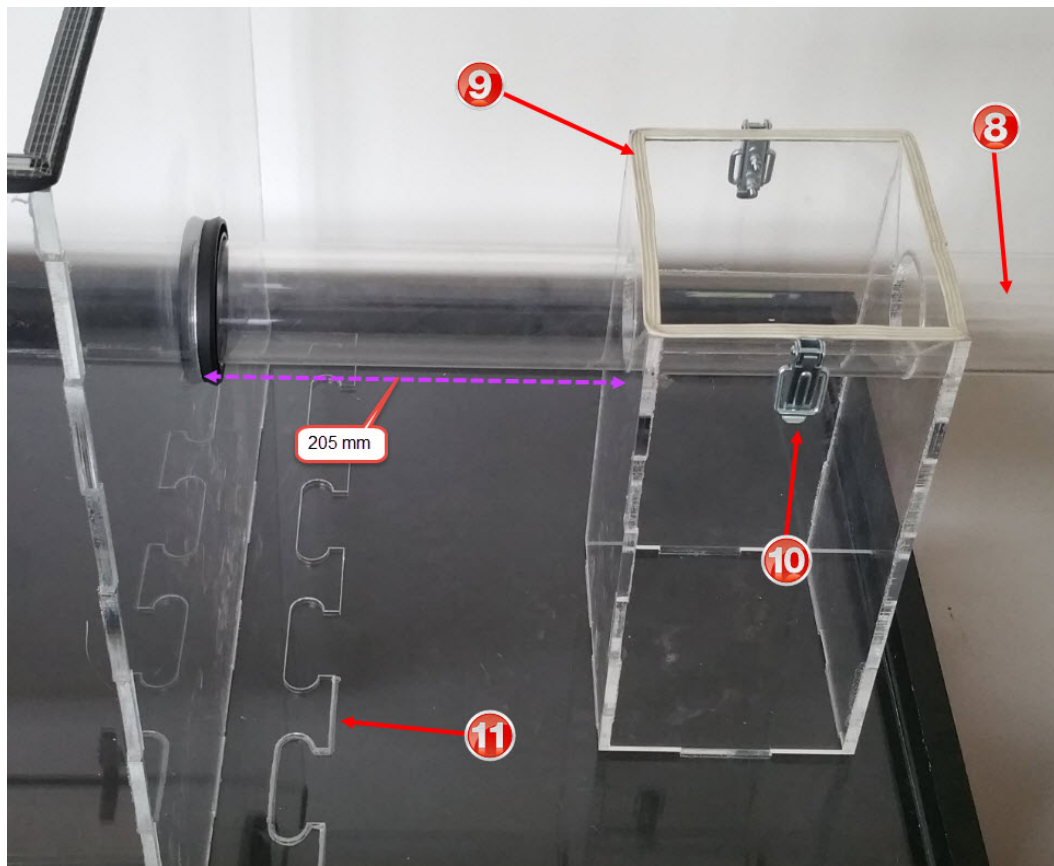


Figure 3.30: Test environment dispenser location

The dispenser goes directly on the dispenser seat (9) in Figure 3.30 and is clamped (10) down, creating a seal so the air only enters through the air intake (8) where wind speed measurements are taken. If for any reason it is of interest to lengthen the pipe from the dispenser seat to the sampling chamber there is a jigsaw connection (11) that allows for that entire section with the dispenser seat on to be moved further away than it's current distance of 205 mm.

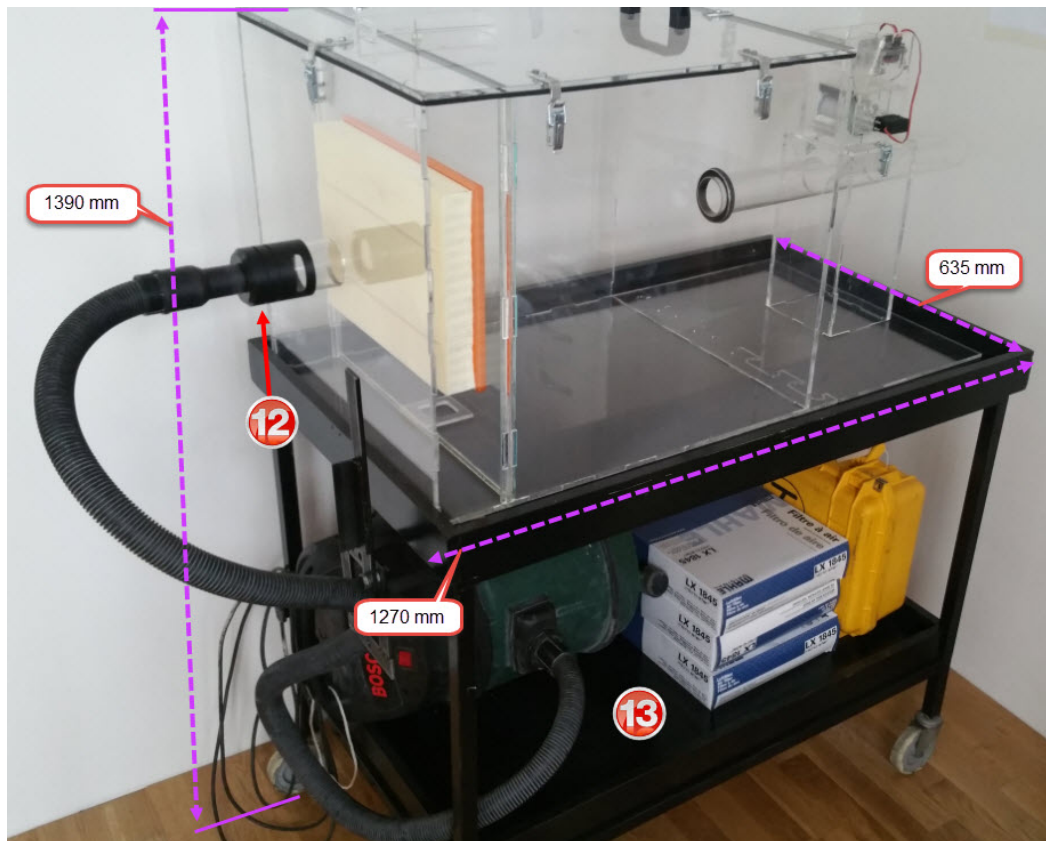


Figure 3.31: Test environment ready for dispenser output experiment.

Overall dimensions are shown in Figure 3.31 as  $127\text{ cm} \times 63.5\text{ cm} \times 139\text{ cm}$ . There is sufficient storage space (13) underneath the environment to store everything needed to conduct an experiment. The vacuum cleaner is connected to a lathed POM cylinder (12) that fits tightly over the plexi glass pipe out of the clearance chamber on the environment. The hole in the POM where the vacuum cleaner attaches is a standard size of 35 mm and fits most vacuum cleaner hose ends. There were two other POM cylinders made that have not been drilled out if this is not the case.

### 3.4.2 Filter selection

After talking with Þórhallsson about the DustLoop project it became apparent that the filter used in this project would have to be of high quality. Þórhallsson mentioned that several times during the testing of DustLoop, he felt irritation in his throat and lungs. This was despite the fact he had worn a suitable disposable dust mask and was dealing with approximately 2 g of ash in each test and that the DustLoop is a closed loop system. Calculations had not been made yet for the ash amount that would be used in dispenser testing, but it was likely that the ash amount used during testing would be at least that if not more. The ash is dropped from a dispenser unit into an air stream leading into the box, where the filter is located and preferably all of the ash is caught. This would allow for a cheap vacuum cleaner to be used as a source to create the air stream, alternatively a more expensive vacuum cleaner with a high-efficiency particulate air (HEPA) filter would have to be used, to ensure that minimal amounts of ash would escape into the working area.

### 3.4.2.1 HEPA filter

HEPA filters were the first to be looked into. A HEPA filter is a filter that is at least 99.97% [26] efficient by volume on  $0.3\mu\text{m}$  particles. They are used in cleanrooms [27] in various industries so it sounded like it would do well in this application. After talking to various Icelandic companies that specialize in filtration systems, it became apparent that this type of filter was not going to suit this project on its current scale. Guðmundur Jóhannsson at Rafloft ehf., a local company that specializes in heating, ventilation and air conditioning (HVAC) systems, provided valuable insight into HEPA filter systems. He said that a HEPA filter is almost never used on its own, but rather as a last filter with a series of pre filters before it [28]. The quantity of the pre filters depended on the situation, but a minimum of two was the starting point for any system. The main reason for the pre filters is that HEPA filters are expensive and can cost twice as much as a pre filter. The smallest HEPA filter they had along with its dimensions can be seen in Figure 3.32. The HEPA Alusep HDP filter costs roughly 60 000 ISK.

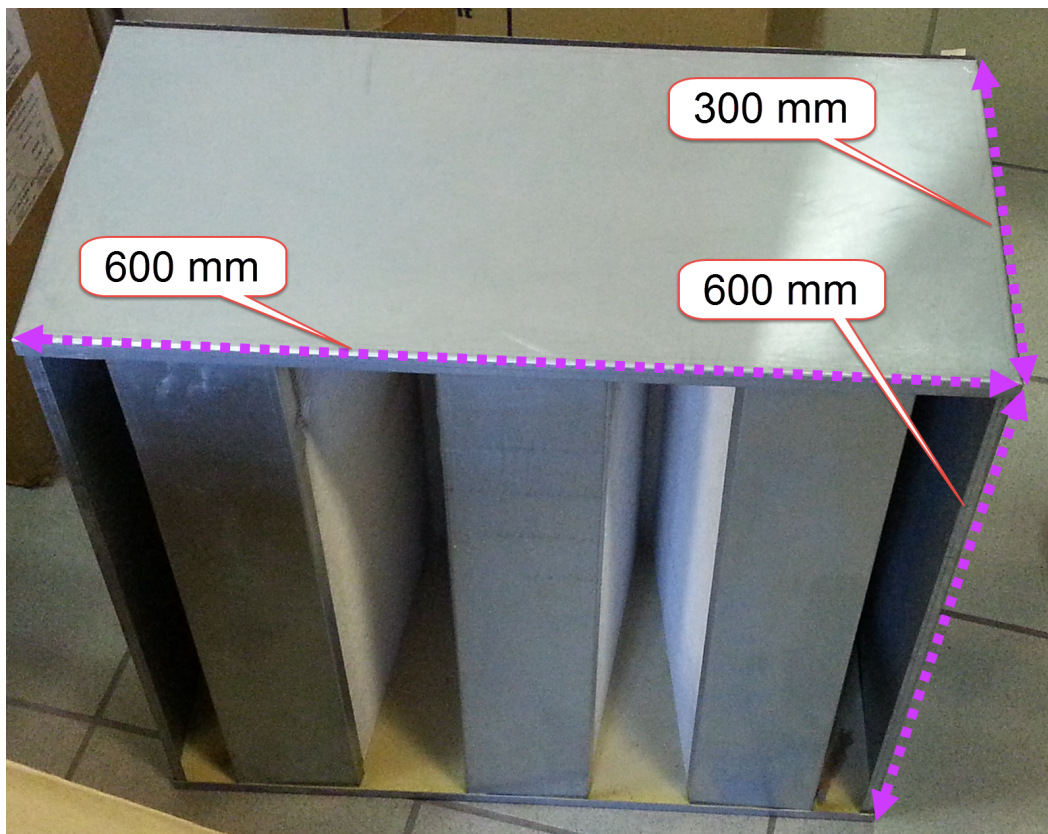


Figure 3.32: HEPA Alusep HDP filter that Rafloft ehf. had available for 60 000 ISK.

The two pre filters that were recommended were a V-50 Panel Filter as the first one where most of the ash would be caught, the second was a TC-60 Multifold Pocket Filter. The TC-60 was priced at 30 000 ISK, and the V-50 at 10 000 ISK, roughly. They would then be placed in a stack as illustrated in Figure 3.33

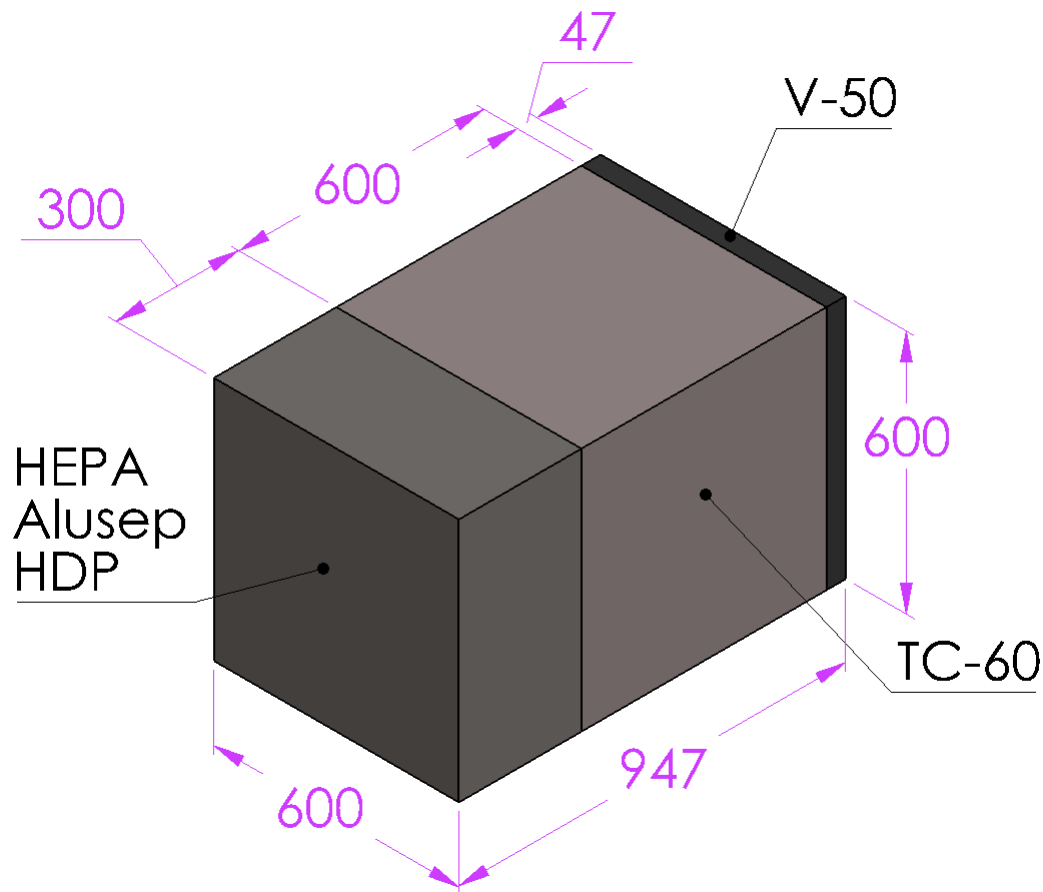


Figure 3.33: Filter stack illustration, composed of HDP 610610 HEPA filter, TC-60 Multi-fold Pocket Filter and the V-50 Panel Filter

In light of the price of around 100 000 ISK. for the filters, that would have to be replaced after each test performed for consistency and the sheer size of them, this solution was deemed not feasible. It should be noted that Rafloft ehf. offered to give Reykjavík University the first set of filters free of charge.

### 3.4.2.2 Automobile filters

At the time of the eruption there were quite a few cars exposed to large amounts of ash in the vicinity of the volcano, law enforcement, media and so on. News footage showed reporters in their vehicles in broad daylight trying to spot road markings as the ash cloud surrounding them was so dense that it appeared to be dark outside.

Yet the cars kept running, this lead us to investigate further into automobile filters as a possible solution. They possessed some desirable factors, like reasonable pricing and availability. Kristinn Jónsson, manager at REKI ehf., a company that specializes in filters for anything that has an engine, was very helpful during this project. His knowledge of filters quickly narrowed our search for an ideal filter for the job to the LX 1845, datasheet available in Appendix A.9.

It's a filter used in Mercedes Benz Sprinter and Volkswagen Transit cargo vans and has been tested in accordance with ISO-5011 standard [29]. It costs 3579 ISK. and is readily available. REKI ehf. is an authorized dealer for Donaldson Company, an American filter production company. Jónsson said that as an authorized dealer there are rules that they have



to follow from Donaldson, one of which is for this particular filter, REKI ehf. must have a minimum of 5 LX 1845 in their inventory at all times [30].

### 3.4.3 Environment assembly and testing

The entire test environment was drawn in Solidworks 2015 and laser cut at the workshop in Reykjavík University. Pieces were glued together with Acrifix 1S 0116.

Leak tests were performed on every joint after assembly with a vacuum cleaner attached and running. A smoke making wick used for leak testing in HVAC systems was then slowly moved along every glued connection to see if smoke got sucked in through. After completing fabrication, a smoke machine was used to generate smoke to see the flow going through the environment shown in Figure 3.34.

Visual results from that simulation support what was suspected, that the stream going through the centerline of the box is steady and that placing the sensor there for sampling the ash should increase chances of getting a steady state readout from it.

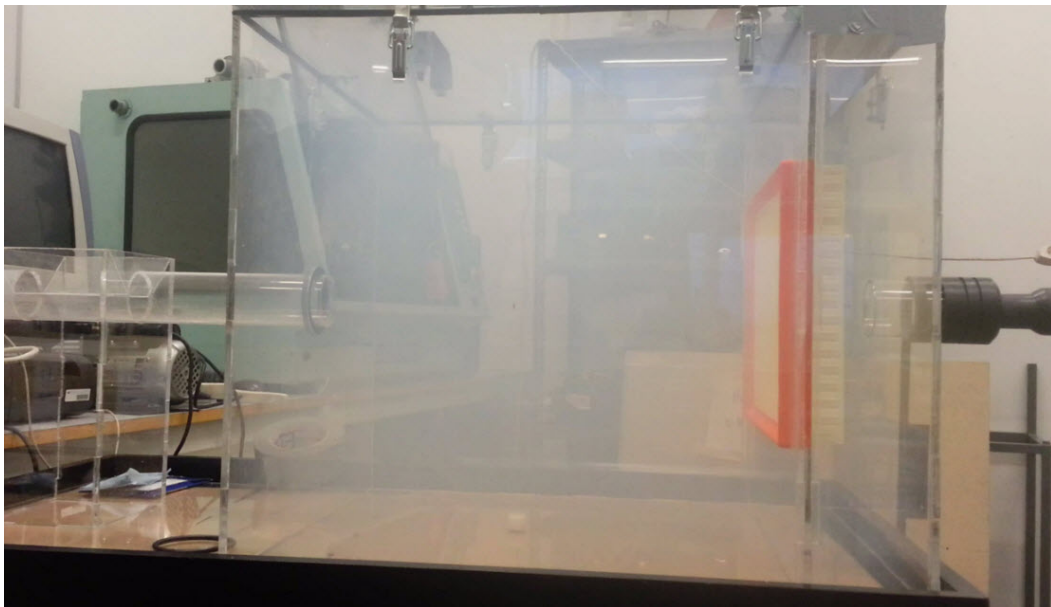


Figure 3.34: Smoke machine flow simulation

Gylfi Árnason, who had extensive knowledge of the DustMate sensor, said that any test conducted with it in these conditions should last at least 60 s at a bare minimum. This posed a problem as the dispensers current setting would output 420 g in that time and was deemed excessive. Running further tests on the dispenser while trying to reduce the ash output as much as possible was stopped when it's gap size reached minimum at 1.10 mm and it's ash output of 264.3 g. A great oversight was discovered while calculating the expected concentration levels in the environment at those dispenser settings.

Calculations that are available in Appendix A.7 showed that the dispenser with a gap size of 1.1 mm and rotational speed of 0.48 RPS outputs ash concentration equivalent to  $168\,362\text{ mg/m}^3$  in regards to the environments airflow and the DustMate has a maximum sampling concentration of  $60\text{ mg/m}^3$ . In light of this discovery it was clear that it was not possible to bridge that gap with the current dispenser, test environment and sensors.

### 3.5 Total cost

The total cost of items that had to be purchased for the project was 92 463 ISK as listed in Table 3.5. Some items were obtained within the school and borrowed temporarily like the stepper motors and control boards. What is still left to purchase is a vacuum cleaner as the one used is borrowed and has to be returned.

Table 3.5: Bill of materials

Item	Supplier	Quantity	Unit cost [ISK]	Total cost [ISK]
Rubber cord 2.0 mm	Landvelar	4	396	1584
LX1845 Filter	REKI	4	3579	14 316
AL pipe 50x3.0 mm	Malmtaekni	0.5	1149	575
AL pipe 69x3.0 mm	Malmtaekni	0.5	1834	917
Labor	Malmtaekni	1	299	299
Plexi pipe 60x56 mm	Fast	1	2503	2503
Plastic handle	Fast	2	810	1620
Plexi sheet 6 mm	Merking	3.46	9783	33 849
Plexi glue	Merking	1	1434	1434
Labor	Merking	0.25	8333	2083
Fasteners	BYKO	1	5249	5249
Insulation rubber lists	BYKO	1	2922	2922
Steel tube 2 mm	Metal	1	5188	5188
Arduino Pro Mini	Sparkfun	2	1346	2692
Servo AR3606HB	Pololu	2	1630	3260
Servo 1501MG	Pololu	2	2800	5600
Power supply	Ihlutir	1	4572	4572
Miscellaneous	Various	1	3800	3800
<b>Grand total</b>				<b>92 463</b>

### 3.6 Results and discussions

#### 3.6.1 Dispenser testing

All dispenser testing experiments were carried out identically as described in Section 3.2.7. They were all performed in the Civil engineering lab V-113 at Reykjavík University. All results from the ash output testing on the dispenser are presented in tables 3.6-3.9 with an error and uncertainty (E&A) of  $\pm 0.5$  g. Dispenser settings, gap size and rotational speed are listed with every result. More detailed information on experiments is located in Appendix A.6.

### 3.6.1.1 First dispenser test series

This was the first complete dispenser test. Micro controller was fully automated after switching on, so the total time, opening/closing of the silo, roller start/stop would be exactly the same every time. Speed adjustments for roller servo were close enough to 0.5 RPS. Opening and closing of the silo door were satisfactory to the point that they did not obstruct the ash flow and stopped it completely once closed. The gap size was set to  $3.09 \text{ mm} \pm 0.05 \text{ mm}$  and rotational speed of roller was 0.48 RPS.

Table 3.6: Dispenser ash output results, 1st series.

First test series, 42 individual tests total							
Average (g)		St.Dev (g)		St.dev.EOM (g)			
88.0		5.3		0.126			
Test #	Weight (g)	Test #	Weight (g)	Test #	Weight (g)	Test #	Weight (g)
1	92.8	12	78.3	23	91.0	34	92.3
2	87.8	13	96.2	24	89.8	35	78.7
3	96.1	14	88.2	25	84.9	36	87.0
4	93.0	15	93.9	26	89.6	37	78.8
5	93.6	16	89.6	27	83.9	38	76.7
6	88.2	17	88.9	28	81.9	39	84.3
7	92.9	18	89.4	29	91.7	40	84.9
8	90.4	19	79.5	30	86.4	41	83.4
9	94.1	20	97.6	31	90.0	42	87.4
10	89.4	21	80.4	32	84.9		
11	87.4	22	84.7	33	93.0		

Average ash output from the dispenser was 88.0 g, or 7.4 g/s with a standard deviation of 5.3 g and a standard error of the mean of 0.126 g. After the silo door closed the roller turned for 2 s and then stopped. There was noticeable ash leftover on top of the roller after each test. This caused the standard deviation to be the highest in this test series out of the four series. For when the roller came to a hard stop, it was up to chance how much ash fell off the edge of it and onto the scale.

### 3.6.1.2 Second dispenser test series

The second series was performed with the same gap size of  $3.09 \text{ mm} \pm 0.05 \text{ mm}$  and rotational speed of roller at 0.48 RPS. Changes were made in the Arduino code that lengthened the time from when the silo door closes to when the roller stops spinning. The time was increased from 2 s to 4 s.

Table 3.7: Dispenser ash output results, 2nd series.

Second test series, 42 individual tests total							
Average (g)		St.Dev (g)		St.dev.EOM (g)			
97.2		3.1		0.074			
1	88.9	12	94.2	23	96.8	34	93.7
2	103.0	13	93.6	24	98.0	35	95.3
3	103.1	14	99.4	25	94.2	36	99.2
4	94.7	15	97.0	26	102.7	37	96.8
5	100.2	16	97.8	27	98.1	38	97.9
6	95.1	17	94.0	28	93.9	39	99.6
7	93.6	18	98.9	29	100.4	40	99.0
8	93.4	19	100.3	30	94.4	41	94.4
9	99.0	20	100.6	31	101.2	42	96.2
10	98.1	21	97.9	32	94.1		
11	100.0	22	96.1	33	98.7		

No visible ash was on top of the roller during this test series, so the changes made to the Arduino code worked as planned. Average ash output from the dispenser was 97.2 g, or 7.0 g/s with a standard deviation of 3.1 g and a standard error of the mean of 0.074 g. This was the lowest standard deviation and standard error of the mean in all four test series.



### 3.6.1.3 Third dispenser test series

The third series was again with the same gap size of  $3.09 \text{ mm} \pm 0.05 \text{ mm}$  and rotational speed of roller at 0.48 RPS. Changes were made in the Arduino code that extended the total time of the experiment from 20 s to 29 s, but earlier changes in the code were not changed back.

Table 3.8: Dispenser ash output results, 3rd series

Third test series, 15 individual tests total					
Average ( <i>g</i> )		St.Dev ( <i>g</i> )	St.dev.EOM ( <i>g</i> )		
172.3		3.5	0.231		
<i>Test #</i>	<i>Weight (g)</i>	<i>Test #</i>	<i>Weight (g)</i>	<i>Test #</i>	<i>Weight (g)</i>
1	177.7	6	166.8	11	175.3
2	169.9	7	176.5	12	174.2
3	171.6	8	167.8	13	169.8
4	173.2	9	170.7	14	175.0
5	176.8	10	170.8	15	168.6

Average ash output from the dispenser was 172.3 g, or 6.9 g/s with a standard deviation of 3.5 g and a standard error of the mean of 0.231 g. As the difference in the standard deviation between test series 2 and 3 was 0.4 g and 0.1 g/s in ash output. It was deemed unnecessary to perform more than 15 tests in this series as the only change made was the length of the program was increased by 9 s.

### 3.6.1.4 Fourth dispenser test series

To reduce the ash output as much as possible for the current roller speed setting of 0.48 RPS, the only change made in the fourth series is that the gap size was reduced from  $(3.09 \pm 0.05)$  mm to  $(1.1 \pm 0.5)$  mm.

Table 3.9: Dispenser ash output results, 4th series

Fourth test series, 15 individual tests total					
Average ( <i>g</i> )		St.Dev ( <i>g</i> )		St.dev.EOM ( <i>g</i> )	
100.8		3.4		0.231	
<i>Test #</i>	<i>Weight (g)</i>	<i>Test #</i>	<i>Weight (g)</i>	<i>Test #</i>	<i>Weight (g)</i>
1	102.3	6	103.8	11	100.0
2	102.0	7	104.4	12	94.2
3	103.3	8	99.2	13	96.4
4	98.4	9	101.1	14	99.4
5	106.4	10	104.1	15	97.0

Average ash output from the dispenser was 100.8 g, or 4.4 g/s with a standard deviation of 3.2 g and a standard error of the mean of 0.231 g.

## 3.7 Conclusions

Ash clouds from volcanic eruptions pose a very real threat to modern aviation, the Eyjafjallajökull eruption in 2010 was responsible for closing down vast amounts of airspace in Europe for several days. To be able to predict, analyze and study this type of situation, there is a need for simulating these conditions in a controlled environment.

By developing a dispenser capable of dispensing fine ash particles at a controllable rate from the hopper on a crop-spraying aircraft while it follows a defined flightpath that makes up a test volume, will result in such conditions. For practical and financial reasons, a scaled down version of a dispenser was build and in order to calibrate it in an environment closer to it's normal operation a test environment was created.

A dispenser mechanism based on a rotating roller and controllable inflow gap is best suited for creating a controlled stream of volcanic ash. A reduced scale of 1:14.6 version delivered a reliable ash stream of 7 g/s with a 10.1 % repeatability under test conditions for ash with a dimension of less than  $80\text{ }\mu\text{m} \pm 5\text{ }\mu\text{m}$  with 99.7 % confidence.

However with the scaling factor in mind, the ash output from the scaled down version should be 14.1 g/s and therefore the requirement to create an ash cloud containing the equivalent concentration level of  $1000\text{ }\mu\text{g}/\text{m}^3 \pm 100\text{ }\mu\text{g}/\text{m}^3$  is not fulfilled.

This is a direct result of the test environment being the place where calibration of the dispenser was to take place in conditions closer to it's area of operation, so they of course share design parameters. The scaling factor of 14.6 was determined from the air intake on the test environment and because of it's size and single filter setup, focus was on reducing the ash output and not increasing it to meet the requirement of 14.1 g/s.

Because the dispenser is only scaled in length, the width of 16.1 cm will be the same on a full size version prototype. It could then be inserted through the bottom of the hopper on board the Piper Pawnee airplane with dimensions 85 cm  $\times$  20 cm [L x W] and be bolted there. It's height would also be the same as the scaled down version of 16.5 cm which is within the requirements of the maximum of 30 cm.

The larger version of the dispenser would be fabricated from 2 mm thick stainless steel, which Solidworks 2015 reports a weight of 14 kg. This leaves  $11\text{ kg} \pm 1\text{ kg}$  for 2 servos and unforeseen problems before passing the  $25\text{ kg} \pm 1\text{ kg}$  requirement restriction.

The test environment was placed on a cart with wheels that make it mobile and easily transported by one person, fulfilling the first requirement of mobility. The storage space underneath the environment on the cart can hold everything needed for conducting an experiment, so the requirement of getting it from storage to test ready state takes less than 30 min is fulfilled as it takes 20 min for one person, leaving 10 min for unforeseen issues. The environments are 120 cm  $\times$  64 cm  $\times$  137 cm which is well under the 250 cm  $\times$  80 cm  $\times$  200 cm [L x W x H] requirement restriction. A small feature was added to the DustMate sensor requirement as there is now a DustMate dust detector dock on top of the lid on the environment, ensuring that sensor placement is always the same between experiments.

That being said, a great oversight was discovered once testing with the DustMate was underway. Calculations that are available in Appendix A.7 showed that the dispenser with a gap size of 1.1 mm and rotational speed of 0.48 RPS outputs ash concentration equivalent to  $168\,362\text{ mg}/\text{m}^3$  in regards to the environments airflow and the DustMate has a maximum sampling concentration of  $60\text{ mg}/\text{m}^3$ . To be able to calibrate the dispenser with the current setup, either the airflow would have to be increased from the current setting of  $0.026\text{ m}^3/\text{s}$  to  $80\text{ m}^3/\text{s}$ , close to a factor of  $\approx 3000$  or the output from the dispenser reduced from  $4400\text{ mg}/\text{s}$  to  $\approx 1\text{ mg}/\text{s}$ .

It's clear by this point that if both the dispenser and the test environment are to work together, another particle sensor will have to be sourced that can handle the load from the dispenser, that is if one exists.

The two devices can work on their own as they were originally intended, as the test environment could function with a different dispenser that outputs less ash same as the dispenser can work in the bottom of a hopper on a crop-spraying aircraft creating a controlled stream of volcanic ash. They do however not work together.

### 3.8 Future work

In order to meet the requirement of dispensing  $14.1 \text{ g/s}$  to create an ash cloud containing the equivalent concentration level of  $1000 \mu\text{g/m}^3 \pm 100 \mu\text{g/m}^3$ . Experiments with increased rotational speeds of the roller are of utmost importance. Results from those would greatly increase chances of funding for completing the large scale design that currently is in its later modeling stages in Solidworks 2015, finding suitable industrial servos and if one servo will be able to open and close the silo door, bill of materials with cost estimates for required parts and finally integrating top of dispenser silo with the interior of the hopper in such a way that ash is directed into it and not around it.

In regards to the test environment; source for a sensor that can handle extreme loads in order to conduct a test, calculate what can be considered a feasible and achievable balance between airflow, intake size and ash output goals while staying within the  $250 \text{ cm} \times 80 \text{ cm} \times 200 \text{ cm}$  [L x W x H] requirement restriction as priority one.

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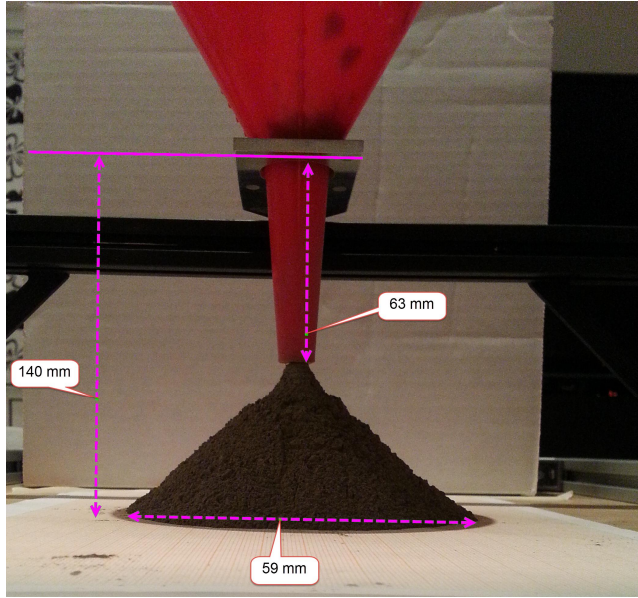
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# **Appendix A**

## **Appendix**

## A.1 Calculations Angle of repose

### Angle of Repose



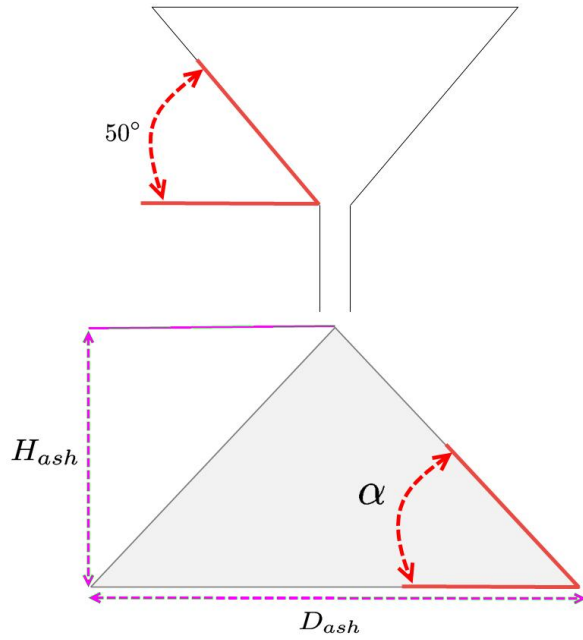
Where:

$$H_{total} := 140 \text{ mm}$$

$$H_{funnel} := 63 \text{ mm}$$

$$H_{ash} := H_{total} - H_{funnel} = 77 \text{ mm}$$

$$D_{ash} := 59 \text{ mm}$$



Then the angle of repose is given by:

$$\tan(\alpha) := \frac{H_{ash}}{0.5 \cdot D_{ash}}$$

Rearrange for  $\alpha$

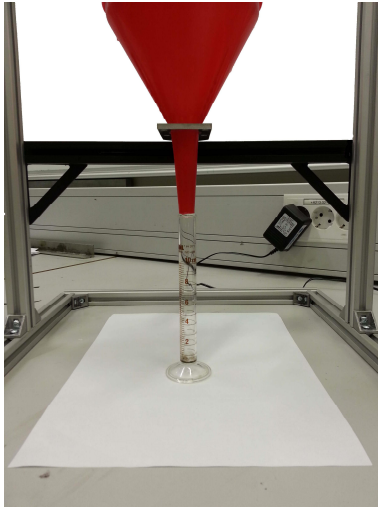
$$\alpha := \text{atan}\left(\frac{H_{ash}}{0.5 \cdot D_{ash}}\right) = 69 \text{ deg}$$

So in order to avoid the ash sticking to the sides of container, the angle of the container walls has to be more than 69 degrees.



## A.2 Calculations Ash density

### Ash density



Graduated cylinder

$$Gc_{empty} := 23.91 \text{ gm}$$

$$Gc_{water} := 14.38 \text{ gm}$$

$$Gc_{dia} := 11.9 \text{ mm}$$

$$Gc_{length} := 126.6 \text{ mm}$$

$$Gc_{vol} := \frac{\pi}{4} \cdot Gc_{dia}^2 \cdot Gc_{length} = 14.08 \text{ mL}$$

As the results of the weight and volume of the water measured is so similar, assuming that the density of the water is 1, it is concluded that the volume of the Graduated cylinder is indeed  $Gc_{vol} = (1.408 \cdot 10^{-5}) \text{ m}^3$

Maximum and minimum of ash density, fill up 10ml Gc in 2 different ways. First as loosley as possible and then packed with a force of 147 Newtons.

#	Loose (gm)	Packed (gm)
1	13.11	17.90
2	12.86	18.05
3	12.82	18.01
4	12.57	18.07
5	12.87	17.93
6	13.00	18.00
7	12.90	18.08
8	12.97	18.03
9	13.01	17.96
10	13.13	17.99

The average valu of the experiment are:

$$Ash_{loose\_ave} := \text{mean}(Loose) = 12.92 \text{ gm}$$

$$Ash_{packed\_ave} := \text{mean}(Packed) = 18 \text{ gm}$$

$$Ash_{Gc\_ave} := \text{mean}(Loose, Packed) = 15.46 \text{ gm}$$

and a standard deviation of:

$$Ash_{loose\_stdev} := \text{stdev}(Loose) = 0.15 \text{ gm}$$

$$Ash_{packed\_stdev} := \text{stdev}(Packed) = 0.06 \text{ gm}$$

$$Ash_{Gc\_stdev} := \text{stdev}(Loose, Packed) = 2.54 \text{ gm}$$

Setup equation, solving for x, to find out how many graduated cylinders it takes to get a volume of  $1\text{ m}^3$

$$One_{cube\_Gc} := Gc_{vol} \cdot x = 1 \xrightarrow{\text{solve}, x} \frac{0.071020297984549978268}{mL}$$

Now as the average weight of the ash measured was  $Ash_{Gc\_ave} = 15.5\text{ gm}$ , it is concluded that the density of the ash available is:

$$Ash_{density} := Ash_{Gc\_ave} \cdot One_{cube\_Gc}$$

$$Ash_{density} = 1098 \frac{kg}{m^3}$$

### A.3 Calculations Ash density E&U

#### Density experiments error and uncertainty

Volume of Gc 14.08 ml  $\pm 0.2$  ml  
 Ave weight total 15.46 g  $\pm 0.03$  g

Gc volume $\pm 0.2$ ml		
min	ave	max
13.88	14.08	14.28

Intermediate calculations		
min	ave	max
0.07205	0.07102	0.07003

Ave weight $\pm 0.03$ g		
min	ave	max
15.43	15.46	15.49

Calculate worst senarios			
	min weight	ave weight	max weight
min vol	1.112	1.114	1.116
ave vol	1.096	1.098	1.100
max vol	1.081	1.083	1.085

Deviation from average		
max	average	max
1.081	1.098	1.116
0.017	1.098	0.018

Calculated E&U for density experiments  
 $\pm 0.018$  kg

Ash density is then  
 $1.098 \text{ kg} \pm 0.018 \text{ kg}$

#	Weight (gr.)	
	Loose	Packed
1	13.11	17.90
2	12.86	18.05
3	12.82	18.01
4	12.57	18.07
5	12.87	17.93
6	13.00	18.00
7	12.90	18.08
8	12.97	18.03
9	13.01	17.96
10	13.13	17.99
Average	12.92	18.00
Average	15.46	

St.dev of sample	
0.16	0.06
2.61	

St.error of the mean	
0.0512	0.0187
0.615	

## A.4 Calculations $V_{REF}$ steppermotor

Reference voltage for A4988 stepper driver.

Wantai steppermotor:

Max current per coil

$$I_{max} := 1.7 \cdot A$$

Sense resistor

$$R_{sx} := 0.05 \cdot \Omega$$

Recomended current load

$$I_{Norm} := I_{max} \cdot 0.7$$

Solve for  $V_{REF}$

$$I_{max} = \frac{V_{REF}}{8 \cdot R_{sx}} \xrightarrow{\text{solve, } V_{REF}, \text{ explicit}} 8 \cdot R_{sx} \cdot I_{max}$$

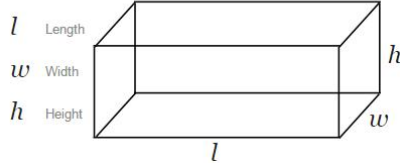
Substitute  $I_{norm}$  for  $I_{max}$

$$V_{REF} := 8 \cdot R_{sx} \cdot I_{Norm} = 0.476 \text{ V}$$

## A.5 Calculations Test volume and dispenser ash output

### Test volume and dispenser mechanism ash output

$$V = w h l$$



Where

$$w := 100 \text{ m} \quad l := 1000 \text{ m} \quad h := 300 \text{ m}$$

The volume of the test area is:

$$Vol_{Test} := w \cdot l \cdot h = (3 \cdot 10^7) \text{ m}^3$$

Airplane assumptions and stats

$$HP := 235 \text{ hp} \quad Speed_{max} := 108 \text{ knot} \quad Speed_{cruise} := 80 \text{ knot} \quad Speed_{stall} := 53 \text{ knot}$$

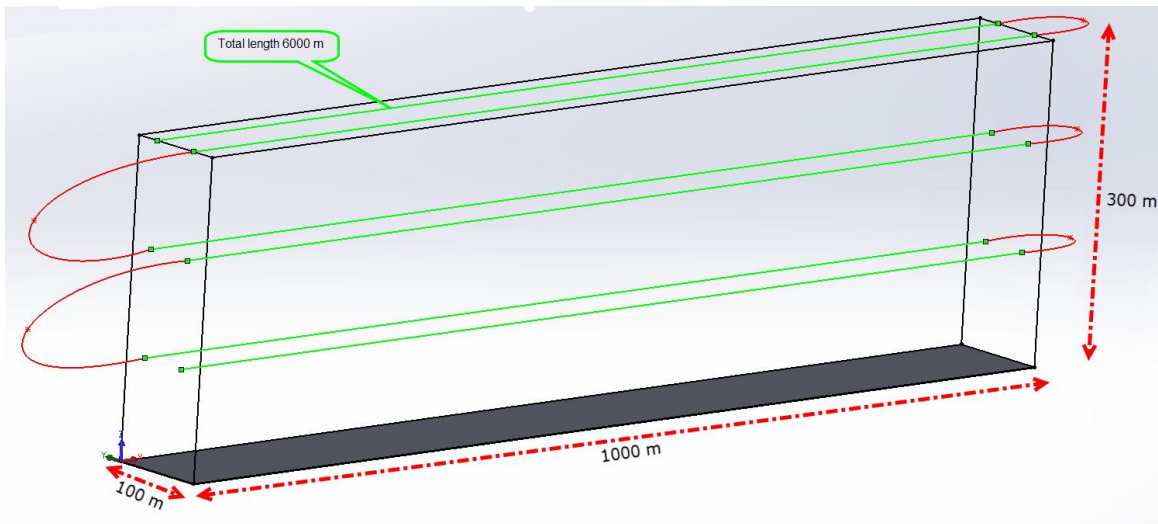
$$Weight_{gross} := 2900 \text{ lb} \quad Weight_{empty} := 1576 \text{ lb} \quad Fuel_{cap} := 36 \text{ gal} \quad Range := 222 \text{ nmi}$$

$$Climb_{rate} := 700 \frac{ft}{min} = 3.556 \frac{m}{s} \quad Dispersion_1 := 50 \text{ m}$$

The plane travels at a cruising speed of  $Speed_{cruise} = 41.156 \frac{m}{s}$ . The width of the Test volume is  $w = 100 \text{ m}$  and it is

assumed that the ash dispersion is 25 meters from each side of the plane, so total dispersion width per pass is

$Dispersion_1 = 50 \text{ m}$ . The plane will need to make one pass through the Test volume and make a U turn and go back, parallel to the pass just made but 50 meters from it.



The plane only dispurse ash on the green lines, so it will take 6 passes to cover the test volume the total length the plane of the flight path is  $Distance_{total} := 6 \cdot l = (6 \cdot 10^3) \text{ m}$ . Then the total time it takes the plane to dispurse the ash is

$$Time_{total\_1\_pass} := \frac{Distance_{total}}{Speed_{cruse}} = 145.8 \text{ s} \text{ or } Time_{total\_1\_pass} = 2.4 \text{ min}$$

The goal ash consentration in the testvolume is  $Ash_{consent} := 1 \cdot 10^{-6} \frac{kg}{m^3}$

Density of the ash is  $Ash_{density} := 1098 \frac{kg}{m^3}$

So the required ash amount for 1 full scale test is  $Ash_{weight\_total\_1\_pass} := Ash_{consent} \cdot Vol_{Test} = 30 \text{ kg}$

The plane travels at

$$Speed_{cruse} = 41.156 \frac{m}{s}$$

Therefor the dispenser will have to output  $Disp_{sec} := \frac{30 \text{ kg}}{Time_{total\_1\_pass}} = 205.778 \frac{gm}{s}$

Scaling factor for large roller vs. small

Diameter is the same in both  $D_{roller} := 50 \text{ mm}$   $r_{roller} := \frac{D_{roller}}{2} = 0.025 \text{ m}$

Length  $L_{rollerL} := 820 \text{ mm}$   $L_{rollerS} := 56 \text{ mm}$

As the length is the only factor that changes between the large and small version of the roller dispenser, scale is.

$$Scale_{factor} := \frac{L_{rollerL}}{L_{rollerS}} = 14.643$$

## A.6 Calculations dispenser ash output testing

Dispenser ash output testing at 3.09 mm gap size and rotational speed of 0.481 rev/sec

Test #	Read [gr.]
1	92.76
2	87.82
3	96.13
4	92.98
5	93.58
6	88.21
7	92.93
8	90.37
9	94.10
10	89.37
11	87.41
12	78.33
13	96.16
14	88.15
15	93.91
16	89.58
17	88.93
18	89.36
19	79.52
20	97.63
21	80.39
22	84.71
23	91.01
24	89.84
25	84.90
26	89.56
27	83.87
28	81.92
29	91.73
30	86.39
31	90.03
32	84.91
33	93.87
34	92.26
35	78.67
36	86.96
37	78.80
38	76.67
39	84.34
40	84.86
41	83.37
42	87.44

Tests were carried out in the Civil Engineering Lab V-113 at Reykjavik University

Test	Date	Temperature [°C]	Humidity [%]
1-16	27.02.2015	25	55
17-42	28.02.2015	25	55

	St.dev.S	St.dev.error of mean
87.95	5.31	0.126

---

 7.40

### Dispenser code timer settings

Stop	0	
Ready	2	
Start	2	
Open	4	
Ash ON	4.11	
Close	14	sec of ASH output
Ash OFF	16	
Stop	18	

### Average Ash output per rotation

Ave rot		per/sec
Ave ash sec		gr/sec
Multy for 1 rotation	2.079	
Ave Ash out per rot		gr/rot

---

 Ash total for 60 sec Dustmate test  
 gr.

Dispenser ash output testing at 3.09 mm gap size and rotational speed  
of 0.481 rev/sec

Increase time from roller stop after silo door closes from 2 -> 4 sec.

Test #	Read [gr.]
1	88.91
2	103.04
3	103.11
4	94.69
5	100.2
6	95.1
7	93.6
8	93.42
9	99.00
10	98.06
11	99.99
12	94.16
13	93.60
14	99.41
15	97.01
16	97.75
17	94.04
18	98.93
19	100.28
20	100.62
21	97.90
22	96.07
23	96.76
24	98.00
25	94.21
26	102.71
27	98.12
28	93.90
29	100.41
30	94.37
31	101.21
32	94.13
33	98.74
34	93.74
35	95.33
36	99.16
37	96.79
38	97.91
39	99.60
40	98.98
41	94.43
42	96.20

Tests were carried out in the Civil Engineering  
Lab V-113 at Reykjavik University

Test	Date	Temperature [°C]	Humidity [%]
1-42	2.05.2015	25	55

Average	St.dev.S	St.dev.error of mean
97.23	3.11	0.074

Average gr. ASH per sec
7.00

Dispenser code timer settings			
Stop	0		
Ready	2		
Start	2		
Open	4		
Ash ON	4.11		
Close	14	13.89	sec of ASH output
Ash OFF	18		
Stop	20		

Average Ash output per rotation			
Ave rot	0.481	per/sec	
Ave ash sec	7.00	gr/sec	
Multy for 1 rotation	2.079		
Ave Ash out per rot	14.553	gr/rot	

Ash total for 60 sec Dustmate test	
419.99	gr.



Dispenser ash output testing at 3.09 mm gap size and rotational speed of 0.481 rev/sec

Time of ash output increased to 23 sec

Test #	Read [gr.]
1	177.68
2	169.86
3	171.6
4	173.16
5	176.78
6	166.79
7	176.48
8	167.83
9	170.70
10	170.84
11	175.30
12	174.19
13	169.83
14	175.02
15	168.57

Tests were carried out in the Civil Engineering Lab  
V-113 at Reykjavik University

Test	Date	Temperature [°C]	Humidity [%]
1-15	4.05.2015	24	53

Average	St.dev.S	St.dev.error of mean
172.31	3.47	0.231

Average gr. ASH per sec
6.89

Dispenser code timer settings

Stop	0	
Ready	2	
Start	2	
Open	4	
Ash ON	4.11	
Close	23	22.89 sec of ASH output
Ash OFF	27	
Stop	29	

Average Ash output per rotation		
Ave rot	0.481	per/sec
Ave ash sec	6.89	gr/sec
Multy for 1 rotation	2.079	
Ave Ash out per rot	14.329	gr/rot

Ash total for 60 sec Dustmate test
413.54 gr.

Dispenser ash output testing at 1.1 mm gap size and rotational speed of 0.481 rev/sec

Gapsize decreased

Test #	Read [gr.]
1	102.26
2	101.96
3	103.29
4	98.41
5	106.42
6	103.78
7	104.41
8	99.24
9	100.99
10	104.08
11	99.99
12	94.16
13	96.40
14	99.41
15	97.01

Tests were carried out in the Civil Engineering Lab  
V-113 at Reykjavik University

Test	Date	Temperature [°C]	Humidity [%]
1-15	10.05.2015	25	55

Average	St.dev.S	St.dev.error of mean
100.79	3.41	0.227

Average gr. ASH per sec
4.40

Dispenser code timer settings

Stop	0	
Ready	2	
Start	2	
Open	4	
Ash ON	4.11	
Close	23	22.89 sec of ASH output
Ash OFF	27	
Stop	29	

Average Ash output per rotation

Ave rot	0.481	per/sec
Ave ash sec	4.40	gr/sec
Multy for 1 rotation	2.079	
Ave Ash out per rot	9.154	gr/rot

Ash total for 60 sec Dustmate test

264.19	gr.
--------	-----

## A.7 Calculations environment ash concentrations

### Expected ash concentration in test environment

Environment variables

Intake diameter is  $Intake_{dia} := 55 \text{ mm}$

Intake airspeed is  $Intake_{airspeed} := 11 \frac{m}{s}$

Intake flow rate is then  $Intake_{flow\_rate} := Intake_{dia}^2 \cdot \frac{\pi}{4} \cdot Intake_{airspeed} = 0.026 \frac{m^3}{s}$

Air density at 20 degrees C  $\rho_{air20} := 1.205 \frac{kg}{m^3}$

Intake mass flow rate is then  $Intake_{mass\_flow\_rate} := Intake_{flow\_rate} \cdot \rho_{air20} = 31.492 \frac{gm}{s}$

Dispenser variables

Dispenser current ash output  $Dispenser_{output\_sec} := 4.4 \frac{gm}{s}$

DustMate Max sampling settings  $ug := 10^{-6} \cdot gm$

When set to micro grams/m3  $DM.micro_{max} := 6000 \cdot \frac{ug}{m^3}$

When set to milli grams/m3  $DM.milli_{max} := 60 \cdot \frac{mg}{m^3}$

Comparison of dispenser output VS. DustMate max sampling setting with current environment

$$Dispenser_{output} := \frac{Dispenser_{output\_sec}}{Intake_{flow\_rate}} = 168362 \frac{mg}{m^3} \quad \text{VS.} \quad DM.milli_{max} = 60 \frac{mg}{m^3}$$

## A.8 Piper Pawnee hopper diagram

PIPER AIRCRAFT



CORPORATION

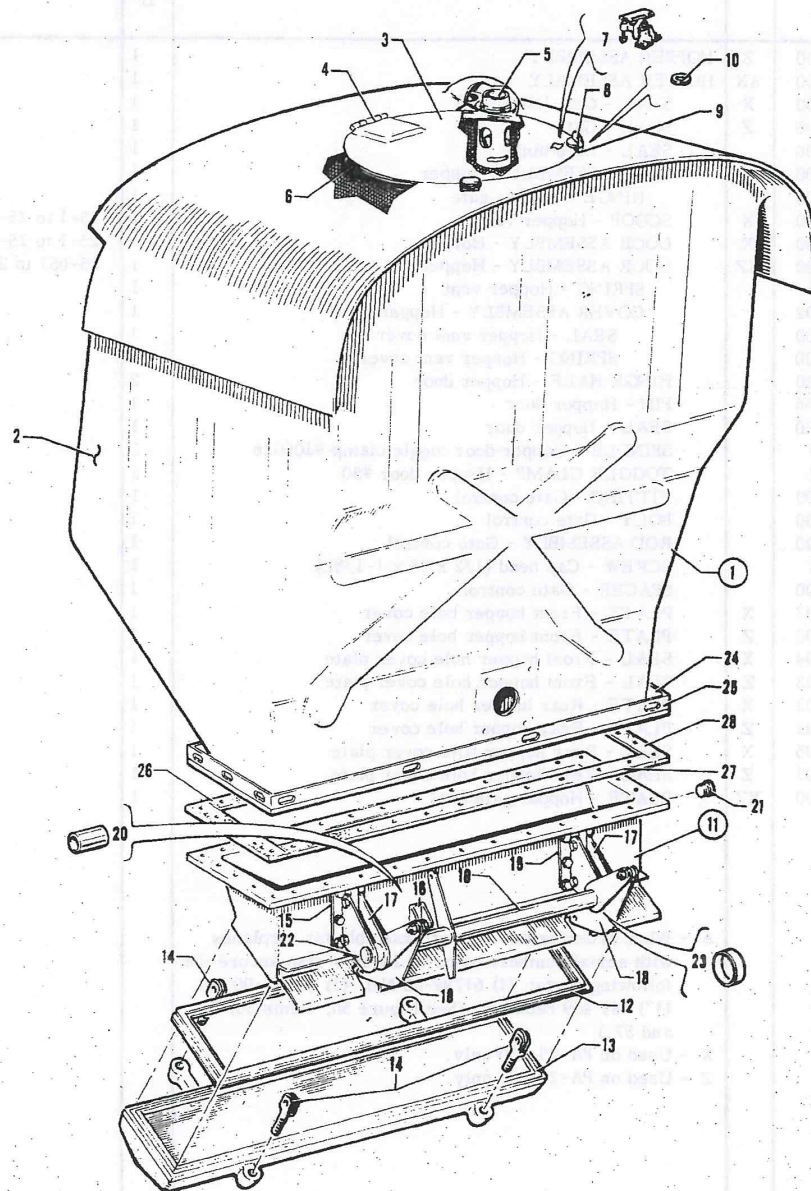




Figure 49. Hopper Assembly  
(Serial Nos. 25-2986 and up)

## A.9 LX 1845 filter datasheet

Technical data sheet Air filter element / Aftermarket		 Driven by performance	
<b>1</b>	<b>Allgemeine Daten</b>	<b>General data</b>	
1.1	Verkaufsbezeichnung	Sales naming	<b>LX 1845</b>
1.2	Materialnummer verkaufsfähiges Produkt (MAHLE)	Material number saleable product (MAHLE)	70342059
1.3	Materialnummer verkaufsfähiges Produkt (KNECHT)	Material number saleable product (KNECHT)	70342058
1.4	Dokumenten-Nummer Produkt	Document number product	5600-20021263-S00
1.5	Erstellung Datenblatt	Completion data sheet	22.05.2013 [date]
1.6	Herstellerland	Country of origin	Austria [choose]
1.7	Version des Datenblatts	Version of the data sheet	02 [choose]
<b>2</b>	<b>Produktgeometrie</b>	<b>Product geometry</b>	
2.1	Filterform	Shape of filter	panel element [choose]
2.2	Abmessungen des Filters	Dimensions of filter	
2.2.1	Plattenelement (Länge x Breite x Höhe)	Panel element (length x width x height)	352 x 264 x 57,3 [mm]
2.2.2	Rundelement (Durchmesser x Höhe)	Round element (diameter x height)	n/a [mm]
2.3	Faltenzahl (minimum)	Pleat number (minimum)	137 [-]
2.4	Faltentiefe (minimum)	Pleat depth (minimum)	47 [mm]
2.5	Faltenbreite (minimum)	Pleat width (minimum)	251,6 [mm]
2.6	Filtrationsfläche (minimum)	Filtration area (minimum)	30598 [cm²]
<b>3</b>	<b>Filtermediendaten</b>	<b>Filter medium data</b>	
3.1	Filtermedium	Filter medium type	A13F [choose]
3.2	Bubble Point First (minimum)	Bubble Point First (minimum)	1,5 [kPa]
3.3	Luftdurchlässigkeit [2 hPa]	Air permeability [2 hPa]	260 ±60 [l/m²s]
3.4	Berstfestigkeit (minimum)	Paper burst strength (minimum)	200 [kPa]
3.5	Flächengewicht (minimum)	Basic weight (minimum)	120 [g/m²]
3.6	Dicke (minimum)	Thickness (minimum)	0,4 [mm]
<b>4</b>	<b>Filtrationsdaten</b>	<b>Filtration data</b>	
4.1	Nennvolumenstrom	Nominal flow rate	18,36 [m³/min]
4.2	Durchflußrichtung	Flow direction	n/a [-]
4.3	Anfangsdurchflußwiderstand	Initial restriction	4,8 [hPa]
4.4	Staubkapazität (minimum) G20 = dp initial + 20 hPa	Dust holding capacity (minimum) G20 = dp initial + 20 hPa	508 [g]
4.5	Anfangsabscheidegrad nach DIN ISO 5011	Initial efficiency acc. to DIN ISO 5011	n/a [%]
4.6	Abscheidegrad bei angegebener dp Erhöhung nach DIN ISO 5011	Filtration efficiency at specified dp increase acc. to DIN ISO 5011	99,7 [%] 20hPa
4.7	Teststaub nach DIN ISO 12103	Test dust acc. to DIN ISO 12103	A4 [-]
<b>5</b>	<b>Verpackung</b>	<b>Packaging</b>	
5.1	Art der Verpackung	Kind of packaging	one-way packaging
5.2	Größe der Faltschachtel (Länge x Breite x Höhe)	Size of folding box (length x width x height)	290 x 75 x 365 [mm]
5.3	Anzahl in / Art der Sammelverpackung	Quantity and type of collective packaging	6 shrinked [pcs]
5.4	Größe der Sammelverpackung z.B. Karton, Schrumpfeinheit (Länge x Breite x Höhe)	Size of collective packaging e.g. carton box (length x width x height)	290 x 450 x 365 [mm]
5.5	Anzahl Produkte auf der Palette	Pallet quantity	72 [pcs]
5.6	Größe der Gesamtverpackung (l x b x h)	Size of overall packaging (length x width x height)	1200 x 800 x 980 [mm]
5.7	Art der Palette	Kind of pallet	one-way pallet [choose]

Sachbearbeiter / responsible person	geprüft / approved	
Zeichen/sign	Zausnig Peter / BDFDE3	
Datum/date	05.08.2013	

## A.10 Arduino Servo Control Code

```

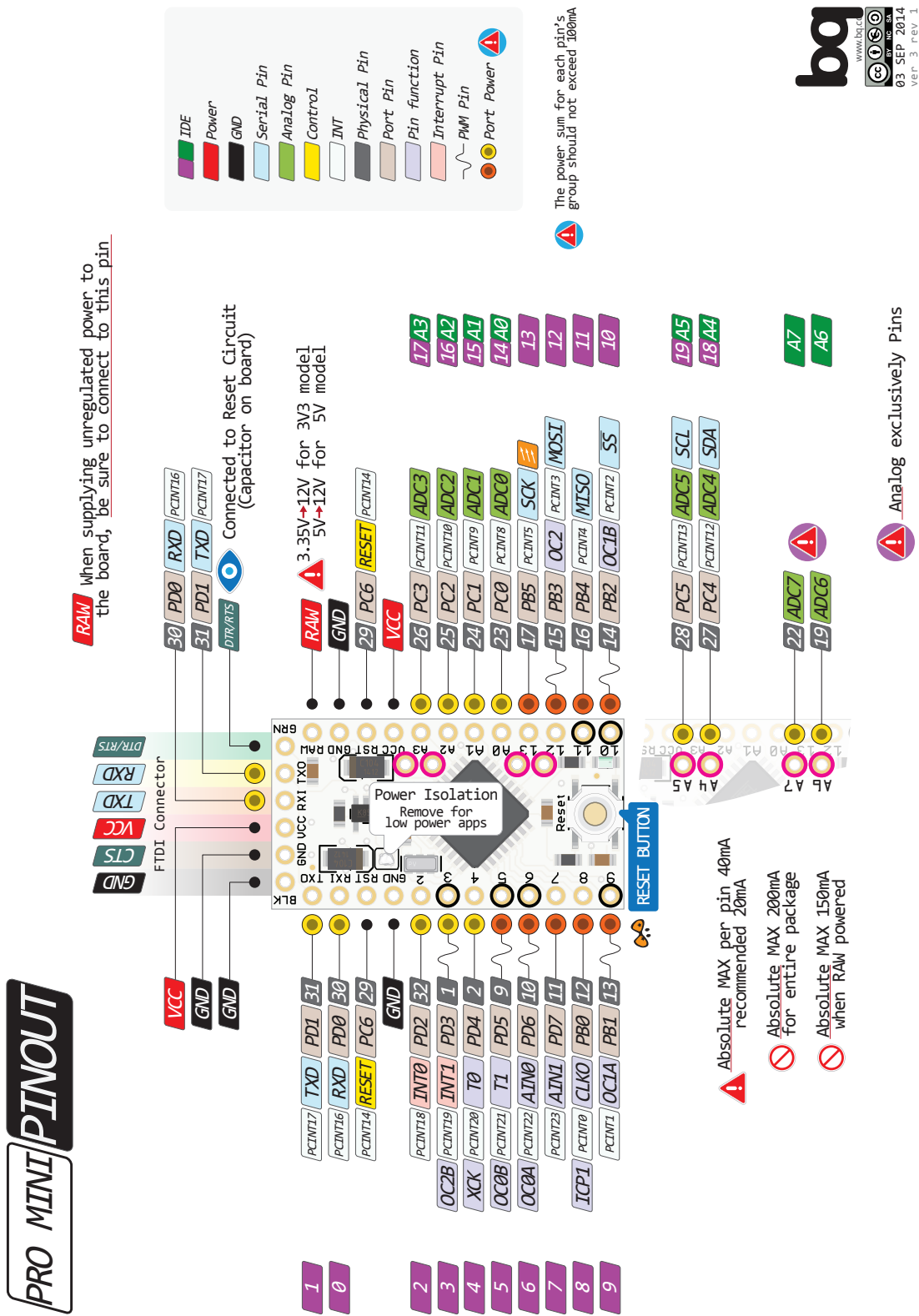
1  /*
   DustMaker final project
3  Servo control
   Eidur Thorsson
5  Reykjavik University
   */
7
   #include <Servo.h>           // Include Servo library
9  #include <avr/io.h>         // Include Input / Output library

11 // Initialize objects and pins
   // Servos
13 Servo servol;               // Name the Servo object Servol for Door servo.
   Servo servo2;               // Name the Servo object Servo2 for Roller servo.
15 const int switchPin = 4;    // Declare Digital Pin 4 on Arduino for toggle ↔
   ↔switch.
   const int servolPin = 9;     // Declare Digital Pin 9 on Arduino for servol.
17 const int servo2Pin = 10;   // Declare Digital Pin 10 on Arduino for servo2.
   long useconds = 0;           // The last time the output pin was toggled
19 long debounceDelay = 50;    // The debounce time
   long lastuseconds = 0;      // Time the last time the switch was turned on
21
   void setup() {
23     //Servo
     pinMode(switchPin, INPUT_PULLUP);
25     servol.attach(servolPin); // Attach servolPin to servol object.
     servo2.attach(servo2Pin); // Attach servo2Pin to servo2 object.
27     // initialize Timer1
     servol.write(10);
29     servo2.write(90);
     void loop() {
31         useconds = millis() - lastuseconds;
         if (digitalRead(switchPin) == HIGH) {
33             delay(5);
             if (useconds >= 2000 && useconds < 14000) {
35                 servo2.write(115); // Start roller
             }
37             if (useconds >= 4000 && useconds < 10000) {
                 servol.write(10); // Open door
39                 //delay(5); // Debounce
             }
41             if (useconds >= 15000) {
                 servol.write(110); // Close door
43                 //delay(5); // Debounce
             }
45             if (useconds >= 17000) {
                 servo2.write(90); // Stop roller
47             }
             else {lastuseconds = millis();}
49         }
     }

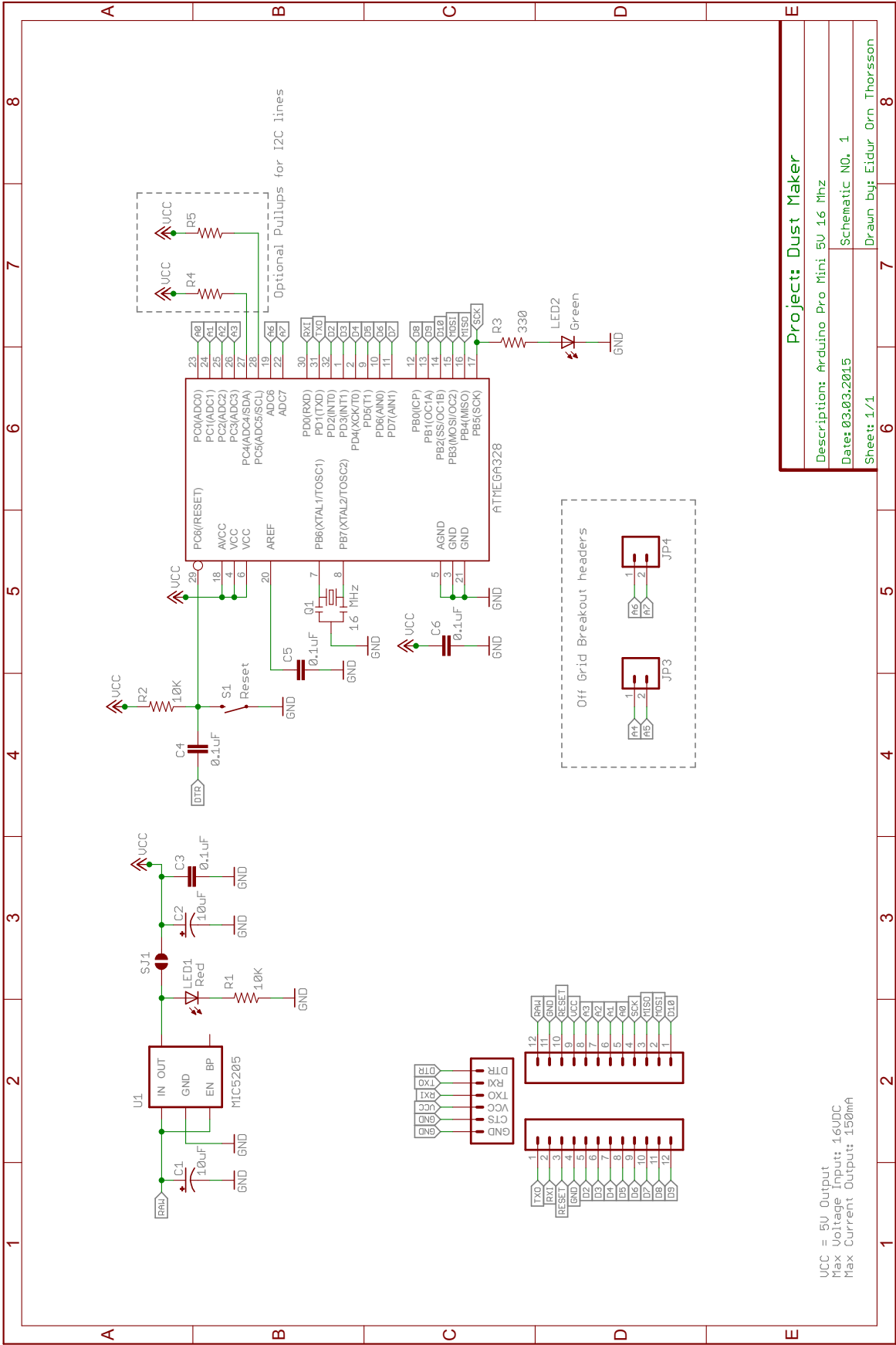
```

CODE A.1: The Arduino program that controls the servos in the Dust Maker.

# A.11 Arduino Pro Mini Pinout

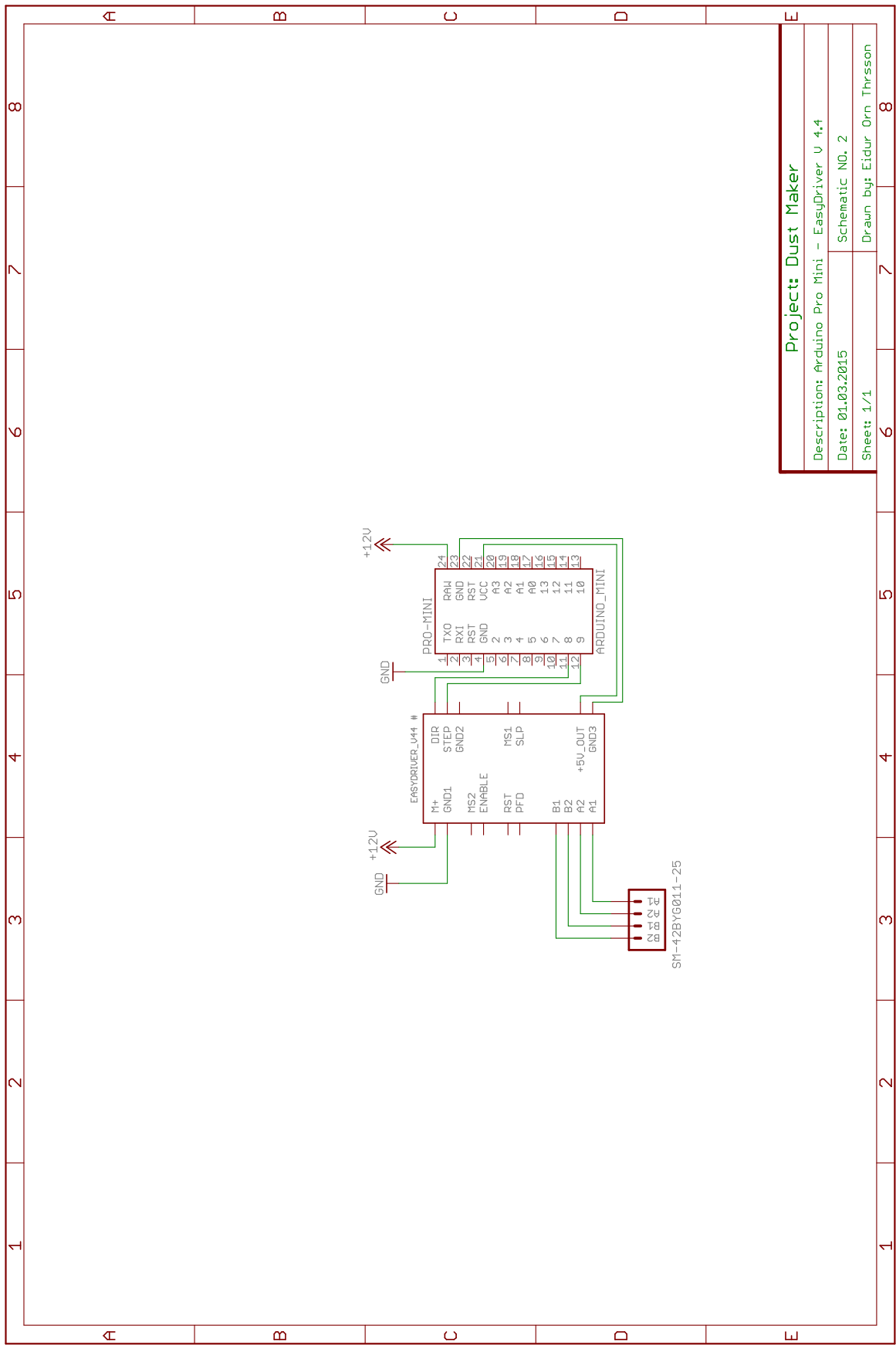


A.12 Arduino Pro Mini schematic

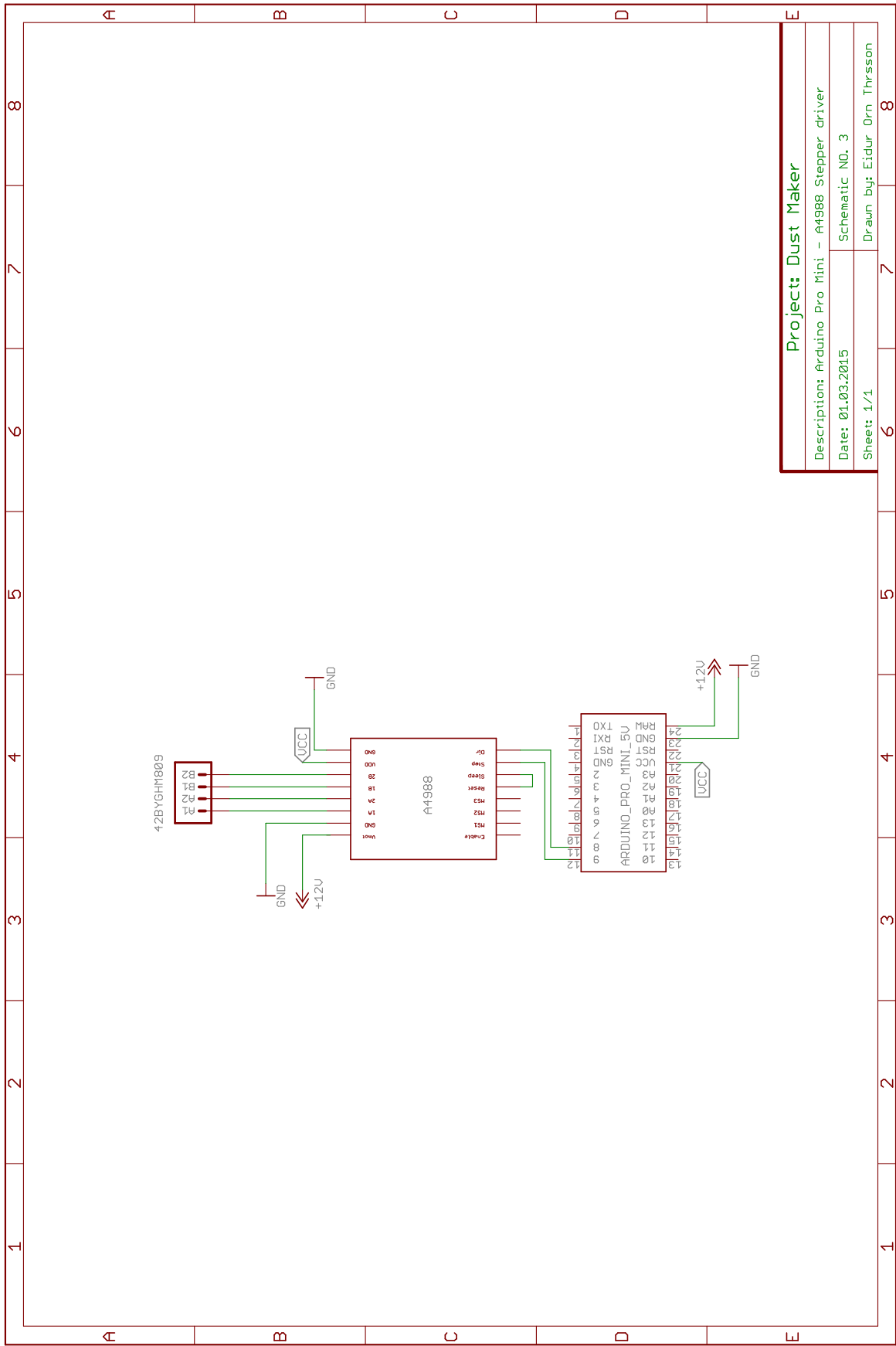




A.13 Arduino Pro Mini connection with EasyDriver V4.4



A.14 Arduino Pro Mini connection with A4988



## A.15 Mercury Stepper Motor Datasheet

[illegible]

HYBRID STEPPING MOTOR MOD.

☐ COLORS OF LEAD WIRES

☐ DIMENSIONS

unit=mm

☐ SPECIFICATIONS

PHASE	相数	2	PHASE	COMMENT
STEP ANGLE	步距角	$0.9 \pm 5\%$	°/STEP	
VOLTAGE	静电压	3.06	V	
CURRENT	电流	1.7	A/PHASE	
RESISTANCE	电阻	$1.8 \pm 10\% \Omega$	/PHASE	
INDUCTANCE	电感	$2.8 \pm 20\% mH$	/PHASE	
HOLDING TORQUE	静转矩	48	N.cm Min	
DETENT TORQUE	定位转矩	2.2	N.cm Max	
INSULATION CLASS	绝缘等级	B		
LEAD STYLE	引出线规格	AWG26 UL1007		

设计

20110114

审核

技术规格书

42BYGHM809

工艺

批准

版本 NR

共 张 第 张

www.wantmotor.com

## A.17 Continuous Rotation Servo Datasheet



**HuiDa RC International INC.**

Address : 1707, Huashang Building, Xiapu district, Huizhou, Guangdong, China  
E-mail: info@chd.hk Tel: 86 752 2118844 Fax: 86 752 2118860 WWW.CHD.HK

### 1. 使用環境條件

Apply Environmental Condition :

No.	項目	規格 standard
1-1	保存溫度 Storage Temperature Range	-20°C ~ 60°C
1-2	操作溫度 Operating Temperature Range	-10°C ~ 50°C
1-3	操作電壓 Operating Voltage Range	4.8V ~ 6.0V

### 2. 測試環境

Standard Test Environment :

2-1	測試環境 Standard Test Environment	<p>每一个检查必须是正常的温度和湿度进行测量，温度 <math>25 \pm 5^\circ\text{C}</math>，相对湿度 <math>65 \pm 10\%</math>，在按照本规范的标准测试条件下判断特征。</p> <p>Every characteristic of the inspect must be normal temperature and humidity carry out the test, temperature <math>25 \pm 5^\circ\text{C}</math> and relative humidity <math>65 \pm 10\%</math> of judgment made in accordance with this specification standard testing conditions.</p>
-----	-----------------------------------	--

### 3. 外觀檢查

Appearance Inspection :

No.	項目	規格 standard
3-1	外觀尺寸 Outline Drawing	40.5 x 20.0 x 38.0
3-2	外觀 Appearance	无损坏，不允许影响功能



Product Name  
**360° Analog Servo**

Model No.  
**AR3606HB**

Version  
**V1**

Page  
**1/3**

#### 4. 電 氣 特 性

Electrical Specification (Function of the Performance) :

No.	Item	4.8V	6.0V
4-1	空載轉速 Operating speed (at no load)	0.16 sec/60°	0.14 sec/60°
4-2	空載電流 Running current (at no load)	250 mA	300 mA
4-3	停止扭力 Stall torque (at locked)	6.0 kg-cm,	6.7 kg-cm
4-4	停止電流 Stall current (at locked)	800mA	900mA
4-5	待機電流 Idle current (at stopped)	4 mA	5 mA

注：項目 4-2 定义平均值时，伺服器无负荷运行

#### 5. 機 械 特 性

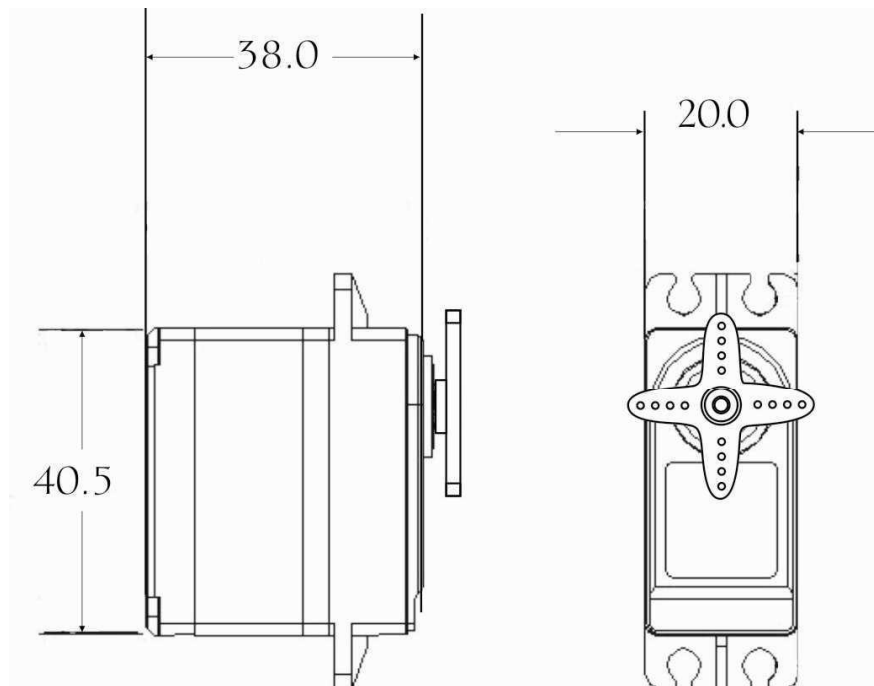
Mechanical Specification :

No.	項目	規格 standard
5-1	外觀尺寸 Overall Dimensions	40.5 x 20.0 x 38.0 (mm)
5-2	機構極限角度 Limit angle	∞°
5-3	重量 Weight	40 ± 2 g
5-4	導線規格 Connector wire gauge	#28 PVC
5-5	導線長度 Connector wire length	300 ± 5 mm
5-6	舵片規格 Horn gear spline	25T/ $\phi$ 5.80
5-7	舵片種類 Horn type	圓盤 X 2
5-8	減速比 Reduction ratio	240: 1

## 6. 控制特性

Control Specification :

No.	項目	規格 standard
6-1	控制系統 Control system	改变脉冲宽度 PWM
6-2	放大器種類 Amplifier type	模拟控制器 Analog Controller
6-3	操作角度 Operating travel	360° (在 800→2200 $\mu$ sec)
6-4	中立位置 Neutral position	1500 $\mu$ sec
6-5	脈波訊號虛位 Dead band width	5 $\mu$ sec
6-6	旋轉方向 Rotating direction	逆时针 (在 1500→2000 $\mu$ sec)
6-7	脈波寬度範圍 Pulse width range	800→2200 $\mu$ sec
6-8	可作動角度範圍 Maximum travel	大約 360°(在 800→2200 $\mu$ sec)



## A.18 Servo Datasheet



**HuiDa RC International INC.**

Address: 1707, Huashang Building, Xiapu district, Huizhou, Guangdong, China  
E-mail: info@chd.hk Tel: 86 752 2118844 Fax: 86 752 2118860 WWW.CHD.HK

### 1. 使用環境條件

Apply Environmental Condition :

No.	項目 item	規格 standard
1-1	保存溫度 Storage Temperature Range	-20℃ ~ 60℃
1-2	操作溫度 Operating Temperature Range	-10℃ ~ 50℃
1-3	操作電壓 Operating Voltage Range	4.8V~6.0V

### 2. 測試環境


Standard Test Environment :

2-1	測試環境 Standard Test Environment	<p>每一个检查必须是正常的温度和湿度进行测量，温度 <math>25 \pm 5^{\circ}\text{C}</math>，相对湿度 <math>65 \pm 10\%</math>，在按照本规范的标准测试条件下判断特征。</p> <p>Every characteristic of the inspect must be normal temperature and humidity carry out the test , temperature <math>25 \pm 5^{\circ}\text{C}</math> and relative humidity <math>65 \pm 10\%</math> of judgment made in accordance with this specification standard testing conditions.</p>
-----	-----------------------------------	---

### 3. 外觀檢查

Appearance Inspection :

No.	項目 item	規格 standard
3-1	外觀尺寸 Outline Drawing	尺寸见附件 Dimension see the attachment
3-2	外觀 Appearance	无损坏，不允许影响功能 No damage which affects functions allowed

	Product Name 模拟伺服器 Analog Servo	Model No. 1501MG	Version V1	Page 1/3
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#### 4. 電氣特性

Electrical Specification (Function of the Performance) :

No.	項目 item	4.8V	6.0V
4-1	空載轉速 Operating speed (at no load)	0.16 sec/60°	0.14 sec/60°
4-2	空載電流 Running current (at no load)	400 mA	500 mA
4-3	停止扭力 Stall torque (at locked)	15.5 kg-cm	17 kg-cm
4-4	停止電流 Stall current (at locked)	2300 mA	2500 mA
4-5	待機電流 Idle current (at stopped)	4 mA	5 mA

注：項目 4-2 定义平均值时，伺服器无负荷运行

Note: Item 4-2 definition is average value when the servo running with no load

#### 5. 機械特性

Mechanical Specification :

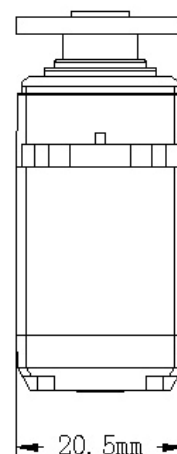
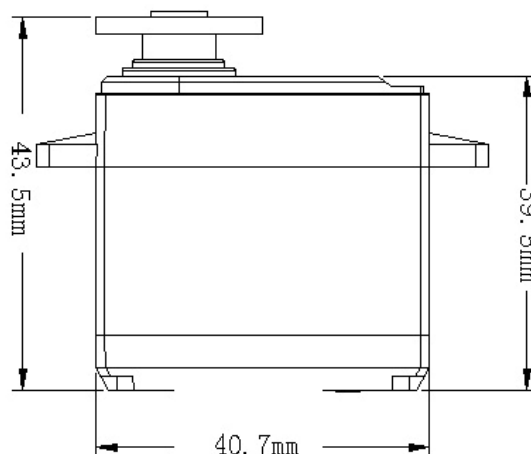
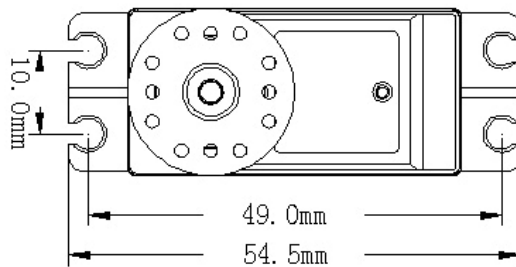
No.	項目 item	規格 standard
5-1	外觀尺寸 Overall Dimensions	见附件 See the drawing
5-2	機構極限角度 Limit angle	180°± 10°
5-3	重量 Weight	63 ± 1g
5-4	導線規格 Connector wire gauge	# 28 PVC
5-5	導線長度 Connector wire length	300± 5 mm
5-6	舵片規格 Horn gear spline	25T/ $\phi$ 5.80
5-7	舵片種類 Horn type	条型, 半臂舵板 Single, Double
5-8	減速比 Reduction ratio	1/298

	Product Name	Model No.	Version	Page
	模拟伺服器 Analog Servo	1501MG	V1	2/3

## 6. 控制特性

Control Specification :

No.	項目	規格
6-1	控制系統 Control system	改变脉冲宽度 Pulse Width Modification
6-2	放大器種類 Amplifier type	模拟控制器 Analog Controller
6-3	操作角度 Operating travel	90° (在 1000→2000 $\mu$ sec)
6-4	中立位置 Neutral position	1500 $\mu$ sec
6-5	脈波訊號虛位 Dead band width	2 $\mu$ sec
6-6	旋轉方向 Rotating direction	顺时针 (在 1500→2000 $\mu$ sec) Counterclockwise (when 1500→2000 $\mu$ sec)
6-7	脈波寬度範圍 Pulse width range	800→2200 $\mu$ sec
6-8	可作動角度範圍 Maximum travel	大约 165° (在 800→2200 $\mu$ sec) Approx 165° (when 800→2200 $\mu$ sec)



Product Name  
模拟伺服器 Analog Servo

Model No.  
1501MG

Version  
V1

Page  
3/3

# Glossary

$V_{REF}$	Reference voltage pin Eq (3.1)	14
$\bar{X}$	Sample mean Eq (3.3)	27
$\hat{\mu}$	Average value of sample Eq (3.3)	27
$\sigma$	Standard deviation Eq (3.4)	27
$\sigma_{\bar{X}}$	Standard deviation of the mean Eq (3.5)	27
$n$	Total number of samples Eq (3.3)	27
$\alpha$	Angle of repose Eq (3.2)	20
AoR	Angle of repose	xxiii, 20, 23, 24, 31
APP	Adobe Premiere Pro CC 2014	29
ASTM	American Society for Testing and Materials	17
AVOID	Airborne Volcanic Object Identifier and Detector	1
DC	Direct current	16
DMM	Digital multi meter	14
E&U	Error and uncertainty	27, 31, 40
EASA	European Air Safety Agency	1
FPS	Frames per second	29
Gc	Graduated cylinder	23, 24, 31
GND	Ground connection	14
HD	High definition	29
HEPA	High-efficiency particulate air	36, 37
HVAC	Heating, ventilation and air conditioning	37, 39
ICAO	International Civil Aviation Organization	1
POM	Polyoxymethylene	24, 36
RC	Radio Controlled	15
RPS	Revolutions per second	7, 8, 39, 41–45
VAA	Volcanic ash advisories	1
VACC	Volcanic Ash Advisory Center	1
VADAS	Volcanic Ash Detection and Awareness System	1





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