Appetite for Ice: Technical Report

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Introduction

The existence of water on Mars and its implications, has sparked a growing curiosity in humankind to know more about its ancient red neighbor, and what its current state may mean for the future of Earth. The results at hand, from previous expeditions and the advancement of relevant technology, has brought the prospects of Mars closer to the earth than it ever were. With the nearing launch of NASA's "InSight" Mars mission and the increased payload size that the Space Launch System will make possible, scientists and engineers can explore bolder avenues of space exploration. In-situ resource utilization (ISRU) is a difficult and cumbersome process requiring adaptation of earth based technologies to harsher environments. However challenging, ISRU technologies are required for the 3rd phase of NASA's Journey to Mars: Earth Independence. In this paper, an efficient design is discussed, to excavate and process Martian Ice. A critical resource for future research on making Mars habitable is water. In its natural state, i.e. briny, frozen and buried under the unrelenting Martian surface, it is not a usable resource. Making this resource available will open doors for future missions to further our path to colonization. The design explores the feasibility of a drilling auger that descends through the subsurface of mars, excavates ice and process it into liquid water. The device will draw, a power of 1150W at peak loads during drilling and melting of ice.

System Description

The entire task for this competition has been discretized into different subsystems and described below. A glossary of important/frequently referred components have been named and described in Table 1 (appendix)

Mounting System

The design of the base frame comprises four 80/20 aluminum channels in a rectangular formation around the drilling area. Two of these have a cross-sectional area of 1"x1" ("single" channels) and a length of 34.5", and the other two have a 2"x1" cross-section ("double" channels) and a length of 39". On each of the "double" channels, two ½" diameter thru-holes are drilled 36.5" apart. The carriage bolts that protrude from the ice chest lid go through these holes, and are fastened down at the top faces of the frames. The rest of the drill system is assembled, directly or indirectly, to these channels.

System Excavation Operations

The ice is excavated by an auger drilling system which consists of an auger with 4" diameter flute and a 4.5" diameter ice cutting bit, a PVC shroud with 4.2" OD that encloses the auger and allows material to be transported up, and a corded power drill with a maximum rated power consumption of 840W with an actual rated maximum output of 550W is adapted to serve as the auger motor. A flanged ABS adapter ring connects the shroud to the table. This table along with the shroud and auger is actuated in the vertical direction (the Z-axis) by a ball screw, powered by a geared stepper motor. A through hole load cell is installed on the shank of the auger and mounted onto the table to provide force /weight on bit (WOB) measurements. If the WOB is too close to the prescribed limit of 100 N, the drill is actuated upward for a short distance by controlling the Z-axis stepper motor direction. It is important to note that a neoprene rubber damping pad is used on either side of the table to dampen the vibratory and WOB loads that are transmitted through the auger shaft to other components mounted on the table and ensure that most of the load path flows primarily through the load auger load cell.

The operational parameters include a relatively low WOB, corresponding to a low Z-axis motor torque, low auger motor torque, and high auger motor rotational speed. This results in shallower cuts, which produce smaller ice shavings, in a consistency like snow, which is ideal for fast melting in a microwave chamber.

The ball screw and its motor, is fixed to base, which can traverse along the horizontal (XY) plane. Each of the corners of the base rests on a linear bearing carriage, which slides along Y-rails, enabling Y axis actuation. Each end of the rails is mounted to X-axis carts, allowing motion in the X axis. Power is provided by a pair of 19:1 geared NEMA 17 stepper motor, one for each axis. A timing belt and pulley arrangement translates the rotational motion of the motors to linear motion of the belts. The X-axis belt is fastened to one of the ends of the 80-20 rails, while the Y-axis belt is fastened to one of the sides of the base.

The PVC shroud, which encloses the auger, has a hole on its side, collocated vertically at the end of the auger flute. Saddle tap, allows the ice duct to be attached to the shroud hole. The other end of the duct exits into the microwave chamber. An opening hatch is located on the underside of the duct, which can be opened using a DC servo motor.

The first step in the excavation process is to actuate the auger drill in the horizontal plane to its drilling site, keeping it fixed above the overburden. The horizontal motion is an optimized staggered pattern, which maximizes the number of possible drill sites in the available drilling area, and minimizes drilling through overburden that has already been excavated. Once stably positioned, the auger motor is powered on, and the z-axis motor lowers the drill into contact with the overburden. As the drill descends, the drilled overburden is transported up through the shroud and out through the hatch in the ice duct. While the overburden is being transported through the duct, the ice hatch blocks the duct passage leading upto the MW chamber, to prevent the overburden from going in the microwave chamber. The shape of the duct and the positioning of the hatch contribute to expel the overburden away from the drilling hole. After the auger drills into the ice and ice could be seen flowing out of the hatch, the hatch is set to closed position to bridge the gap in the duct, and allow the ice to enter the microwave chamber. To ensure that no overburden will be left inside the duct when the hatch is actuated, as well as to ensure the ice is transported effectively to the MW chamber, the duct is inclined downward by about 9 degrees from the exit hole of the shroud to the entrance of the microwave chamber.

The microwave is mounted to the table through the MW load cell at the end of an aluminum strut assembly connected to the table. This load cell, henceforth referred to as MW load cell, measures the instantaneous weight of the MW chamber to sense when the chamber is filled with ice to capacity or empty. Once the chamber is near its predetermined full capacity, the auger motor is stopped, the extraction tube hatch is elevated back again, sealing the chamber from microwave radiation leakage and the auger drill is lifted above the overburden level.

Solution to deal with the overburden

As the auger drills through the overburden, it is transported up the shroud and out the hole at the top end of the auger flute. It then exits through an open hatch in the bottom of the ice transport duct, which also seals the microwave chamber shut to prevent any overburden from entering. The expelled overburden falls back to the drilling area, but away from the borehole being currently drilled. The ice extraction system moves around the drilling area in a pattern that allows it to avoid excavating the discarded overburden.

Process for managing temperature changes to prevent drill from freezing in the ice

Ice frozen well below 0^0 C behaves differently than freezing ice at 0^0 C as the surface temperature of the ice quickly removes heat from any liquid water that is in contact with it. The drill removes ice volume in chips/shavings. Even though increased pressure on ice lowers its melting point, the auger's drilling action not only puts pressure on ice but also fractures the ice surface and transports it up through the flute. The ice auger drill used here is made of carbon steel and is meant to perform on frozen lakes and can withstand sustained temperatures of ~ -45^0 C. This is well lower the temperature to be ever encountered in the competition. It is also to be noted that the drill does not operate when the MW is running or when the auger is relocated to the next drilling hole position, hence it is running at just ~40% duty cycle.

Water Extraction System/Technique

The collected ice in the MW chamber is converted to water via MW heating. Care has been taken to ensure minimal leakage of electromagnetic radiation (EMR) and sparking as elaborated in the safety plan. The MW chamber in its current form has been redesigned based on a few preliminary experimental observations carried out in the recent past. One major structural modification was shifting from a sheet metal monocoque design to a rigid structural frame made of square aluminum tubing. The advantages were manifold, the significant ones being the robustness of mounting the MW chamber to the Z axis table anywhere on the parallelepiped square tubing frame, structural rigidity and modularity. Since all the 6 faces of the chamber are made of separate rectangular aluminum sheets, damage or design changes at any of the faces simply requires changing the affected face. Based on experimentation, it was observed that the melting rate is favorably affected by the accumulation of meltwater within the chamber. To further facilitate this the MW bottom face has been provided with a sump, where the ice collects and melts. When the meltwater reaches a specific level, it drains out passively from the staggered holes as seen in Figure 1 below. The sump also serves the dual function of allowing the overburden, if any in the water, to settle down before the water flows out of the chamber and into the filtration tube vi

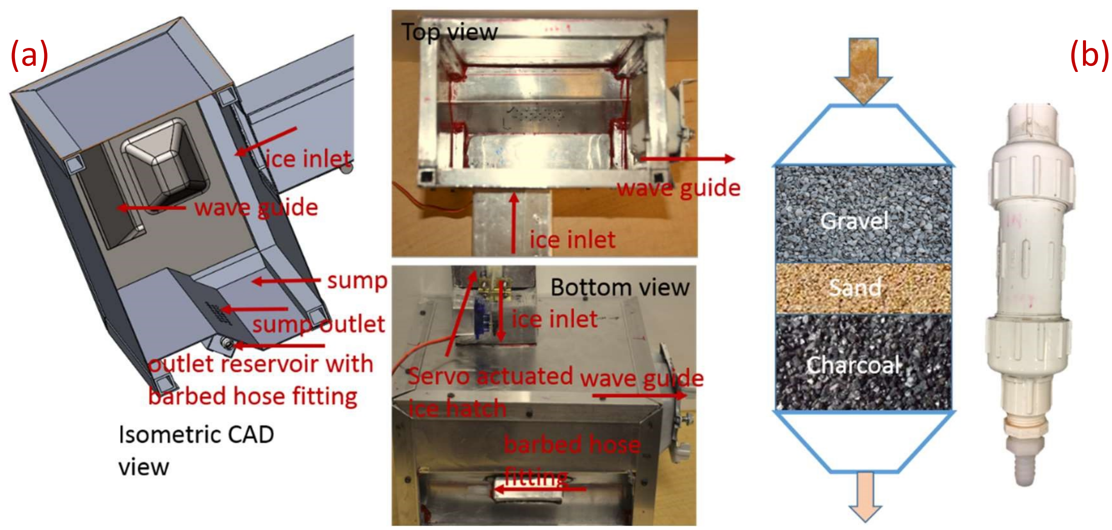

Figure 1. (a) The MW subsystem showing the important design features in CAD and in actual photograph. (b) Filtration system schematic with actual photograph.

The water sealing inside the MW chamber is ensured by using elevated temperature resistant (~ 340^0 C) RTV silicone sealant and gasket maker.

Filtration and Water Collection

The water discharged by the MW chamber undergoes a passive gravity assisted filtration process, where the water trickles through layers of gravel, sand and charcoal and is guided outside the drilling area via quarter inch recoiled air hose. The current passive filtration system has been constructed out of a PVC 1 inch compression coupling layered with gravel, sand and charcoal and held in place by screen wire mesh filters. The filtration rate has been observed to be at least twice the ice - melting rate of ice in microwave ~ 400 g/min. Hence, the filtration system would never be the bottleneck of the system. A bypass tube from the inlet of the compression coupling connects at the outlet tube as a safety measure to prevent backflow of water into the MW chamber, in case the melting rate exceeds the filtration rate due to clogging or blockage of the filter.

Control and Communication System

Control signals are sent to the Arduino Mega R3 2560 microcontroller as sen in the bottom right of the electronics enclosure as shown in Figure 2, via a standard USB cable from a remote laptop with serial protocol.

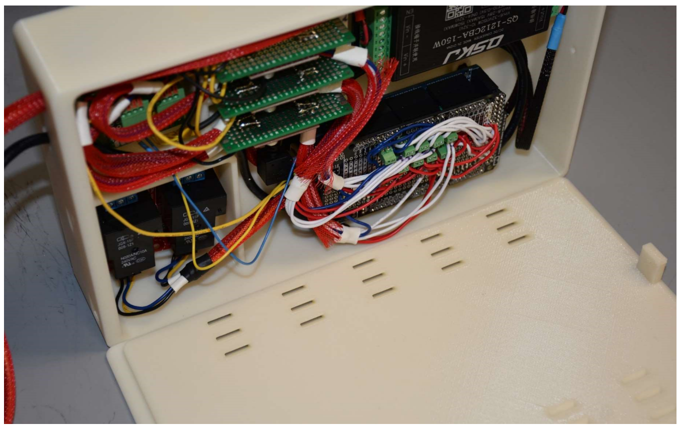

Figure 2. Electronics enclosure photograph housing the microcontroller, AC relays and stepper motor drivers.

The control software prompts the laptop through the serial port for various initial inputs such as desired stepper speed, manual or automated timings, and preferences on drilling efficiency vs power. Numerous values are predefined such as drilling grid locations, calibrated stepper values, calibrated drilling times and depths, and microwave duration. The user has the flexibility to manually trigger any timed event or stop them if already in progress. The power switching of the drilling activity and microwave activity is governed by the snap action limit switches and a strain gauge load cell, respectively. The former are switches attached to the two extremes of every axis, to bring the drill to a 'home' initially in addition to, making sure it comes to a controlled stop at the physical boundaries of the system. The microcontroller has been coded, to start microwave operations when the chamber is ~ 65% filled. It has knowledge of this value, from the strain gauge load cell, which is attached to the chamber. The magnetron has a graceful failure mode if overheating occurs which is discussed further in the microwave safety plan. The thermal fuse activates at a temperature of 184^0 C, which is standard for the magnetron applied in our design. Safety is thus hardwired and coded into the system.

All powered radiating or actuating components are physically or electrically detached from power. If power is lost to the controller while any other device is powered on, that device will also power off as a 'on' command requires available voltage and current to the microcontroller. AC components are physically disconnected by default from power via relay switches. The USB cable will not provide power to the Arduino as the FET has been removed. This allows a failsafe physical switch to cutoff power to the Arduino and thereby all other components. Also connected to the microcontroller, is the card reader as shown in , that holds the micro-SD card, for data logging.

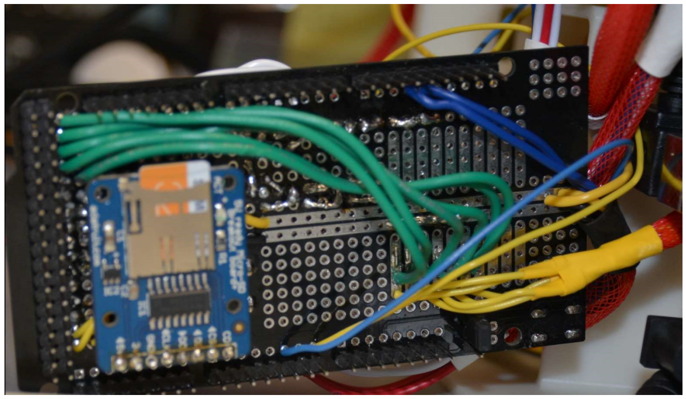

Figure 3. Onboard physical data storage, micro SD card.

The value of force on bit, over time and depth of drilling, is read from the donut cell. This analog reading, is then calibrated and written on to the SD card, by means of file handling on the Arduino IDE.

Technical Specifications*:*

Table 1. The table summarizes the system specifications and the motor properties.

System Specifications	
Overall mass	46.2 kg
Overall volume	2.06 m^3
Length of drill bit	1.34 m
Max weight-on-bit/drill force	103 N
Max drilling speed (full speed)	3.12 mm/s in ice
Drill operating speed	1500 RPM
Drill operating torque	1.25 N-m
On-board computer system	Arduino Mega2560 R3
Communications interface	Arduino serial monitor
Software	Arduino 1.8.2
Max power – MW operation	1150 W
Max power – drill operation	450 W
Motor Specifications	
X- and Y-Axis Motors	
Rated voltage	2.8 VDC/phase (2 phases)
Rated current	1.68 A/phase (2 phases)
Holding torque	0.44 N-m (before gearbox)
Gear ratio	19:1
Z-Axis Motor	
Rated voltage	2.8 VDC/phase (2 phases)
Rated current	2.0 A/phase (2 phases)
Holding torque	0.59 N-m (before gearbox)
Peak torque	0.42 N-m
Speed at peak torque	90 rpm
Gear ratio	5:1
Auger Motor	
Rated voltage	120 VAC
Rated current	7 A
Max output power	550 W

The weight distribution for our system to be used for the competition is shown in Figure 4 below.

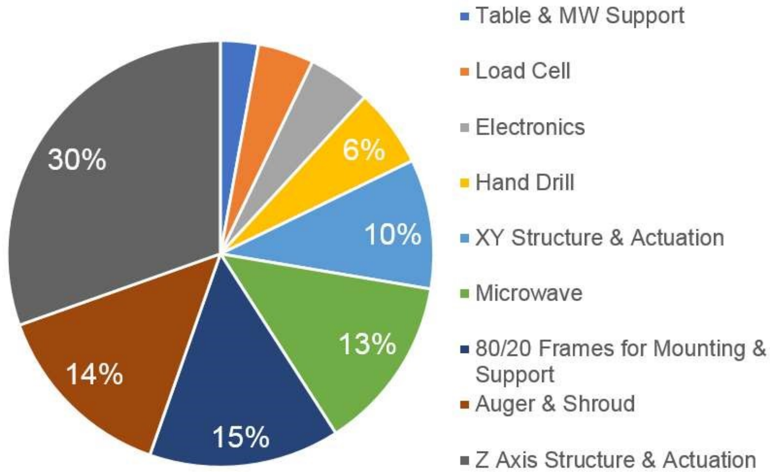

Figure 4. The weight distribution schematic.

Design Changes/Improvements*:*

Initially, the microwave was designed to be mounted to the side of one of the vertical support rods by corner braces. However, this would have required routing the extraction duct around the support rod, which would hinder the movement of ice into the microwave chamber. So, the microwave position was changed to be opposite the ball screw relative to the auger, between the two support rods. A more rigid L-shaped aluminum strut channel assembly replaced the corner braces.

The auger motor was changed from an AC motor that was supplied with a previously purchased auger to a commercially-available, corded power drill, to reduce weight and power consumption. Since the auger motor was one of the heaviest single components in the entire system, reducing its weight was key to reducing the weight of the overall assembly. The corded drill that was selected provides a fourfold weight reduction and power consumption within safe limits of competition constraints.

The new design for the auger load cell assembly involves mounting directly to the table using coupling nuts, rather than mounting to the shroud using brackets, as originally designed. This was changed to avoid excessive stress in the shroud caused by transferring the WOB to it, as well as making the auger load cell assembly more rigid to ensure that nearly all WOB is supported by it instead of the auger bearing and motor mounting plate.

The original design for the XY-plane actuation incorporated the use of linear ball bearings on steel rods, but there were complications with achieving adequate shaft alignment and maintaining proper, level orientation of the base, due to poor constraint of the shafts in bending and torsion. As a result, the rods and bearings were replaced by 80/20 aluminum channels with sliding carriages. The channels are much more resistant to bending, and the carriages are well constrained in the torsional direction of the channels. This modified design has the added benefit of being significantly lighter as well.

The original design for separation of ice and overburden called for two separate holes in the shroud, to be actuated separately depending on which region was being drilled. The hole for ice would be connected to the microwave chamber via a round duct, fitted with a butterfly valve to prevent leakage of microwaves. This design would require three separate servo motors, besides the difficulty to actuate openings on the shroud itself. The current design now calls for a simple hole in the shroud, with the saddle tap making the transition. The ice duct has a hinged ice flap, that can be actuated like a door. When horizontal, the flap allows the ice to be fed into the microwave chamber, and when vertical, the flap closes the chamber, sealing it from microwave leakage when the magnetron is melting the ice, or preventing the overburden from entering the chamber, when overburden is being drilled.

A gearbox was added to the z-axis motor to provide higher torque. This allows the ball screw to support a greater vertical load required to overcome the system friction and the WOB load, while allowing the auger to descend at an adequate speed during the drilling operation. This comes as a tradeoff with ascent speed when retracting the drill. However, since this ascent of the auger system is a minor portion of the operation, the tradeoff was adjudged worthwhile.

Based on test results and the feedback given for the midpoint review, it was determined that the original shroud was causing unnecessary resistance for the descent of the auger during drilling operations. This was most likely due to its outer diameter being larger than the diameter of the cutting bit of the auger. In response, a new shroud with a smaller outside diameter than the cutting bit was implemented.

Three DC relays which previously toggled power to the stepper motors are no longer needed due to the "enable" function on the more advanced Big Easy stepper motor drivers. This design change saved weight without reducing system functionality. Additional electronics design changes include a modular wire input/output control board for quick teardown and assembly. The wire gauge of the stepper motors was reduced from 16 AWG to 20 AWG after analyzing the peak loads and allowable voltage drop to the stepper motors. The electronics box design was changed to allow for better wire management and improved cooling. The modified design was 3D printed in ABS plastic, which does not deform at higher temperatures and provides suitable rigidity.

Challenges

1. Mechanics
    a. XY bearings alignment - ran into problems to get the Y-axis rails parallel, which caused the entire assembly to move with more friction than anticipated. Solved by maintaining the same distance between each pair of bearing by attaching them with the X-axis cart, so they move in a coupled fashion
    b. Manufacturing planning - machine shop available for use by the mechanical engineering department had a long backlog of jobs, which led to delays or even cancellation of machining jobs of important parts, such as the table and base. Mitigated by obtaining access to shopbot from the NC State Entrepreneurship Garage for precision milling and drilling
    c. manufacturing planning - machine shop available for use by the mechanical engineering department had a long backlog of jobs, which led to delays or even cancellation of machining jobs of important parts, such as the table and base. Mitigated by obtaining access to shopbot from the NC State Entrepreneurship Garage for precision milling and drilling.
    d. Hole size and tolerances - concerns with alignment and the precision of the diameters. Mitigated by using Shopbot machining.
    e. Vibration of the Z-axis structure - the high RPM of the auger causes the table and all components attached to it (such as the ball screw, the microwave chamber, the shroud, and the Z-axis guide rods) to vibrate, which may cause screw loosening. Mitigated by making the hole on the base where the shroud slides through with a very tight tolerance around the shroud, constraining its motion. Also, by welding a 0.25" drill bit to the tip of the auger, a pilot hole is drilled before the main blades touch the overburden. Since the drilling system is being constrained in two points, the vibration was significantly reduced. Finally, splitlock washers were added to the screws that were prone to vibration loosening.
2. MW subsystem

   a. Structural strength of MW chamber was inadequate, with the low rigidity resulting in mounting and alignment issues with the sheet metal monocoque design. The modified design used aluminum tubing for the MW frame which facilitates easy mounting and significant improvement of structural strengths.
   b. MW leakage prevention was a serious safety issue and ensuring hole sizes or gaps in the MW chamber lesser than 10 mm helped prevent leakage. Also, ensuring electrical continuity across the MW chamber and then grounding the chamber solved the issue of arcing from sharp metal edges inside the MW chamber.
3. Electronics & Controls
   a. Wire gauge & optimization: The location of electronics box is a compromise between wire weight and proximity to sensors. To reduce weight and improve sensor readings, care was taken to use minimum wire gauge and take voltage drop into consideration for sensor readings.
   b. Wire management: The large amount of connections forced smart wire management, careful consideration was taken to shorten wires and stagger their lengths to reduce wire mass and obstruction.
   c. Heat management: The stepper motor drivers produce a considerable amount of waste heat, so the electronics enclosure was redesigned with air vents at 45° angles to the top and bottom of the enclosure. The hottest components were placed at the top of the box to facilitate cooling from ambient draft.
   d. Arduino startup protocol: The Arduino digital pin 13 rapidly goes high/low at startup. The AC relays were wired to pins 13 and 12 before this was known. After troubleshooting the symptom of the startup protocol pins 12 and 11 were used.

Summary of Integration and Test Plan

The system integration involves bringing together the three subsystems, namely: electronics, mechanical and MW, for prototyping a fully functional drilling system capable of extracting ice from the subsurface of Mars. The interfacing components between mechanical and MW subsystems have been designed to facilitate quick connection and disassembly as well as seamless functionality.

The MW system is interfaced with the mechanical subsystem through a L-shaped aluminum strut channel with a cantilever load cell and is fixed to the table. The struct channel is positioned not at the geometrical center of the MW system but at the center of gravity which is biased towards the magnetron, which is the biggest contributor towards the weight of the MW chamber. A rectangular ice duct was designed to connect the shroud covering the drill bit, to the microwave chamber, thereby allowing the materials extracted by the drill to be transported for heating. The ice duct is connected to the saddle tap on one end, which is fixed to the shroud, the other end is connected to the microwave chamber via its flanged end. An actuated hatch in the base of the pipe allows for the rejection of overburden when opened, and the accepting ice when closed.

The mechanical and microwave systems were integrated with the electrical system, through the electronic box, mounted onto the base frame. Power supply to the drill and microwave transformer was given through 16 gauge wires and was monitored, by AC beefcake relay switches, that are triggered by PWM pins on the Arduino Mega 2560 R3 microcontroller. The microwave transformer ups the input power supply and outputs 2KV which is sent to the microwave magnetron via 12 gauge wires. The microcontroller also actuates the stepper and servo motors and drives the entire sequence of operations, with inputs from the various sensors in place.

For our testing plan, we used a fiberglass tote box (L=42.5", W= 20.25", H= 14.25") as our test bed, where we had 60% V/V% of the tote with ice and the remaining 40% packed with the overburden mixture of 1 inch angular gravel and mound clay. The drilling system was partially placed on a hydraulic lift and partially on a table with the auger drill placed between the gap of these two supporting structures and lifted above the height of the tote. The tote was then positioned under the drilling system, mimicking the drilling section on the test bed at the competition. An initial system check with calibration of the load cells, as shown in Figure 6, and sensors was performed. This includes the Z axis actuation to measure the actuation speeds, debugging Arduino code and checking vibration levels at maxed out drill speed.

A detailed flowchart enumerating the sequence of operations along with the power consumption at every stage is shown in Figure 5.

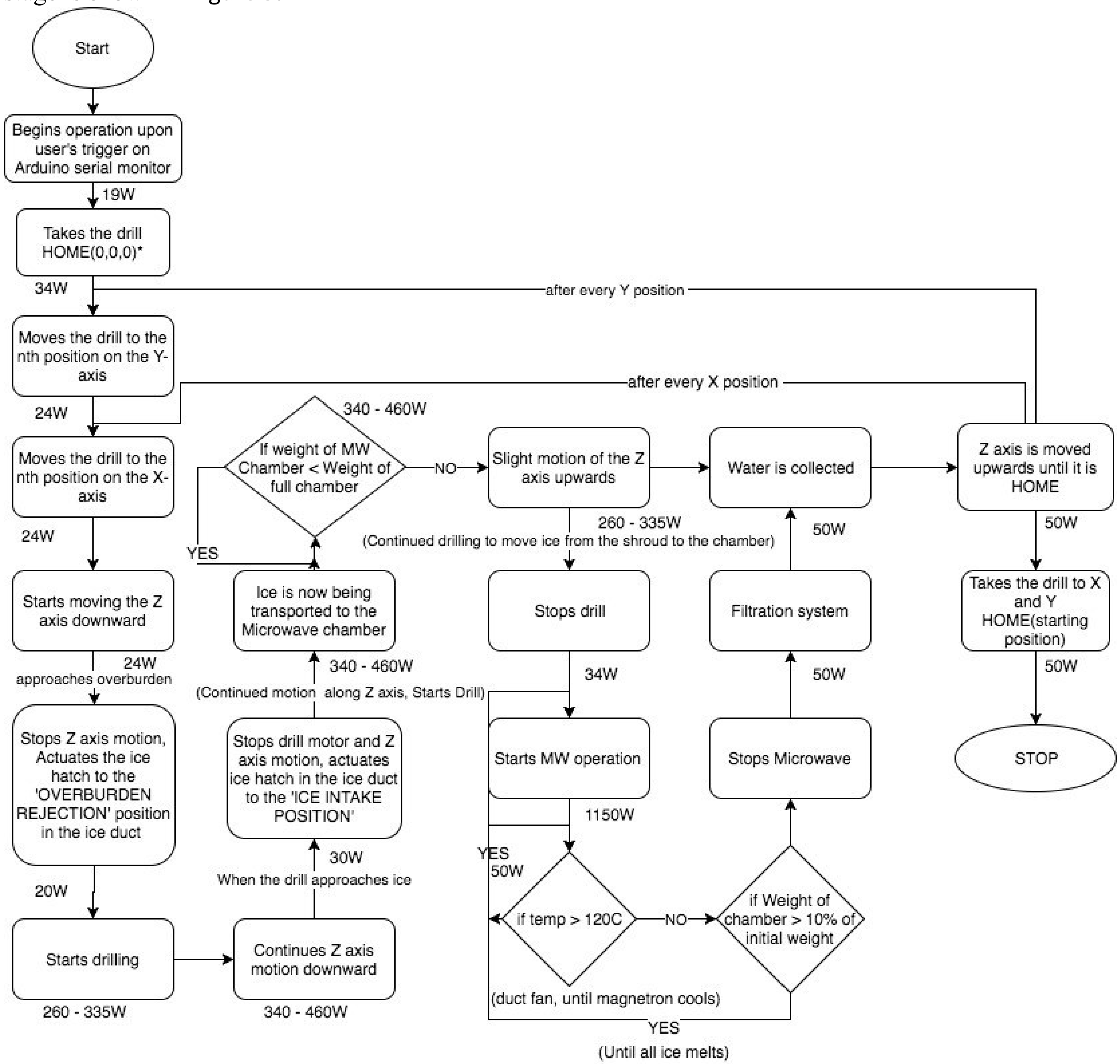

Figure 5. A flowchart illustrating the overall sequence of operations along with power consumption (in W) at every step of operation.

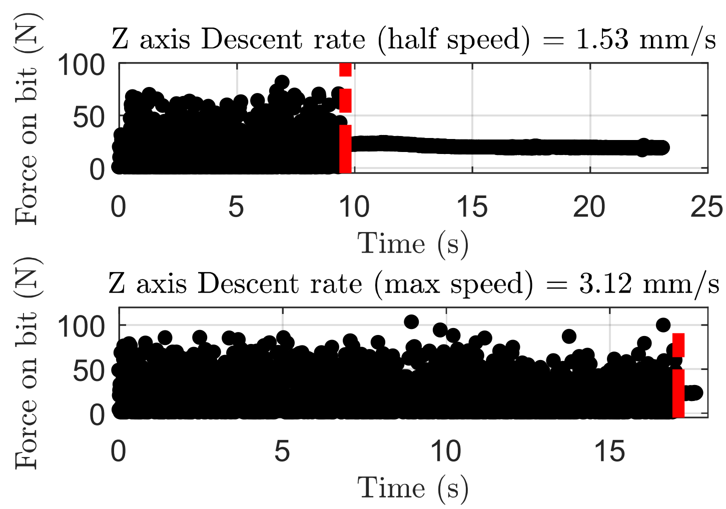

Figure 6.The plot shows the variation of force on bit as a function of time for half speed and full speed travel of the Z axis. The red dashed line marks the point where the power to the drilling system is cut-off.

Tactical Plan for Contingencies/Redundancies

1. Obstruction of ice duct - In the event that there is a blockage in the ice duct, the entire operation will be stopped and the servo can be used to actuate the ice hatch to and fro, to clear it.
2. Excessive microwave or water leakage - The source of leakage, will be identified and sealed using an aluminum tape/faraday fabric or sealant.
3. Melt water backflow - The melt water rate leaving from MW chamber might have a higher rate than what the filtration system can process or in case of blockage at the filtration unit. The backflow might cause the MW chamber to fill up and water to seep up to the waveguide level. Any seepage into the waveguide would render the magnetron inoperable due to electrical short circuiting. To prevent this a bypass valve at the inlet of the filtration unit bypasses overflow, unfiltered water into the collection unit
4. Ice formation - shroud and drill assembly are pulsed during inactive periods as well as offset from undrilled ice to reduce crystallization and heat transfer respectively.
5. Cracked plastic - while loads on the shroud and other plastic parts are minimal, the team has prepared spares of all plastic parts should any fail during the hands-on part of the competition
6. Non-tightened bolts - Extra bolts will be available on the hands-on day, to replace any lost in transport or fallen into overburden.
7. Damaged wires - Soldering station and spare wires will be available.
8. Uncontrollable/Unpredictable motion - The microcontroller has a kill-switch, that is coded to stop all operations.

Safety Plan

a. MW leakage radiation is a serious health hazard and one should be aware of the potential risks it poses towards human eye and reproductive systems. However, containing the MW inside the chamber means ensuring holes/gaps are well below the household MW wavelength of ~ 12 cm. Care has been taken that gaps/holes are less than 10 mm in size within the MW chamber.
b. Overheating of the magnetron is another cause of electrical hazard. Even though a forced convective cooling is applied at the magnetron fins, addition temperature sensors and a thermal

fuse, allows complete shut-down of power flowing into the MW system. The magnetron power will be cut off in the event that the temperature sensor measures a temperature on the surface of the microwave greater than 120^0 C, to be restored when the fan cools the magnetron to a safe level. If the sensor fails to report an overheating event the 155^0 C thermal fuse will sever the power preventing an accident from occurring. A schematic outlining the safety circuit can be seen in Figure 10 (appendix). Since strength of MW radiation scales inversely with square of distance, standing beyond 5 meters would be safe as observed by MW leakage testing contour shown below in Figure 7.

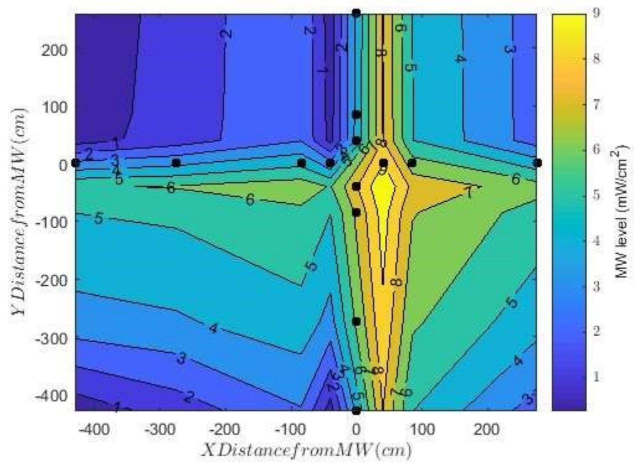

Figure 7. Contour plot showing the experimentally detected MW radiation levels. The black dots are the actual data points. The MW is placed at the origin with the ice duct and magnetron facing +Y and -X respectively.

Path-to-flight*:*

The drilling and excavation of ice from the Martian sub-surface, would pose significant challenges, a lot different from those on the simulated Martian conditions. The red planet, as the name suggests, has a surface, that has a very high concentration of oxidized iron (rust). Drilling through such a terrain, would require thorough analysis before implementation. Where and when to drill, are of crucial importance. The study of the polar ice caps and the recurring slope lineae (RSL), would be very helpful to understand the geography of the planet, in terms of its ice/water presence and their climatic conditions. It must be considered, that the water on mars is merely just hydrated salts and it is required to be prepared for the changes that this could demand on the drilling, heating and filtration. The environment has an abundant supply of highly reactive elements like sodium, magnesium, basalt, perchlorates and iron. It is thus recommended to be prepared for the same, by a better choice of materials. For the auger, titanium, would be a better fit, as opposed to steel - for its ability to withstand extreme temperature conditions, while being chemically inert. The harsh environmental conditions, could result in the absorption, dissolution and freezing of local gases, by conventional off-the-shelf materials. This would lead to undesirable effects such as outgassing. To combat this, they could be substituted by materials that are known to perform well in vacuum. Most plastics are known for their very high outgassing rate and it would be efficient to replace parts made of PVC (shroud), with a material that has a lower rate, like Polytetrafluoroethylene (PTFE). The neoprene, used in arresting vibrations, has a very high outgassing rate and must be replaced by a material with similar stiffness and low outgassing property. The two-part epoxy adhesive used to bond components like the water outlet of the MW chamber could be easily adapted for use in space as the outgassing property of such adhesives are significantly improved and lowered well below the ASTM E595 standard by allowing the epoxy to cure through a heating cycle. Silicone sealing used in the MW chamber could also be adopted in the vacuum conditions of Mars as they have been shown to be resistant to outgassing [1]. Adhesive used in this design however, is Loctite Hysol - 1C, which if safe for use on Mars. The lubrication of bearings for the system, would have to be performed with unconventional lubricants, for the same reason. Additionally, it will be crucial, to make sure that these lubricants, do not freeze in extreme freezing conditions. Hexagonal boron nitride for instance, could be used as a dry lubricant, for the linear carriage bearings. Castrol Braycote 601EF, that is known for its low outgassing rate and ability to withstand very high ranges of temperature -80C to 204C, has been used in the past on the curiosity rover and is thus recommended. The bearings, will also have to be provided with lip seals to prevent dust particles from entering them and contaminating the lubricants [2], [3].

It is important to consider the effects that the lower atmospheric pressure on Mars, has on the drilling operation. The atmospheric pressure on Mars is very close to the triple point of water. As the cutting bit drills through the ice, it can heat it to vapor temperatures at that pressure, resulting in sublimation or rapid evaporation of the ice shavings. The resulting gas expands rapidly and blows the shavings upward [4]. This aids in the transport of ice up the auger, though care needs to be taken to ensure that the shroud is sealed well from the atmospheric gas for two reasons. A good seal at the bottom of the shroud, which may be aided by a pile of cuttings outside the shroud because of the difference in cutting bit and shroud outer diameters, is important for allowing most of the ice shavings to take the path of least resistance inside the shroud rather than outside of it. However, if this does not form an effective seal, a modification to the shroud design, such as making its outer diameter large, may need to be considered in order to form a seal with the outer walls of the bore hole. Alternatively, an additional shroud which seals the excavated hole at the surface would prevent cuttings from exiting the hole. In addition to effective ice cutting transportation, the issue of preventing ice from adhering to the shroud or auger and causing an obstruction must be addressed. One possible solution is running a highly thermally conductive material from the cutting bit up the auger to prevent the water vapor from depositing on the auger until it can escape through the top of the auger. Treating the material with a hydrophobic coating, if such a coating can survive the conditions in space and on Mars without outgassing or eroding, would be another possible solution.

The atmospheric pressure, being 0.6% of that on Earth(600Pa), is very close to the triple point of water, shown in Figure 8. Adding heat energy to ice at this pressure will directly convert it to its vapor state. This suggests that our microwave chamber, will require alterations to carry out the melting process under the required conditions. As more ice is converted to vapor, the pressure rise inside the chamber will reconvert this vapor to water. Hence, the microwave chamber needs to withstand high pressure, which will prevent ice from undergoing rapid vaporization or freezing. Current scientific information hypothesizes that the ice found trapped underneath the Martian surface will be mixed with mineral salts in varying type and concentrations which increases the electrical conductivity of ice. This in turn increases the microwave absorption by ice making this technology even more attractive.

Outside of the sphere of the earth, electrical and electronic components are subject to Single Event Effects (SSE) and Total Ionizing Doses (TID). These include upsets and burnouts, where charged particles lose energy due their exposure to radiation. This corrupts information on registers and memory elements and draws large currents, destroying circuits. The electronics involved in the powering and actuation of this system, would thus, should be modified significantly, for smooth functioning. This could be done, by implementing materials and semiconductors that provide resistance to radiation and electrostatic discharge. Memory can be secured, by using programmable read only memory (PROM), Chalcogenide random access memory (CRM) or field programmable gate arrays (FPGAs), in the place of conventional or earth based, digital memory. It would be convenient, to use microcontrollers that have incorporated the aforementioned in the past, such as those manufactured with HARDSIL technology (by Vorago technologies). The more recent products in this line, are even Arduino compatible (eg. VA10800).

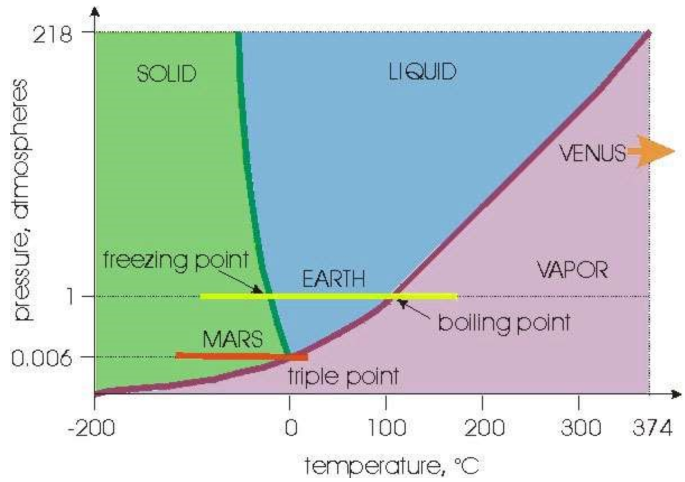

Figure 8. Triple point of water (courtesy: Center for ice and climate - Neils Bohr institute)

The soldering on the circuits, must be performed with lead-free eutectic tin, that can endure elevated temperatures while preventing whiskers, which would otherwise grow out of solders, in the presence of vacuum. Insulating tape, that combines polyimide film with a 3M adhesive and a fiberglass reinforcement layer, could be used as multilayer insulation (MLI), for all the electrical wiring. This will act to thermally protect systems, to maintain temperatures in very specific ranges. For optimum insulation if required, successive metallic layers separated by materials with low thermal conductivity like Nomex or Polyester netting, can be implemented. One layer of such an MLI structure has been proven in the past, to reflect as much as 97 percent of the incident radiation.

The system, would be best transported, if it is broken into sub-assemblies, which are then easily assembled on Mars. This will help with the packaging and will reduce the assembly time and effort. The entire system, can be supported by the base of a suitable vehicle, which can assist with transportation on Mars.

The reduced gravitational acceleration constant on Mars causes several differences in how the drill operates. First, the lower weights resulting from this approximately 60% reduction would tend to decrease the torque required to actuate the system in the XY-plane due to lower resulting friction, the torque for lifting the drill in the z-axis, and the power draw from the auger motor for transporting the ice up the auger. It would also decrease the bending load from offset masses, such as the microwave, resulting in better alignment for more ease of motion of the ball screw and z-axis linear bearings. However, a considerable disadvantage emerges in systems that rely on passive motion of particles and fluids. Overburden and ice particles would not move down the ice duct as quickly, and water would take longer to diffuse through the filter as well. If it is necessary to hasten these processes, active methods, such as the use of small pumps, can be employed without forcing the system to draw too much power.

The ice drill system will undergo extensive launch and space environment testing and validation before it begins its journey to Mars. Payload integration design must be carefully considered to ensure that no critical damage occurs to any components before they reach their final destination. It is recommended that all load-bearing parts - especially slender members, including the ball screw, support rods, and all aluminum channels - may need to be disassembled before being packaged in the payload bay if it is not designed to withstand inertial and vibrational launch forces, as doing so could result in an over-engineered system for operational conditions on Mars. This method of packaging would also limit the volume occupied, allowing adequate space for other payloads. Otherwise, major subassemblies could be pre-assembled before launch integration. Also, parts that are critical for motion, including bearings and motors, should be packaged so that internal components are not loaded to failure.

With respect to the space environment, the packaging should be designed to protect vulnerable electronic parts from intense radiation and outgassing from volatile materials. It must regulate temperatures to prevent lubricants from freezing, moving components from locking, and electronics from overheating. To prevent cold welding, metal parts of like material must be packaged separately, treated with protective coating (Ti6Al4V) [5], or be made with a sufficiently low purity. The procedure for validating the payload integration design, based on the aforementioned criteria, will involve extensive random vibration and thermal vacuum chamber testing to simulate the launch and space environments, respectively.

Table 2. Technological readiness level (TRL) of different components used in the design of the system.

Technology	Application	TRL
Magnetron	Heating of the collected ice	6-7
Auger	Drilling through overburden and ice	6-7
Stepper motors	Actuates the drill along X,Y and Z axis	7-8
Servo motors	Actuates hatch	7-8
Auger load cell	Measures force on bit	7-8
Arduino Microcontroller	Controls and actuation	7-8
Transformer	Stepping up voltage from 110V to 2kV	7-8
Temperature sensor	First safety measure - temperature of microwave system(Magnetron) up to 125C	6-7
Thermofuse	Second safety measure - temperature of microwave system(Magnetron) up to 185C	6-7
Drill Motor	Powers the Auger drill bit	6-7
Snap action Limit switches	Senses the drill, when it approaches frame boundary	6-7
Noise filter	Removes noise from electrical signal to give better transformer output	6-7
MW load cell	Measures weight of Microwave chamber	6-7

Budget

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the Oval NCSU dining, for supplying us with ice and other testing materials like containers and carts. EI garage also supported us by providing access to its machines and tools. A detailed budgetary distribution is shown in Figure 9.

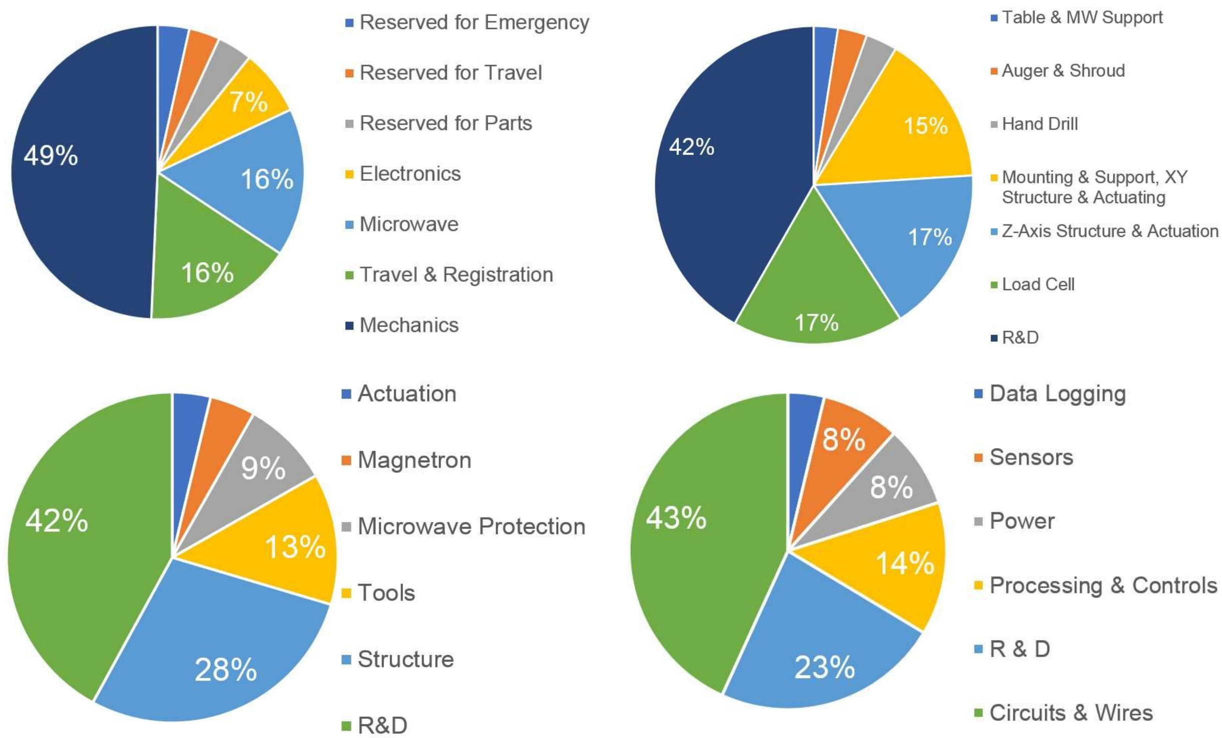

Figure 9. (top left) Shows the breakup of the total expenditure incurred for this project, $17,200. (top right) budget breakup of for mechanics subsystem. (bottom left) Budget breakup for MW and filtration subsystem. (bottom right) Budgetary breakup of electronics subsystem.

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Appendix

Table 3. Glossary of important components/parts and its brief functionality referred to in the report.

Component/part name	Description and functionality	Subsystem
MW load cell	The strain gauge sensor measuring instantaneous weight of MW chamber	MW, electronics
Ice duct	The square cross sectional connecting tube for transporting overburden out of the auger shroud and ice into the MW chamber	MW, mechanics
Ice hatch	Servo controlled hatch located at underside of Ice duct, preferentially rejects overburden and accepts ice into MW chamber.	MW
Table	the Z axis aluminum platform on which auger motor is mounted	mechanics
Base	the aluminum platform through which the shroud passed and ball screw motor is mounted	mechanics
Ball screw	converts rotary to linear motion, controls the Z axis actuation of the auger drill.	mechanics
Auger load cell	Through hole biaxial load cell, FUTEK LTH 500, cell senses real time force on bit. -60 F to 200 F	Mechanics, electronics
Magnetron	2.45 GHz 660 W household magnetron drawing 1100W max power	MW
Saddle tap	a 3D-printed part that makes the transition between the circular hole in the shroud and the square ice duct	mechanics
Auger	Fluted screw conveyer designed to carry material	mechanics
Auger drill	Auger with the ice cutting bit	mechanics
Y-rails	80/20 channels where the base will indirectly rest on to, via the linear carriage bearings	mechanics
X-axis carts	ABS piece where the Y-axis rails rests on top of, and which slides on the single 80/20 channels of the frame mounting	mechanics

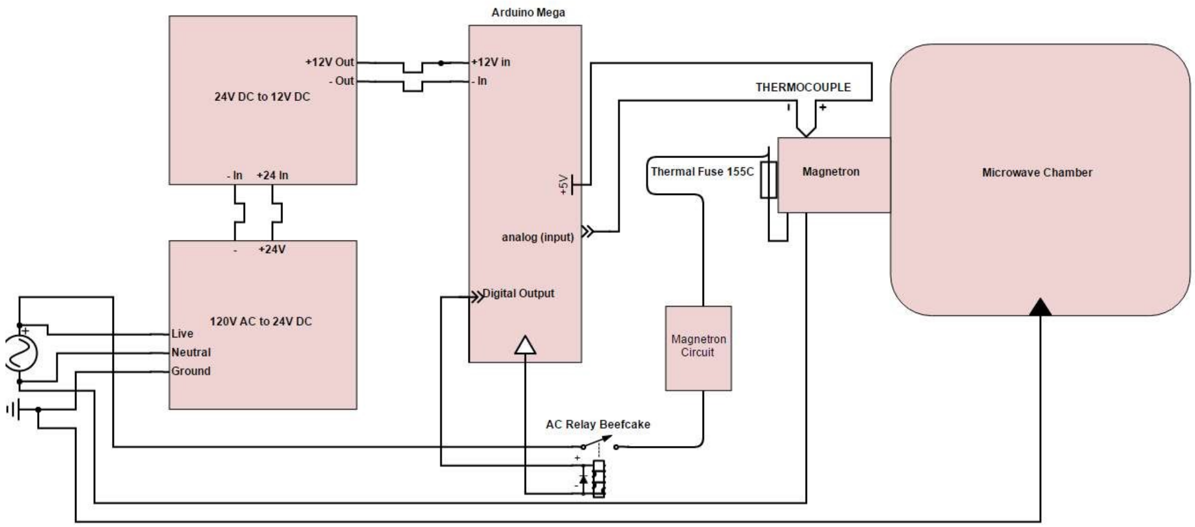

Figure 10. The circuit diagram for MW system, outlining the safety fuses.

Detailed assembly plan

1. Place the double 80/20 channels on the mounting bolts
2. X-axis cart assembly:
   - Place the X-axis cart (wood) onto two linear carriage bearings at the designated location
   - Place two 1”x1” L-bracket on top of the X-axis cart, in line with the linear carriage bearing screw holes
   - Insert the 0.25” screws through the L-brackets and the bearing holes
   - Repeat the process above for the second linear carriage bearing of the X-axis cart
3. Slide the carriage bearings of the X-axis cart onto the slots of the single 80/20 channel
4. Put four (two on each end) 1”x1” L-brackets on the ends of each single 80/20 channel
5. Slide the single 80/20 channels into the double 80/20 channels slots via the guide fasteners of the 1”x1” L-brackets.
6. Repeat procedure 3-5 for the second single 80/20 channel
7. Slide the Y-axis (the second pair of double 80/20 channels) rails through the channel guide fasteners on the 1”x1” L-brackets of the X axis cart.
8. Make measurements and adjustments to all channels to ensure accurate parallelism & positioning before tightening all the screws (0.25” dia. black head).
9. Proceed with the tightening of all screws
10. Mounting block / ball screw / ball nut assembly:
    - Slide the mounting block in the machined end of the ball screw all the way in, such that some of the threaded part of the ball screw extends below the mounting block
    - Tighten the locknut in the thread of the ball screw using a fixed-hook spanner. As the locknut travels in the thread of the ball screw, it will pull the ball screw further in the mounting block, until the top bearing of the mounting block touches the underside of the ball screw
    - Insert the internal ball bearings in the ball nut; when done, screw the flange in
    - Slide the ball nut onto the top of the ball screw
11. Base assembly:
    - Screw the remaining four linear carriage bearings to the corners of the base using the ¼” dia. button head screws, and fasten using 0.25” nuts
    - Fasten the flanged shaft collars to their respective locations using #8, 1” long hex head screws
    - On the top surface of the base, on their respective holes, attach two 4” long aluminum plates for gripping the Y-axis belt, using 0.25” screws
12. Pass the auger through the central hole in the base from the bottom
13. Slide the base onto the Y-axis rails through the channels via its linear carriage bearings, making sure that the hole for shroud is to the back, and the hole for the ball screw is to the front; another person needs to hold the auger vertically
14. Put the mounting block assembly on the base such that the machined end of the ball screw goes in its hole in the base
15. Z-axis motor assembly:
    - Fasten the 5:1 geared NEMA 17 stepper motor to its off-the-shelf bracket using four M3x10mm screws
    - Attach the bottom of the NEMA-bracket to the 3D-printed Z-axis bracket using four M4x16 screws
    - Slide the Z-axis shaft coupling onto the shaft of the Z-axis motor and tighten its set screw using an Allen key
16. Place four M10x80mm screws through the through holes of the mounting block
17. Put the Z-axis motor assembly in its place by sliding the other side of the Z-axis motor coupling onto the machined end of the ball screw, and the two through holes of the 3D-printed Z-axis bracket onto the two M10 screws. Secure the screws in place by using a split-lock washer and nut
18. Place shroud over auger and through the central hole in base

19. Slide the load cell shaft collar onto the auger, such that the bottom face of the shaft collar is 106 mm from the top of the auger
20. Insert the Z-axis guide rods in the flanged shaft collar on the base and tighten its set screws using an Allen key
21. Auger load cell (LC) assembly:
    - Screw four coupling nuts of 0.25”-20 thread,1.75” length to the underside of the mounting plate of the LC using 0.25”-20, 1” long screws
    - Insert four 0.25”-20 thread, 1” long threaded rods onto the ends of the coupling nuts. Half of the length of the threaded rods should stick out of the coupling nuts
    - Screw the other four coupling nuts to the protruding ends of the threaded rods
    - Using construction adhesive glue, join on top of the mounting plate the LC washer, the LC, LC load washer, and LC bearing, in that order
22. Table assembly:
    - Fasten the two linear Z-axis bearings to the side through-holes of the table using four #8 thread, 1.25” screws for each bearing
    - Screw the four 1”x1” brackets for the hand drill support to the table, slide the hand drill support in the space between its brackets, and screw the components together
    - Attach the two foam pieces to the top and bottom surfaces of the table, such that their center holes match
    - Place the hand drill bearing on top of the top foam, and screw using four 0.25”-20 thread, 2” long screws, with nuts on the bottom.
    - Place the auger coupling in the extension rod of the drill bearing
    - Fasten the LC assembly to the bottom of the base, screwing the coupling nuts to its designated holes using 0.25”-20 thread, 1” long screws
23. Mount the table assembly to the rest of the prototype by sliding the other end of the Z-axis support rods inside the Z-axis flanged shaft collar on the base, sliding the end of the ball screw in the hole for it on the table, and the top of the auger inside the auger coupling
24. Tighten the screws of the flanged shaft collar, the auger coupling
25. Bring the ball nut up until it touches the bottom surface of the base, and screw it to its designated holes using 0.25”-20 thread, 1.25” long screws
26. Holding up auger, tighten the auger coupling to the auger
27. Tighten the shroud collar to the table using 0.25”-20 thread, 1.25” long screws
28. Mount the hand drill to the hand drill support using the provided U-bolt
29. Connect the hand drill to the auger adaptor shaft and tighten the chuck
30. Fix two 2”x2” brackets to the end of the double 80/20 channel of the base on either side.
31. Fasten a 2” long 80/20 extension to each of the pairs of 2”x2” brackets
32. Secure a pair of 4” long aluminum plates to the 80/20 extensions to the left, and a pair of 2” long aluminum plates to the 80/20 extensions to the right
33. On the 4” aluminum plates, screw two NEMA brackets in place, and one on the 2” aluminum plates
34. Using construction adhesive, secure a 0.375” ID oversized washer to the front face of the NEMA bracket on the right, and another to the front NEMA bracket on the left, and a 0.25” ID flanged sleeve bearing to each of the washers
35. Fasten one of the 19:1 geared NEMA 17 stepper motor to the back face of the back NEMA bracket on the left using four M3x10mm screws
36. Attach one of the XY shaft couplings to the shaft of the NEMA motor, and one of the rod extensions for XY pulleys to the other side of the shaft coupling, making sure the rod goes through the sleeve bearing
37. On the NEMA bracket on the right, insert a rod extension in the sleeve bearing, and secure its back side using a set screw shaft collar
38. Slide the pulleys on the rod extensions, tightening the set screws, and place the belt around them

39. On the Y-axis rail to the left, slide four 4” long aluminum plate extensions, two from the front and two from the backside
40. Repeat steps 34-38 to install the pulley system for the Y-axis rails
41. To grip the belts in place, screw a pair of 2” long aluminum plates on top of the 4” plates extending from the side of the base, and slide another pair from the front of the Y-axis rails
42. Fasten the microwave support vertical strut channel to its connector, and attach that connector to the microwave support extension on the table using 0.25”-20, 1.25” long screws
43. Microwave assembly:
    - One end of the ice duct is attached to the rectangular opening of the saddle tap 9° below horizontal
    - The other end of the ice duct is connected to the microwave chamber
    - A water exit tube is used to connect the microwave to the filter
44. The microwave chamber is then fixed to the microwave support strut channel.