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Robots Made From Ice: An Analysis of Manufacturing Techniques

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***Abstract*— Modular robotic systems with self-repair or self-replication capabilities have been presented as a robust, low cost solution to extraterrestrial or Arctic exploration. This paper explores using ice as the sole structure element to build robots. The ice allows for increased flexibility in the system design, enabling the robotic structure to be designed and built post deployment, after tasks and terrain obstacles have been better identified and analyzed. However, ice presents many difficulties in manufacturing. The authors explore a structure driven approach to examine compatible manufacturing processes with an emphasis on conserving process energies. The energy analysis shows the optimal manufacturing technique depends on the volume of the final part relative to the volume of material that must be removed. Based on experiments three general design principles are presented. A mobile robotic platform made from ice is presented as a proof of concept and first demonstration.**

I. INTRODUCTION

When operating in remote or extraterrestrial environments, it can be expensive to ship materials or robots to the site. Revzen et al. [1] demonstrate a solution, deploying a single robot to build others using an expanding foam as the structure for new robots. Brodbeck et al. [2] present a similar solution using hot melt glue but instead focus on adding additional functionality.

Using found material at the site of deployment is one means of reducing transportation costs [3]. Maekawa et al. [4] do this in a forest, building and testing a walking robot from sticks. Theoretically, given the right set of resources, this robot would be able to repair itself ad infinitum.

There are a number of cold environments unsuitable for humans that require exploration or work where such a robot would be ideal. These areas include Antarctica, the North Pole, Enceladus, Europa, and Mars's polar ice caps. Due to their prevalence in these types of environments, obvious potential building materials are ice and snow. Ice is significantly stronger than snow. A downside to using ice is the dependency of material properties on temperature, strain rate, and grain diameter [5].

With a readily available supply of ice, such as one might find in an Arctic environment, robots can be shaped and redesigned on-the-fly using both additive and subtractive manufacturing processes. In turn, modular robots with this capability makes these types of robots ideal for self-reconfiguration, self-replication, and self-repair tasks [3], [6]–[8]. Self-reconfigurable modular robotic systems are designed to adapt to unknown tasks and environments post-deployment in the field. The strength of these systems lies in their ability to operate as a cohesive unit; making mechanical [9], [10] or magnetic connections [11], [12] with each other to form larger robots capable of performing different tasks. The modules act as joints, sensors, even structural elements for these new robots [9].

This paper presents the design considerations for creating a 2-wheeled rover dubbed *IceBot* whose structural elements are made from ice. The rover design is chosen based on rovers designed for the Antarctic [13]–[16].

We envision self-reconfiguration, self-replication, and self-repair tasks taking place through a modular actuator joint (not built from ice). Ice is manufactured to the desired shape and this joint is inserted into a block. Melting elements allow us to remove or re-position the joint (by refreezing or welding). From the point of view of self-repair, there are two cases: a joint breaks or a structure fails. In the case where the joint breaks, we remove it and replace it with another. If the structure fails, we can shape a new body and place joints from the existing robot into the new one. For self-reconfiguration we extract joints and move them into new positions around the body giving the robot a different set of functionality than it had previously. The modular joint and specifics regarding reconfiguration, replication, and repair tasks are left to future work.

Sec. II presents the assumptions and constraints on design. Sec. III analyzes the energy usage for three manufacturing methods. The robot is presented in Sec. IV as are methods to further extend its capabilities. A discussion and conclusions follow.

II. DESIGNING A ROBOT FROM ICE

We divide the design process into two parts, 1) operational considerations for ice as a structure and 2) ice manufacturing methods for examining the energy consumed as energy is likely to be limited in remote settings.

The design process discussed in this paper relies on two assumptions:

1) The robot operates in subzero temperatures. All theoretical calculations use the average yearly temperature at McMurdo Station, Antarctica, -17°C [17], as the ambient temperature.
2) Blocks of ice are readily available for use in the construction process.

As our robot does not experience large torques or forces, our primary design considerations for operation when using ice as a structure focus on localized ice melt. Should the ice begin to melt, two problems arise — the robot structure becomes compromised and the excess water can short electronics. If not properly handled, high powered actuators [18],

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batteries [19], and some electrical components (e.g. motor drivers) can add unwelcome heat into the system. Therefore, thermal management systems such as those discussed in [20] should be employed to isolate these components. Additionally, the casings around these components should be designed to route the heat such that the impact to sensitive structural elements is minimized.

If possible, designs should minimize heat generation. Generally, we recommend designing the robot as a system of modules, (e.g. building separate body modules, wheel modules, and control modules) and insulating each larger assembly of the robot from others, regardless of the presence of high temperature components. By isolating the modules from each other, if a component generates an excess of heat and melts the module into which it is incorporated, the isolation between modules not only limits the effect the excess heat has on the rest of the robot, but enables a new module to quickly replace the broken one, reducing system downtime during its mission.

If melting were to occur, the designer must consider the possibility of the generated water shorting or otherwise harming system elements. To preserve the integrity of the robot's mission, any electronics, actuation and power sources should be protected in waterproof enclosures. When the location of the electronics or power source is unimportant, they should be placed at the highest point on the robot as water will flow away from this point. By designing with these key components in mind, the robot, and the mission, has a greater protection against failure.

A. Design Principles

From the considerations above and experiments presented in Sections III and IV we propose the following three design principles.

1) Components should be designed to minimize and isolate heat generated.
2) Electronics, power sources, and actuators should be waterproofed or placed away (e.g. upstream) from runoff locations.
3) The ideal method to shape the ice components of the robot depends on the final volume of the part relative to the volume that must be removed from a raw slab of ice.

III. Manufacturing a Robot from Ice

Manufacturing components for robotic modules can be grouped into two categories: manufacturing structural components and actuator integration. Actuators need special attention since they impart forces other than gravity on structures and they often generate heat. All other manufactured components are assumed to be rigid bodies of ice.

In popular manufacturing databases such as the Cambridge Engineering Selector [21] the process of manufacturing is often broken down into two components: 1) Materials and 2) Processes. In our case, we consider ice as the material and three categories of compatible processes: 1) Shaping, 2) Joining, 3) Surfacing. This paper focuses on shaping and joining processes.

In remote environments, energy and usability are highly valued commodities. Energy enables a robot to move. Manufacturing and replacing modules requires energy. The less energy it takes to manufacture and assemble the robot the more energy there is for it to use to accomplish its mission. Usability is of maximum importance.

A. Manufacturing parts

Shape manufacture can be an additive or subtractive process. Three processes for shaping ice are examined: molding, 3D printing, and CNC machining. As discussed in Sec. II, blocks of ice are assumed to be readily available for manufacturing so the energy cost to collect these blocks of ice is considered negligible. The results of our analysis are summarized in Table I.

TABLE I
COMPARISON OF MANUFACTURING TECHNIQUES

Description	Design Flexibility	Energy Cost [J/mm^3]	Manufacturing Time
Molding	Low	0.37	Slow
3D Printing	High	$\leq$0.37	Medium
CNC Machining	High	0.02	Medium to Fast

1) Molding: Molding modules is not nearly as flexible as CNC machining or 3D printing the modules with respect to the variety of shapes that can be generated. In order to have design flexibility similar to that afforded by machining or printing, the system would need to be sent with a large library of molds. This is the opposite of a lightweight robotic system capable of operation in remote or extraterrestrial environments.

To create the modules via molding, blocks of ice are melted and the liquid poured into the molds. The energy cost, Q, associated with creating a module of volume, V_{part}, is given by (1):

$$Q = V_{part}\rho[\Delta H_f + (T_2 - T_1)C_p] \tag{1}$$

where ρ is the density of ice, ΔH_f is the heat of fusion of water, C_p is the heat capacity of water, T_2 is 0°C, and T_1 is the ambient temperature. With the exception of volume, since all of the variables are constant we can write the energy cost as cost per unit volume. For molding, the cost is 0.37 J/mm^3. The energy cost to create a wheel module, sized 76.2 mm x 25.4 mm (0.112 kg water), for IceBot is about 43,000 J. A hole for the actuator is not included in the mold to allow for both greater flexibility in choosing the optimal location and properly sizing it for required tasks.

2) 3D Printing: The energy cost to 3D print modules is dependent on both the final volume of the part and the part infill. The 3D printing process involves printing an exterior wall and using a repeating pattern to fill in the remainder of the part. When the volume of the wall is negligible relative to the volume of the total part (common and semi-intricate shapes) we assume the energy cost to print a module is a percentage of the energy cost to mold that piece. The percentage is equivalent to the infill of the printed part. In other words, if a part is printed with a 50% infill, the energy cost to print the piece is about 50% of the energy cost to mold it.

The printing process is generally also faster than molding in the expected cold environment at our length scales. Each layer must be frozen before the next can be placed. There is more exposed surface area during the process than with molding meaning the final part will be completed more quickly than the same part that is molded.

3) Machining: The energy cost associated with machining is expressed as energy per unit volume of ice that must be removed. To test the practicality of this method, a rotary power tool (i.e. Dremel) was used to determine how much power is needed to cut through ice. At slower removal rates, 8000 mm^3/s, the machine used about 160W of power or 0.02 J/mm^3. Assuming the wheel module is cut, using the same Dremel, from a block of ice that is 100 mm x 100 mm x 30 mm, the energy cost is about 3,700 J. This method is possibly the fastest of the three, as it does not require time for water to freeze. For simplicity, this paper uses blocks of ice that were molded in the laboratory.

B. Joining

Joining includes methods for assembling and fastening multiple components together. This section examines welding as a potential joining method.

The unique property of ice to melt under higher pressure makes the high normal-force clamping type methods of joining that rely on friction to be less desirable. Gluing as a non-water bonding agent to ice is also difficult to use. However, welding is uniquely advantageous in an environment in which water solidifies.

When joining two pieces of ice together, the surface finish of each piece must be clean and flat. These surfaces can be machined or placed against a flat, heated metal plate in order to reach the required finish. In practice we found the simplest way to join the two pieces is to place them in contact with each other and use a syringe to wet the area between the surfaces. The syringe provides the user with greater control over where the liquid goes and the water wicks between the two pieces filling any small gaps between the surfaces. When the "welding agent" freezes, the two parts are rigidly joined together.

For this experiment, a jig is used to hold the pieces together while they freeze. In the absence of a jig, liquid nitrogen or a similar substance can be used to tack weld the two pieces together. Another option is to use a material that locally changes the melting point of the ice (e.g. salt). This creates a weak, temporary bond between the two parts that will hold them together until they freeze. The downside is that attaching the parts in this way tends to cause them to crack. We hypothesize this is due to the difference in temperature between the tacking agent and the parts. Ice is brittle; if there are many small connections between the two pieces, the voids between the connections act as cracks and lead to fracture at smaller loads. This was most evident when the parts that were being joined had rough finishes. Instead of creating a solid connection they would separate under small loads. By flattening these surfaces and creating a large contact area at the joint between the two parts the connection became much more rigid.

C. Actuator Integration

To ensure a strong connection between the actuator and the structural elements of IceBot four subtractive techniques are explored: carving, melting via an open flame, melting via a heated rod, and machining. The goal is to use these methods to create a large enough pocket for the actuator to be completely surrounded by water and frozen into place. The effectiveness of each method to create a hole for the actuator is summarized in Table II.

TABLE II
EFFECTIVENESS OF ACTUATOR INTEGRATION TECHNIQUES

Description	Effectiveness	Time
Carving	Fail	Slow
Open Flame Torch	Low	Slow
Heated Rod	Medium to High	Fast
Cutting	Medium to High	Slow to Fast

1) Carving: In carving, an instrument (e.g. a chisel) is used to chip away at the module and form a hole in which the actuator can be placed. While this technique may work well on larger modules, for modules of the same scale as IceBot, the blanks would often break before the hole was sufficiently large to hold an actuator. For this reason we do not explore the technique further. On larger blanks where the actuators are placed a significant distance from the edge of the part, this technique may work well.

2) Open Flame: An open flame from a torch melts a hole in the ice large enough for the actuator to be placed (Fig. 1). The advantage to this technique is simplicity. A lighted torch is placed roughly over the center of the blank until a hole of the correct size is created. The height of the flame above the blank does not need to be exact as the heat disperses over the blank to create a hole more than wide enough for the DC motors used in our robot. The larger sized hole ensures that the motor can be positioned in the center of the wheel even if the torch was not precisely centered over the wheel blank.

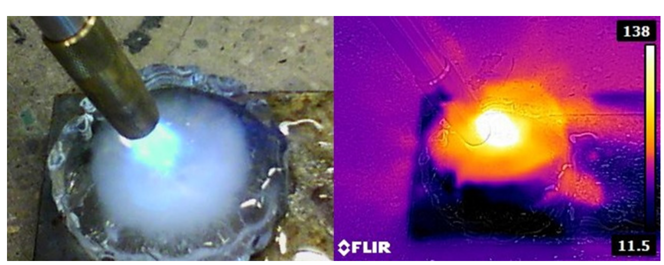

Fig. 1. Left: A butane torch being used to melt a hole in the ice blank. Right: A heat map (in °C) of the butane torch and ice blank.

Melting a hole large enough for the actuator takes time. In a warmer environment the excessive time can cause the structure itself to begin to melt and deform during the process. The problem is exacerbated by the amount of water generated as the torch melts a hole in the blank. As there is no clear run-off path for the water, it flows over the top of the blank, covering it completely. The water, now carrying large amounts of heat from the torch (40°C to 60°C as seen in Fig. 1), melts the areas near the edges of the blank resulting in a nearly unusable structure. In one of the tests with this method, a 2.5 cm thick blank melted to about 1.25 cm thick before the hole was large enough to fit the mounting hub. The technique took between 15 to 45 seconds to create a suitably sized hole.

3) Heated Metal Rod: Another approach is to use a heated metal rod to provide heat at a localized point on the structure. This technique took between 10 and 25 seconds. The hole needs to be large enough for the actuator, but depending on how precise the placement needs to be, a larger or smaller rod can be used. The closer the rod is to the motor size, the more precisely the hole must be located. The larger the rod, the more imprecise the location of the hole can be but more energy will be required, scaling with the cross-sectional area of the rod.

As with the torch, this method generates water runoff (albeit less than in the open flame method). When the rod is inserted from above, the water collects near the edges of the hole and melts the structure as it flows away. As shown in Fig. 2, while less water is generated, the water flowing away from the rod and in the region around the rod is about 30°C. This method still results in a deformed blank, but unlike with the torch method, the blank was still usable.

Designing the module to include holes for drainage or changing the orientation of the part when the hole is created should increase the usability of the final part.

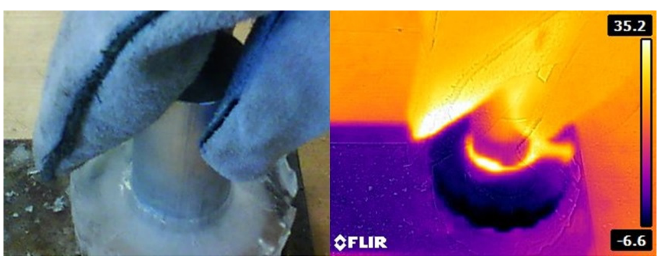

Fig. 2. Left: A heated rod being used to melt a hole in the ice blank. Right: A heat map (in °C) of the heated rod and ice blank.

4) Cutting: For cutting experiments, a hole saw (any large diameter bit will work) is used to cut a space in the wheel for the actuator. The only heat generated from cutting comes from friction between the walls of the hole and the cutting tool. As shown in Fig. 3, the generated heat is very small and there is no water runoff over the part.

This method took the longest (1 to 2 minutes) but the timing can be attributed to the tooling used. When tested with a Forstner bit of similar size the test took at most 15 seconds.

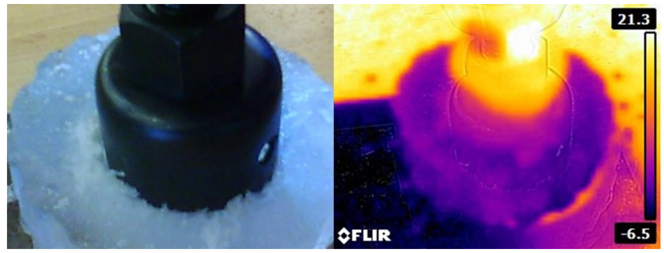

Fig. 3. Left: A hole saw cutting a hole in the ice blank. Right: A heat map (in °C) of the drill and ice blank.

5) Energy Costs: The energy costs associated with these techniques are presented in (Table III).

In addition to the energy associated with making a space for the actuator we assume the user must melt down enough water to surround the actuator and freeze it in place. In environments like McMurdo station, melting a hole for the actuator and enough water to freeze the actuator in place is 2 to 7 times more expensive than cutting away ice from the blanks. These calculations assume the blanks and any equipment used are perfectly insulated and that the heat is generated by the drill bit is negligible.

TABLE III
THE ENERGY COST TO CREATE A POCKET AND MERGE THE MOUNTING HUB WITH THE ICE BLANK

Method	Energy [J]
Butane torch	14,600
Heated 30mm rod	5,870
Heated mounting hub (Fig. 4)	1,580
30mm drill bit + ”free” water	3,700
30mm drill bit + melted water	5,840

D. Actuator Accessories

Once the modules have been prepared to accept the chosen actuator, the actuator and the module can be joined together. Actuators are placed into the modules and surrounded by water. The water freezes and the actuators are fixed in place. We focus on DC motors though other actuators are possible (hydraulics or pneumatic). As long as there is a sufficient thickness of ice between the actuator and the edge of the blank, the actuator will remain in place for the duration of its operation. During the experiments the sufficient thickness was determined to be greater than 6 mm. If the wall thickness was less than that, the ice had a tendency to fracture as the hole for the actuator was being cut.

When the actuator is frozen into the module, it must resist torsional and axial forces. Intuitively, increasing the amount of surface area between the ice and the motor results in a stronger bond between the two. To protect the motors in IceBot, each slip-fits into a waterproof 3D printed sheath (Fig. 4). To prevent the motor from sliding out of the sheath, a set screw fixes the motor in place. A hole at the top rear surface of the sheath allows for wire routing between the motor and the motor driver. Hot glue seals these two points prior to the motor and sheath being placed into the water. A flange at the rear of the sheath prevents the motor from being pulled axially from the body module and the rectangular shape of the sheath prevents the motor from rotating in the body module.

We performed torque tests on 10 motor housings embedded in ice to determine the maximum amount of applied torque before either the motor housing yielded or the ice fractured. For each test, a replica of the housing with a 19.05 mm (0.75 in) hex was centrally located and embedded in a 140 mm x 100 mm x 60 mm block of ice. A torque wrench interfaced with the hex on the replica and was used to apply the loads. In each of these tests the ice fractured prior to plastic deformation of the housing. The average applied torque at failure was 21.2 Nm with a standard deviation of 3.8 Nm.

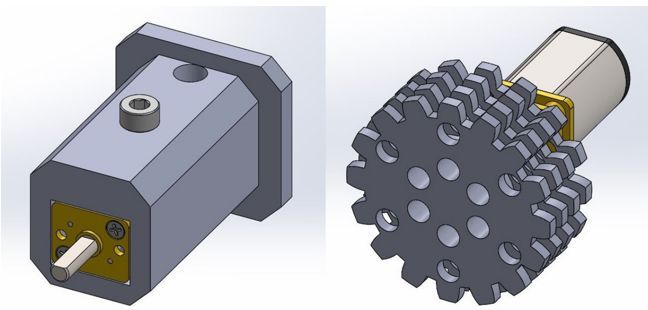

Fig. 4. A CAD representation of the motor housing (left) and the mounting hub (right)

Mounting the wheel module directly to the motor shaft makes for a weak connection. Not only is there a limited surface area (99 mm^2), the metal shaft easily conducts heat causing this point to be the first to slip and fall off. A 3D printed mounting hub designed to maximize the area in contact with the ice (4,490 mm^2) and to prevent relative rotation and axial movement. This was used to secure the wheel module to the motor shaft. The flanges and holes through the hub mean the ice must shear before the wheel and motor hub separate due to torsion about the axle. The multi-tiered design prevents the hub from moving axially, again requiring that the ice experience mechanical failure before the two parts move relative to each other.

IV. IceBot

Using the techniques presented we built a two wheeled robotic platform (IceBot) (Fig. 5) similar to wheeled designs used to explore the Antarctic in the past [13]–[16]. IceBot weighs around 6.3 kg and fits in a 140 mm by 200 mm by 130 mm design envelope. A 40 mm ping pong ball acts as a caster wheel for IceBot, though a ball of ice could have been used with a way to manufacture spheroids. An Android phone sends commands to a microcontroller (Arduino Micro) via an HC-06 Bluetooth module. The actuators are $12V$ micro metal gear motors which are controlled via open loop. The two wheeled design was chosen for the ease of control.

The joining of passive pieces of ice is demonstrated through the addition of a plow to the front of the robot. The energy costs associated with the act of joining two parts is negligible, however, preparing the surfaces of the additional piece and the location on the robot where it will be placed may require energy and should be considered.

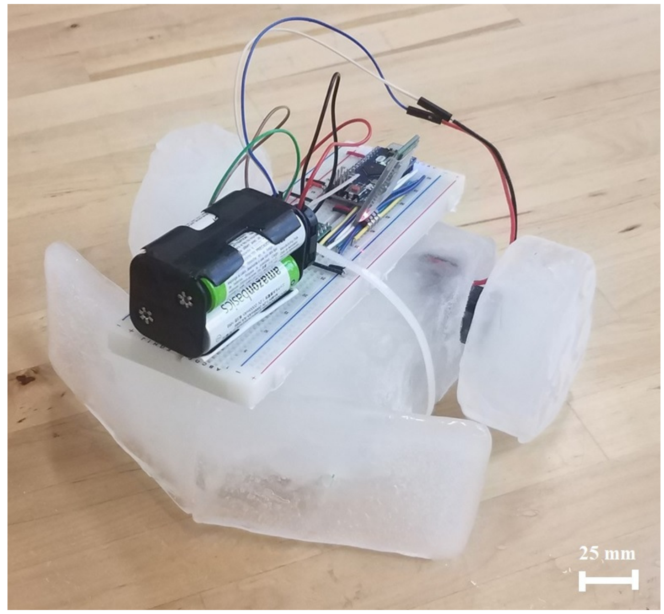

Fig. 5. IceBot with an attached plow. The robot is able to navigate and turn while on hard surfaces and climb icy ramps up to 0.026 radians independently.

Initial driving tests were performed on a hard, smooth, rubbery surface in the lab at a temperature of 23°C. On this type of surface, the robot was able to travel for 15 second increments without human interference. After about 15 seconds a boundary layer of water formed between the wheels and the floor and the robot was unable to gain any traction. Adding weight over the wheelbase temporarily overcomes the boundary layer and gives the robot more time to operate in the environment.

To test the robot's ability to perform in Arctic environments, driving tests were also performed on sheets of ice in a freezer at -17.4°±0.5°C. Following each successful crossing of the ice sheet, the sheet was raised an additional 0.009 radians [0.5°]. At angles less than or equal to 0.026 radians (1.5°) the robot was able to traverse the sheet of ice without noticeable slippage. Between 0.035 radians (2.0°) and 0.044 radians (2.5°) the robot was able to climb the ramp with occasional human assistance to help the robot over some of the larger imperfections on the sheet. At ramp angles of 0.052 radians (3.0°) and larger the robot wheels would often slip and IceBot was unable to make it up the ramp.

V. Discussion and Conclusion

This paper presents a modular robot in which ice is the sole structural element. We explore molding, 3D printing, and machining as possible manufacturing methods, analyzing each for energy usage and effectiveness. The method that costs the least energy depends on the ratio of the volume of the final part to the volume of material removed. Actuator integration with the ice modules is also explored. Cutting a hole in the module for the actuator was the most effective method of creating space for the actuator. Actuators augmented with 3D printed accessories that increase the surface area contacting the ice were frozen into the module to create a strong, lasting connection between the parts. In addition, a method of attaching passive pieces to the robot is presented.

Sensors can be integrated with the robot in much the same way as the actuators or passive blocks of ice. If needed, 3D printed accessories can hold the sensor. The assembly can then be joined to the robot using the techniques described in Section III.

The main logistical challenge in building this robot is the operating environment. After 15 minutes at room temperature, handling and preparing the blanks, they must be returned to the freezer to cool. Working for longer periods deforms the blanks past usability. Similarly, temperature differences make pieces tack welded together susceptible to fracture. The instantaneous change in temperature of the two pieces when locally frozen tends to cause the blanks to shatter. Both problems could be solved by using larger blanks or by working in appropriately cold environments.

The other challenge encountered is the low friction coefficient of the ice. As the ice melts and a boundary layer of water forms between the wheels and the floor, the wheels tend to slip. This is overcome by adding additional weight over the wheels. In simulated Arctic environments, we show the robot is capable of traveling across sheets of ice and can climb icy inclines of up to 0.026 radians without assistance. In colder environments (less than -17°C) we expect the maximum climbable angle to increase because the coefficient of friction of ice increases with decreasing temperature.

This work is a step towards a lightweight, adaptable robotic system capable of operation in subzero environments. This system lends itself to self-reconfiguration, self-replication, and self-repair. To push towards the development of automated methods for creation and assembly of this system we plan to pursue a joint module that can be easily integrated with passive blocks of ice. This will reduce the overall complexity of the system, remove the need for wire routing and increase the modularity of the system. Also of interest is the use of a hot-wire to cut the modules for the robot. The wire will either need to have a diameter large enough to prevent runoff from refreezing or have some other way to draw off the melt water. Additional future work includes: determining a general class of surface on which this system can move, methods of using ice elements to interact with the environment, and further investigation into the strength limits of the connections between actuators and the ice.

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