Materials and Mechanisms for Amorphous Robotic Construction

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***Abstract*— We present and compare three different amorphous materials for robotic construction. By conforming to surfaces they are deposited on, such materials allow robots to reliably construct in unstructured terrain. However, using amorphous materials presents a challenge to robotic manipulation. We demonstrate how deposition of each material can be automated and compare their material properties, cost, and cost in time in order to evaluate their suitability for developing amorphous robotic construction system.**

I. Introduction

A. Motivation

Ideally, robots effectively perform tasks that humans find tedious, difficult, or dangerous, such as construction. In the well structured environment of manufacturing facilities robots are highly successful: Enabling new manufacturing techniques, increasing throughput, quality, and safety. Construction in less controlled environments, however, presents a challenge for current robotic technologies. It is also a dangerous job. According to the U.S. Bureau of Labor Statistics 2009 data, construction has a rate of 12.4 fatal injuries per 100,000, which is 3.5 times higher than average occupations. In the assembly of pre-fabricated architectural elements, robotics already enables new techniques [3]. We want to develop robust autonomous construction techniques for unstructured environments, such as building ramps over arbitrary irregular obstacles. In particular, we want to explore approaches where mobile robots repeatedly deposit relatively small amounts of amorphous materials to build large structures, Fig. 1. Such autonomous construction techniques might find applications in remote or hazardous environments, e.g. building infrastructure for extra-terrestrial exploration where long communication delays require autonomy or building shelter and support structures in unstructured hazardous environments such as disaster areas or inside mines. Here, we focus on the problem of selecting materials for developing such construction systems.

The contribution of this paper is a feasibility study and selection guide for *amorphous* construction materials, i.e. materials whose exact shape is defined by the environment. Rather than focusing on material properties alone, our selection metrics also explicitly take into account issues related to automation in robotic test beds. We present several materials inspired by a range of biological systems, Fig. 2, demonstrate their feasibility for robotic use, and compare and contrast the potential for developing an autonomous construction platform.

[1]The photos in (a) and (b) are used under the Creative Commons license. For (a), top to bottom, they are attributed to, Steven Wayne Rotsch, Walter Siegmund. For (b) they are attributed to Thomas Schoch and Harald Süpfle. The photos in (c) are by our lab member Kirstin Petersen.

Fig. 1. Diagram of mobile robot building a large ramp in unstructured terrain using amorphous materials. The robot starts on the left and is trying to reach the right. It builds ramps over features it cannot climb using an amorphous material (gray) that conforms to arbitrary obstacles.

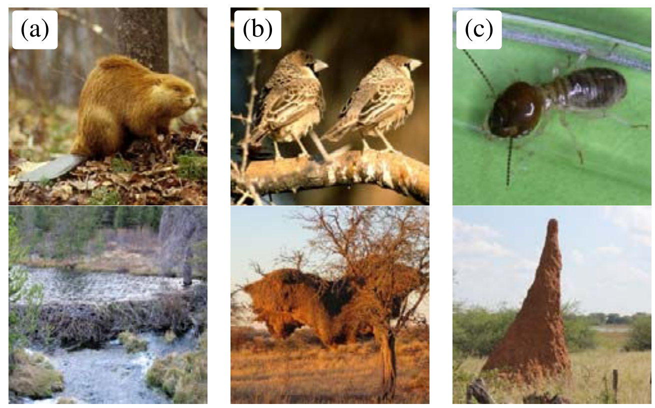

Fig. 2. Examples of animals and structures they build. The given relatives sizes are computed by comparing the longest dimension (instead of volume). (a) Beaver and a beaver dam. The dam is constructed with a combination of sticks that are sealed with mud and gravel. The finished structure is ≈10 times larger than an adult beaver.(b) Sociable Weaver Bird and its nest structure. The communal nest is built by judiciously inserting twigs and dry grasses into the growing structure. The finished structure is ≈30 times larger than an individual adult. (c) A major worker termite and a termite mound. Termites deposit small pieces of mud to build a mound which is ≈400 times larger than an individual worker.[1]

The requirements for amorphous materials to be suitable for robotic construction are described in Sec. II, as are the three material choices: Rigid pre-fabricated components and adhesive, compliant pre-fabricated parts, and amorphous materials that cure into solids. Section III describes mechanisms we developed to demonstrate suitability for robotic use. Material properties and experimental findings are described in Sec. IV. Directions for future research in mechanisms and control algorithms are presented in Sec. V.

B. Related Literature

One approach to autonomous robotic construction is treating it as a special case of modular robotics when active robots (re-)configure passive construction materials, [15], [5], [6]. In this setting much time and effort goes into designing the passive materials, especially the connectors. Robust operation of these systems requires both high-level planning in the abstract space of connection topology between components, such as [10], [8], and designs that allows robots, to reliably connect components [6], [9], [11]. In various test beds the active robots can be, stationary [5], drive [2], [11], climb the built structure [8], or fly [9], yet the topology of construction materials is essentially the same: a rectangular lattice of passive component, sometimes with diagonal supports for strength [6], [8], operating in a well structured environment, i.e. level and without obstacles.

Instead of using lattice like building materials and tackling uncertainty in the high-level planning algorithm, we look at the use of amorphous materials. By allowing materials to deform, comply, and ooze into the construction environment, we remove the problem having match up our structures with the decidedly non-lattice like world and with each other. Similarly, recent advances in the reconfiguration, or even on-the-fly creation, of modular robots have explored the benefits of amorphous materials [12].

We draw inspiration from biology. The animal kingdom provides impressive examples of construction in unstructured environments. Animals that manipulate construction materials to build comparatively large structures are of particular interest. The following three species, Fig. 2, exemplify different approaches to using amorphous materials which this paper explores for robotic use:*Castor canadensis* (beaver), *Macrotermes michaelseni* (termite), *Philetairus socius* (sociable weaver bird).

Beavers construct dams from branches, sticks, and twigs, of various sizes that are packed with mud and gravel to form a structurally sound and watertight barrier. This strategy exemplifies building with two different components, sticks for strength, and mud to solidify the stick structure making it water tight.

Sociable weaver birds are communal breeders that create large nest structures from small twigs and grasses. These structures are built without the help of binders, but careful placement of and insertion of twigs [4]. This strategy exemplifies the use compliant, prefabricated components that are carefully arranged to create a large structure.

Termites (*M. michaelseni)* build mound structures to regulate temperature and moisture [13, CH 11]. They create a paste of water, sand, clay, and polysaccharides and deposit these mud balls while wet. The depositions are allowed to dry and create a solid structure. This strategy exemplifies the use of a single, material that is amorphous during deposition, but cures into a solid.

II. Amorphous Materials for Robotic Construction

For autonomous robotic construction with amorphous materials several, sometimes competing, material properties need to be taken into account:

1) The material should be amorphous or compliant in nature. Deposited material should absorb environmental uncertainty and fit into the environment.
2) In order for one or more robots to build large structures, the deposition mechanism needs to incrementally deposit material, and successive deposition episodes need sufficient strength. We measured (A) the deformation due to normal forces (stress-strain curve) as well as requiring that robots navigate a test structure made from each of the tested materials Sec. IV.
3) The material should be easy to use: (B) Simple to deposit with a robot, (C) reasonably inexpensive to acquire, (D) and not require much preparation before it can be utilized by robots. We focus on readily available mass produced items, such as construction adhesive and filler materials available in bulk. Good materials should also (E) deposit quickly, (F) cure quickly, and (G) have a high *expansion ratio*, i.e. the ratio the volume taken up by a built structure, including internal voids, and the initial volume taken up by construction materials. It is a measure of how much robots can build per unit of cargo space: The larger, the better as it implies less frequent reloading.

By design, all materials described in the reminder of the paper are amorphous. We compare the relative merits of materials by using the second two criteria, strength (A) and suitability for robotics research (B)-(G). Ease of use is rather vague, however, it is paramount in design, so we chose to include it. We strive to apply these metrics explicitly and consistently while remaining practical. Table I in Sec. IV summarizes the our best estimate for (A)-(G) for each of the following three types of amorphous construction material.

A. *Adhesive and Rigid Pre-Fabricated Components*

Using relatively small pre-fabricated components and some kind of fastener or adhesive is a common construction technique, for example, brick and mortar, or lumber and nails. The advantage of using two different materials is that structures can take advantage of the good mechanical properties of one component type, for example the considerable compressive strength of bricks, while the joining mechanism can add other properties to the final structure, such as compliance, or eliminating leaks between the components.

The main drawback of this approach is that material handling and deposition mechanisms can be complicated. Robots need to dispense and apply glue/fasteners, handle rigid pre-fabricated components, and place them in some sensible fashion to build structures. The more careful the last step takes place, the more finely a robot can control the properties of the final structure. For example, the careful arrangement of lumber in a house frame allows it to be strong and yet have a large void space. As a first step, we allow for random attachment and note that a more sophisticated mechanism could take great advantage of carefully controlling deposition. In Sec. III-A we present a mechanism for dispensing toothpicks and glue. The toothpicks are light, stiff, and strong. The glue allows arbitrary attachment points and orientations, so that we can build random structures that are strong and still have a relatively large expansion ratio, Fig. 3(a).

B. *Compliant Pre-Fabricated Components*

Similar to the nest structure of weaver birds, an attractive option of constructing in an uncertain, irregular environment is to use pre-fabricated compliant components that are held in place by jamming and friction. This approach is also used in human construction when inexpensive, non-permanent support structures need to be built quickly in unstructured terrain, for example, emergency shelters [1], or levees [14].

While sand-bag based construction can have both binders, and interface layers to increase friction [1], we restrict our

Fig. 3. Different construction materials. (a) Structure of randomly arranged toothpicks with hot-melt glue. Each toothpick from an 800 count package was covered with glue on both ends and then thrown onto a cardboard target. The resulting structure is roughly conical in shape and can support the weight of a brick (≈ 1.8 kg/4 lbs). (b) Differently sized and shaped bags considered for material testing. The top row of the scale bar is marked in 5 cm increments. (c) A mound of foam built with two component casting foam. After mixing, the liquid foam is deposited in small increments. With this strategy, even steep features can be build with liquid depositions.

attention to the to case where the compliant components remain compliant and are used by themselves as a homogeneous material. In particular, we focus on bags with various fillers, 3(b). While this material has essentially no expansion (expansion ratio of 1) and does not create permanent structures, it has the advantage of being inexpensive, simple, and quick to deposit, making this a good candidate for some applications.

C. Amorphous Materials Curing Into Solids

Examples of amorphous construction materials that cure into solids are plentiful, for example, concrete used by humans and mud used by termites. Here, we focus on foams for their practical expanding property. Materials that are used in rapid prototyping, such as thermo plastic filaments and UV-curing resin, or (on a much larger scale) contour crafting [7], such as concrete and clay, are ill suited for mobile autonomous robots. They are dense and do not expand.

Using foam as a construction material presents several difficulties: Actuation/mixing, controlling deposition shape/location, and preventing clogging. Although there are many options for underlying foam chemistry, we focus on poly-urethane foams. They are readily available in bulk, come in both single-component and two-component varieties, and have a wide range of material properties. By choosing a suitable deposition strategy, even liquid foam precursors can be used to build structures with steep features Fig. 3(c).

III. Deposition Mechanisms

This section describes two robotic mechanisms we developed to automatically deposit toothpicks with adhesive and two-component urethane foams. The compliant bags analyzed in Sec. IV-B were sized such that they could be pulled by a robot equipped with a gripper, of which many designs exist in the literature. A brief section regarding compliant bags is included to consistently compare materials following the ease of use metrics: mechanism complexity (B), deposition rate (E), and the amount of preparation time required for the construction material (F). When tradeoffs were necessary, priority was given to minimizing preparation time, over mechanism complexity and deposition rate.

A. Toothpicks and Glue

We designed a mechanism to individually dispense, deposit glue on, and propel toothpicks. The glue covered toothpicks form a loose pile and once the glue is cured, the resulting structures are strong due to the stiffness of individual toothpicks. While we believe this mechanism could be shrunk to fit on an autonomous robot, we did not pursue this approach in the current study of materials. In terms of selection criteria for materials, we note that the complexity of the dispensing mechanism is high compared to the other material choices. The material preparation is minimal, since readily available adhesive cartridges and toothpicks can be loaded directly into the mechanism.

To dispense toothpicks individually we motorized a commercially available toothpick dispenser, often found in restaurants. A grooved cylinder rotates under a reservoir of toothpicks. When the groove rotates into the reservoir, a toothpick falls into it. When the groove rotates out of the reservoir a single toothpick falls into a chute and slides out of the dispenser. We modified the chute to feed into a mechanism that transports, aligns, applies glue to, and flings individual toothpicks, Fig. 4.

The motion of the cylinder is restricted by two stops and coupled to a motor with a rubber belt that can both stretch and slip. During each dispense operation, the motor was programmed to move the cylinder into the stops in both directions, resulting in a self-aligning mechanism that can recover from jams. The stretch absorbs shocks and slipping re-aligns the relative rotations of the motor and cylinder after a jam.

The transport mechanism consists two sets of belts that pinch a toothpick against a retaining plate and roll it along. IR-sensors are used to sense and align the toothpick. The plate only covers the center portion of each toothpick, leaving the two pointed ends free for applying adhesive. Each set of belts consists of a wide belt, for transport, and a thin band for flinging. The bands are configured such that the wide belt keeps a constant distance from the plate, sized to pinch and transport a toothpick. The thin belt is guided past the edge of the plate, so that a toothpick has to depress it while moving along, Fig. 4(b)-Fig. 4(c). When the toothpick reaches the end of the plate, the stored energy is suddenly released and propels the toothpick away from the mechanism.

The mechanism is built from 6 mm acrylic sheets and glued with a solvent-based adhesive. The retaining plate is

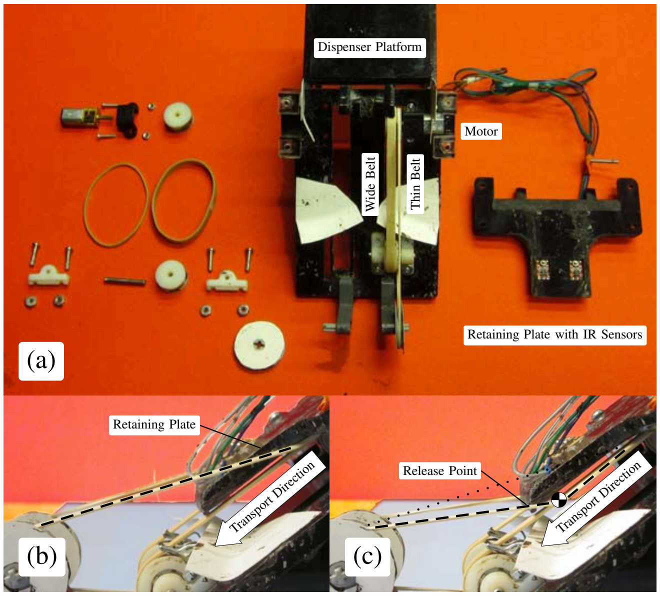

Fig. 4. Transport mechanism. (a) Top view of partially assembled mechanism. (b) Side view without toothpick. The thin belt (dashed line) moves past the retaining plate. (c) Side view with toothpick. A toothpick (cross mark) is transported along the retaining plate. As it moves, the toothpick increasingly deforms the thin belt. At the end of the plate, the thin belt releases and snaps back to its original position (dotted line) propelling the toothpick away from the mechanism.

attached with bolts, so the height between the wide transport belt and the retaining plate can be adjusted with spacers. Pieces of thin plastic sheet (white) are attached with double-sided tape and act as guides for the toothpick and drip guards for glue.

Two modified, electric caulking guns dispense a small steady bead of adhesive and are positioned along the path of the two free toothpick ends as it moves along the mechanism. Replacing the caulking guns with a custom glue dispenser, such as a syringe based mechanism similar to Sec. III-C could significantly reduce the overall size and weight. The deposition mechanism is able to autonomously, dispense, apply glue, and fling toothpicks at a rate of approximately $15\ \text{toothpicks}/\text{min}$. With a final volume of $2.6\ \text{ml}/\text{toothpick}$, see Sec. IV-A, the resulting deposition rate is $\approx 39\ \text{ml}/\text{min}$.

B. Filled Bags

Deposition amounts to gripping, dragging, and releasing bags. Problems such as handling liquids, applying tacky adhesives, and clogging are not an issue since the components do not cure. Several off-the-shelf grippers combined with the fact that many suitable designs exist in the literature, lead us to conclude that the mechanism complexity is comparatively low from a systems design perspective.

As opposed to the other mechanisms, the limiting factor to deposition rate is the travel time to and from the deposition site. However, such algorithm specific quantities are difficult to include in our analysis. As a result, the deposition rate metric for compliant bags and latching prefabricated components from other platforms is left blank in Tab. I.

For a consistent evaluation between materials, all design decisions, such size and weight, were made so the bags could be used by a similarly sized robot compared to the

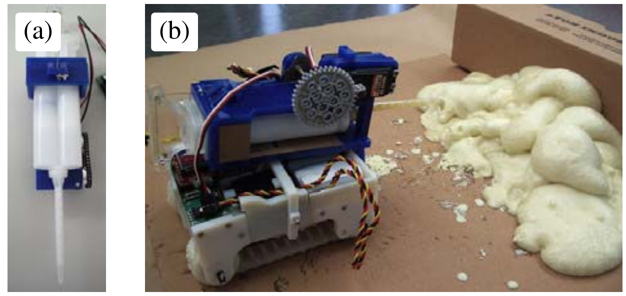

Fig. 5. (a) Bottom view of syringe dispenser for casting foam. The two compartments are actuated by the same plunger and both feed into a single static mixing nozzle. (b) Dispenser mounted on a small remote controlled robot. Cured previous depositions are shown right.

other material analyses. We bought cloth bags of appropriate size and each need to be filled and sewn. This construction material requires a moderate amount of preparation. We considered ready-made alternatives but did not find bags of appropriate size, weight, and surface texture, Fig. 3(b). The closest candidates were various types of pre-packed dried foods, such as beans, rice, or popcorn kernels, however they were typically too large.

C. Urethane Casting Foam

We focus on casting foams as opposed to pre-packaged urethane foams that come with built in deposition mechanisms. We encountered issues with nozzle clogging when using fast-curing single component foams, such as GreenIt used in [12]. Casting foams react relatively slowly, which reduces to risk of clogging due to periods of inactivity. Instead, the primary issue is adequately mixing. We chose to use a static mixing tube and two component syringes typically used for epoxy adhesives, Fig. 5(a). This approach uses the geometry of the syringe to ensure a proper mixing ratio and allows us to use a single, open-loop actuator for deposition. As a result, the complexity of the overall mechanism is only moderately complex.

The foam deposition mechanism is comprised of a gear motor, a shaft that acts as a spool, a fixture for holding the syringe, an attachment with rollers for the back of the syringe plunger, a wire rope, and some additional gearing. The wire rope is wound around the shaft, guided over the rollers attached to the back of the syringe plunger, and firmly attached to fixture with the other end. The design provides a theoretical pulling force of 930 N, well beyond the structural capabilities of both the gears and fixture. This large safety factor allows dispensing partially reacted pre-cursors that are quite viscous.

The fixture for holding the syringe is made from 6 mm thick acrylic sheet glued with a solvent based adhesive. The two cylinders of the syringe have a combined volume of 50 ml. With this particular deposition combination of parameters the rate of deposition for the mixed, still liquid (uncured) foam is $0.14\ \text{ml}/\text{sec}$. With an expansion ratio of ≈ 22, the deposition for the final structure is $3.1\ \text{ml}/\text{sec}$.

Since the two components come in contact before exiting, not dispensing for extended periods will always result in clogging. In periods of inactivity, the mixing nozzle needs to be purged periodically. We tested the feasibility of this strategy by dispensing the entire volume of the mixing

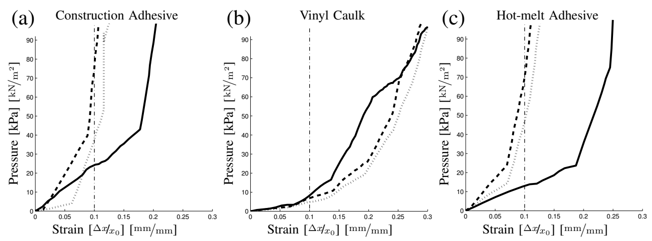

Fig. 7. Stress-strain curve of toothpick structures. The plots were created by measuring the displacement of a plunger that pressed on an toothpick structure while measuring the force on a scale. Each test structure was repeatedly loaded, where the first load cycle is shown as a solid line, the second as a dashed line, and the third as a dotted line. (a) Strength of test structure built with Liquid Nails®. (b) Strength of test structure with vinyl caulking adhesive. (c) Strength of test structure built hot-melt adhesive.

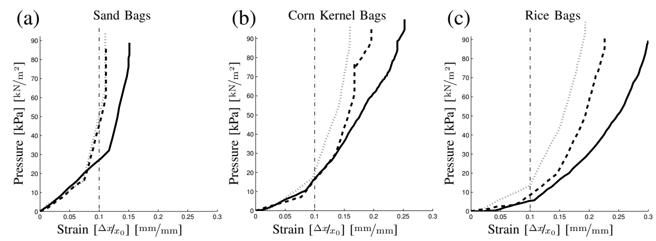

Fig. 8. Stress-strain curve of bag structures. We loosely built a pyramid of 14, (3×3), and compressed them repeatedly. In all plots, the solid black line is the first cycle, the dashed the second, and the dotted line the third. (a) Bags filled with sand. Sand bags had the most compressive strength and displayed the most consistent compression behavior for repeated loading. (b) Bags filled with dried corn kernels. (c) Bags filled with dried rice.

nozzle, waiting a per-determined amount of time and then dispensing the entire volume again. Deposition could resume after waiting 5,10, and 15 min, but the mixing tube clogged permanently after 20 min. We also tested shorter deposition episodes that did not purge the entire content of the nozzle. Here too, waiting times of up to a several minutes could be accommodated without clogging. Since these inter-deposition times are long enough for robots to plan, move, and actuate, we believe that clogging can be managed by periodic purging.

Each two-component syringe is a self-contained disposable deposition and mixing mechanism. Since the two foam pre-cursors can be poured directly into the syringe chambers before installation, we rated the material preparation time as low.

IV. Experimental Results

To test the feasibility of each material, we used them to build ramps allowing similarly sized robots to climb relatively large environmental obstacles, Fig. 6. Strength (A), cure time (F), and expansion ratio (G) for foam and toothpicks were measured on smaller test structures. As mentioned in the beginning of Sec. II, many design choices influence these metrics and often there are tradeoffs. Where possible, we chose a large expansion ratio and considered cost. Optimizing for cure time or strength (beyond sufficient strength to support robots) were secondary.

Strength was measured using a scale, linear actuator, and linear encoder. A 2.0 cm diameter plunger pressed on test structures and we simultaneously recorded the force and deformation (strain) from the point of first contact. Data is reported as pressure (kPa) at the plunger face. The reported strength (A) in Tab. I is at %10 deformation.

A. Toothpicks and Glue

We built test structures from ≈300 toothpicks using three different types of adhesive: Liquid Nails®, a vinyl adhesive caulk, and hot-melt glue. The aligned, closely packed 300 toothpicks have a volume of 77 ml and weigh 31.2 g. In the force ranges of interest, the tested toothpick structures exhibited primarily elastic deformation and sprung back after the load was removed, Fig. 7. Where deformation was not elastic, we suspect that some adhesive joints broke. In most cases, the first load cycle compressed the structure resulting in a smaller but stiffer configuration.

The three adhesives vary in their initial tackiness, viscosity, and final compliance, which has an effect on both the strength and expansion ratio, Fig. 7. To compute the volume of the irregularly shaped sample structure, we took photographs from two orthogonal side views and approximated the structure as stacked elliptical disks. Each photograph was used to measure one of the elliptical axes. Using an error of ±5 pixels in each lateral direction the computed volumes are: 757–805ml for Liquid Nails®, 631–675ml for adhesive caulk, and 916–978ml for hot-melt glue. Disregarding initial adhesive volume and using the center of each estimated volume range, the expansion ratios of the three randomly built test structures are 10 Liquid Nails®, 8.4 for adhesive caulk, 12 hot-melt glue.

The ramp in Fig. 6(a) was allowed to cure for ≈20 min after deposition stopped before being successfully climbed by a remotely operated robot. Some glue joints were still quite soft. The sample structures were allowed to cure at least 24 h before testing. Differences in cost depended on both the expansion ratio and per-toothpick adhesive cost. Hot-melt glue is both more expensive and more viscous so that after applying adhesives each toothpick had ×3 the amount, compared to the other two adhesives. The costs, including toothpicks and adhesive, for structures that use Liquid Nails®, vinyl adhesive caulk, and hot-melt glue are 1.09 $/l, 1.20 $/l, and 1.80 $/l respectively.

In addition to strength and expansion ratio, different adhesives allow different structures to be built. For example, the initial tack, high viscosity, and quick setting time of hot-melt glue enabled us to build a structure by flinging toothpicks onto a vertical surface, potentially allowing the construction of bridges and arches. The long cure time and lower tack of other adhesives prevent such structures from being built.

B. Sand Bags

We experimented with the size, filling material, and filling fraction of bags. Since these three factors directly affect weight, we are constrained by the robot's locomotion power. It could carry a larger bag of a less dense filling material or one with a smaller filling fraction.

Considering robots of similar size as for the other materials, we chose to use small (4 in×6 in) cloth bags (ULINE part number S872). To evaluate the relative quality of filling materials we compared bags filled with sand, dried corn kernels, and dried rice. Sand was by far the strongest as least expensive. The different granule geometries have a pronounced effect on the strength Fig. 8. Where flexibility is

Fig. 6. Ramps built from various amorphous materials. The step in each example is 10 cm up leading to a 20 cm×20 cm platform. (a) Ramp made from randomly deposited toothpicks and glue. The deposition mechanism from Sec. III-A was aimed at an artificial ramp and deposited four 800 count (3200) toothpicks. (b) Ramp built from compliant bags. (c) Ramp built by a remote controlled robot with the foam deposition mechanism described in Sec. III-C. The ramp was built with eight 50 ml syringes worth (400 ml) of liquid casting foam.

required, some of these alternatives might be good options. Including the cost of bags ($0.23 each) the 200 g bags of sand, 150 g bags of rice, and 150 g bags corn have a cost of 1.98 $/l, 4.04 $/l, 3.45 $/l. For sand the cost was dominated by the bagging material.

C. Casting Foam

The deposition mechanism was mounted on a small remote controlled mobile robot, Fig. 5. The ramp building strategy was to try driving up to the platform. If the robot could not reach the top, the operator made a deposition in front of the insurmountable feature or into a depression that got the robot stuck. The deposition mechanism was also remote controlled so we could test several different deposition techniques.

The most challenging aspect of using this material is that it is designed to be used with molds. When first deposited, it is liquid, yet we would like to build freestanding structures with relatively steep features. We found two approaches for working around this problem. First, the obvious approach of waiting. Steep features can be built by depositing and letting the deposition cure. Even if much of the liquid uncured foam flows way, its high viscosity leaves a thin coating that expands. During the next round of depositions, these features trap more liquid uncured foam. With this strategy we were able to create a relatively steep (35-65 deg) mound by repeatedly depositing small pools on the same spot, Fig. 3(c). Second, we dispensed small drips of uncured foam while moving the robot. The surface tension of each drop keeps it in place until the foam expands and cures. This approach also results in a textured surface that provides traction to robots, Fig. 6(c).

Good mixing of the two components is important for achieving complete curing and the specified expansion ratio. Foam from our deposition mechanism has a comparable but slightly lower expansion ratio than samples prepared according to the manufacturer's instructions, ≈ 22 instead of 25-30. We tested two different mixing nozzle lengths, 94 mm and 155 mm. Both gave satisfactory mixing results, and we used the more conveniently sized 94 mm mixing nozzle.

While the mixing was sufficient for complete curing and similar expansion, it is likely not as thorough as batch mixing and can influence the curing process. The curing speed of casting foams is given in terms of the pot life, working time, and time to demolding. Typical urethane casting foams have working times in the 45 sec–210 sec range and a demold time of 20 min–120 min. The particular foam (US Composites #2) we used is on the quick curing end of the spectrum.

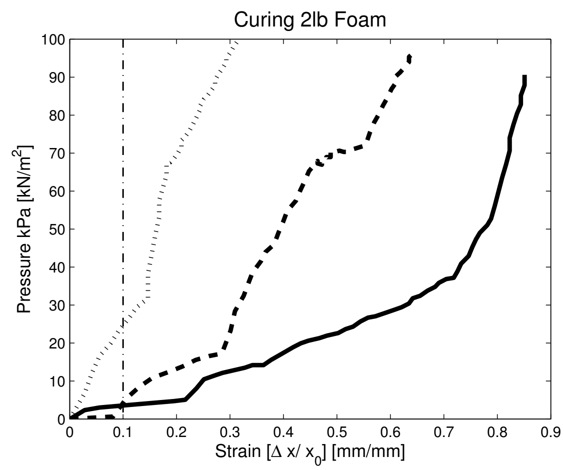

Fig. 9. Stress-strain curve of foam at different stages of curing. The solid line is 20 min after mixing, the dashed line after 25 min, and the dotted line after 30 min. After 20 min the foam is still very soft and compresses almost completely.

Since we are interested in using foam in a different way we examined the curing process in more detail. After 10 min a skin forms, after 20 min the deposition is quite sticky and easily deformable, after 35 min the foam is tacky and deformable with force, and after 50 min the foam is solid and only slightly tacky, Fig. 9. Faster curing urethane foams do exist, e.g. spray insulation foam. However, we found controlling depositions and clogging a challenge and a more complicated mechanism would likely be required.

While a single deposition through the syringe results in similar expansion ration compared to casting applications, repeated deposition into uncured foam and driving over partially cured foam both decrease the expansion ratio. As a result, the deposition and locomotion strategy can both lower the expansion ratio.

Assuming single use of each 50 ml syringe, an expansion ratio of 22, and pricing for 16 lbs bulk packs of foam, the cost for building structures is 3.51 $/l. Buying foam in larger quantities, using larger syringes, or reusing syringes and mixing nozzles are all possible ways of reducing cost.

The manufacturers reported compressive strength of the cured, expanded, foam is 270 kPa. We also tested the strength of partially cured foam, see Fig. 9.

	(A) Strength kPa (@ 0.1)	(B) Mechanical Complexity	(C) Cost $/l	(D) Preparation Time	(E) Deposition Rate ml/s	(F) Cure Time min	(G) Expansion
Foam	26	med	3.51	low	3.1	30	22
Toothpicks	24	med	1.09	low	0.65	20	10
Compliant Bags	28	low	1.98	med	N/A	0	1
Other Platforms							
Factory Floor [5] / 4-Rotors [9]	high	med	med	high	N/A	0	13
Termes [11]	high	high	med	high	N/A	0	1

TABLE I

COMPARISON OF MATERIAL PROPERTIES FOR ROBOTIC, AUTONOMOUS CONSTRUCTION. FOR A DETAILED DISCUSSION SEE THE RESPECTIVE SECTIONS ON MECHANISM DESIGN (SEC. III) FOR (B),(D),(E) AND EXPERIMENTAL RESULTS (SEC. IV) FOR (A),(C),(G).

V. CONCLUSION AND FUTURE WORK

A. Comparing Building Materials

Results from the previous sections are summarized in Tab. I. Two lattice based construction materials are included for reference. Where quantitative results were not available, they were substituted with qualitative ones.

Besides applications where materials need to be chosen for particular properties, we draw the following general conclusions: Casting foams have the largest expansion ratio, which makes them an attractive option for autonomous, untethered operation, especially where the relatively long cure times are not a problem. The benefit of using compliant bags is their simplicity. However, having an expansion ratio of one, means robots cannot build much before having to resupply. Adhesive covered objects, such as toothpicks, seem most useful for depositions over distances or against steep features.

B. Conclusion

We described three different materials types for amorphous construction: Stiff pre-fabricated components and adhesive, compliant pre-fabricated components, and liquid depositions that cure into rigid structures. These biologically inspired construction materials fit into and comply to the environment. We built automated—and in the toothpick case novel—deposition mechanisms and evaluated their suitability for use in a robotic construction platform. Our goal is to create a test bed for robotic construction that enables distributed, incremental building and can cope with irregular environmental features. In our opinion, amorphous construction materials are the simplest way of accomplishing these goals and the contribution of this paper is to evaluate materials and mechanisms for future research in area. While the short list of materials is by no means exhaustive, we hope to highlight the wealth of possibilities and present a starting point for other researches interested in pursuing robotic use of amorphous materials.

C. Future Work

In addition to improving and fine-tuning deposition mechanisms, our ambition is to use the presented materials in autonomous construction systems that effectively operate in unstructured environments. Specifically, we plan to implement autonomous adaptive ramp building based on our experience using controlled robots. We expect that amorphous materials not only allow construction in the face of environmental uncertainty, but also enable smooth collaboration between multiple robots. Uncertainty can come from either the original environment, or previous actions of other robots.

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