Structure synthesis on-the-fly in a modular robot

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Abstract

We describe a mobile modular robot system that can generate foam to make structural elements. The mobile platform itself is built of CKBot modules and carries extra modules along with a foam generation device. We demonstrate the system synthesizing new robot morphologies: a snake-like robot and a legged robot. We also use the foam structures to encapsulate and pick-up objects and to modify the environment by blocking a door. Our presentation describes the issues that arose in implementing and using this technique.

1 Introduction

One of the key aims of modular robotics is to allow robots to be quickly adapted to unanticipated task requirements *after* being deployed to the field. Modular robots aim to address this requirement by having many *modules* from a small set of *module types*, that can be rearranged into an appropriate robot *morphology* to accomplish the desired task. Modular robot architectures such as Chirikjian (1994); Fukuda and Kawauchi (1990); Kirby et al. (2007); Kotay et al. (1998); Yim et al. (2000) and surveyed in Yim et al. (2007a) have few module types and allow modules to be rearranged and reconnected easily, either under a modules' own power or with minimal tools. At the extreme of autonomy, a central or distributed planner algorithm controls reconfiguration (Murata et al., 2002). At the other extreme *robot kits* consisting of many types of modules (parts) are used to manually build a multiplicity of robots.

Modular robots typically address the need for structural components by using modules as structural elements (Terada and Murata, 2006), assuming that such modules will be plentiful and arguing for an analogy to biological systems composed of many similar cells. However, biological cells are immensely complicated and specialized systems. Biomechanists have come to realize the passive mechanical structures and structural properties often play a central role in the control of animal movement (Blickhan et al., 2007; Holmes et al., 2006). Similar to a cell, a module with a load-bearing structure that also carries its own power, performs its own actuation and has the circuitry to perform sensing, computation and communication is a mechatronic system of substantial complexity. It is likely that modules allocated to implement those parts of a robot morphology that perform simple mechanical tasks – such as bearing structural loads – will under-perform compared to simple bulk materials, while leaving most of their own motor and computational capabilities unused (Christensen et al., 2010). This under-utilization is also implied by the number of inactive modules in the demonstrations shown in Rubenstein and Shen (2010).

Drawbacks of using multiple active modules to build a passive structure necessary for a modular robot include: (1) expense, (2) weight, (3) power usage, (4) shape resolution (modules must use whole units to approximate shapes) and (5) robustness to the environment (water, heat, dust, etc.).

We have begun investigating an approach that addresses these disadvantages and promises to greatly expand the adaptive capability of modular robots by allowing the robots to synthesize structural material on-the-fly. Possible uses include structures that attach to active modules, grasp and conform to objects in the environment, or even repair or mitigate structural failures in the robot.

2 Rigid foams as modular structures

One attractive class of materials for on-the-fly synthesis are binary rigid foams. These foams are generated when two reagents are mixed and are often used in the construction industry for thermal insulation and fire-proofing. The materials are relatively safe, cost little, and provide a large *expansion ratio* – ratio of final volume to reagent volume, typically on the order of $\times 10$ to $\times 20$. Even a small robot can carry reagents that allow creating large structures.

Mobile foam synthesis was first demonstrated in a search and rescue context, where a robot used the foam to stabilize the cervical spine of an unconscious victim for transportation (Yim et al., 2009a). A related concept called *Contour Craft-*

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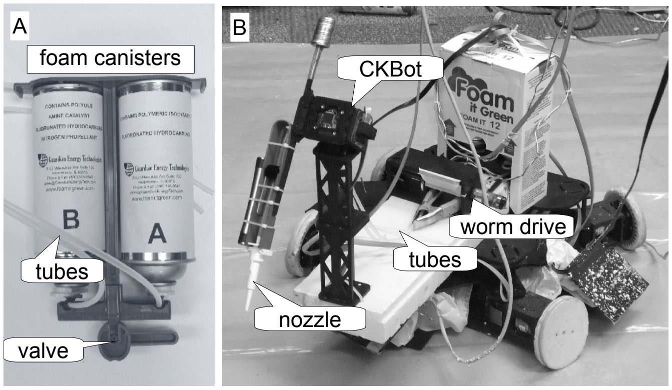

Figure 1: Foam synthesizer system. **A** Two part foam with flow valve. **B** Foam system on a 4-wheel CKbot mobile base with nozzle mounted on an arm.

ing (Khoshnevis, 2004) creates large building structures by ejecting a quick-setting concrete to form walls in a manner similar to a large 3D printer. Assembly of building-like structures using a swarm of robots was the goal of Bowyer (2000), which suggested to do so but did not implement the idea in practice. Both Khoshnevis (2004) and Bowyer (2000) differ from our work in that we focus on passive structures that are part of a robot, rather than constructing a structure in the environment. We also implemented a means to synthesize the structures we proposed and demonstrated their use in multiple scenarios, only one of which is construction-like.

2.1 A brief review of foams

Foams are a two-phase material comprising thin layers of solid surrounding gas pores. Foams differ in the size of pores they contain. This size is related to the reaction rates and viscosity of the reagents, and to the presence and pressure of *blowing agents* – materials that generate the gas filling the pores. Industrial foam reactions use a variety of volatiles as blowing agents (CFCs, carbon dioxide with a combination of ethanol, pentane, etc.), and thus often require in addition to the two reagents, a pressurized feed of the blowing agent.

The expansion of foams is typically an exothermic reaction. Foams are thus also characterized by their *core temperature* – the temperature inside an "infinitely large" volume of foam as it expands. This rise in temperature can be an issue, for example if it comes in contact with human skin (Yim et al., 2009a). The process mixing, rising and curing is characterized by three time constants. The *cream time* is the duration from mixing until the foam reagents begin reacting and form a "cream". It is followed by the *tack free time* at which the foam finishes rising and hardening sufficiently to no longer be tacky, and finally by the *cure time* or *demold time* at which the foam material properties have stabilized.

2.2 Foam properties

In selecting a foam to use, we explored commercially available products that do not require pressurized blowing agents, nor vent dangerous fumes. One class of such foams are binary polyurethane foams, such as BJB TC300, which ranges in density (when fully expanded) 40 to 256 $gram/liter$. In the USA these foams are classified by "poundage" ranging 2.5 to 16 lb/ft^3. In our own tests we poured and mixed 128 $gram/liter$ foam at room temperature, rather than the 80°C recommended by BJB, achieving expansion ratios of around $\times 10$. The foam hardens sufficiently to allow centimeter-scale features to be de-molded after 15 min. To get a rigid and uniform density foam to form, the A and B foam reagents need to be mixed in a high-shear mixing device. Once set, the mechanical properties of polyurethane foams vary widely. The hardness and stiffness of the foams in this paper are on the order of light woods such as balsa.

The relatively long setting time of TC300 led us to explore a spray-on foam, the BJB SP301. This is a fire-retardant foam that is normally sprayed on wood using a spray gun. The nominal density of SP301 is 64 $gram/liter$. With a tack-free time of 12 sec, the SP301 can be formed and removed within less than a minute, although because it is not fully cured we usually waited 5 min – three times faster than TC300.

Because of the difficulty of mixing binary foams with a robot, we switched to a pre-packaged spray foam for our demonstrations. We chose to use the "Foam it 12" kit from greenfoam.com, a home insulation foam kit comprising two half-liter pressurized canisters (see fig. 1-**A**). Each kit generates approximately 28 liters of foam, for a $\times 28$ expansion ratio. The foam emits isocyanates – somewhat hazardous sensitizing agents – when sprayed, but is safe to use in areas with good ventilation. The resulting block of foam inflated for approximately half a minute, with a core temperature of 32.6 ± 0.6 °C. It cured to a density of 39.3 ± 0.37 $gram/liter$ and a bulk modulus of 998 KPa[1]. One or both supply tubes frequently failed, generating an improper mixture that makes a softer, tacky foam.

The modular robotic "synthesizer" cart that carried the foam kit is shown in fig. 1-**B**. We controlled foam generation by operating a spring-clamp that pinched the supply tubes between the reagent canisters and the mixing nozzle. The clamp was released with a worm-drive motor, providing high mechanical advantage but slow switching rates.

The key disadvantage of the "Foam it 12" kit is that it requires somewhat continuous operation. If the foam generation pauses for too long, the foam in the mixing nozzle hardens requiring a replacement nozzle. In addition, because it sprays foam broadly, the robot joints require splatter protection to avoid being jammed by the foam. We are currently exploring designs that mitigate these issues by using mechanically mixed binary foams.

[1] all material property measurements in this paragraph were done in our lab on 10 replicates

2.3 CKBot modules

We use the CKBot (Connector Kinetic robot) modular robots as the basis platform for our investigation (Yim et al., 2009b). Each module consists of a one DOF motor, a microcontroller and communication means. These modules are available in two different geometries: U-bar with one moving face, and an L-7 with two moving faces, allowing interconnections on different rotational axes. An additional module type contains continuous rotation servos useful for wheels.

Interconnections between modules are established with the help of connectors and are fastened with screws or magnets (Yim et al., 2007b). Communication between adjacent modules may use an infra-red port, while the global communication uses a Controller Area Network (CAN) protocol (Gomez-Ibanez et al., 2004). When used autonomously, the modules are powered by on-board lithium polymer battery packs. However, they can also be powered externally via a tether as in the experiments in this paper.

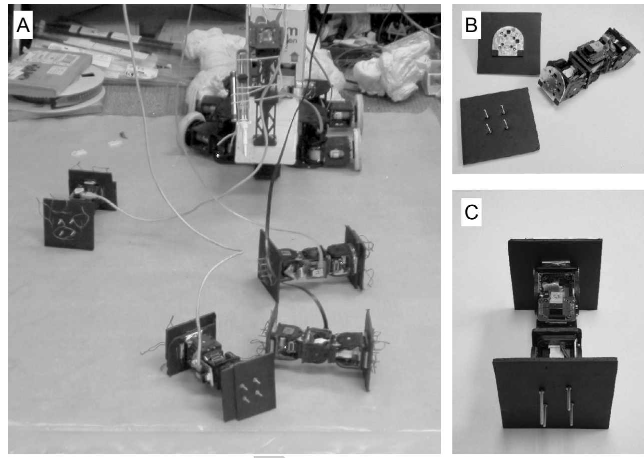

Figure 4: Four clusters deploy from the synthesizer cart (**A**). Each cluster comprises three CKBot modules attached to foam interface plates via magnetically locking plates (**B**). Each cluster is a small mobile unit (**C**) capable of moving back and forth, rotating, and flipping to either side. In experiments clusters also had a nylon splatter shield cut from a shopping bag (not shown here; see videos)

3 Applications

Using the CKbot system we demonstrated structure synthesis on the fly for several tasks: hazard disposal, robot construction, and door jamming. The material accompanying this paper contains a video showing highlights of our results; detailed videos are found at `http://www.modlabupenn.org/foambot-videos`. The first two tasks required additional modules which the foam synthesizer carried as a payload. The robots were controlled remotely and powered via a tether for reliability reasons; all individual actions are known to be controllable via Zigbee (IEEE 802.15.4) wireless links to battery powered robots.

3.1 Hazard disposal

Robots are often used for handling and disposing of hazardous materials: radiologically and biologically contaminated items and armed or unstable explosives. In such applications one of the key difficulties is that of manipulation. Robot arms mounted on mobile systems tend to be bulky and imprecise; those that are not, are expensive. Thus a tension exists between the ability to pick up and handle irregularly shaped hazardous objects and the cost of the robot that may be destroyed or contaminated in the process. Foam synthesis offers a solution, by allowing an inexpensive robot to carry away irregularly shaped hazards. In the approach we demonstrate, the synthesizer robot pours foam around the hazardous materials. The foam structure safely encapsulates the hazard and also functions as the body for a minimalistic (and possibly disposable) robot that ferries the hazard away.

This task demonstrates several key capabilities of synthesis on-the-fly: (1) construction of conforming structures, allowing manipulation of small, fragile or unstable objects; (2) sacrificial use of synthesized material where primary robot hardware is at a premium; (3) use of synthesized material as the body of a robot constructed on the fly.

The hazard disposal process is accomplished by our synthesizer robot, and a payload consisting of a "wheel-arm" robot and a passive "skid plate". The wheel-arm and the skid plate both carry loops of wire that provide a convenient feature for foam to lock on to. The wheel-arm comprises three CKBot modules: a drive module, a steering module and a latch module. This last module is attached to a series of magnetically latching plates that allows the wheel-arm to move under a heavy payload (fig. 2).

We made dual use of the wheel-arm magnetic plates. While their primary purpose is to allow the wheel-arm to pull up its attachment plate, we also used the magnet plates to lock the passive skid plate in place. By twisting the magnet plate with the steering module, the wheel arm breaks the contact between its plate and the skid plate, releasing the skid plate from the synthesizer robot that carries it.

The hazard disposal process is summarized in fig. 3 and hazard removal video.

3.2 Robot construction

We constructed two different robot morphologies starting from identical configurations. We did so with no direct physical contact with the robot[2]. The cart carried four mobile clusters of modules (fig. 4-**A**), each of which had minimal motility. Each cluster consisted of three CKBot modules. The two

[2] during the snake robot synthesis we belatedly realized that we forgot to release the foam kit safety. This is the only instance in which we touched the robots

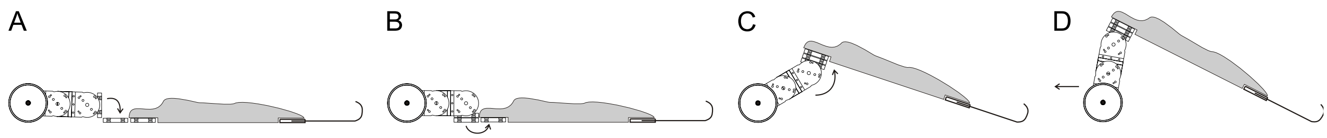

Figure 2: How the wheel-arm situates under the foam plate to lift it up. The wheel-arm latch module locks to the first magnet plate bringing the wheel-arm close to the foam (**A B**). Rotating it upward (**C**) locks the third plate embedded in the foam. Further rotation of the latch module pulls the wheel-arm under the foam plate (**D**). Once the foam-encapsulated hazardous material is lifted from the ground, it can be driven away.

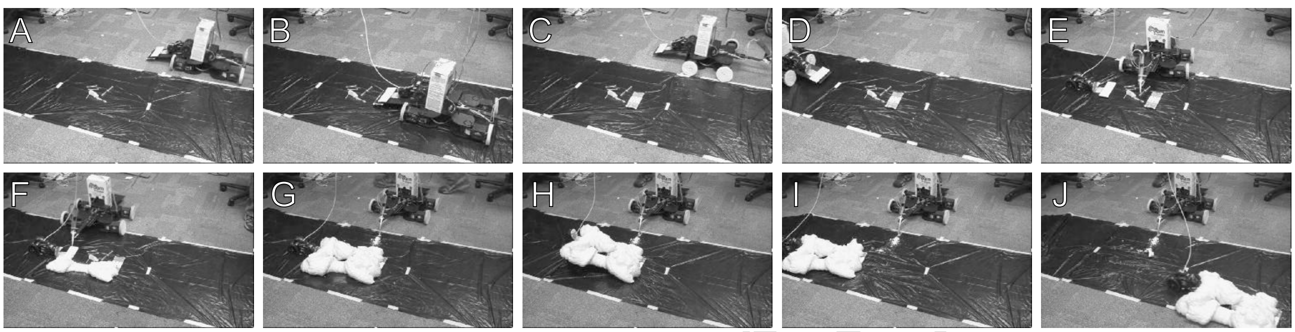

Figure 3: Hazardous material needs to be removed from the floor (**A**). We drove the synthesizer cart to deploy the skid plate (**B,C**) and wheel arm (**D,E**). A foam plate sprayed from the robot captures the hazardous waste and provides a body for the removal robot (**F,G**). The wheel-arm uses the magnetic plates to situate under the plate (**H**) and drive the material away (**I,J**).

modules at the ends had their axes parallel to each other, and the middle module had its axis orthogonal to both the cluster axis and the end-module axes (fig. 4-**B**). Each end module attached magnetically to a plate with protrusions that embed in the foam (fig. 4-**B,C**), making the connection between cluster and foam body reversible and allowing clusters to be re-used in other bodies.

We drove these clusters into positions functioning as joints for a legged robot, whose body and limbs are synthesized from foam (fig. 5 and quadruped video).

In a second instance, we laid the clusters out as segments in a long snake-like robot (fig. 6 and snake video).

Through these examples we demonstrate our ability to select significantly different robot morphologies on-the-fly, after the robot was deployed in the field. The robots synthesized have very different modes of locomotion, showing a means of adapting to operational requirements that were not known in advance. Both robots were large compared to the synthesizer, showing foam expansion can be leveraged into an increase in deployed robot size.

Figure 7: Foam synthesizer pours a doorstop that firmly locks a door in place

3.3 Passive stabilization

Synthesized material need not only be used on the robot itself. It may also be used to directly manipulate objects or the environment, for example constructing a neck brace for victims (Yim et al., 2009a). Another capability that can be of great utility in rescue, firefighting and urban warfare operations is the ability to control doors – lodging doors open to allow for rapid entry or evacuation, and blocking doors shut to seal areas of a building. On-the-fly synthesis easily allows spring-loaded doors to be fixed in place by pouring a rigid foam around the door itself (fig. 7 and door video).

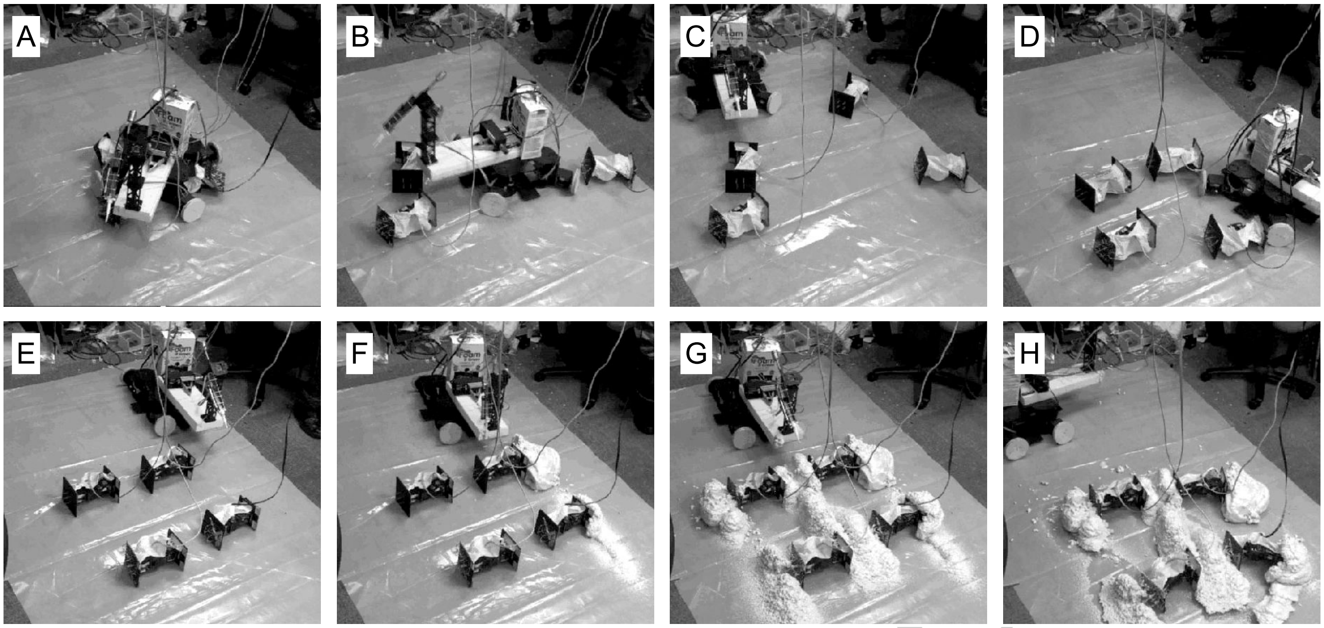

Figure 5: Steps in forming and moving the a foam quadruped robot. We drove the synthesizer cart (**A**) and used it to deploy (**B**) four 3-module clusters (fig. 4). Using the clusters' ability to move and the cart's ability for pushing them, we aligned the clusters in a rectangular formation (**B**-**D**). We commanded the clusters to flip on their side so that joint axes are aligned appropriately for a quadruped (**E**) and then sprayed foam to form feet and a body (**F**,**G**). Once the foam hardened, the newly formed quadruped broke free of the ground and executed a breast-stroke like (symmetric) gait (**H**)

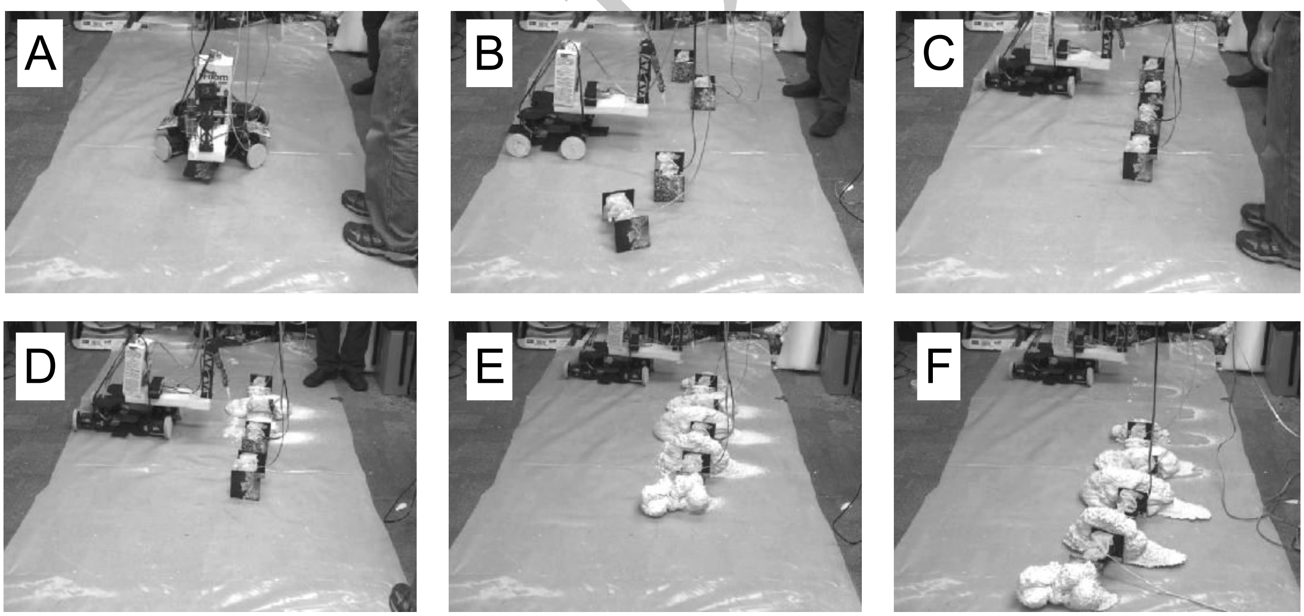

Figure 6: Steps in forming and moving a foam snake robot. We activated the synthesizer cart (**A**) and used it to deploy four 3-module clusters (**B**). Using the clusters' ability to move and the cart's ability for pushing them, we aligned the clusters in a straight line (**C**) and poured foam between consecutive clusters bonding them (**D**). Once the foam expanded and hardened (**E**), we used gait commands to the newly formed "foam-snake" to cause it to move in both inchworm (**F**) and side-winding gaits.

4 Discussion

While each of the tasks described in Section 3 is in itself non-trivial, the particular contribution of our work lies in having a single robotic system capable of performing all these tasks. We have shown synthesis of passive structures can make modular robots better able to adapt to and accomplish unanticipated tasks. Still, several issues remain.

4.1 Technical challenges

Most obvious among these is the challenge of allowing foam to be mixed at will. Binary foams that cure solid also tend to cure in any mixing device. For "Foam it Green", this meant that once foam synthesis was started we could not stop spraying for longer than 18 *sec* without the nozzle blocking. Each experiment we conducted required several "dry" rehearsal runs to practice our timing an ensure that this constraint was obeyed.

We also explored a variety of methods for mixing the binary TC-300 and SP-301 foams. When mixing the reagents with an impeller, we also had to ensure that the cavity in which the mixing occurred would not clog up with foam.

Both poured and sprayed foam tends to adhere to most things including the robot and the environment. A covering had to be placed over moving components in the robot to protect from errant foam. In our experiments, a plastic sheet sprayed with cooking oil prevented foam structures from adhering to the ground. In field conditions, foam pouring in the environment would have to be done on surfaces with natural release agents like sand, light gravel, dust or loose soil. Alternatively, the robot may carry a release agent.

Teleoperated assembly and control of modular robots occupies a middle ground between fully autonomous modular robots and manually assembled robot kits.

One advantage of developing autonomous control would likely be a shortening of the execution time, ideally making the curing time the limiting factor. With the remote controlled approach we used in synthesizing the quadruped robot, teleoperated placement and adjustment of the clusters took five minutes – about half of the total synthesis time.

4.2 Other approaches to on-the-fly structures

There are a variety of ways to improve the process and structures including: higher expansion volume (allowing one robot to build larger or more structures), more precise control of structure shape and the ability to start and stop deployment of foam at will.

One approach toward simpler, but more constrained structure formation could include carrying lightweight trusses that would be cross-linked by foam to form large truss structures, or even scavenging such truss substitutes in the field, such as found sticks. Another approach could include synthesizing foam pieces in a mold, and attaching them to each-other to form large structures. Bowyer (2000) suggests a similar approach, with swarm members depositing foam blocks. Careful selection of molds and perfection of de-molding techniques may allow the foam to be used to synthesize higher precision parts. By carrying a selection of collapsible molds and a foam generator, a robot could form end effectors on a task-by-task basis – for example, forming wheels for driving on land, impellers and floats for crossing water, and high aspect ratio wings for gliding across ravines. Molds could also be made of disposable material (e.g. paper) that forms part of the final structure. Even less carried overhead is possible by creating ad-hoc molds: making a groove in the ground or placing found objects next to each other.

4.3 A challenge in robust control

Versatile applications and highly variable structural properties imply that autonomous or even partially automated control of the robots whose body was synthesized on-the-fly poses significant challenges to control theory and practice, not unlike the challenges faced by the control systems of animals whose bodies change material and structural properties over time. Our robot construction task illustrated this problem in that each body morphology required its own gaits; we manually created gaits in advance, but they required substantial tuning after the robot was fully formed.

4.4 Biogenic foams

Foams can be generated biogenically rather than chemically. One foam commonly used throughout history is bread – a biogenically created foam, with carbon dioxide bubbles generated by yeast. One may imagine a "construction bread" paste, containing yeast or bacteria, which when activated rises as a structurally useful foam.

5 Conclusions

This paper presents a way of creating passive structures on-the-fly both within a modular robot and as means of interacting with the environment. Future work includes improvements in foam synthesis reliability and utility, such as avoiding clogging, self-cleaning, shape forming and improved foam properties.

On the theoretical front, future advances require methods for gait specification and control that work over a wide variety of morphologies and are robust to the high variability of on-the-fly synthesized robot bodies. Biology teaches us that many animals function effectively despite fatigue, injury and even extreme injury such as dismemberment. We hope that bioinspired designs may provide some useful approaches for improving the generality and robustness of on-the-fly synthesized robots.

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