Automated Construction using Co-operating Biomimetic Robots

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Technical Report 11/00

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Abstract:

An outline of a robotic system based on social insect building behaviour is described. The intention behind the system is to have a group of small walking and climbing robots build structures (particularly walls and arches) out of polymer foam at a scale useful to people. Initial experiments on the foam and on a prototype climbing-robot leg design are described, along with preliminary results from a three-dimensional software simulation of building algorithms derived from observations of termite behaviour. The report ends with a list of technical challenges and a description of the research that will be needed to overcome each of them.

Keywords: biomimetics, social insects, construction, self-assembly, robotics.

Introduction

This report is about making a collection of small robots that will build three-dimensional structures in a similar way to the manner in which the social insects construct their nests. The project that the report presages will concentrate on getting the robots to build the two fundamental structures of civil engineering---the wall and the arch---on a scale useful to people, that is with typical dimensions of about two meters.

The purpose of this Technical Report is to describe some initial ideas and experiments on the project. It is hoped that it will form the basis of a research grant application.

The robots

It is anticipated that the robots will be about 0.4m long, and will be legged rather than wheeled as they will need to be able to climb. The bodies of the robots will probably be made from carbon-fibre-clad honeycomb, which is extremely light and rigid. The robots will be electrically powered, and will have re-charging stations to which they will return when their batteries get low (see the section on powering the robots below). These stations will also clean off any accumulated building material that may be impeding the robot. (An appealing alternative would be to have the robots groom each other on a chance encounter, but we will not rely on this initially; see below.) Finally, the stations will replenish the robots' supplies of the building material.

The robots will have on-board micro-controllers that will be sufficient to decide their behaviour and to make them autonomous. They will all communicate with a single data-logging computer using Bluetooth [2] or by means of infra-red links. This computer will not be controlling the individual actions of the robots---social-insect building (and other) behaviour is an emergent property of their individual autonomous actions [6]---but it will be used to monitor what is going on, and to change strategy when necessary.

Each robot will also have access to its position and orientation in space using infra-red/ultrasound triangulation and tilt sensors. The position information ought not to be needed if the behaviour is properly programmed, but it will still be useful for measuring and gathering statistics.

The software controlling each robot will be downloaded from the central computer using the link. This will make it simple to change the behaviour of each robot as construction progresses.

It is not intended that the robots will move very quickly. We wish to demonstrate that our proposal represents a feasible method of construction and we have no intention of competing on speed with conventional building techniques initially. Slow robots will be more efficient in their use of electrical energy, prolonging battery life. They will also be easier to program, as it will be possible to ignore dynamic considerations in movement and to concentrate on kinematics.

Building

The building material

The robots will use polymerized diphenylmethane 4,4'-diisocyanate foam as their construction material. This is the basis of the commercial filler in the *Gap Gun* marketed by ICI/Polyfilla and made by Polypag. The company has premises conveniently located in Bristol, and contact with them has already been established.

The foam is very light, is non-toxic, and expands on being deposited as the propellant driving it evaporates within it. This last fact means that a robot can have small foam and propellant tanks and still do a lot of building before they need to be replenished.

This project is intended to prove the concept of biomimetic robot building. There is no reason, once this has been established, why other materials could not be used as long as they can be supplied to---and carried by---the robots. Ordinary cement comes to mind as an obvious alternative for a follow-on project.

Figure 1: A small arch made by repeatedly depositing by hand lumps of diphenylmethane 4,4'-diisocyanate foam similar to the example on the right. In front is a foot rule.

Figure 1 shows a small arch made by repeatedly depositing lumps of foam about the size of the isolated example piece on the right of the figure. The arch was made by creating a layer of lumps by hand, allowing them to set (which took about 15 minutes), and then putting another layer on top. The finished arch was strong enough to support a person standing on it. The addition of a small amount of water to the foam as it was deposited would speed up setting times.

The foam has a density slightly higher than that of expanded polystyrene.

The building process

Termite nests are the most complicated built structures in nature, and can be up to 10^5 times bigger than the individual termites that build them. This ratio is only exceeded by the largest human cities.

Considerable research has been done by a co-applicant of the author's [4] and others on the nest-building behaviors of termites and other social insects. In particular it has been shown that a single set of building rules can lead to a wide variety of useful structures if the build material emits a pheromone the strength of which depends on how recently the material was laid down, and which is carried by air currents.

At a more basic level, a multiply-arched structure can be achieved by the following simple algorithm, which was derived from observations of social insects:

1. Is there a pile of building material of height at least h_1 within a range d_1?

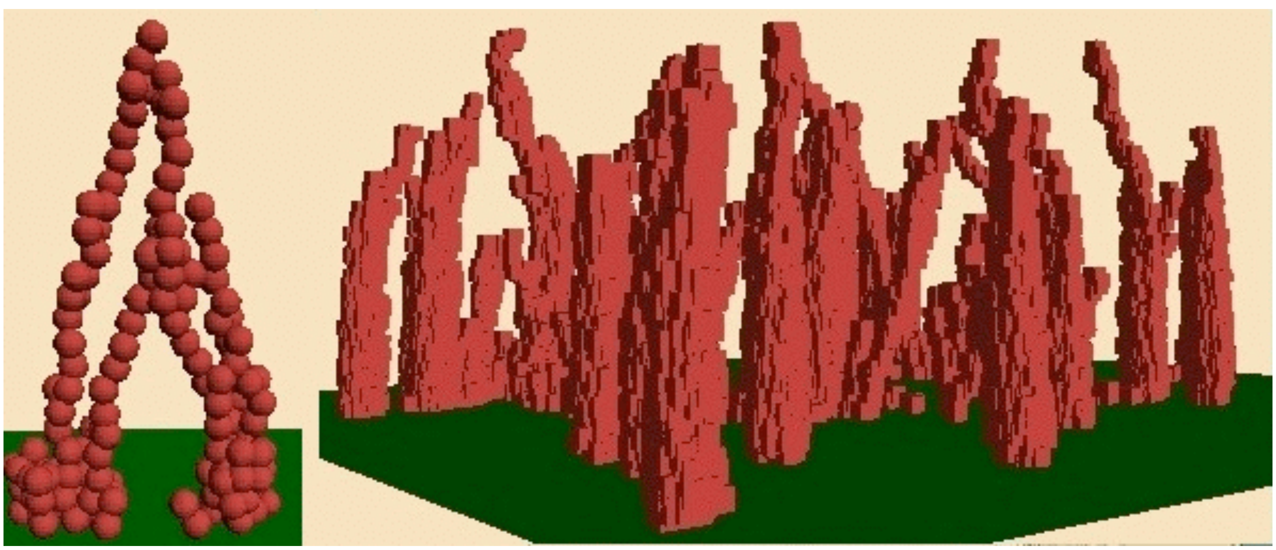
   Yes: Go and make it higher.
   No: Start making your own pile.

2. When your pile has reached height h_2 look for a pile or arch within a distance d_2.

   Found: Build a bridge to it, then go to Step 3.
   Not found: Go to Step 3.

3. Walk somewhere else at random, then go to Step 1.

The resulting structure will depend on the values of h_1, h_2, d_1 and d_2, of course, but the right values will generate self-supporting structures of considerable complexity. We have written a



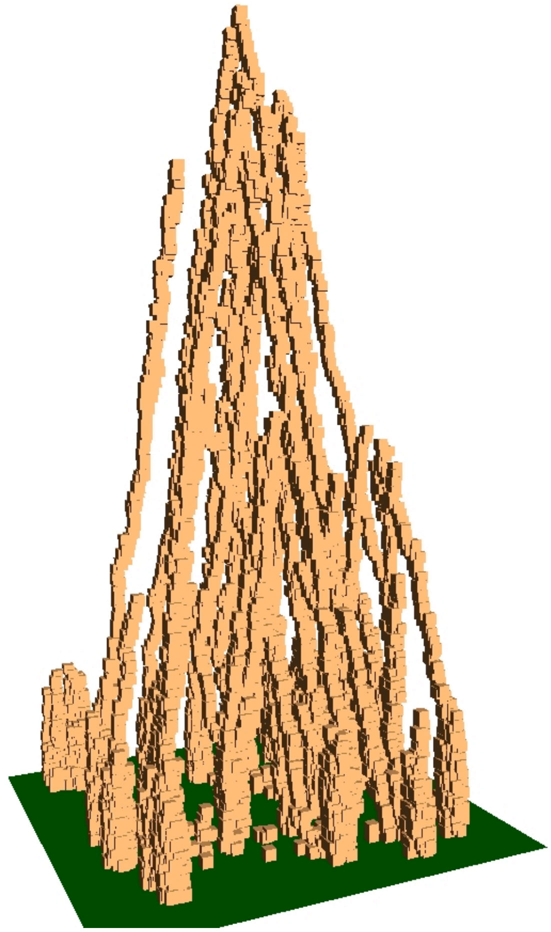


Figure 2: Three simulations of the simple termite building algorithm, showing how structures such as crenellations, arches, and flying buttresses emerge automatically.

C++ simulation program for investigating such building behaviour. Figure 2 shows three results of running it on the above simple algorithm with different sets of input parameters.

If the robots can walk, climb, sense their immediate surroundings (probably by touch and smell---see below), and deposit lumps of building material, they can follow this procedure---and similar ones.

Technical challenges

We anticipate that the hardest challenges in this project will be mechanical. The following is our current list of the main problems in rough order of difficulty (hardest first):

Automatically cleaning foam from the robots

The foam can be prevented from adhering to a surface if the surface is made oily. Vegetable oil works particularly well, and has the advantage of being environmentally-friendly. It may be possible to cover the robots almost completely in an absorbent material (such as cloth) and to soak this in vegetable oil each time the recharging station is visited. Alternatively the robots could simply be smeared with grease.

In either case, it is important that the protective oil or grease is not shed onto the structure being built, as that would obviously prevent adhesion where it *was* wanted.

However, a better scheme may be to use the lotus effect (named after the plant, *Nelumbo nucifera*) [1]. Lotus leaves are covered in a hydrophobic wax that, crucially, has a special microstructure to its surface roughness that not only repels water, but ensures that any water running over the surface carries away the maximum amount of contaminants (in the case of the plant, the principal concern is to remove infectious fungal spores). Figure 3 shows a lotus leaf being cleaned by the effect.

Figure 3: A lotus leaf that has been contaminated by sprinkling a fine red powder on it (Sudan-III pigment powder: 1 - 20 μm, Merck) cleaning itself using rain (after Barthlott and Neinhuis [1]).

Biomimetic research into this in Germany has already led to the commercial development of a paint [5] that could make a good basis for a robot covering.

The recharging station could also be equipped with rotating brushes (like a car wash) to remove any foam adhering to the robots.

The cleaning problem will be minimized by getting the robots to avoid areas where foam has been very recently laid down (see sensors below).

Removing as well as depositing foam

If social-insect building behaviour is observed, it quickly becomes apparent that sometimes material is being deposited and at other times it is being removed. In order to mimic this we have the choice of equipping each robot with a foam cutter to remove set foam, or of having two classes of robot: builders and removers. The foam is easily abraded, so a low-power cutter should suffice to remove it. Also, the resulting dust fills a far smaller volume than the original foam (which was mostly voids), and (at least initially) could probably be left where it falls without getting in the way.

Getting the robots to climb the foam

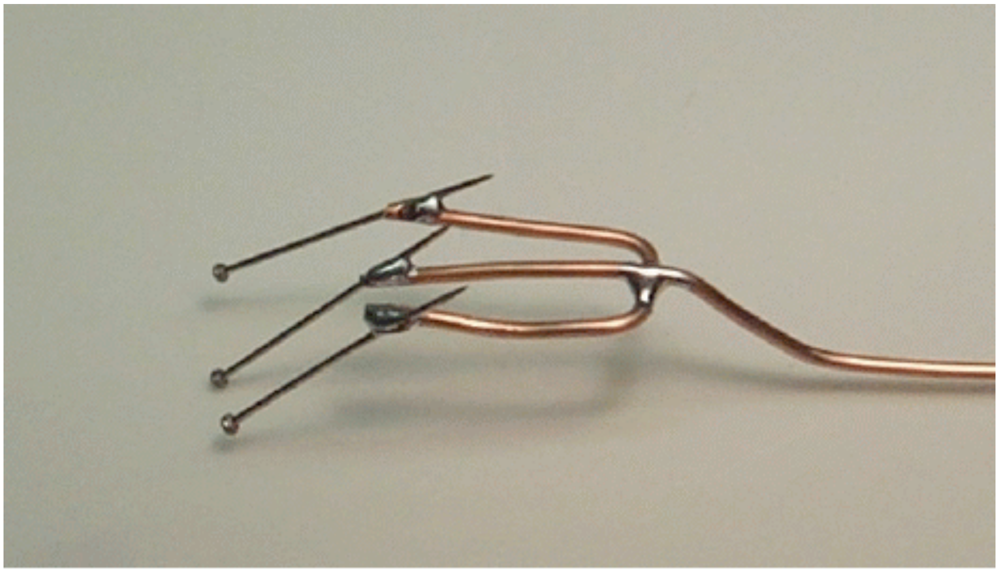


Figure 4: A crude claw made from sewing pins soldered to copper wire. This supported a load of over 1.5kg. Dragging it over the foam with no extra downward force was sufficient to lock it into the surface. It could be removed by reversing its direction; this required no discernible force at all.

The solidified foam is strong, and its surface is quite hard. But it is easily punctured by a sharp object. If the robots' legs were to be equipped with claws (possibly modelled on squirrels' feet, which are perfectly attuned to climbing both up and down vertical surfaces---see Figure 4) it ought to be possible to have them climb. The damage done to the foam surface should not be significant. It may even be possible to make the robots cling underneath an overhang.

The robots would also be designed sufficiently robustly that occasional falls from a height would not harm them.

Ensuring the foam applicators don't get blocked

The foam, when liquid, is extremely sticky. It dissolves in acetone, but once it has set it is almost completely inert, and will not dissolve at all except in some very noxious substances.

The liquid foam in its tank needs continuous agitation, which will probably be achieved using a disconnected magnetic stirrer like those used in chemical experiments. It also needs a gas propellant. This is usually butane, which obviously will need to be handled carefully and ventilated well. But it ought to be possible to design the foam nozzle such that the foam is in its pressurized liquid form right up to the point of application. An auxiliary line from the propellant tank could then be used to blow clean the very last section of the applicator after foam has been deposited from it.

Clearly this problem is related to the cleaning problem discussed above, and the lotus effect may well prove beneficial here too.

Allowing the robots to sense their immediate surroundings

As was mentioned, the robots will need legs rather than wheels if they are to climb. The simplest sensors would probably be touch-probes mounted on the legs, which would function like the hairs on many animals that make good proximity sensors. The touch-probes could be quite simple, with each giving a binary signal: *touch/no-touch*. There would need to be some redundancy, as doubtless some sensors will get stuck by pieces of foam.

We propose to mimic the social insects' use of pheromones to control their building behaviour. Semiconductor gas sensors are readily available that will detect a variety of gases and vapours, and equipping the robots with these would allow them to detect recently deposited foam if it were laced with the appropriate vapour-emitting solvent. Three or four sensors at the extremities of each robot (possibly also on the legs) should allow concentration gradients to be roughly estimated. Ethanol or acetone would work quite well; Polypag have been consulted on this, and say that acetone has the advantage as it would not affect the foam chemically.

It may prove advantageous to have one chemical marker for the foam, and another as a trail left by the robots all the time to mark the paths they take. Though gas sensors are available for specific substances (like ethanol and acetone), the manufacturers [3] have also been consulted and say that there would be considerable cross-interference between two sensors nominally intended for two different organic solvents. However, a reducing-agent sensor would allow a clear discrimination to be made. Sensors are available for chlorine, which is obviously too toxic for this application. But those sensors may well also respond to iodine, the solid form of which emits small amounts of vapour under ordinary conditions, and which is comparatively benign. A suspension of small quantities of iodine in water may make a good second marker substance.

It would be possible to equip the robots with small CCD cameras, but we hope to manage without this. In particular, it should be recalled that termites are blind.

Powering the robots

A widespread aspect of existing small walking robots is that industrial actuators are neither small enough nor powerful enough to drive them satisfactorily. Most researchers therefore use model aeroplane servos; some of these are as light as 6g, including the electric motor (see Figure 5).

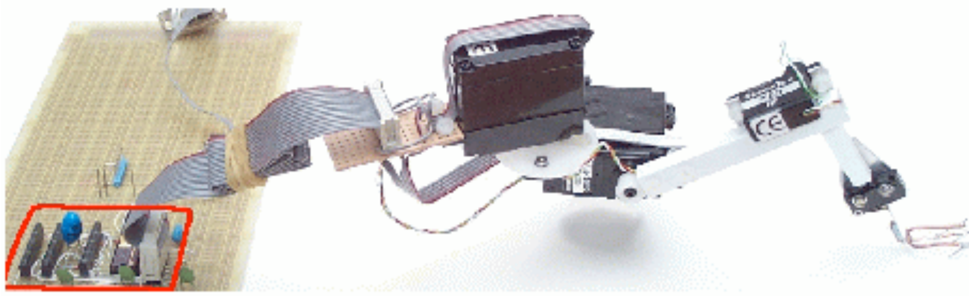


Figure 5: An experimental robot leg made from model aeroplane servos. The knee joint weighs only 6g. The microcontroller and three H bridges outlined in red on the left are all the electronics needed to control the leg.

We have conducted experiments on these, with the preliminary results that, though the mechanics of such devices are excellent, the requirement for them to be driven by a simple low-frequency PWM signal, which is an inheritance from the early days of radio-control, makes them prone to jitter and hunting. A good solution is to keep the servo mechanics and the feedback potentiometer, to throw away the electronics, and to drive the servo motor from a microcontroller with inbuilt A-to-D converters such as a PIC [8] feeding into an H-bridge. One PIC can drive several servos, and thus can be used to control an entire leg. This mimics a widespread biological phenomenon---that of autonomic control of part of an organism by local nerves. PICs have inbuilt UARTS, and so arranging a number of them in a token ring is a simple low-wire-count method of data distribution and control if several are to be used.

It may transpire that ordinary nickel metal-hydride batteries are sufficient to power the robots. But walking robots are notoriously power-hungry, even if power conservation is explicitly programmed into all their servo controllers. An alternative that may be worth investigating is powering the robots with a (well silenced) model aeroplane engine connected either to a DC motor acting as a dynamo---which would be simple, and could double as a starter motor---or to a small alternator---which would be more efficient. These engines can easily generate several hundred watts, and a volume of fuel the size of a battery pack would let them run for quite a long time. They could also be refueled in seconds. Given the falling costs and rising energy densities of fuel cells, a methanol fuel cell might be another alternative[7].

Conclusions

There will, of course, be unanticipated problems in addition to those that have been foreseen and described above---such is the nature of research. But we have at least investigated the anticipated problems sufficiently to be confident that they can be overcome.

A particularly strong aspect of the proposed project is that we have already written, as part of these initial investigations, a complete simulation program for robot/social-insect building behaviour. This will allow us to try out a wide range of building algorithms speedily before committing the robots to the much slower task of doing the actual construction. The ability to set the robots building using only pre-tested algorithms that thus have a good chance of success should save considerable time. (We also plan to use the software in pure social insect behaviour research independently of this project.)

The vast majority of existing co-operating robot work is either in two dimensions, or is done *only* by simulation. To the best of our knowledge this project will be the first to build real useful three-dimensional structures on a human scale using robots programmed from observations of the social insects.

References

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7
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8
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Notes

...rigid
There is considerable experience of this material at Bath, as it was used in our latest car to enter the Shell Mileage Marathon; this won the diesel class.

...property
: Sometimes such properties and behaviours are called *stigmergy*.

...engine
: This idea was engendered by the need to read through many geek's model catalogues looking for appropriate servos...