

# Modeling and Implementation of Solder-activated Joints for Single-Actuator, Centimeter-scale Robotic Mechanisms

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**Abstract**— We explain when, and why, solder-based phase change materials (PCMs) are best-suited as a means to modify a robotic mechanism’s kinematic and elastomechanic behavior. The preceding refers to mechanisms that possess joints which may be thermally locked and unlocked via a material phase change within the joint. Different combinations of locked and unlocked joints can yield several one-DOF mechanisms states. One actuator may be used to control motion allowed by a first state, then a new combination of locked/unlocked joints may be set and the actuator then controls motion allowed by the new state. Compared to other thermo-rheological fluids, solders yield joints with the (i) highest strength and stiffness, (ii) fastest lock/unlock speed, and (iii) lowest lock/unlock power. Herein, we cover physics-based design insights that provide understanding of how solder-based material properties and joint design dominate/limit joint performance characteristics. First order models are used to demonstrate selection of suitable PCMs and how to set initial joint geometry prior to fine tuning via detailed models/experiments. The insights and models are discussed in the context of a joint for a crawling robot that uses a single spooler motor and three solder-locking joints to crawl and steer.

## I. INTRODUCTION

Most troublesome problem in multi degree-of-freedom, cm-scale robot design is the need for multiple sub-cm actuators. It is often impossible to find off-the-shelf actuators that exhibit the requisite force/torque, power and speed characteristics in a sub-cm package. Even if one could find suitable actuators, there are other practical issues

associated with miniaturization. For example, it is difficult to create suitably small, stiff and strong mounting points for many actuators upon a mechanism. Also, the packaging of requisite electronics and routing of power lines to multiple actuators is non-trivial.

These problems may be avoided when a robot’s mechanism possesses joints that may be thermally locked and unlocked via a phase change material (PCM) within the joint. Different combinations of locked and unlocked joints yield several one-DOF mechanism states. One actuator may be used to control motion allowed by a first state, then a new combination of locked/unlocked joints may be set and the actuator then controls motion allowed by the new state. Our example robot, Squishbot1 shown in Fig. 1, was designed to be 1.5cm in diameter when extended. It contains 3 solder locking joints (see inset) and one DC motor spooling mechanism. This actuator-joint combination enables states that permit locomotion along the robot’s axis, side-to-side steering and lifting of the front (rightmost) half of the robot.

The use of phase change materials, a thermo-rheological (TR) fluid, for mechanism fixation has been examined within MEMS mechanisms and micro-optical alignment [1]. In these prior works, the mechanism was fixated by the PCM, thereby enabling position/orientation holding without powered actuation. This differs from our approach as it does not change the mechanism’s kinematic or elastomechanic behavior. The scope of this paper

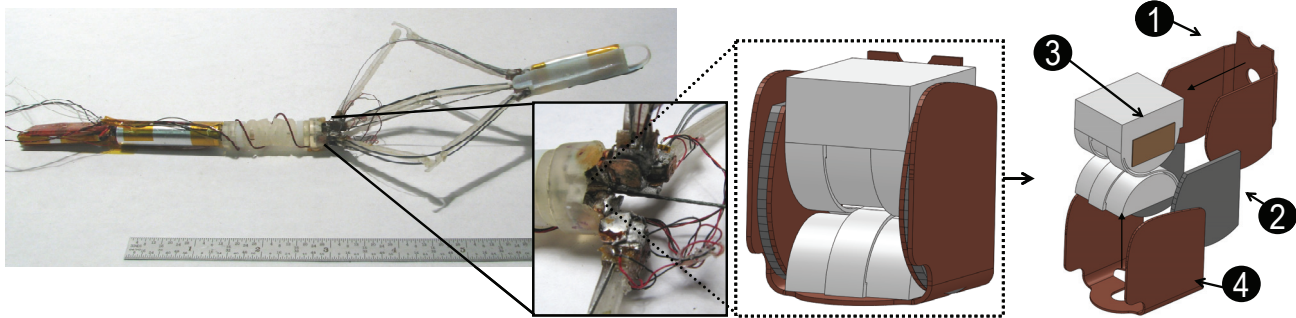


Fig 1. Squishbot1 – A single actuator robot. The first inset shows three solder-locking joints. The second shows a solid model of one of the rolling flexure locking joints to wherein u-shaped copper elements (1 & 4) are attached to the sides of the top and bottom joint elements. The flexure joint, a Jacob’s ladder joint, uses flexures to keep the top and bottom half-cylinders in contact. Rolling of the top half-cylinder over the bottom is constrained when the solder (2) between their side plates is solidified. Current is run through a strain gage (3) within the joint to melt the solder.

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encompasses the use of PCMs that lock and unlock joints, thereby altering the mechanism’s kinematic and elastomechanic behavior. The use of PCM joints was first suggested and experimentally verified via bench-level experiments (using hot glues) by Boston Dynamics.

This approach enables a new means of achieving complex motions/tasks with small-scale robotics, but it is not a panacea. Key performance characteristics – strength, stiffness, speed, weight – depend upon proper PCM selection and component design. The most salient issue is power. The phase change process can be prohibitively power-intensive and slow if one does not select a suitable PCM and properly design the thermal and mechanical behavior of the components that supply and withdraw heat from the material.

The robot/joint design problem is multi-domain and highly coupled, therefore modeling + experimentation rather than intuition + iteration are the fastest means to achieve useful performance. Herein we provide the basis to understand (i) the physics that dominate and limit joint performance, (ii) how to select the PCM, and (iii) how to rapidly use 1<sup>st</sup> order models to set an initial joint geometry for specific performance characteristics. We use the preceding to show that solder-based PCMs are generally the best for applications that require joints which possess the (i) highest strength and stiffness, (ii) fastest lock/unlock speed, and (iii) lowest lock/unlock power. The preceding is put in context via discussion of application to Squishbot1.

#### A. Squishbot Performance Requirements and Constraints

Squishbot1, created during the DARPA Chemical Robots Challenge, is a step toward the creation of small-scale, soft robots that can deform to gain access to spaces with small openings. Table I provides a summary of the functional requirements and constraints encountered in the design.

TABLE I REQUIREMENTS AND CONSTRAINTS

<b>Power supply</b>	2 - 150mAh batteries <sup>+</sup>
<b>Minimum range</b>	5 meters
<b>Minimum speed</b>	4.2 mm/sec
<b>Cross section size</b>	Travel through 1cm hole

+ Li-ion polymer battery, model GMB051235 from the Guangzhou Markyn battery company.

A key driver in the design was the need to travel through a 1 cm hole. This requirement placed difficult size constraints upon mechanism, actuator, on-board electronics and power source. Power limitations required the reduction of robot weight. These weight limits and difficulties in finding and integrating suitable sub-cm actuators drove the decision to use one actuator with locking/unlocking mechanism joints.

## II. BACKGROUND

In general, joint locking and unlocking may be achieved with a variety of ‘active fluids’, i.e. materials that can change from liquid to a solid or semi-solid state. This paper focuses on PCMs; however we provide an overview of competing materials as a basis for arguing why solder-based PCMs are well-suited for small-scale robotics applications.

#### A. Overview of Active Fluids

Active fluids possess tunable rheological properties. They

are classified by the means used to cause a change in state within the fluid. For example, the resistive shear stress within magneto-rheological (MR) fluids is proportional to the magnetic field within the fluid. Failure stresses of 50kPa (7.25 psi) have been reported [2]. These materials have been used in vibration dampers, and locking spherical joints [2,3]. The failure stress within electro-rheological (ER) fluids is controlled by the electric field within the fluid. Failure stresses of 130 kPa (18.9 psi) have been reported [4]. The imposition of a field in MR and ER fluids forces nanoscale particles to align within the fluid thereby enabling the fluid to resist deformation [2,4]. This alignment mechanism endows them with millisecond response times but places fundamental limits on failure stresses (at practical field strengths). Their low failure stresses limit the strength of a locked joint and therefore the strength of the mechanism.

The change in state of photo-rheological (PR) fluids is caused by exposure to ultra violet light. This induces a chemical change within the fluid that leads to a change in deformation resistance characteristics. Viscosity changes of 4 orders of magnitude have been reported, however the highest absolute viscosity is comparable to that of honey [5]. For robotic applications, the fluid must be reversible, i.e. switch between ‘soft’ and ‘hard’ states. Most PR fluids are non-reversible, meaning they cannot be returned to their original ‘soft’ state once activated. There are a limited number of newly-available reversible PR fluids; however their response time is slow, e.g. 4 minutes [6]. A favorable characteristic of PR fluids is that they do not require constant energy input to maintain a locked state, unlike MR and ER.

Thermo-rheological (TR) fluids achieve a change in state via temperature change. For practical purposes, we limit our discussion to those which change phase within temperatures that are reasonable for robotics applications, e.g. within a few 100°C of room temperature. We consider TR fluids to be in their ‘off-state’ at room temperature.

Common TR fluids - solders (~ 40 MPa), and hot glues (~ 5 MPa) - exhibit failure stresses that are well above those of MR, ER and PR fluids. For a given joint geometry, they will provide higher strength; however this is ‘for naught’ if the fundamental issues governing the (i) energy requirements and (ii) lock/unlock speed are not addressed. Phase change is inherently energy intensive, which is problematic given the limited energy that may be stored on-board a small robot.

The thermal characteristics of the PCM – specific heat, latent heat and melting temperature – must be selected so as to minimize melting energy. This is critical as there are no suitable small-scale heat recovery devices, e.g. thermoelectrics, therefore melting energy is unrecoverable. It is important to note that the limits of solidification/lock and melting/unlock speeds (equate to robot speed) are defined in-part by thermal characteristics. Melt time is inversely proportional to power (which is in limited supply)

and the brevity of cooling time is determined in-part by the PCM's thermal diffusivity (varies widely between TR fluids) and the free convection of heat out of the PCM.

The Pugh chart in Table II contains a qualitative comparison of the different types of active fluids. The table contains two types of TR fluids to better represent the wide range in properties that may be seen in TR fluids.

TABLE II PUGH ACTIVE FLUID COMPARISON CHART BASED ON COMMON CONSIDERATIONS IN ROBOTIC DESIGN<sup>†</sup> [2,4-9].

	PR	MR	ER	Wax	Solder
<b>Speed</b>	0	++	++	0	+
<b>Weight</b>	0	-	+	+	++
<b>Strength</b>	0	+	+	+	++
<b>Power</b>	0	0	0	0	+
<b>Scalability</b>	0	--	-	0	0

<sup>†</sup>PR is used as a baseline for qualitative comparison

### B. The Case for Solder as an Active Fluid in Robotics

The strength of solder in its locked state is at least an order of magnitude larger than that of the other active fluids. Solder has a high thermal diffusivity, typically an order of magnitude, or larger, than waxes and glues. This enables solder to quickly spread thermal energy throughout its volume thereby speeding melting and solidification. The relevant thermal property, thermal diffusivity, is the key to obtaining short response time in TR fluids. Glues and waxes have low diffusivity and are therefore slow to melt/solidify. In contrast, anyone who has soldered wires for electronics knows how rapidly solders may be melted and cooled.

The electronics packaging community has created many different solders, and characterized/optimized their melt energy, melt times and solidification times. Therein lays a wealth of knowledge regarding material properties of solders and guidance on customizing properties. When competing thermal and mechanical requirements are not satisfied by off-the-shelf solders, it is possible to modify their composition and obtain the desired characteristics.

Squishbot1 uses solder as its locking fluid. The high failure stress of the solder was necessary given the small area available for locking in the mm-scale joints. The mechanical and thermal elements of the joints were easily scaled down to mm-size. The mechanical components are 3D printed, laser cut and/or CNC micromilled. Heat is easily delivered to the joints via current routed through small strain gauges that act as heaters. A perfect solder was not found within off-the-shelf solders, therefore we selected one that was close and therefore easily modified to minimize (i) the amount of energy needed to unlock the joints and (ii) the lock/unlock cycle times.

## III. JOINT DESIGN

### A. Joint Mechanical Modeling

There are several concepts for joint designs where locking could be used. We classify them by loading mechanism. Shear and tension are the most common, but torsion,

compression, and combinations are possible. The shear and tension modes are shown in a generalized geometry within Fig. 2.

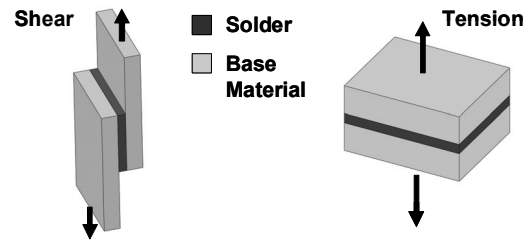


Fig. 2. Generalized shear and tension solder joint geometries.

The strength of a TR joint may be calculated using the appropriate failure stress (shear or tension) of the solder and the surface area of the joint. Equation (1) links failure load to failure stress via the area over which the solder resists load.

$$F_{load} = A \times \sigma \quad (1)$$

The failure stresses of solders are readily obtained from standard electronics handbooks [7-9] or from manufacturers. Most solders are metal alloys, and changing the mass fraction of alloying elements can induce large changes upon thermal and mechanical properties. Other properties of the joint may affect strength. Changes in the gap (ideally 10-100 micrometers) may affect the strength of the joint as detailed in [7]. It is also known that one must consider the characteristics of the base material, for example copper-lead joints generally have the highest shear strength. The joining and operating temperatures may also affect strength [8]. The number of factors that may affect strength are many, therefore it is typically best to use standard failure stress data to obtain a first approximation for joint strength and follow best practices [7-9] for other factors. If other factors become relevant, experimentation is used to quantify effect on performance.

### B. Joint Thermal Modeling

Complex thermal models are time and resource intensive, especially for phase change and transient problems. In locking joints, model accuracy depends upon the accuracy of convection coefficients, which may vary with joint design and joint orientation during operation. As a result; FEA-type models have limitations. It is possible to use first principles to obtain rapid, practical estimates of melting energy, melt time, and solidification time. This information may be used to set the initial design of a joint, which may then be finely tuned via experiments or more detailed thermal modeling. Our focus in this section is the means one can use to (i) understand how performance scales with geometry/material properties, (ii) select desired materials and (iii) set initial design parameters for joint geometry.

A convenient way to approach modeling heat transfer is modeling via thermal circuits where each component of the joint has a thermal resistance. Equation (2) calculates the conductive thermal resistance,  $R_{cond}$ , where  $k$  is the thermal conductivity of the material,  $L$  is the length the heat must

travel and  $A_k$  is the area perpendicular to the heat flow.

$$R_{cond} = L/A_k k \quad (2)$$

Equation (3) is used to estimate convective thermal resistance,  $R_{conv}$ , where  $h$  is the thermal convection coefficient ( $\sim 10\text{W/m}^2$  in air) and  $A_h$  is the surface area exposed to the air.

$$R_{conv} = 1/A_h h \quad (3)$$

The act of thermal resistance modeling forces one to think in terms of joint geometry and material properties that govern heat flow. A high thermal resistance indicates a low heat transfer rate. The heat transfer rate,  $q$ , depends on thermal resistance and temperature difference,  $\Delta T$ :

$$q = \Delta T/R \quad (4)$$

The first step is to ‘break’ the joint into elements of a thermal circuit. Fig. 3 shows the thermal circuit for half of a joint in Squishbot1. Heat flows from the heater through the copper and solder layers via conduction before dissipation to the ambient via convection. Heat also flows from the heater into the Teflon via conduction.

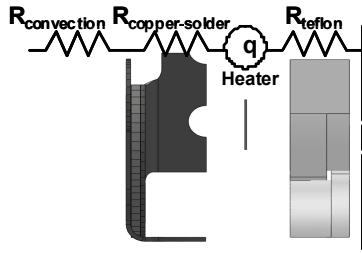


Fig. 3. Half Squishbot1 joint with corresponding thermal circuit

Next we find the equivalent resistance for each of these paths by adding the resistances as in electric circuit modeling. As Table III shows, in Squishbot1 the low thermal resistance (Degree Kelvin per Watt) of the copper and solder layers indicates that these will quickly adjust temperature. The high convection resistance (due to the product of small surface area and small convection coefficient) indicates low heat transfer rate to the environment. There is less resistance to heat that travels through the Teflon than heat that is convected to the environment. This is important to consider, particularly for the cooling time.

TABLE III THERMAL RESISTANCES FOR COMPONENTS OF SQUISHBOT1 JOINT

	$R_{convection}$	$R_{copper-solder}$	$R_{teflon}$
Resistance (K/W)	$4.34 \times 10^3$	$2.15 \times 10^{-3}$	$3.68 \times 10^{-2}$

The lumped thermal capacity model is used to simplify transient analysis. This is a valid assumption if the Biot number of a component is less than 0.1, which occurs when the temperature within the system being modeled will not differ from that at the surface by more than 5%. The Biot number is a ratio of the internal conduction resistance to external convection resistance, as shown by (5) [10].

$$Biot = hL/k \quad (5)$$

In Table VI we can see that the Biot number is less than

0.1 for all the components of the Squishbot1 joint, the lumped model is appropriate. Another parameter to consider is the characteristic time for conduction within each component. Equation (6) shows the formula used to calculate the characteristic time, which depends upon the distance heat must travel,  $L$ , and the material’s diffusivity,  $\alpha$ .

$$t_c = L^2/\alpha \quad (6)$$

Table IV lists the characteristic times for each component, which indicate how quickly a component will adjust its temperature.

TABLE IV JOINT PARTS BIOT NUMBERS AND CHARACTERISTIC TIMES.

	Outer Cu	Solder	Inner Cu	Teflon
Biot #	$3.3 \times 10^{-6}$	$5.0 \times 10^{-5}$	$3.3 \times 10^{-6}$	$6.4 \times 10^{-2}$
$t_c$ (s)	$1.4 \times 10^{-4}$	$1.9 \times 10^{-3}$	$1.4 \times 10^{-4}$	$2.7 \times 10^1$

It is important to understand how these numbers will affect the joint’s thermal performance. Materials with low Biot numbers and short characteristic times will adjust quickly to temperature changes. This will help shorten heating and cooling cycles, however a material with a higher characteristic time can store heat, thereby keeping the joint close to melting temperature between cycles.

The amount of energy needed to melt the solder is important given limited power. During the heating step, the thermal energy that is put into the joint is distributed between (i) raising the temperature of the joint components, (ii) heat loss during melting (typically a fraction of the melting energy and may assumed to be small), and (iii) the energy, i.e. latent heat of fusion, that is required to induce the phase change in the solder. Equation (7) may be used to calculate the energy required to melt the solder in the joint. The total heat required,  $Q_t$ , is estimated from first principles using the specific heat capacity for the materials,  $c$ , the mass of the materials,  $m$ , and the change in temperature,  $\Delta T$ . The energy to achieve the phase change is calculated using the material’s latent heat of fusion,  $L_f$  and the mass of the material.

$$Q_t = (mc\Delta T + mL_f)_{solder} + (mc\Delta T)_{jointmaterials} \quad (7)$$

The temperature rise in each material depends on its characteristic time scale. Those with time scales that are orders of magnitude shorter than the cycle time will be heated to at least the melting temperature of the solder during the heating time. The temperature reached by components with longer characteristic times depends upon heat flow within the joint and is therefore difficult to obtain without complex FEA/experimentation. We can, however, rapidly obtain a lower bound upon the required energy by calculating the energy required to melt the solder,  $Q_{solder}$ . This may be estimated via (8). The results provide insight into what is required to reduce the lower bound. For example a reduction in the solder mass leads to a proportional reduction in energy. We also desire to select a solder that exhibits a low melting temperature, as well as low specific heat and low latent heat of fusion.

$$Q_{solder} = (mc\Delta T + mL_f)_{solder} \quad (8)$$

For Squishbot1 we chose 60/40 solder as our starting point because it is widely available and its properties are well-known. This solder has a composition that is close to the eutectic composition of lead-tin solders (63% tin and 37% solder). This yields one of the lowest melting points for pure lead-tin solders, 190°C. Using (8), and the thermal properties of 60/40 solder, we estimate that melting 0.5 grams of this solder requires 34 Joules. Given the heater power,  $P$ , and the total melt energy,  $Q_t$ , it is possible to estimate melting time,  $t$ , via the relation in (9).

$$P = t \cdot Q_{solder} \quad (9)$$

Power limitations made it necessary to limit melting power to 0.7W, which yields an unlocking time of at least 40 seconds. This made clear the need to alloy the solder and thereby tune melting temperature for better performance. The alloying process and other factors that influenced final solder selection/design will be discussed in Section IV.

The time calculation in (9) assumes that 100% of the heat is used to melt the solder. In practice, heat is lost to the adjacent joint materials, therefore this estimate is a lower bound on unlock time. A more detailed model would consider the energy required to raise the temperature of each component. Transient temperature simulations must be used to determine temperature rise in components with characteristic time scales that are approximately the same as, or larger than, the length of the heat cycle.

The second part of the thermal analysis – cooling time – is more complex given that the heat transfer out of the solder depends upon the temperature of other components during the cooling cycle. We may begin to understand where the heat will travel by comparing the thermal resistances. As there is a low convection coefficient for Squishbot1 the heat transfer rate to the Teflon will be larger than the convection transfer rate. This indicates that the temperature of the Teflon will continue to rise a small amount during the cooling step. To obtain a lower bound of the cooling time we consider (i) the latent heat of fusion of the solder and (ii) the energy that must be lost to decrease the temperature of the solder below melting temperature. The heat of fusion will dominate for small superheating. We may calculate a cooling time for the joint for a given temperature of the Teflon, as shown in (4).

In Squishbot1 the modeling results for lower bounds on melting time indicated the need to use a solder alloy. The thermal circuit modeling results highlighted the need for (i) a high resistance material between the heater and Teflon to reduce heat transfer to that material during heating and (ii) a resistance on the Teflon side of the heater that is lower than the convection resistance to help decrease cooling time. Finally calculating the Biot and characteristic time scales gives an insight into the materials behavior during cooling and heating. Normally we would want to use materials with low characteristic times to reduce cycle time. Given the limited convection area, we obtain a counterintuitive result, it works in our favor that the Teflon does not reach the

melting temperature and this helps reduce cooling time. This type of insight demonstrates the power of first order models, though more accurate modeling is still useful for fine tuning of joint performance.

#### IV. FLUID DESIGN

##### A. Solder Composition

In many designs, we have observed that the mechanism’s components break before the solder joints. This ‘over performance’ is useful as strength may be ‘traded off’ to obtain more favorable thermal properties. There are many alloying elements that may be added to a common lead-tin solder to tune material properties. Table V shows the trends in several key properties of the solder when a few common alloying elements are added [7-9]. Table V portrays general trends that are appropriate as guidelines for 1<sup>st</sup> order design. More details may be found in the table’s references [7-9].

TABLE V TRENDS IN SOLDER PROPERTIES WITH ADDITION OF ALLOYS<sup>+</sup>

Element	Strength	Ease of Soldering	T <sub>Melt</sub>	Creep Strength
Indium	↓	↓	↓	↓
Bismuth	↓	↓	↓	↓
Antimony (<6%)	↑	↓	≈	↑
Silver (<5%)	↑	↑	↑	↑

<sup>+</sup>Symbols indicate whether adding the element to lead-tin solders increases (↑), decreases (↓), or has little effect (≈) on the properties.

For Squishbot1, we focused on Indium and Bismuth as they lower the melting point of the solder. The wettability of pure Indium and Bismuth to Copper is poor; therefore we combined them with 60/40 solder to overcome this limitation. We considered the alloys listed in Table VI.

TABLE VI POSSIBLE ADDITIONS TO LOWER 60/40 MELTING POINT.

Alloy	Composition by %	T <sub>Melt</sub>
Chip Quik	10-30 In, 10-30 Pb, 7-13 Sn	58°C
Bismuth Alloy	52.5 Bi, 32 Pb, 15.5 Sn	95°C
Indalloy 117	44.7 Bi, 22.6 Pb, 8.3 Sn, 5.3 Cd	47°C

##### B. Unlocking Temperatures

When the materials in Table VI are combined with 60/40 solder, the solder’s melting temperature decreases. The unlocking temperature of the three custom mixes was determined experimentally. A shear joint was created by nesting one copper rod within a copper cylinder and then soldering the two together. The joint was heated until it unlocked under its own weight. The average radial gap between rods was 175 microns and the axial overlap was 1.27cm. Two k-type thermocouples were used to measure the temperatures on the (i) outer surface of the joint and (ii) at the heater. A Mitutoyo 543 indicator was used to detect joint motions that signaled an unlocking event.

Fig. 4 contains the temperatures of the heater and the outer thermocouple when release of the inner joint was observed. These results provide rapid, useful estimates of melting temperature for first order performance models.

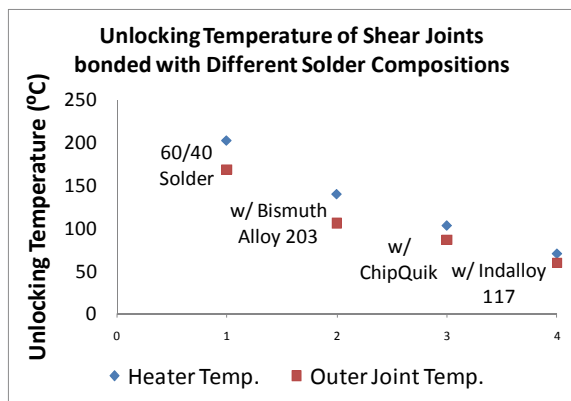


Fig.4. Measured unlocking temperatures with different alloying elements

### C. Importance of Cycling

A thermally activated joint must be able to withstand multiple cycles before de-wetting, delamination or crack formation. These types of failures are not deterministic and therefore investigated via experimental thermal cycling. For example, Indium base solders may fail because of phase segregation when there is an extreme and unidirectional thermal gradient across the joint. Bismuth may become brittle if it is solidified rapidly [7]. From experience, it is known that the best means of ascertaining the risk associated with these failures is to conduct failure tests. As part of the Squishbot1 development, the joints were cycled 20+ times to ensure suitable lifetime. During this testing, practical issues with respect to other failure modes were discovered. For example we found wiping of the solder off the locking surfaces when the joint slid into/out of contact. We found that smaller gaps and blunting modifications to the ‘wiping’ edges of the joint removed this failure mode. It is highly recommended that designers plan to conduct cycling tests early on in the prototyping phase to discover changes that preserve expected performance or yield improvements in performance.

### D. Final Solder Selection

We elected to alloy the base solder with “Chip Quik” as this lowered the melting temperature to a point that was easily achieved with available heaters. Chip Quick is also not toxic, unlike “Indalloy 117” which contains Cadmium.

## V. RESISTIVE HEATERS

Resistive heaters are widely available in varied geometries and capabilities. They are heated via Joule heating that is induced by running a current through an internal wire. The link between heat generation and current is therefore easily known and the heater’s temperature is easily set via current control. Cartridge heaters are too large to use in our application, however small strain gages are well-suited for use as miniature heaters. We used Vishay 062AK EA series strain gages with 120 Ohm resistance. They have a footprint of 1.6x1.6 mm<sup>2</sup>. At each joint, we placed two in parallel to reduce the total resistance to 60 Ohms and to enable us to heat the joint on both sides. These

heaters were capable of delivering 0.7 Watts of power into each joint.

## VI. COMMENTS ON THE NEED FOR SENSING

Temperature sensors can reduce the cycle time by ensuring that the solder is heated to just above the melting point, thereby reducing the time/energy required to cycle the joint. Currently Squishbot1 is equipped with thermistors; however we are working to integrate polymer-based piezoresistors and MEMS piezoresistors that gather thermal (know if the PCM is solid or liquid) and strain information (robot motion and displacement) within the robot.

## VII. SQUISHBOT’S PERFORMANCE CHARACTERISTICS

Squishbot1 was able to locomote along its axis, steer left and right, and lift its front while using one actuator and 3 solder-activated joints. The robot was able to crawl at 17.5 mm/s and steer at ~37 degrees/step as shown in Fig. 5. Post optimization, joints require 15s cycle time to reconfigure.

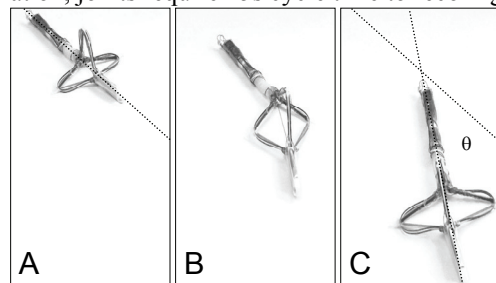


Fig.5. Squishbot1 executing a turn. In A, the joints are configured in an axial crawling state. The joint lock/unlock states are reconfigured to a turning state between A and B, and then the robot turns between B and C.

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