Reconfigurable Robot Components Based on Liquid Metal
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Abstract
This paper presents initial results of a project to develop reconfigurable robots. Amongst other elements, all robotic devices incorporate a mechanical structure and actuators to move the structure and to cause it to act upon its environment. Actuators and their associated sensors and power electronics are expensive components and it would normally be important to minimise the number used. There are a number of situations where a robotic mechanism could benefit from additional articulations such as during initial deployment where a robot is unpacked from a compact storage configuration, or while negotiating confined places where a robot is reconfigured to fit through a narrow gap. In these cases an articulation is required that will only be adjusted very infrequently. This paper proposes the use of phase change in a low melting point metal alloy as a means of selectively reconfiguring a robot structure and even providing a degree of self-repair. The background to this project is described and results of initial experiments involving a reconfigurable robot leg joint are presented.

1 Introduction
There is interest in constructing robotic system that can radically alter their shape. Such robots could be stored very compactly and extend to assume their functional shape when required. This could be likened to a moth emerging from its chrysalis. The emergent moth expands its body and deploys its wings [Wigglesworth, 1967]. When negotiating a cluttered environment such as damaged buildings, rock falls, etc. the exploration range of the robot could be increased if it could reconfigure to squeeze through narrow gaps and the return to its original shape on the other side of the obstacle. It could also be envisaged that the robot could reconfigure to change its means of locomotion to match its environment. Such a robot could conceivably switch between legged, rolling and serpentine locomotion. This more radical restructuring of the robot could be likened to metamorphosis of insects that occurs between the lava and adult stages.

The vast majority of work in this area has concentrated on modular reconfigurable robots. One of the first examples of this kind of system is the Dynamically Reconfigurable Robotic System described by Fukuda and Nakagawa [1988]. The system comprised a number of equal sized units of a small number of different types. Some units were mobile and could move themselves and other units around. Units could autonomously dock and undock with each other. Since then a number of other projects have explored modular reconfigurable robots. One of the most ambitious projects involves the development of 'programmable matter' [Glodstein et al. 2005]. The aim is to form structures, including robots, from miniature homogeneous elements that integrate computing, sensing, actuation and locomotion. An important capability of the elements (called claytronic atoms or catoms) is their ability of stick together and to dynamically reconfigure their mutual position. Recently, articles in the IEEE Robotics & Automation Magazine have reviewed progress in this area [Yim et al. 2007, Murata and Kurokawa, 2007].

In this project the aim is to implement robots with a degree of reconfigurability but without the modular concept. The inspiration for the project is similar to the metamorphic robot described by Nakai et al. [2002]. In this project the limbs of a robot were made of low melting point alloy and were capable of being melted and reshaped in order to perform different tasks. In the project reported in this paper the aim is to reduce the energy required to modify the limb configuration and to investigate a range of methods for actuating the reconfigurable joints.

Section 2 of this paper proposes techniques for constructing and actuation of reconfigurable joints based on low melting point alloy. A prototype reconfigurable leg joint is introduced in Section 3 and results of preliminary experiments are presented Section 4. Conclusions and proposal for further work are given in Section 5.

2 Operating Principles
In principle it is possible to construct extended structures out of low melting point alloy and to mould them to different shapes while in the liquid phase. The metamorphic robot legs reported by Nakai, et al. [ 2002] are constructed largely of low melting point alloy in a flexible elastomer sheath. The large surface area of the legs increases the power requirements to melt the alloy and makes it difficult to accurately reshape the legs. In
this project it was decided position relatively small quantities of the alloy within reconfigurable prismatic or rotary joints.

2.1 Prismatic and rotary joints
The articulations that will provide the ability for a robot to reconfigure will be either prismatic or rotary. Both will contain a quantity of low melting point alloy that will lock the joint when it is solid. When the alloy melts the joint will unlock and able to move. Figure 1a shows a cross-section view of a reconfigurable prismatic joint. When the low melting point alloy is solid it locks the two parts of the joint (parts A and B) together. The keying structure ensures that part A is firmly held. When the alloy melts the square cross-section rod A is free to slide with respect to B (Figure 1b).

![Figure 1. Concept for a reconfigurable prismatic joint.](image1)

A reconfigurable rotary joint can be designed using a similar principle. As illustrated in Figure 2, solidified alloy prevents circular shaft A rotating with respect to B. The keying structures help to prevent rotation. When the alloy melts the shaft is free to rotate.

![Figure 2. Concept for a reconfigurable rotational joint.](image2)

In both cases the low melting point alloy acts as a mechanism for locking and unlocking the joint. However, as so far described there is no means of actuating the joint so that it can be moved to a desired position/orientation when unlocked. The next section considers methods of providing this control over the position/orientation of the joint.

2.2 Actuation
The low melting point alloy incorporated into a reconfigurable joint provides a means of selectively releasing and locking the joint. An external force must be applied in order to change the position or orientation of the joint. A number of techniques for actuating the joint have been identified and these are described below:

2.2.1 Gravity
The mass of material on the distal side of a reconfigurable joint can provide a force to rotate the joint when the alloy melts. In Figure 3, releasing the joint allows the right-hand link to rotate until it meets the ground or another part of the robot structure (Figure 3b). Providing a mechanical stop helps to define the final configuration of the joint. By choosing the relative positions of the joint and the mechanical stop the final angle of the joint can be controlled.

![Figure 3. Using gravity to reposition a reconfigurable rotational joint.](image3)

2.2.2 Contact with an external object
If the robot can be manoeuvred in such a way as to press the distal part of a reconfigurable structure against an external object then this action can be used to alter the angle or position of the joint (Figure 4).

![Figure 4. Pressure from an external object rotates the joint to the desired angle.](image4)
By controlling the movement of the robot the final angle of the joint can be adjusted before the alloy is allowed to cool and lock the joint.

2.2.3 Internal spring
A displaced spring can provide the force or torque required to actuate a reconfigurable joint. While solid the low melting point alloy prevents the spring from moving the joint. However, when melted the joint is free to move until it hits a mechanical stop that establishes the actuated state of the joint. This form of actuation is illustrated for a rotary joint in Figure 5.

![Diagram of internal spring actuation](image1.png)

Figure 5. Heating unlocks the reconfigurable joint and allows the spring to rotate the joint until further rotation is prevented by the mechanical stop.

2.2.4 Out of range motion of an actuator
All robotic devices will contain actuators. If the actuator has a limited range of movement in normal operation then movement outside of this range can be used to position a reconfigurable joint. In Figure 6 the servomotor has a normal range of rotation. To alter the reconfigurable joint the alloy in the joint is melted and then the servomotor rotates beyond its normal range of operation in order to reposition the joint (see Figure 6).

![Diagram of out of range actuation](image2.png)

Figure 6. After unlocking the reconfigurable joint, rotating the servo motor outside its normal working range repositions the joint.

2.2.5 Separate actuator
If other forms of actuation are not available then a single additional actuator could be employed to reconfigure a number of joints. One possible method of actuating multiple reconfigurable joints is by the use of a rocker arm mechanism. As illustrated in Figure 7, a single linear actuator pulls a tendon connected to a rocker arm. This mechanism equalises force transmitted to the links connected to A and B. Provided at least one of the reconfigurable joints is heated the linear actuator will be able to change its/their configuration.

![Diagram of separate actuation](image3.png)

Figure 7. Actuating multiple reconfigurable joints using a single servo motor.
As presented here the actuation has been unidirectional and associated with revolute joints. All of the actuation techniques can be readily modified for use with prismatic joints also. In addition, bi-directional actuation can be achieved by using a combination of techniques. For instance, the prototype leg joint described in the following section uses gravity to flex the joint and pressure against an external object to achieve extension.

3  Reconfigurable leg joint

As a proof of concept it was decided to implement a reconfigurable knee joint for a robot leg. The angle of the joint was to be normally held constant but capable of being altered to another fixed value. A cross-section view of the joint is shown in Figure 8. The proximal and distal segments of the leg are made from carbon fibre rod and the actual joint is machined out of brass. An internal cavity is filled with MCP61 a lead and cadmium free low melting point alloy from Mining and Chemical Products Ltd. in the UK. The melting point of this alloy is 62°C (158°F). Other material properties provided by the supplier include: density 8.10 g/ml, Brinell hardness 4.5 to 5.1, Specific heat (solid 25°C) 0.196 J/g°C, and Latent heat of fusion 26.9 J/g [Mining and Chemical Products Ltd., 2004]. Heat to melt the alloy is provided by a 1W surface mount resistor soldered to the brass knee joint. This structure was constructed from brass to provide an enclosure for the low melting point alloy that would provide a path with good thermal conductivity between the alloy and the external heater and temperature sensor. The temperature of the joint is monitored by an LM135 temperature sensor IC and joint angle is measured using a magnetic sensor. The graph in Figure 9 shows the change in leg joint temperature as the joint is heated from a room temperature of about 25°C to the alloy melting point and then allowed to cool down again. Note that the latent heat of fusion slows down the rate of temperature change about the point where the alloy undergoes phase change.

During these experiments the leg was actuated by an HS-85MG radio control servo. Overall control of the system was performed by an Atmel AVR microcontroller system programmed in assembler.

3.1  Alloy phase change

Control of the leg joint temperature was managed by a timer interrupt routine that interrupted every 20ms. The same routine was used to time the start of the pulses controlling the HS-85MG radio control servo (pulse width was determined by a second timer interrupt). A flag bit indicated whether heating was required. If the flag was set then power was removed from the leg joint heater. When the heat flag was set an analogue to digital conversion was initiated to convert the output voltage of the LM135 temperature sensor. The melting point of the alloy, 62°C corresponds to a sensor voltage of 3.35V (10mV per degree starting with a voltage of 0V at 0°C, (273.16+62)*0.01=3.35 ). Therefore, for a 10 bit A/D converter with a 5V reference the melting threshold value was 0x294. If the temperature was below this threshold value the heater was turned on for the next 20ms and turned off if the temperature was above.

The graph in Figure 9 shows the change in leg joint temperature as the joint is heated from a room temperature of about 25°C to the alloy melting point and then allowed to cool down again. Note that the latent heat of fusion slows down the rate of temperature change about the point where the alloy undergoes phase change.

Commands were sent to the controlling microcontroller to request changes in the angle of the leg joint. In order to monitor the actual leg joint angle a simple magnetic sensor was implemented.
3.2 Monitoring joint angle

A low friction leg joint angle sensor was required so that it would not interfere with the process of reconfiguring the leg joint.

For this application a magnetic sensor was implemented consisting of a neodymium disk magnet (3mm diameter and 2mm long) on the distal part of the joint and an SS495 Hall effect sensor on the proximal part (Figure 8). As shown in Figure 10 the magnetic field sensed by the SS495 sensor depended on the joint angle although the relationship is non-linear. It is envisaged that an improved implementation of the magnetic sensor can greatly enhance the operating range of this sensor.

4 Experimental results

In order to test the reconfigurable leg joint a number of commands were implemented that could be transmitted to the Atmel AVR microcontroller via an RS232 serial connection. These commands were:

a – reset the leg joint to angle A
b – reset the leg joint to angle B
c – allow the leg joint to cool down
d – rotate the leg down
h – heat the leg joint
s – read the joint angle and temperature sensors
u – rotate the leg up

Commands ‘a’ and ‘b’ requested a change in leg joint angle. In Figure 11 the knee joint is initially at angle ‘A’ and is command to reconfigure to angle ‘B’. The leg joint was heated until the alloy melted. At this point the distal link of the leg rotated under its own weight until its tip contacted the ground (Figure 12). The servo was then commanded to rotate the proximal link either clockwise or anti-clockwise until the knee joint achieved the required angle (Figure 13). The heater was then switched off and the joint allowed to cool until its temperature fell below 55°C. At this point the alloy solidified and the leg could be raised and the knee joint maintained its new angle (Figure 14).

Figure 11 To increase the knee joint angle, the leg is held above the table surface and knee joint heated.

Figure 12 When the alloy melts, gravity flexes the knee joint until the end of the distal segment touches the table.

Figure 13 To reduce the knee joint angle the alloy is melted and the leg pressed down to extend the knee joint.

Figure 14 After the alloy has solidified the knee joint is held at its new angle.
4.1 Joint strength and self-repair

With the current design of leg joint, in its locked state, the joint can withstand applied forces without significant permanent deflection up to the point where permanent damage occurs to the brass body of the joint. It is envisaged that by redesign of the joint initial failure could be made to occur in the low melting point alloy. By strategically positioning this kind of deformable joint throughout a robot structure damaging forces and deflections could be absorbed. Later, the affected joints could be returned to their original configuration by melting the alloy and repositioning the joint.

5 Conclusions

The ability to radically alter body shape or metamorphose is a characteristic of many creatures including insects. Not only does this process permit growth of the creature, it also allows functional reconfiguration. For instance larvae are essentially feeding machines whereas the mission of the adult is reproduction. The form of larval stage and adult are specialised for their specific mission.

In a similar manner a biomimetic robot could metamorphose to unfold from a compact storage configuration to its working configuration. Shape changing could also be used to change the function of appendages perhaps from walking to manipulation.

In order to achieve this kind of metamorphosis the robot structure must articulate. Some researchers position a full actuator system at each articulation point. This greatly increases the size, complexity and cost of the robot. In this project the use of reconfigurable joints has been proposed based on the use of low melting point alloy. Techniques of constructing such joints have been discussed along with methods of actuation. As an example, a prototype knee joint has been built and tested. This demonstrates the feasibility of this approach.

The next stage of this project will be to build a complete robot that can change its configuration using low melting point alloy joints. The prototype knee joint uses two of the five actuation techniques suggested in Section 2 and it is intended that the complete robot will act as a test-bed for other actuation techniques.

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References


