

Liquid Metal Motor Design

Literature Review

Introduction & Background

Soft robots are the next frontier in robotics.

Traditional robots rely on rigid materials for actuation, which can be easily and precisely predictable. However, these benefits come at the cost of flexibility and human friendliness [1].

Over the two decades, research has turned to the possibility of robots and actuators made with mechanically compliant materials. The promise of soft robots is that they would be adaptable in unpredictable conditions and comfortable for wearable use [2].

Research in soft robots have mostly focused on chemical, pressure-based (pneumatic or hydraulic) and electroactive elastomer actuation [1], which [3], [4] and [5] are typical of respectively. Electromagnetic actuation that most traditional robots rely on has been relatively overlooked and gained interest only over the past 4 years. Jin et al. published [6] in 2015 introducing an voice coil actuator that is effective under large deformations – one of the first studies that explored electromagnetic actuation in soft designs.

Highly Deformable Materials

Soft robots are made possible by the increasing availability of highly compliant yet tough materials. These materials tend to fit in the categories of rubbers, elastomers, polymers and polymer composites. Silicones, a type of synthetic polymer, are known to be the most suitable materials available for most soft robot construction. This is due to silicones' low elastic moduli, high resilience and toughness, ability to actuate over millions of cycles and rich body of literature [7]. Research for this literature review found no published soft robot research designs that did not involve silicones in some way. Some designs used a combination of soft and hard components [8] or silicone composites [9].

Gallium-Indium Eutectic Alloy

A large challenge that prevented the use of electromagnetic actuation in soft designs was the lack of good conductors that maintain their properties under large deformations. Older approaches like conductive silicone rubber have hugely varying electrical properties under deformation [10].

Gallium-Indium Eutectic Alloys (eGaIn) have emerged as a potential solution. eGaIn is a family of alloys that contain gallium, indium and sometimes tin and other metals. One eGaIn formula is sometimes sold under the trade name Galinstan. A typical tin containing eutectic alloy such as Galinstan can have 68.5% Ga, 21.5% In and 10% Sn [11], while a typical alloy without tin can have 75% Ga and 25% In [12]. Galinstan is reported to melt at as low as -19°C [13], while

others report that 75% Ga 25% In eGaIn melts at 15.5 °C [12]. In either case, under most lab conditions eGaIn should be liquid.

Using a liquid metal as a conductor means the surrounding body can undergo large deformations without large changes to material properties of the conductor, as the liquid will conform to the shape of the deformed cavity. Liquid metals also do not undergo strain hardening or fatigue. This means liquid metals can be better used in soft robots which are expected to undergo large and repeated deformations than solid metals.

eGaIn is also advantageous among other liquid metals in that it has low toxicity [12], compared to mercury which is highly toxic. eGaIn is also stable in atmospheric conditions, compared to sodium-potassium alloy which is pyrophoric [14], and has low vapour pressure. eGaIn does however form an oxide layer on contact with oxygen which hinders its fluid properties [11].

Galinstan is reported to have electrical resistance of $0.435 \times 10^{-6} \Omega m$ [13], which is about 2 orders of magnitude less than pure copper, commonly used as a solid conductor. This means that while Galinstan is a good conductor, circuits employing it will dissipate more heat and require more power input than equivalent solid circuits employing more conductive materials.

Electromagnetic Actuation using Liquid Metal

There have only been a few examples that incorporated liquid metal into their electromagnetic actuator designs. All of them used some variety of eGaIn as their metal conductor and silicone to build the soft body.

Jin et al. pioneered this field with the 2015 paper [6], which described the design, manufacture and testing of a stretchable loudspeaker. The body of the loudspeaker was silicone while the voice coil was a spiral channel carved in the body and injected with eGaIn. Guo et al. extended [6] with [15] describing the design and characterisation of mechanical actuators such as pincers and a swimming fish robot. Both studies produced Lorentz force actuators using eGaIn voice coils and permanent neodymium magnets. Guo et al. used an airbrush spray gun to apply their liquid metal instead of the syringe and Scotch tape combination Jin et al. used. It is interesting that Guo et al. did not report any problems with oxidation of eGaIn, or any steps taken to limit oxygen contact, given they used an airbrush to apply the liquid metal which would mix the metal with air as it was being used.

Do et al. takes a different approach to Jin and Guo in [16]. Instead of using microchannels in silicone Do et al. injected eGaIn into silicone tubes which are then coiled. This study also included two example applications of their techniques, Soft Vibrotactile Actuators (SVAs) and a Miniature Soft Electromagnetic Gripper (SEMG).

In the same study Do et al. also described the creation of a soft permanent magnet through mixing crushed neodymium magnet powder with liquid silicone and aligning poles while the silicone cures by placing the mould on a permanent magnet.

No study so far has explored creating soft counterparts to traditional electromagnetic motors, linear or rotational.

Traditional Electromagnetic Motor Design

Design and characterisation of stiff electromagnetic motors is a field that is comparatively more mature, with a wealth of books and studies written on the subject such as [17].

Linear voice coil motors are a type of motor that are relatively easy to construct and control.

Linear voice coil motors produce movement via Lorentz force produce by interaction of a current carrying coil on a magnetic field produced by a permanent magnet.

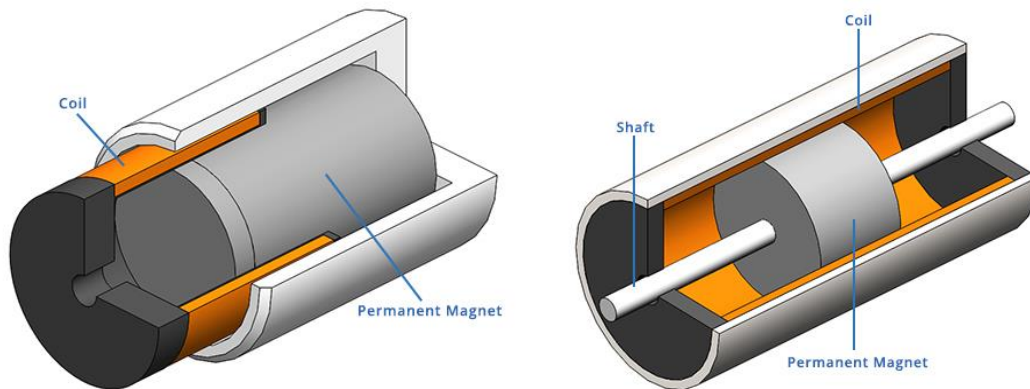


Figure 1: Two main configurations of linear voice coil motors. Reproduced from [18].

As shown in Figure 2, there are two main configurations of linear voice coil motors: moving coil (left) and moving magnet (right)

As skeletal muscle can be approximated as a linear actuator, linear voice coil motors are also valuable for robot designs that seek to mimic biological function. A detailed guide on analytical modelling, optimisation and design strategies of linear direct-action motors by Ruddy and Hunter [19] will be valuable especially for muscle-like linear motor design.

Liquid Metal Electromagnetic Motor

This literature review affirms the thus far overlooked opportunity to design, build and characterise an electromagnetic motor using liquid metal.

Such an electromagnetic motor will benefit from past research on soft voice coil actuation in [6], [15] and [16], especially their manufacturing methods.

This approach to soft actuation also allows the transfer of research on stiff actuators such as [19], rather than reinventing the wheel by designing other actuator modalities.

Statement of Research Intent

Motivation/Purpose

To design, build and characterise, using liquid metal conductors, an electromagnetic motor that is effective under large deformation and capable of driving a fluid pump.

Aims and Specific Milestones

The aim by the end of this project is to have a motor that is

- Effective under large deformations of $>50\%$,
- Outputs enough power to demonstrate drive of a fluid pump,
- Dissipates heat well enough while driving the fluid pump that it does not fail due to overheating,
- Well characterised in terms of efficiency and time response under undeformed and deformed conditions.

Iteration

Being a design project there will need to be iteration. Each cycle of design iteration will be viewed as a separate milestone.

Design

The body and coil of the motor will need to be designed each iteration, and each design consists of a milestone.

Interface with pump and interface with power supply should only need to be designed once, and completion of these designs are a milestone.

Build and Assemble

Successful strategies to mould silicone motor bodies and apply liquid metal to a silicone motor body are milestones.

A functional assembly with a fluid pump is also a milestone.

Characterise

Once all else is complete, characterisation of motor properties and characterisation of motor-pump system properties are milestones.

Method

It is unclear at this stage which methods will feasibly achieve the Aims. Therefore, this section will be a discussion of approaches and associated methods that will be evaluated because they appear at present promising or interesting to explore.

Linear Voice Coil Motor with Silicone Tube Wiring

A linear DC direct-drive voice coil motor will be the main avenue of exploration.

The design process will start with a stiff analogue design, optimised using methods outlined in [19] using values associated with eGaIn.

The design will be iterated to include an interface to a specific liquid pump design, the other half of this pair project.

The stiff design is then tested so it meets the goals set out in the Aims. If it does not meet those goals the design is iterated.

After the stiff analogue design is complete, manufactured and tested, another device is made where the solid wires are substituted with silicone tubes of equal outer diameter where the inside is filled with eGaIn. This step has the potential to be practically challenging. The stiff casing will also be substituted with silicone tubing.

The second, partially stiff design will then be tested against the Aims and iterated.

Finally the magnetic core will be replaced with a soft magnet as presented in [16]. This step necessitates silicone casting, which can also be practically challenging and will need to be trialled and refined.

The final design is tested and iterated.

Brushless Rotational Motor with Reinforced Rotor

Another interesting idea would be the use of a fibre reinforced rotor in a soft brushless rotational motor. This is not a priority however and will only be explored if there is time.

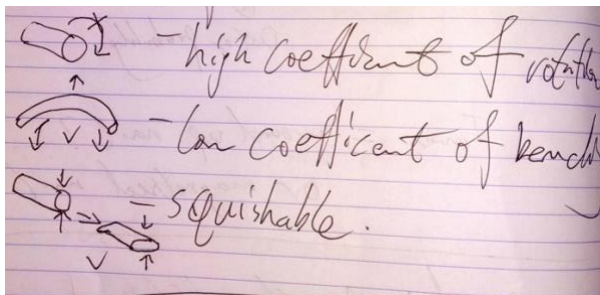


Figure 3: Reinforcement method for rotor

Ideally, the rotor will have a high torsional stiffness but maintain similar compression, tension and bending stiffnesses as the silicone on its own.

This approach will follow much of the same method as the Linear Motor approach, with the exception of the rotor requiring reinforced design and silicone casting with fibre reinforcements.

The permanent magnet components will be made soft using the method in [16].

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