Introduction

In the recent decades, there has been a wave of technological progress due to the advancements in miniaturisation. This trend to create smaller and more efficient devices has led to giant leaps in technological advancement. This era of miniaturisation, often referred to as the Second Industrial Revolution, was sparked by the creation of the integrated circuit. The exponential scaling and miniaturisation of silicon transistors has led to computers, filling entire rooms, being transformed into handheld devices that fit in one's pockets. This trend has allowed electronics to have faster performance, lower power consumption and be cheaper than its predecessor. This translates to market share as well as miniaturisation has given a competitive edge to technological and commercial products over its competitors. This age of miniaturisation has not been restricted to electronics but has also impact mechanical and optical devices. Motors, sensors and other such devices have all gone through the same trend in reduce footprint and increase performances resulting in a market where miniature actuators and sensors are readily available for relatively low prices.

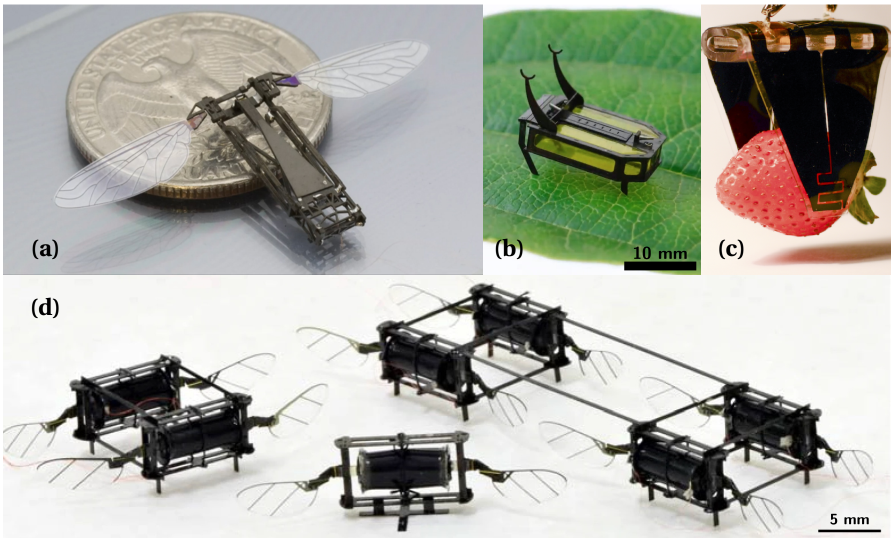

Figure 1: Miniature actuators powered by Smart Materials. (a) A piezo-powered flapping insect robot by [**?**] (b) An untethered shape memory alloy- powered beetle robot powered by [**?**] (c) A soft gripper based on electrostatic actuation by [**?**] (d) A dielectric elastomer actuator-based flying micro-robot by [**?**].

The basic component of any robotic system is the actuator which is responsible for moving and controlling the system. The principle behind creating miniature robotics systems, thus, consists of downsizing actuators. The design and sizing criteria for actuators can not be necessarily applied from the macro scale when downsizing. However, the primary agent for the miniaturization of actuators has been the proliferation of Smart Materials. These materials, often referred to as artificial muscles, are able to provide some form of work as a response to a certain stimulus such as stress, an electric or magnetic field. The reactive nature of these materials allows them to be used as actuators or sensors in creating compact and integrated actuators. These materials can be integrated and tailored to fit within a certain use case based on the physical requirements of the application. These applications can range from micro-grippers, biomimetic robots to crawling robots as shown in figure fig. 1.

The choice of smart material depends on a range of parameters notably the activation stimulus, the time response, and its work density. When considering miniaturisation and creating actuators for compact and lightweight systems, the work density is often used as the leading parameter in choosing the smart material. As shown in fig. 2, among most smart materials, the material, that presents with the highest work density and is, thus, the primary candidate for miniature actuators, is the Shape Memory Alloy (SMA). These alloys, often composed on Nickel and Titanium, is a brand of smart material that reacts to temperature. Variants of these alloys that react to a magnetic field are also present. But the thermoelastic variant of the shape memory alloys are more widely used and can be obtained in different shapes and sizes. There are different varieties of the thermally activated SMAs but the alloy that is the most widely available is the Nickel-Titanium alloy, often known as NiTiNOL. The properties of the material can be changed by modifying the atomic percentages of the alloy or by doping the alloy with other metals.

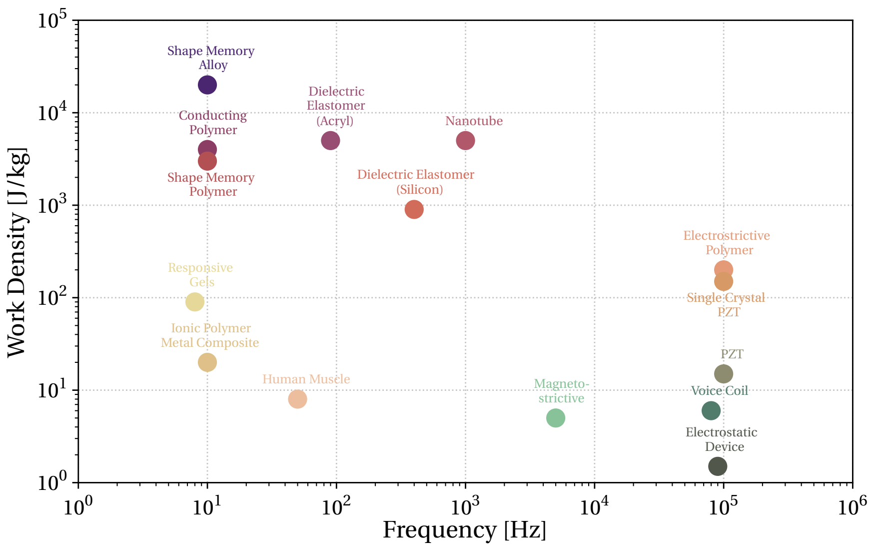

Figure 2: Comparison of different smart materials based on their work density and their time response (from [**?**])

Design Considerations

As stated, due to the high work density of the material, SMAs are generally used in applications where low weight and a compact footprint is required. However, as observed in the fig. 2, the requirement to heat the active element, results in SMAs having relatively low time responses. Cooling, when executed passively, results in extended waiting time before the repeated actuation of the SMA actuator. This results in the material being primarily used in systems that do not require high bandwidths. However, when downsizing the actuator, the volume-to-surface area ratio increases, resulting in faster cooling times. Thus, SMAs are often used in applications such as micro-actuators and grippers. Furthermore, due to the bio-compatible nature of the alloy, they have been used in biomedical applications for smart catheters and minimally invasive surgery robots. Recently, there has also been a surge of work done where SMAs are used in create autonomous, walking robots and self-reconfigurable robots. All of these applications require actuators that have high work outputs while remaining light and compact. Thus, SMAs have become an ideal candidate for these use cases.

As the commonality in these application is the limitations in space and weight, the design specification of the required actuators often take into account the final weight and size of the system. These SMAs are able to return to revert back to their original shape when heated. This behaviour, often referred to as the Shape Memory Effect (SME), is exploited to create these actuators. After some deformation alters its shape, this behaviour simply alloys the active element to perform some work when heated. This, these SMA actuators requires various transmission stages and sensors when implemented for a certain application. Thus, as SMA actuator are required to output more work while staying compact, the implementation of such actuators take into consideration how the final work density is affected by the additional of these external components. Due to the strengths of the SMA with regards to its work density, the main design consideration taken into account is the design of these external components and the minimisation of the extra weight and volume added to the overall actuator.

SMA actuators when implementing into compact system result in noiseless operation and their high force-to-weight ratio and muscle-like actuation make them suitable for soft robotics and biomimetic/bio-inspired robots. However, as previously mentioned, they have small bandwidth and low operating frequencies, primarily due to their large cooling times. As explored in the work by [**?**], this poses the principle challenge when designing SMA actuators. Furthermore, the force output of SMAs are relatively low and this is, often, counteracted by using bundles of SMA wires. However, by increasing the volume of SMAs also increase the cooling time and further decreases the operating frequency, creating a trade-off between the two parameters. Finally, the shape memory effect and the thermo-mechanical behaviour of the SMA is highly non-linear and complex. This makes the actuators difficult to control and requires special methods and sensors to control them.

When combined, these factors make the design of SMA actuators and their integration into complex applications difficult and cumbersome. Due to the various trade-offs that exists when designing the active element, accurate sizing of the actuator is critical to optimize the final footprint and weight of the system. When volume and weight constraints are present, a holistic design approach is required where the entire system and the actuator is considered in the design process. Due to the complex nature of the smart material and the sometimes complex nature of the application, the sizing of the active element becomes difficult and results in a system that is not fully optimised or is oversized. These concessions in the design process results in a degradation of the overall work density of the SMA actuator.

Thesis Statement

Thesis outline and Contributions