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Smart Artificial Muscles

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Abstract

Dielectric Elastomer Actuator(s) (DEA) are compliant polymers that can be made to deform upon the application of an electrical stimulus. They have long been referred to as ‘artificial muscles’ because like muscle they are inherently soft and lightweight, yet they are capable of outperforming muscle in terms of active strain, speed, pressure, and energy density. However, muscle is more than simply a soft actuator; it is a smart structure. Muscle is incredibly successful because it provides position feedback, has a tuneable stiffness, and feels pain. Mimicking these core functions using DEA requires self-sensing. By using the DEA as an actuator and a sensor simultaneously, a true engineering analogue to muscle can be created.

No example of self-sensing from the prior art is capable of measuring all three of the key electrical parameters of a DEA: electrode resistance, capacitance, and the leakage current through the dielectric membrane. A majority of the techniques employed to perform self-sensing have been developed without thought for their practical implementation, and require bulky, high power electrical hardware that is at odds with the compact, low power form factor of DEA. Furthermore, there are no examples from the prior art of self-sensing being used to control the output of a DEA independently of external mechanical influences. This thesis seeks to address these shortfalls.

In this thesis the first DEA self-sensing system to enable all three of the key electrical parameters to be estimated simultaneously and in real-time whilst the DEA is being actuated is described. Targeted at portable applications such as fully functional, life-like prosthetic devices, the system is readily compatible with microcontroller architectures, specifically accounts for the capabilities and limitations of low power driving electronics as well as non-linear and non-ideal behaviours exhibited by DEA, and generates feedback data using an algorithm that is inherently robust to noise. This self-sensing system has been experimentally validated, and has been used to demonstrate control of position and stiffness. It has also been used to establish a foundation for monitoring the health of the DEA. Thus, a true artificial muscle has been developed.
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Introduction

Robotic devices are playing an ever increasing role in today’s society. For this trend to continue it is no longer sufficient to assume robots are operating in a tightly controlled workspace; special consideration must be given to how the robot interacts with its environment. In this chapter the limitations of conventional robotic technology and the potential benefits of compliance in robots will be discussed. Muscle, ubiquitous in the animal kingdom, provides an excellent example of the success of active compliant structures. The structure and control of muscle will be reviewed and the functions that would be beneficial to implement in robotic devices will be identified. Electro-active polymers (EAP), and specifically a type of EAP known as Dielectric Elastomer Actuator(s) (DEA) offer a promising basis for artificial muscles. A brief overview of DEA will be given, highlighting their potential, and the challenges that must be overcome to realise this potential. This chapter concludes with the research objectives and contributions of this thesis.

1.1. Evolving robotics

Since the introduction of the first industrial robot, Unimate (Figure 1-1), to the assembly line of General Motor’s New Jersey plant in 1961, industrial robotics has become a US$12 billion dollar industry spanning an extensive range of manufacturing operations [1]. The proliferation of robots has been driven by their ability to execute repetitive, menial tasks, often in hazardous working conditions, with precision and reliability. Significant advancements in electronics, actuators, control theory, and the power of computers and embedded systems has since seen robots expand beyond the confines of the factory floor. Increasingly they are becoming part of our everyday lives. However, the same principles that have contributed to their success in an industrial setting, i.e., high gain position control using rigid, stiff components and highly geared
1.1 Evolving robotics

actuators, limit their usefulness when applied to situations where robots and humans must coexist, or where delicate operations are required. For robots to succeed outside of a tightly controlled workspace, heavy unyielding structures present a major safety concern. In particular, inadvertent collisions risk damage not only to the robot and the environment, but also pose a significant danger to humans.

![Unimate, the first industrial robot](image.png)

Figure 1-1: An image of Unimate, the first industrial robot.

Currently robots that operate around humans are safe because they are slow and do not have the ability to exert large forces on their environment (e.g. robots that vacuum floors, clean swimming pools, or are toys for our entertainment). To progress beyond these low power activities however, a departure from the high stiffness paradigm prevalent in industrial robotics is necessary. We can look to nature for inspiration: soft actuators and flexible, lightweight structures are commonplace. Muscle is an incredibly successful, highly versatile actuator that is ubiquitous in the animal kingdom. By controlling stiffness, muscle is capable of adapting on-the-fly to an impressive range of loads and speeds; and in stark contrast to what is seen in industrial robotics, muscle is an inherently soft, elastic structure. Clearly high stiffness is not a pre-requisite for achieving useful actuation. Mimicking the soft nature of muscles by introducing controllable mechanical compliance to actuators generates a number of potential benefits for robotic devices.

1.1.1. The benefits of compliance in robotics

In industrial applications positional accuracy is paramount. Rigid, stiff components and highly geared actuators are well suited to this task. Discrete sensors placed at key locations can be used to determine the position of any point in the kinematic chain with a high degree of accuracy. Furthermore, high stiffness limits the influence of disturbances on the desired output, and
enables the control system to operate at high frequencies without becoming unstable [2]. This paradigm has carried over into many of the non-industrial robots we see today; embedded systems controlling stiff structures actuated by electromagnetic motors are a combination that is well understood (Figure 1-2). However, moving out of the highly structured factory environment into an unstructured environment, especially if this environment is shared by humans, introduces a new set of control objectives beyond simply tracking a position setpoint.

Figure 1-2: (a) A Roomba autonomous vacuum cleaner [3]; (b) a Robosabien robot [4]; and (c) an electromechanical scorpion created with Lego Mindstorms [5].

Devices with high stiffness and large gear reductions have no inherent mechanism for damping vibrations and mechanical shock loads. Small changes in displacement can result in large changes in force, and in an unknown environment this can compromise the stability of a robot or result in damage to the robot or the environment, particularly if it encounters an unexpected object or change in conditions. To a limited degree this can be rectified using force feedback sensors and strain gauges to modify the control input to the actuator, however these sensors provide noisy data and information localised to the sensor position [6]. Furthermore, due to a strain gauge’s own inherently high stiffness it requires a stable contact with the environment [6]. Maintaining steady contact with the environment however requires the actuator to have sufficient power and speed to respond to very small changes in displacement. This in itself is potentially dangerous, and ultimately relies on software to make the device safe, providing no inherent mechanical safeguard [7].

Safety and stability issues in an unstructured environment can be addressed by introducing mechanical compliance to the robotic device. Series Elastic Actuators (SEA) attempt to create a biomimetic muscle-like actuator by introducing an elastic element between a traditional actuator such as an electromagnetic motor and the load upon which it acts (Figure 1-3) [2]. Simple passive elastic elements incorporated into the robot make it more robust to disturbances
by improving shock tolerance and reducing the overall stiffness, thus simplifying the task of controlling force [2]. These elements even provide an energy storage mechanism [2]. In bipedal walking robots for example, compliant joints in the legs greatly improve stability by ensuring the feet do not bounce upon landing and good contact is maintained between the robot’s feet and the ground, particularly when traversing uneven terrain [8, 9]. In manipulation tasks, compliant grippers naturally damp disturbances and inherently adapt to the shape of the object being gripped, making them well suited for manipulating objects that are soft or have an unknown shape or orientation [10].

Active control of the compliance of the device confers further benefits. Passive dynamic walking robots in their simplest form are mechanical legs with freely rotating hip and knee joints and no on-board power supply (e.g. [11]). When placed on a downward sloping ramp, these robots naturally fall into a dynamically stable walking gait; the momentum of the legs determines the orientation of each leg segment. Thus with a small energy input from gravity small losses in the system can be overcome. Strictly controlling joint angles (c.f. Honda’s ASIMO humanoid robot) offers more control, but high gain position control requires large gear reductions that severely limit the backdrivability of the joints. Mimicking the free swinging pendulum action of passive dynamic walkers is therefore not possible. Any movement requires input energy from the actuators, thus energy consumption is high. Active control of the compliance of the leg actuators, i.e., controlling stiffness rather than position, however develops a compromise between control authority and energy consumption. Significant reductions in the input energy required to achieve locomotion can therefore be achieved [8, 9, 11-13].

Figure 1-3: Schematic representation of a Series Elastic Actuator.
1.2. Muscle: nature’s smart actuator

Departing from the high stiffness paradigm of industrial robots leads to new control challenges. Compliant robots cannot be simplified to a series of rigid links connected by revolute joints, thus new control systems and strategies must be developed. We can look to nature for inspiration for this: muscles have evolved into highly versatile, smart actuators capable of adapting to an impressive range of activities. Muscles generate linear motion, exhibit excellent overall actuation performance without excelling in any one area, act as an elastic element with tuneable stiffness, and provide sensory feedback. In this section the significance of these characteristics will be discussed following a brief overview of the basic principles of muscle contraction.

1.2.1. Muscle structure and contraction

The fundamental building block of a muscle is the sarcomere (Figure 1-5) [16]. The interaction of thick myosin and thin actin filaments that run parallel to each other along the length of the sarcomere governs actuation. Known as the “Sliding Filament Theory” [16], when relaxed, the myosin and actin filaments are relatively free to slide past each other, offering little resistance to motion. When stimulated, numerous cross-bridges on the myosin filaments bind with the actin filaments and pivot to pull on the actin filament. After pivoting the myosin cross-bridges release and reach out to bind with another site further along the actin filament, and the cycle repeats. Thus the myosin filaments ratchet along the actin filament, drawing the actin filaments in and causing a contraction of the overall length of the sarcomere.
1.2 Muscle: nature’s smart actuator

Figure 1-5: Schematic diagram of a sarcomere: (a) in a relaxed state; and (b) after contraction.

Sarcomeres are arranged serially in long myofibrils within the muscle. Bunches of myofibrils form muscle fibres, and bunches of muscle fibres form motor units. Muscles are parallel arrangements of many independent motor units bound together and connected to the skeleton by highly elastic tendon tissue. Motor units can vary in size both within a muscle and between different muscles, but each motor unit is effectively a binary element that is either on or off. That is, if a motor unit’s activation threshold is exceeded, all of the sarcomeres within will attempt to contract, otherwise they will remain in the relaxed state where the myosin and actin filaments are free to slide past each other.

Figure 1-6: Basic composition of muscle tissue.

1.2.2. Linear versus rotary motion

From an engineering perspective, rotary motor actuators coupled to wheels or props are undoubtedly one of the most significant developments in human history [17]. The ability to transport heavy loads over long distances at high speeds has made journeys convenient and accessible; journeys that no more than a few hundred years ago were unimaginable. Compare this however with examples of rotary motion in nature: except for the bacterial flagella, it does
not exist [18]. In a review by Labarbera [18], the potential advantages and disadvantages of rotary motion are discussed from an efficiency perspective. On land, wheeled locomotion is considerably more efficient than legged locomotion over hard, flat terrain. This efficiency advantage quickly disappears however when travelling over soft or irregular surfaces such as sand or rocky terrain. Furthermore, the manoeuvrability of wheeled locomotion around or over obstacles, particularly in tight confines or where the obstacle is taller than the radius of the wheel, is severely limited [18]. Underwater, cavitation effects at the tips of a propeller at high angular velocities limit efficiency to the range of 60-80%, whereas oscillating fins can reach as high as 98% [18]. Above ground, the efficiency of propellers can reach as high as 88%, but at low speeds the efficiency of fixed wings drops off dramatically, and at the scale of birds and insects the increased manoeuvrability, ability to hover, and short take-off and landing ability enabled by flapping wings have significantly more utility [18]. In short, there has been little evolutionary pressure to develop rotary mechanisms.

1.2.3. Muscle as a general purpose actuator

Muscle is truly remarkable for its excellent overall performance. The combination of speed, strain, pressure, density, and efficiency that muscle possesses is unmatched by any engineered alternative [19]. Conventional actuator technologies are often capable of outperforming muscle in a specific measure of performance (e.g. speed or pressure), but they typically must be coupled with a secondary mechanism in order to achieve a useful output. Electromagnetic motors for instance are heavy and rigid, and often require significant gear reductions to produce torque and speed in a useful operating range. Piezoelectrics are capable of high active speeds and pressures, but unlike muscle, they are extremely brittle and have very small output strains. Shape memory alloys can produce high pressures and moderate strains, but are slow and susceptible to fatigue failure after repeated cycling. These technologies partially replicate muscle’s function, but not its form. Pneumatic McKibben muscles share the compliant properties of muscle, but as with hydraulic devices, active systems ultimately rely on remote electromagnetic devices to generate the pressure differentials that drive actuation and require valves and plumbing to transport the fluid and transmit pressure.

1.2.4. Muscles as tuneable stiffness elements

Muscle behaves as a variable length, variable stiffness spring [20]. Each motor unit within a muscle effectively has its own adjustable “rest” length. Within the bounds of the maximum and
minimum length they can achieve, if a motor unit’s rest length is greater than its actual length it remains in a highly compliant state and the thick myosin and thin actin filaments are free to slide past each other. When the actual length exceeds the rest length, the motor unit will contract. To generate small forces, the rest length is relatively long and only small motor units are activated. As the rest length decreases, larger motor units are recruited and the force generated grows.

In a highly compliant rest state, muscles offer little resistance to motion. We use this to save energy when we walk by letting our arms and legs behave like pendulums during the swing phase of the gait cycle [21]. Equally important however is the ability of muscle to act in a spring like manner and temporarily store elastic energy. When unstretched and used solely as a contractile actuator, the maximum metabolic efficiency of muscle is approximately 25%, but when walking this figure rises to 40%, and when running can reach as high as 80% [22]. Kinetic and gravitational energy from the pendulum-like action of our arms and legs are stored as elastic energy in the muscle and its tendons during one cycle and released during the next. This store-and-release process reduces the amount of positive work the muscle has to add to the cycle, and gives humans great endurance for long distance running [23]. This elastic mechanism is also essential for movements requiring impulsive forces such as hopping, jumping, or kicking a ball for example [24].

Varying stiffness also enables much greater control of the applied force, particularly in the presence of disturbances. The human hand is unsurpassed in its dexterity and versatility [24-26] and even today its abilities have only just begun to be replicated in the most advanced robotics development projects in the world (e.g. the DEKA Arm from DARPA’s Revolutionizing Prosthetics programme). Thumb, fingers, and palm can be reconfigured to grip objects of virtually any shape or orientation. The pressure applied to an object, controlled by the stiffness of the muscles, can be different for each digit, and this stiffness can be further adapted to provide tuneable damping for the object, improving robustness to disturbances. Furthermore, the dexterity coupled with redundancy in the human hand enables objects to be manipulated and reoriented without the need to move the arm itself.

1.2.5. Muscles as sensors

Muscles provide both position and pain feedback. Specialised cells known as muscle spindles sense the length of the muscle and provide position feedback to the central nervous system [16]. This feedback contributes to proprioception, i.e., the ability to sense limb position, and is
crucial to the coordination of different muscle groups necessary for maintaining correct balance and posture [27, 28]. Indeed in some cases automatic reflex actions are triggered that do not involve conscious thought as a result of this stretch sensitive feedback. A common example is the patellar ‘knee-jerk’ reflex: sudden lengthening of the quadriceps as a result of striking the patellar tendon with a rubber hammer causes the hamstring to relax and the quadriceps to contract, resulting in the familiar kicking motion by the lower leg. Without position feedback we would not know where their arms and legs were unless they were within our field of vision. An impaired sense of proprioception therefore makes it extremely difficult to achieve fine motor control and execute fluid motions.

Muscles also have a role to play in what we perceive as pain; generating signals that warn us of potential tissue damage, or remind us to protect damaged tissue while it heals [29]. Nociceptors within the muscle respond to tissue-threatening stimuli, when the stimulation exceeds a threshold, a signal is generated that we interpret as pain [30]. Importantly, nociceptors become active at stimulation levels below which tissue damage occurs. This signal acts as an early warning system that can help to prevent damage to muscle from occurring. Where damage has occurred, this signal is a reminder to avoid using that particular muscle in order to allow it to heal.

1.3. Artificial muscle actuators for robotic devices

Mimicking the properties of muscle offers a number of potential benefits with regard to efficiency, safety, manoeuvrability, and control for robotic devices. However, replicating the characteristics of muscle using traditional actuation technology typically requires cascading several mechanical and sensing elements together. Distinct actuator, transmission, elastic, and sensing elements contribute to increased mass, complexity and component count. To avoid a trade-off between complexity and function it is necessary to look to entirely new actuation mechanisms to find a single, unified element incorporating these desirable parameters. Before this can be done however, it is necessary to define what makes an artificial muscle.

To replicate muscle’s impressive overall performance, a true artificial muscle would be:

1. **Lightweight and compliant.** Compliance improves safety and enables much greater control of applied forces. It allows a robot to conform to the load or object being driven or manipulated, and provides an inherent mechanism for dampening vibrations and
disturbances by ensuring good, stable contact is maintained between the load and the actuator.

2. **Capable of linear actuation and large strains.** Reciprocating linear mechanisms coupled with inherent elasticity and the ability to store and recycle mechanical energy enable the generation of highly efficient locomotion without the need for complex transmission systems whether swimming, flying, walking, or hopping.

3. **Capable of good energy densities.** The active forces able to be generated are equally important as the scale of the output motion; it is the combination of active force and displacement that enables complex transmission systems to be eliminated.

4. **Able to provide position feedback.** Position feedback enables precise movements to be executed, and provides a mechanism to compensate for non-linear behaviour, changes in plant parameters, and the influence of external disturbances.

5. **Able to vary its stiffness.** Tuneable stiffness enables force and position to be adapted to suit a wide range of applications, minimizing unnecessary negative work and enabling improved robustness to external disturbances.

6. **Able to provide pain feedback.** Identifying when an actuator is near its performance limits so that action can be taken to prevent damage from occurring can greatly extend the operating life of the actuator and the robot.

### 1.4. Electroactive polymers

Electroactive Polymers (EAPs) are a very promising field of research that offers the real possibility of combining the key functions of artificial muscles into a single actuation element. EAP are flexible polymer structures that can be made to deform upon application of an electrical stimulus [31]. They have garnered much attention in recent years due to their unique combination of material properties and ability to convert electrical energy into mechanical work. In contrast to most traditional actuation technologies, suitable polymers for EAPs share some of the attractive physical characteristics of muscle, i.e., like muscle they are typically soft, lightweight, and have a high fracture tolerance. Coupled with this they are generally inexpensive, and are able to be moulded into a wide variety of shapes. There is also wide scope to tailor the properties of the final polymer using chemical processing techniques. A comparison between various electroactive polymer types and conventional actuation technology is presented in Table 1-1.
One especially promising type of EAP is Dielectric Elastomer Actuator(s) (DEA). Other electroactive polymers typically out-perform muscle with regard to a specific metric, but DEA are capable of outperforming muscle across the board. Like muscle, DEA are inherently compliant devices that are capable of producing mechanical work on demand. They have demonstrated impressive actuation performance in terms of strain, speed, pressure, and energy density [32]. Most importantly however, their low material density, compliant nature, and silent operation capture many of the desirable physical properties of muscle [33]. DEA represent one of the first useful technologies that allow the combination of properties that muscle possesses to be reproduced in an engineering context in a single actuator. This has led to them often being referred to as “artificial muscles”.

### 1.5. Dielectric Elastomer Actuators

A DEA consists of a highly compliant, volumetrically incompressible polymer membrane dielectric sandwiched between compliant electrodes (Figure 1-7). When a voltage is applied to a DEA, the electrical charge that accumulates creates a surface pressure that results in a through thickness compression and in-plane expansion of the membrane. Independent of absolute size,
1.5 Dielectric Elastomer Actuators

if the planar dimensions of the DEA are much greater than its thickness, the magnitude of the pressure is defined by Equation 1.1 where $P$ is the pressure, $\varepsilon_r$ is the relative permittivity of the dielectric material, $\varepsilon_0$ is the permittivity of free space ($8.854 \times 10^{-12}$ F/m), $V$ is the voltage, and $d$ is the dielectric membrane thickness [4-6]. When the charge is removed the elastic energy stored in the DEA returns it to its original configuration.

$$P = \varepsilon_r \varepsilon_0 \left(\frac{V}{d}\right)^2$$  \hspace{1cm} 1.1

DEA are fundamentally electrostatic actuators, but they have a number of advantages over conventional air-gap electrostatic devices. The dielectric membrane prevents the ingress of contaminant particles into the device and controls the separation of the electrodes, eliminating the need for separate mechanisms to perform the same function. The membrane also greatly increases the dielectric breakdown strength of the device, enabling the application of much higher electric fields and therefore the generation of much higher pressures. This is further enhanced by having a dielectric material with a relative permittivity greater than 1. The expansion in the area of the electrodes as the thickness of the actuator decreases also serves to amplify the electrostatic pressure by a factor of two over rigid plate electrostatic devices where only the electrode separation changes.

In order to produce useful work, a load can be coupled to either the change in area or the change in thickness of the DEA. When the load is directly coupled to the change in area, the output force can be amplified by creating a laminate of multiple DEA stacked on top of each other (see Figure 1-8), while the output displacement can be increased by increasing the area of the DEA. When the load is directly coupled to the change in thickness the reverse is true, stacking multiple DEA on top of each other amplifies displacement while increasing the area amplifies force. Using this principle a wide range of DEA configurations have been tested including

![Figure 1-7: Basic operating principle of a Dielectric Elastomer Actuator](image)
diaphragms, spring rolls, tubular actuators, push-pull actuators, bow-tie, diamond, and minimum energy structures to name a few (e.g. [34-39]).

![Figure 1-8: Example of DEA with mechanical output coupled to (a) a change in area, and (b) a change in thickness.](image)

1.5.1. Opportunities and challenges

DEA have a unique set of characteristics compared to competing technologies:

- DEA are made from lightweight, inexpensive, widely available soft polymers (e.g. silicone) and can be formed into a wide range of shapes and sizes.

- DEA are linear actuators that can produce “human scale” forces and motions without the need for complex transmission systems.

- DEA are soft: inherent compliance protects the device, its environment, and people, and makes the DEA tolerant to being back-driven.

- DEA are capable of high efficiencies: for an ‘ideal’ DEA, no input energy is required to hold a given position, and due to their capacitive nature energy can be recovered when they are discharged.

- DEA have a broad operating envelope, and work well both fast and slow.

- DEA operate silently, eliminating the whine associated with high speed rotating parts.

- DEA produce lifelike, easily visible motion that offers a powerful visual impact.
1.5 Dielectric Elastomer Actuators

DEA are well suited to applications requiring a combination of speed, stroke, and power-to-weight, offering potential advantages over conventional actuator technologies for a broad range of industries. For example, a lightweight, inexpensive actuator capable of generating silent, lifelike motion and that can be back-driven is ideal for personal robots or toys. As discussed in Section 1.1.1, soft devices that conform to surfaces upon contact offer benefits with regard to safety, stability, and force control for robotic devices, particularly those that must operate in unstructured environments, or that handle delicate or irregularly shaped objects. Portable applications where power budgets are limited will benefit from an efficient actuator with a good power-to-weight ratio that enables the mass of the device, its power supply, or both to be reduced. Soft active devices that are tolerant of large strains have potential to be integrated into smart textiles. Furthermore, actuators capable of replicating the look, feel, and function of human muscles also have obvious use in prosthetic and orthotic devices.

While DEA have tremendous scope, there are several challenges that must be overcome before their full potential can be unlocked. DEA are made from soft polymers that inherently exhibit hyper-elastic non-linear behaviour and hysteresis [40]. The mechanical behaviour of DEA is therefore characterised by significant strain, time, and rate dependent properties, and in extreme cases it can be of the order of tens of minutes after a disturbance or change in the control signal before a true equilibrium state is reached [36]. In quasi-static operation DEA are highly repeatable; the time dependent aspect of their behaviour can be ignored and the non-linearity can be characterised experimentally. However, in many practical applications the DEA will be subjected to external disturbances or a variable load which will cause the output to deviate from an experimentally determined relationship.

DEA are also considerably more susceptible to failure at high electric fields where the electrostatic pressure generated is greatest. Whereas strains of several hundred per cent are possible for DEA with very limited operating lives, DEA materials that are commercially available today are limited to strains of 2-5% in order to ensure they are capable of operating for millions of cycles [41, 42]. The development of better dielectric materials and manufacturing processes will undoubtedly improve reliable active strains, but fundamentally this limitation is because there are currently no methods that enable the failure of a DEA to be predicted and prevented in real time. Thus in practical operation a large safety factor must be applied to all DEA to ensure reliability.
1.6. Artificial muscles using DEA

It is the goal of this thesis to create a smart artificial muscle based on DEA technology. Even if limiting DEA performance to that of today’s commercially available materials, it is clear they are capable of satisfying the first three criteria for artificial muscles identified in Section 1.3. However, in order for DEA to overcome the primary challenges identified in Section 1.5.1, and for them to truly earn the moniker of “artificial muscle” they must be more than actuators, they must be made smart and robust.

Closed loop control is essential for a smart device. Sensory feedback is necessary to compensate for non-linear and time-dependent mechanical behaviour of DEA, and to enable the DEA to respond appropriately to external mechanical influences, particularly when non-deterministic disturbances are present. Feedback is required for applications where positional accuracy is important, or where it is desirable to modify the output force depending on the position. Feedback is also required to monitor the health of the DEA and to prevent it from failing. Thus the scope of potential applications for DEA increases significantly with the addition of feedback.

1.6.1. DEA as self-sensing actuators

Typically robotic devices use discrete rigid strain, displacement, velocity or acceleration sensors to generate feedback data. This inevitably increases the cost and mass of the device, and while such a strategy is effective for traditional, rigid actuators that are part of kinematically constrained structures, directly coupling such a sensor to a DEA would unnecessarily inhibit its motion. Similarly, attaching a sensor to a rigid body to which the DEA is connected may provide useful feedback regarding the mechanical output, but provides limited information regarding the electromechanical state of the DEA itself. The key therefore is in using the DEA itself as a sensor.

The main hypothesis of this thesis is that by measuring some combination of the bulk electrical properties of a DEA while it is being actuated, inferences can be made about its mechanical state and health. In the electrical domain, a DEA can be modelled by a variable capacitor \( C_{DEA} \) in parallel with a variable resistor representing the finite Equivalent Parallel Resistance (EPR) of the dielectric membrane \( R_{EPR} \), both of which are in series with a second variable resistor representing the Equivalent Series Resistance (ESR) of the DEA’s electrodes \( R_{ESR} \) (Figure 1-9). The capacitance of the DEA changes as it deforms. Furthermore, it is not uncommon for
the resistance of the electrodes to be significant (e.g. [43-47]) and dependent on both time and stretch (e.g. [44, 48]), or for the EPR of the dielectric membrane to change by several orders of magnitude at high electric fields [49]. Thus it is important to be able to estimate all three parameters.

Self-sensing feedback will enable DEA to become true artificial muscles. Understanding how stretch affects each of these electrical parameters will potentially give DEA the ability to track a desired setpoint and be able to respond to changing loads and reject disturbances, thereby improving their precision. Being able to estimate the mechanical state of the DEA, e.g., the area of the electrodes or the thickness of the dielectric membrane, will also enable the electric field within the DEA and thus the electrostatic pressure to be estimated. By controlling the electrostatic pressure relative to the mechanical state, the stiffness of the DEA can be modified. Position and stiffness control are two key functions a true artificial muscle must perform.

The final component required to create a true artificial muscle using DEA is developing an analogue to what humans and animals regard as pain. Currently, there is a large difference between the peak performance that has been recorded in laboratory conditions and what is realistically achievable during reliable operation. This is due primarily to four competing failure modes ([36, 50-55]):

1. **Dielectric breakdown.** Dielectric breakdown occurs when the electric field within the dielectric membrane becomes so great that a path of low electrical resistance is formed between opposing electrodes through the dielectric membrane. The resultant sharp increase in current will melt or vaporize the dielectric, creating a mechanical weak
point, and if it is not electrically isolated from the rest of the DEA, a region of greatly reduced dielectric strength that ultimately renders the DEA useless for future actuation.

2. **Electromechanical instability.** When a voltage is applied to a DEA, the dielectric membrane will compress in the thickness direction and expand in the planar dimensions due to the electrostatic pressure. The mechanical stress in the membrane increases as it compresses through its thickness, however, if the voltage is maintained so too does the electrostatic pressure. A stable state of deformation is possible if the electrostatic pressure is less than or equal to the mechanical pressure at some degree of stretch*. Electromechanical instability occurs if the electrostatic pressure exceeds the mechanical pressure and grows with stretch at a greater rate than the mechanical pressure. In this situation the DEA will become unstable and the electrodes will attempt to clamp together. The DEA will fail if the breakdown strength or the tensile limit of the material is reached before a stable equilibrium between the electrostatic and mechanical pressures can be established.

3. **Tensile failure.** Tensile failure occurs when the strain of the membrane exceeds the strain limits of the material. As the bulk of the material stretches the long polymer backbones unfold and slide past each other [40]. At some point however the cross links and chain length will prevent the backbones from extending any further. At this point any additional strain will primarily be placing stress directly on the bonds of the polymer backbone itself. Too much stress will break the bonds, and if enough bonds are broken the material will tear.

4. **Buckling failure.** Buckling mode failure occurs when the combined effect of the electrostatic and mechanical pressure act to generate compressive stresses in the plane of the membrane [51]. The membrane cannot sustain this compression and will subsequently transition from a flat to a complex buckled state [51]. Unlike the first three failure modes this does not necessarily result in catastrophic failure of the DEA, rather the loss in tension of the membrane will impair the DEA’s ability to transmit force to a load.

Whilst the major failure modes of DEA have been clearly identified, preventing failure is a challenging task. The performance of a DEA is defined by its bulk behaviour, yet it typically

* Where stretch is defined as the ratio of the instantaneous value for a dimension of interest, e.g., thickness or area, to the initial “at rest” value of that dimension.
must only fail in a single specific region for the DEA to be rendered useless. The electric field applied to the DEA, the impedance of the load, and external disturbances coupled with microscopic variability in the molecular structure of polymer materials and the presence of defects in the dielectric membrane make it difficult to predict when and by which mechanism failure will occur. However, if the electrical and mechanical stresses acting upon the DEA can be used to determine when the DEA is near the point of failure, and appropriate action can be taken to prevent failure from occurring, their overall reliability will improve significantly.

1.6.2. Practical considerations for self-sensing DEA

The concept of smart artificial muscles is an attractive prospect in itself, but equally important in a real device is the system and techniques used to create this smart behaviour. DEA are soft, lightweight actuators made from inexpensive materials that for similar mass and volume are potentially capable of stretching further, generating more force, and actuating faster than the same muscles we use for every motion we make. A system that requires a bulky bench-top power supply or the computational grunt of a desktop PC will for some applications negate some of the potential benefits of DEA. Thus it is highly advantageous to treat the creation of a smart DEA not simply as an actuator in isolation, but as part of a functionally complete system.

When considering a complete system, the design criteria will depend on the class of applications that are targeted. In this thesis there is a strong focus on developing smart DEA for portable or mobile devices; and the research presented is intended as progress towards the ultimate goal of creating fully functional, life-like prosthetic devices such as an artificial human hand. DEA present a unique opportunity to recreate not only the function but also the look and feel of muscles. For people who have experience wearing prostheses, evaluating a prosthetic device is heavily weighted towards its appearance and its function [57, 58]. Smart and robust DEA have the potential to lead to prosthetic devices that look and feel so much like the real thing that only the wearer would know the difference. Such devices become impractical however if the weight and volume of the driving electronics become much greater than active components. There is significant advantage therefore to designing the whole system, i.e., the DEA and the driving circuitry, to be portable.

DEA, particularly at the scale of portable devices, operate in a high voltage, low current regime. Based on current fabrication techniques (e.g. [36, 59-63]), they require several hundred volts to several thousand volts to achieve significant actuation. Thus for a portable device, generating this voltage will be a key factor in the design of the system. The capabilities and limitations of a
compact power supply capable of generating high voltages will be particularly important with regard to developing a system that is capable of simultaneously actuating a DEA and sensing its electrical characteristics. Equally important are the computational requirements required to perform self-sensing, i.e., its practicality will be judged based on its ability to acquire, interpret, and respond to feedback in a timely manner in a form that is suitable for implementation in an embedded system.

1.7. Research objectives and thesis outline

The aim of this thesis is to make DEA smart and robust so that they can truly be called artificial muscles. There will be a specific focus on creating a system to achieve this goal that is suitable for portable devices of the size and mass of a human hand and forearm. DEA already exhibit excellent performance as actuators. What is most important however is the method by which their performance is controlled. This requires understanding how they behave under the influence of variable electrical and mechanical loads and disturbances, and how to distinguish between different aspects of this behaviour based on the interpretation of measurable feedback signals. Using this knowledge, DEA can be made to exhibit the desirable behaviours of muscle identified in this chapter.

Chapter 2 of this thesis is a critical review of previous examples of self-sensing that have appeared in the literature. Chapters 3-6 address the following research objectives:

1. **Develop a method for estimating the capacitance of a DEA, the ESR of the electrodes, and leakage current through the EPR of the dielectric membrane in real-time.** The primary goal of this thesis is to develop a self-sensing system capable of accurately estimating all three of these electrical parameters in real-time using an approach that is suitable for a portable or mobile device. This requires understanding how the static and transient behaviour of each parameter affects measurable electrical signals coming from the DEA. This is addressed in Chapter 3.

2. **Develop the self-sensing method in a physical system.** In order to experimentally validate the self-sensing method it is necessary to develop it in a physical device. This is addressed in Chapter 4.

3. **Develop a control strategy for achieving position control of DEA using self-sensing feedback.** Closed loop control of position enables greater positional accuracy and makes
it possible to detect and reject external disturbances, enabling DEA to be used in applications where positioning accuracy is important. This is addressed in Chapter 5.

4. **Develop a control strategy for achieving stiffness control of a DEA using self-sensing feedback.** DEA are inherently soft devices and there is a unique opportunity to recreate the tuneable stiffness of muscle, and the benefits this confers, in a single actuator element. This is also addressed in Chapter 5.

5. **Develop a method for interpreting the self-sensing feedback to generate an analogue to what humans regard as pain.** To close the gap between the peak performance of DEA and what is realistically achievable over millions of cycles requires monitoring the health of the DEA. This is addressed in Chapter 6.

The final chapter of this thesis discusses overall conclusions and directions for future work.

### 1.8. Contributions of this thesis

A novel method for estimating the ESR of the electrodes of a DEA, the capacitance of a DEA, and the leakage current through the EPR of the dielectric membrane is presented in this thesis. Each of these electrical parameters has an important role in determining the state and health of a DEA and each influences the others in the estimation process. This is the first DEA self-sensing system that enables simultaneous estimation of all three parameters in real-time. It is also the first system to specifically account for the effects of the rate of change of the capacitance, and leakage current. Also presented in this thesis are the first practical demonstrations of self-sensing being used to control the output of a DEA independently of any mechanical disturbances. More specifically, in this thesis self-sensing has been used to control the area of a DEA, to modify the effective stiffness of a DEA, and to provide the foundation for a pain parameter for DEA.

In this thesis a system has been developed that, in a departure from previous examples of self-sensing systems for DEA, uses Pulse Width Modulation (PWM) to simultaneously generate an actuation signal and provide an electrical excitation that enables the electrical parameters of the DEA to be sensed. The system is readily compatible with microcontroller architectures, specifically accounts for the capabilities and limitations of low power driving electronics as well as non-linear and non-ideal behaviours exhibited by DEA, and generates feedback data using an algorithm that is inherently robust to noise. This self-sensing system has been
experimentally validated, and has been implemented in a controller capable of controlling the position and effective stiffness of a DEA. It has also been used to establish a foundation for monitoring the health of the DEA.
Literature review

The behaviour of DEA is the result of complex interactions between their mechanical and electrical characteristics. Like muscle, all soft polymers have some degree of non-linear strain, time, and rate dependent mechanical behaviour. Furthermore, because DEA are inherently soft, external disturbances and load variations will have significant influence on their mechanical behaviour. The complexity of this behaviour is enhanced with the addition of an electrical stimulus: pressure generated by electrostatic forces modifies both the equilibrium state and the transient behaviour of DEA. Closed loop control is essential to compensate for these complex behaviours and to improve overall reliability, and thus enable DEA to become true artificial muscles.

To achieve muscle-like behaviours such as position and stiffness control, and the perception of pain, it is necessary to acquire feedback regarding the mechanical state of the DEA, control the pressure induced by electrostatic forces relative to the mechanical state, and ultimately recognise when failure of DEA is imminent and take corrective action. This chapter begins with an overview of the relationship between the Equivalent Series Resistance of the DEA, the capacitance of the DEA, and leakage current through Equivalent Parallel Resistance of the DEA and the desired muscle-like behaviours that will enable DEA to function as true artificial muscles. In the first example of its kind, this chapter concludes with a critical review of previously published self-sensing systems for DEA.

2.1. The significance of the electrical parameters of DEA

Controlling position and rejecting external mechanical disturbances requires information regarding the mechanical state of the DEA, e.g., the area of the electrodes or the thickness of
2.1 The significance of the electrical parameters of DEA

the dielectric membrane. Controlling the effective stiffness of the DEA requires controlling the pressure generated by electrostatic forces. Pain feedback requires identifying when a given DEA is close to failure and taking appropriate action to prevent this threshold from being crossed. Each of these tasks can be achieved by monitoring some combination of the $R_{ESR}$, $C_{DEA}$, and leakage current through $R_{EPR}$. However, each of these parameters is interrelated, and their accurate estimation requires knowledge, assumed or otherwise, of all three parameters. In this section the relationship between each parameter and the tasks of controlling position, stiffness, and preventing failure is discussed.

2.1.1. DEA capacitance

A DEA is a soft capacitor and its capacitance is related to its geometry. At the range of pressures a DEA is likely to be subjected to (<10MPa), soft polymers can be regarded as volumetrically incompressible [40, 64-66]. Furthermore, tests where good contact between the electrodes and the membrane has been ensured have shown the dielectric constant of several common DEA membrane materials exhibit little to no stretch dependence over very large stretches (e.g. [67-69]). Thus if the electrodes are assumed to remain substantially parallel, the instantaneous nominal area and the nominal thickness of the dielectric membrane can be estimated using the instantaneous capacitance and the rest capacitance of the DEA (Equation 2.1)*.

$$C_{\text{instantaneous}} = \frac{\varepsilon_r \varepsilon_0 A}{d} = \frac{\varepsilon_r \varepsilon_0 A_0 \lambda_A}{\left(\frac{d_0}{\lambda_A}\right)^2} = C_0 \lambda_A^2$$ \hspace{1cm} 2.1

Capacitance is useful for combating tensile stress failures by indicating the nominal stretch ratio of the area ($\lambda_A$) and the thickness ($\lambda_d$) of the DEA†. Capacitive feedback can potentially identify when the stretch within the DEA is approaching the limits of the membrane material. It is also useful for identifying buckling: in the event of a non-destructive collapse into the complex buckled structure the capacitance of a DEA will increase sharply. Furthermore, accurate and timely feedback regarding the capacitance is essential for controlling the instantaneous electrical charge stored on a DEA. Controlling the relationship between the electrical charge and the voltage potentially enables the effective stiffness of a DEA to be modulated [70, 71].

* Where $C$ is the capacitance, $\varepsilon_r$ is the relative permittivity of the dielectric membrane, $\varepsilon_0$ is the permittivity of free space ($8.854 \times 10^{-12} \text{F/m}$), $A$ is the area of the electrodes, and $d$ is the distance between the electrodes, i.e., the thickness of the membrane.

† Stretch ratio is the ratio of the instantaneous value of a dimension to its “at rest” value, e.g., $\lambda_A = A/A_0$. 

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For example, where position is derived from capacitance, the electrostatic charge can be controlled to be some function of the error between the actual position and a position setpoint. That is, the electrostatic charge can be modified to either reduce the effective stiffness by acting to sustain an external disturbance, or increase the effective stiffness by acting to reject an external disturbance.

Controlling charge rather than the voltage across a DEA has the added benefit of eliminating bulk electromechanical instability, that is, where the electrodes attempt to clamp together but remain substantially parallel in doing so. However, it is important to note that like dielectric breakdown, electromechanical instability can be a localised phenomenon. Electromechanical instability is closely linked to the stiffness of the membrane material ([50, 52, 55, 72]). Localised heating within the dielectric (e.g. due to leakage current, see Section 2.1.3) can contribute to localised softening of the dielectric, resulting in a lower instability threshold for the soft region. Where the local region becomes unstable, the charge density at the locally thin region will increase relative to the rest of the DEA. Thus the surrounding DEA acts like a charge reservoir for the thin region. The resultant effect is that the local region behaves as if it is voltage controlled. Ultimately, this means that while the mean electrical charge on the DEA is controlled, electromechanical instability can still occur at a local scale.

2.1.2. Electrode resistance

Compliant electrodes are of critical importance to the operation of a DEA. Ideally, a flexible electrode will possess the following properties:

- The electrode should remain conductive at large strains. Non-conductive regions will prevent the flow of charge and diminish the performance of the DEA.
- The electrode should not overly constrain the motion of the DEA.
- The volume of the electrode layer should be as small as possible to minimise the inactive volume of the DEA device.
- The electrode material should be resistant to migration. It is undesirable for the conductive material to migrate into insulating areas either due to creep over time or as a result of cyclic loading. Doing so could create regions of poor dielectric breakdown strength that will prevent the DEA from actuating.
- Electrodes should be inexpensive and easy to fabricate.
2.1 The significance of the electrical parameters of DEA

Various materials and techniques have been utilised to produce compliant electrodes for DEA (see [73] for an overview). A common general purpose approach to electrode materials has been the use of carbon particles (e.g., carbon black, single- and multi-wall nanotubes, graphite) either alone or dispersed in a soft polymer matrix to form an electrically conductive rubber-like material (e.g. [44, 53, 74]). A sample of the conductivities of several carbon-based electrode materials capable of remaining conductive at high strains is shown in Table 2-1. The volume resistivity of copper is also shown as a point of reference. Clearly the resistivity of compliant electrodes is high relative to the resistivity of a metal. For example, if we assume a resistivity of $10 \, \Omega\cdot\text{cm}$ and create an electrode that is 10cm long by 1cm wide by 10µm thick, the resistance along the length direction will be $10^5 \, \Omega$. It is not uncommon therefore for the resistance of the electrodes of DEA to be significant. Current flowing through the DEA will therefore result in a voltage drop across the ESR of the electrodes. Furthermore, this electrode resistance will change as the DEA deforms, thus the voltage drop across the ESR of the electrodes is a function of both stretch and current.

Table 2-1: Sample of the conductivities of several carbon-based electrode materials.

<table>
<thead>
<tr>
<th>Electrode Material</th>
<th>Resistivity (Ω-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper [75]</td>
<td>$1.7 \times 10^6$</td>
</tr>
<tr>
<td>RTV 60-CON [43]</td>
<td>5</td>
</tr>
<tr>
<td>Exfoliated Graphite/PDMS [44]</td>
<td>6</td>
</tr>
<tr>
<td>Nyogel 756G [45]</td>
<td>30</td>
</tr>
<tr>
<td>Silopren LSR2345-06 [46]</td>
<td>45</td>
</tr>
<tr>
<td>MG Chemicals Carbon Conductive Grease [47]</td>
<td>117</td>
</tr>
</tbody>
</table>

In order to estimate the capacitance of a DEA, it is necessary to know the voltage waveform across the capacitive component of the DEA. This cannot be measured directly however; the voltage difference between the positive and negative terminals of the DEA is the sum of the voltage drop across $R_{ESR}$, which is dependent on both current and stretch, and the voltage across the $C_{DEA}$. Accurately estimating the instantaneous capacitance of the DEA therefore requires estimating the instantaneous ESR of the electrodes. This is not without its own inherent benefits however, the ESR of the electrodes can act as an indicator of the stretch state of the electrodes (e.g. [48, 76]). Where the DEA can deform along multiple axes, this information could be combined with the nominal area stretch calculated using capacitance measurements to
distinguish stretch ratios in each planar dimension. This would be an important future development, however current DEA electrode materials have exhibited complex stretch, time, and cycle dependent behaviour (e.g. [44, 48, 76]), thus further research, particularly with regard to fabrication techniques, is required to develop this stretch sensing capability.

2.1.3. Leakage current

The effective conductivity of an ultrathin dielectric membrane can increase significantly when it is subjected to very high electric fields [49]. For low power devices especially, this leakage current through the dielectric membrane can become a significant proportion of the current available for charging the DEA. In this situation, it is very important to be able to distinguish between the effects of leakage current and charging/discharging current on the measureable electrical parameters of the DEA. Failing to account for leakage current will affect the apparent rate at which the DEA is charging/discharging, which could ultimately translate into erroneous estimations of the other electrical parameters of interest. Furthermore, leakage current increases with increasing electric field, thus it is linked to a primary failure mode for DEA: dielectric breakdown.

To better understand the link between dielectric breakdown and leakage current, it is informative to consider the four primary mechanisms by which full dielectric breakdown occurs [50]:

1. **Electronic:** Metals such as copper conduct electricity because the electrons associated with each atom are free to move between atoms. This is not the case with insulating polymers; these materials have a very high resistance because the electrons associated with each atom are typically tightly bound to that atom. At very high electric fields however*, even the electrons in polymers may acquire enough energy that they can be freed from their atom, effectively resulting in the material becoming conductive and its effective resistance dropping markedly. The electric field required for this to occur is the ideal breakdown strength of the material.

2. **Electromechanical instability:** As outlined in Section 1.6.1, electromechanical instability occurs in a DEA if the mechanical stresses in the membrane are overpowered by the electrostatic pressure, thereby resulting in a sudden decrease in the thickness of the dielectric. This amplifies the local electric field, and thus results in

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* Approximately 1-10 GV/m for insulating polymers.
increased leakage current through the dielectric. Ultimately this creates the necessary conditions for one of the other three dielectric breakdown mechanisms to occur.

3. **Thermal:** Leakage current through the dielectric causes its temperature to increase. As the temperature rises, so too does the conductivity of the membrane, further increasing the leakage current. This temperature increase also contributes to a reduction in the stiffness of the membrane. For a DEA this softening can amplify the active deformation for a given electrostatic pressure; simultaneously reducing the effective resistance of the membrane due to geometric effects\(^*\) and enhancing the electric field \([50, 55]\). Ultimately, beyond some threshold the combined effect of the softening of the membrane and the increase in electrical conductivity results in leakage current forming a positive feedback loop that leads to catastrophic failure. The heat generated by the runaway current melts or vaporizes the dielectric and effectively creates a low resistance path between the electrodes.

4. **Partial discharges:** Unavoidable physical defects within the dielectric contribute to variable breakdown strength along the thickness direction of the dielectric membrane. For example, a void will typically have a lower breakdown strength than the surrounding dielectric. Local breakdown within the void will create charge carriers that are accelerated across the void by the electric field. If they acquire enough energy, the charge carriers may subsequently damage the void wall and make it larger. The high resistance of the surrounding membrane material however restricts the flow of charge to the partial discharge site, and the sudden redistribution of charge reduces the local electric field to the point that the breakdown event ceases. It also results in a short spike in the leakage current through the dielectric. Where partial discharges act to increase the size of the void, or act to increase the local temperature within the dielectric, repeated partial discharges can ultimately weaken the dielectric sufficiently that full breakdown occurs.

In practical terms, imperfections and inhomogeneities within the dielectric membrane of a DEA are unavoidable. These imperfections act as weak points in the dielectric preventing the dielectric from reaching its ideal breakdown strength. Failure is therefore typically the result of localized instances of electromechanical instability, thermal runaway, and partial discharge events. The overall quality of a DEA can be improved by “burning out” significant

\(^*\) Resistance is proportional to length, in this case the thickness of the dielectric, and inversely proportional to area.
imperfections using self-clearing electrodes (e.g. [63, 77])*. This raises the maximum electric field the DEA can sustain without undergoing breakdown, and provides a mechanism for the performance of the DEA to degrade gracefully in the event dielectric breakdown occurs. However, self-clearing electrodes limit the choice of electrode materials (e.g. carbon nanotubes, sputtered metal), and it may not always be convenient to introduce holes into the DEA. Thus in the general case, there are advantages to investigating how typically localized dielectric breakdown mechanisms affect the characteristic behaviour of the measureable electrical parameters of a DEA, and in particular how they affect leakage current.

2.1.4. Summary of electrical behaviour and failure modes

DEA have exhibited great promise in laboratory conditions, but there is a significant gap between the peak performance that a DEA can achieve without consideration for its longevity, and what is repeatable over millions of cycles. Despite being conceptually simple devices, the intrinsic behaviour of DEA is complex and dependent on a wide range of influences. Feedback is required to reliably determine the instantaneous state and health of the DEA. The mechanical output of a DEA is directly related to its capacitance and the ESR of its electrodes. This feedback is essential for compensating for non-linear and time-dependent effects and for detecting, and rejecting, the effects of external disturbances. Similarly, leakage current through the EPR of the dielectric is related to a major failure mode of DEA, dielectric breakdown. Thus each of the electrical parameters potentially play an important role in enabling DEA to satisfy the criteria defining an artificial muscle, i.e., achieving position feedback, tuneable stiffness, and an analogue to pain.

2.2. Self-sensing DEA

Clearly monitoring the electrical parameters of a DEA offers potential benefits with regard to positional accuracy, robustness, and reliability. The challenge however is to find a way of measuring the capacitance of the DEA, the ESR of the electrodes, and leakage current through the EPR whilst simultaneously actuating the DEA. DEA operate over a wide range of electric fields and can undergo large stretches thus in the general case all three of the electrical parameters of the DEA can change significantly. This section begins with a brief review of the history of dielectric elastomer sensors and identifies the unique challenges of combining this

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* Self-clearing electrodes use the breakdown current to burn away the conductive electrode material around the breakdown site, electrically isolating the defect.
function with actuation in a single active element. This is followed by a critical review of works in which DEA have been used as actuators as sensors simultaneously.

2.2.1. Dielectric elastomer sensors

Since Dielectric Elastomers (DE) were introduced in their modern form by Pelrine et al. [78], it has been known that DE can act both as actuators and as sensors. DE are low elastic modulus flexible capacitors that are capable of undergoing large deformations. There are numerous examples in the literature of this property being exploited in a variety of configurations to sense changes in strain and pressure, and to monitor the health of a range of flexible structures (e.g. [79-87]).

When used purely as a sensor, conventional low voltage techniques for sensing electrical impedance can be applied directly to the DE. For example, a common approach is to use a high frequency AC signal to evaluate the complex electrical impedance of the DE. A simple circuit for demonstrating this capacitive sensing method involves connecting a resistor between the negative terminal of the capacitor and ground, and applying a high frequency AC voltage signal to the positive terminal of the capacitor. By selecting an excitation frequency \( f_s \) to be approximately equal to the corner frequency of the RC circuit (i.e. \( f_s \approx 1/2\pi RC \)), the ratio of the amplitude of the voltage across the external resistor to the amplitude of the AC component of the input signal becomes highly sensitive to changes in capacitance (see Figure 2-1).

![Figure 2-1: Frequency response function of a single pole high pass filter. The ratio of the RMS value of \( V_{out} \) to the RMS value of \( V_{in} \) is highly sensitive to changes in capacitance where the excitation frequency is approximately equal to the corner frequency of the RC circuit.](image)

DE sensors have also been coupled with DEA directly to provide feedback regarding the mechanical state of the DEA (e.g. [88-90]). In these hybrid DEA/DE sensor devices the overall DE structure is subdivided into two electrically isolated sections: a high voltage zone that is
responsiable for actuation, and a low voltage zone that is used for sensing. Coupling DEA with DE sensors has several attractive features:

- The actuator and sensor can be fabricated as part of a monolithic structure, ensuring a good match between the mechanical impedance of the sensor and the actuator.

- Low voltages simplify the task of sensing by eliminating non-linear effects due to the high electric fields due to actuation, and eliminating the need to protect the sensing circuitry from high voltages.

- Monolithic DEA/DE sensor devices also result in reduced part counts relative to control systems for DEA devices that make use of external sensors (e.g. load cell [91, 92], position encoder [91, 93], video feedback [94], potentiometer [95]).

However, while the sensor output is intimately coupled to the mechanical state of the DEA, it shares similar shortfalls as DE devices with external sensors: the properties of the DEA itself are not being monitored and the configuration provides limited feedback regarding the health of the DEA, particularly with regard to dielectric breakdown and electromechanical instability. Furthermore, the addition of a passive sensing region necessarily reduces the volume of the device that contributes to actuation.

It is advantageous therefore to sense the DEA directly as it is being actuated: the active volume of the device is maximised; and the electrical parameters of the DEA itself are being measured, thereby providing a richer set of information related to the mechanical state and health of the DEA. The challenge however is to combine a high voltage actuation signal with methods for sensing the parameters of the DEA. At low voltages, leakage current through the dielectric membrane and current that is induced due to the rate of change of the capacitance are both negligible. It is also unnecessary to compensate for electrical currents induced due to the charging and discharging of the device during actuation. Conventional techniques used to measure the electrical impedance of the sensor can therefore be employed. However, these conditions are no longer valid when actuation and sensing are combined. Furthermore, for portable devices that typically operate at low power, the combination of very high voltages and very small currents introduces additional constraints that will affect the development of an appropriate self-sensing method. This prevents conventional impedance sensing techniques from being applied directly to create self-sensing DEA. Creating a practical method for self-
sensing a DEA is much more than simply applying well-known techniques, and necessitates the creation of new techniques with unique design criteria.

2.2.2. Integrated actuation and sensing of DEA

Despite the field of dielectric elastomers having grown exponentially in the past decade, very few research groups have attempted to simultaneously actuate and sense a DEA. An extensive search of the literature yielded just 7 examples of integrated actuation and sensing of an individual DEA element that were not written or co-written by the author of this thesis*. In this section a critical review of these works is presented. It is a goal of this thesis to develop a self-sensing system that is suitable for portable devices, and it will be important therefore to ensure that the techniques and methods used to achieve self-sensing are compatible with very high voltage, very low current power supplies that are typical of these devices. The examples of DEA self-sensing discussed will therefore be examined from the perspective of their implementation in a compact, portable system.

Toth and Goldenberg [76] superimposed a high frequency sensory tone on a high voltage actuation signal by connecting a function generator to the negative output terminal of a DC-DC converter used to drive a small DEA. A function expressing the stretch dependent resistance of the electrodes was derived from a characterisation experiment and combined with a stretch dependent function for the capacitance of the DEA to create the small signal transfer function of the DEA circuit. Using this model, the capacitance of the DEA was estimated based on the gain of the sensory tone as measured across a simple RC circuit connected between the negative terminal of the DEA and electrical ground. When subjected to a very low frequency (0.025 Hz) sinusoidal actuation signal good qualitative agreement was achieved between the capacitance of the DEA as estimated using the self-sensing system and the capacitance as estimated using video extensometry.

Despite promising results, Toth and Goldenberg’s self-sensing system had a number of limitations. Leakage current had been ignored. Similarly the stretch dependent function for the resistance of the electrodes was not able to be updated during operation, despite the authors demonstrating that the resistance of the electrodes did change over time and as the DEA was cycled. From a practical standpoint, generating a high frequency AC sensory tone is not well suited to a DC-DC converter with limited power capabilities, as evidence by the distortion of

* Combinations of the following terms used to search engineering and science journal databases: “electroactive polymer”, “dielectric elastomer”, “artificial muscle”, “actuator”, “sensor”, “transducer”, “feedback”, “closed loop”
the sensory tone as measured at the positive terminal of the DEA. Their setup also coupled the actuation speed of the DEA to the dynamics of the power supply. Compact high voltage DC-DC converters however typically have rectified outputs (e.g. [96-99]) that limit their ability to sink current and therefore the speed with which they can discharge a DEA. Furthermore, because the DEA was coupled to the power supply, a device with multiple degrees-of-freedom would require as many DC-DC converters as degrees-of-freedom.

In [100], Jung et al. treated a DEA simply as a capacitor, and connected it in series with a fixed resistor and modelled the resultant circuit as a high pass filter. Electrode resistance and leakage current were ignored. In experimental testing, a bench-top high voltage amplifier (Trek 609-E) was used to superimpose a 5 kHz, 100 V peak-to-peak sinusoidal on the actuation signal applied to an expanding dot DEA. Sinusoidal and square wave actuation signals with frequencies of 0.1 Hz, 1 Hz, and 10 Hz, each with a peak amplitude of 3 kV, were applied to the DEA, and the subsequent radial expansion of the DEA was measured using a laser displacement sensor reflecting off a marker placed on the perimeter of the DEA. This displacement was then compared to the peak-to-peak amplitude of the voltage across the fixed resistor. It should be noted that the authors did not calculate capacitance using their system; rather they used the output voltage as a proxy for radial displacement.

For the sinusoidal actuation signals, at 0.1 Hz and 1.0 Hz the amplitude of the output voltage showed excellent agreement with the measured displacement. At 10 Hz however there was a noticeable phase difference between the output voltage and measured displacement that was not entirely the result of the viscous behaviour of the polymer material. Furthermore, for the square wave actuation signals, there was overshoot in the output voltage signal following the rising edge of the actuation signal that was not present in the displacement as measured by the laser displacement sensor. This suggests that significant charging/discharging currents, either from the power supply or as a result of the capacitance of the DEA changing at a fast rate, affected the accuracy of the system. Furthermore, the change in the output voltage was assumed to be solely the result of a change in capacitance. For the DEA used this may not be a significant issue; it was small and the active area strain was less than 11%, hence the resistance of the electrodes and the EPR of the dielectric membrane may not change significantly. However, this assumption may not be valid for larger DEA with greater active strains, or for DEA that are subjected to higher electric fields.
2.2 Self-sensing DEA

In a related work [101], Jung et al. used the same experimental setup from [100], but replaced the purely capacitive element used to model the DEA with a distributed network of resistors and capacitors. This model incorporated the effects of the electrode resistance and leakage current, but except for capacitance, the model parameters were characterised experimentally and there was no provision for them to be updated during operation. As in [100], the changes in the output voltage were deemed to be solely the result of the capacitance of the DEA changing i.e. the ESR of the electrodes and the EPR of the dielectric membrane were assumed to be constant. Like the self-sensing system presented by Toth and Goldenberg, assuming both the resistance of the dielectric membrane and the resistance of the electrodes to be constant will result in erroneous estimations of capacitance if either change significantly. Furthermore, the magnitude and frequency of the reported sensory signal are significantly greater than that employed by Toth and Goldenberg, thus direct implementation of the reported self-sensing system in a portable device would require significant modification to reflect the limitations of a compact DC-DC converter.

Keplinger et al. [102] also implemented self-sensing in an expanding dot DEA by superimposing a high frequency, low amplitude AC signal on top of the actuation signal. The DEA was modelled as a variable capacitor in series with a variable resistance, and a fixed resistor connected between the negative terminal of the DEA and ground was used to recover the sensory signal. In addition to the gain of the transfer function of the circuit, the phase delay was also measured. This is a particularly significant innovation because these two parameters allowed both the instantaneous capacitance of the DEA and instantaneous resistance of the electrodes to be estimated. This eliminated the need to make assumptions about the behaviour of the electrode resistance in order to estimate capacitance. The advantage of this approach was clearly evident when the estimated capacitance of the DEA remains a smooth function of time as the DEA slowly transitioned from a flat to a buckled state as the level of actuation increased, an operating condition that resulted in significant error in the estimated capacitance for the system presented by Toth and Goldenberg.

The DEA self-sensing system presented by Keplinger et al. was a significant improvement over the two previous self-sensing concepts reviewed. However, leakage current through the dielectric membrane was ignored. The same practical issues as Toth and Goldenberg and Jung et al. will also be encountered: generating clean, high frequency AC signals is problematic for compact DC-DC converters, and again the DEA was necessarily coupled to the dynamics of the power supply.
A novel approach to self-sensing the capacitance of a DEA during operation was employed by Matysek et al. [103] to sense the deformation state of a mechanical push button. In the idle state, an infrequent impulse voltage with a very short duration was applied to the DEA to poll the state of the button. The series current through the DEA during the impulse was integrated to calculate the total electrical charge, $Q$, transferred to the DEA. The charge was then divided by the amplitude of the voltage impulse, $V$, in order to calculate capacitance, $C$ (Equation 2.2). Greater pressure on the button resulted in a higher capacitance and therefore a larger $Q$ for a fixed $V$. Individual charge/discharge cycles were imperceptible to the human touch, but by increasing the frequency of impulses to several hundred Hertz when the button was depressed, the DEA would create vibrations in the button that could be felt by the fingertip.

$$C = \frac{Q}{V} \quad 2.2$$

The approach used by Matysek et al. takes advantage of several features specific to tactile feedback to simplify the task of self-sensing. The DEA itself is used to generate vibration that can be felt by a human fingertip, and only toggles between two states: fully charged and fully discharged. There is no provision for intermediate states, a feature that would be useful for greater control of the mechanical output of a DEA in general purpose applications. Furthermore the self-sensing is being used as a threshold detector: if the estimated capacitance is large enough, the button is deemed to be pressed and the control system can respond appropriately. It is not important that the self-sensing provide an accurate estimation of capacitance, rather it is only necessary that a relative change in capacitance can be detected. Sensing of the other electrical parameters of the DEA was not fully explored by Matysek et al. For example, a method for estimating electrode resistance was provided for the ideal case that assumes the power supply has an infinite slew rate, however the authors themselves note that this is not a valid assumption for a practical system. Leakage current acts to inflate $Q$ and would therefore lead to overestimation of capacitance, however this has not been accounted for. Similarly, current induced in a charged DEA when it is mechanically deformed by an external disturbance will also influence $Q$ and distort estimations of capacitance, thereby making the capacitive sensing approach less accurate during dynamic operating conditions.

Not all attempts at DEA self-sensing have been directed towards measuring the capacitance of the DEA. In [48], O’Brien et al. present a self-sensing system developed to estimate the length of a long, narrow DEA by measuring the resistance of the electrodes whilst the DEA was being
actuated. A low voltage circuit superimposed a sensing current along the negative electrode of the DEA and a voltage divider was used to estimate the resistance of the electrode. The relationship between the estimated electrode resistance and length of the DEA was characterised experimentally for a range of steady state displacements and applied voltages. A regression technique was then used to fit a model to training data derived from the characterisation experiment that related resistance and applied voltage to the length of the DEA. In experimental validation, the steady state displacement was predicted to within 5% of the actual value after a 5 second settling time for relatively small strains (<15%). During transient conditions however the sensing system overestimated the displacement for both positive and negative step changes in the actual displacement. The accuracy of this resistive self-sensing system also suffered from low repeatability associated with the various materials used to form the electrodes of the DEA. O’Brien et al. reported that the system had to be periodically retrained offline to update the coefficients of the characteristic formula in order to maintain a good degree of accuracy.

In a more recent work, O’Brien et al. [104] demonstrated Dielectric Elastomer Switch(es) (DES) that exploit the highly sensitive stretch dependent resistance of electrically conductive materials operating near the percolation threshold to obtain mechano-sensitive feedback from a DEA. In their present form, DES consist of thin, electrically conductive traces patterned onto a passive region of a DEA membrane. As the membrane deforms, the density of the conductive particles that make up the trace changes, modifying the overall resistance of the trace. By tuning the density of the conducting particles to be near the percolation threshold, the resistance can be made to change by as much as three orders of magnitude over strains of approximately 40%. In a classical sense, the resistance of the traces could be monitored by a remote controller and used to infer strain directly, but they can also be used to directly control the flow of charge to and from the DEA. O’Brien et al. have demonstrated variable voltage dividers incorporating DES that control the voltage across a DEA to be proportional to the stretch state of the DES. Thus the DES feedback is coupled directly to the behaviour of the DEA without the need for an intermediate computational stage. Furthermore, the DES and DEA need not be co-located on the same dielectric membrane. For example, the deformation of one membrane can be used to trigger the activation of a neighbouring DEA, which in turn triggers the next DEA and so on to create a wave of actuation. The low computational overheads of such a system are particularly well suited for the creation of large biomimetic actuator arrays.
Using DES O’Brien et al. have demonstrated an oscillator circuit and a NAND gate, the functional primitives from which any digital logic circuit can be created. The implications of this are that soft computers can be patterned onto the membrane itself, eliminating the need for hard circuits. The overwhelming advantage of DES therefore is their potential to integrate sensing, logic, and driver functionality in a soft form factor. However, they are still very much in their infancy. Currently for use in DEA circuits, resistance values of the order of $10^6$-$10^9$ Ω are required. When implemented in driver circuits this contributes significantly to the time constant of the DEA and therefore limits the frequency at which they can be actuated. As sensors for DEA devices, their behaviour is intimately coupled to position, but they offer limited potential for monitoring the health of the DEA, particularly with regard to dielectric breakdown and electromechanical instability failure modes. Without external control they are reactive rather than pro-active elements, i.e., their behaviour will only change as a result of an external disturbance that perturbs them from their current state. Furthermore, substantial variability exists between DES due to the rudimentary nature of the fabrication processes used. Current DES also exhibit hysteresis when cycled, and the relationship between stretch and resistance changes gradually with time, number of cycles, and as a result of electrical degradation.

2.2.3. Discussion

Self-sensing reduces the number of assumptions that must be made regarding the behaviour of a DEA when designing a control system. This behaviour can be complex, and developing an understanding of all of the factors influencing it is an on-going process. A more complete picture of how the characteristics of a DEA change during operation, particularly if this information can be obtained in real time, can only aid this process.

There are relatively few examples of self-sensing DEA. Indeed this section represents the sum of research in this area. Undoubtedly each of these systems is capable of achieving good results under specific operating conditions. In practice however, the systems reviewed have not incorporated all of the expected characteristics of a DEA. No example of DEA self-sensing has an explicit mechanism for measuring the leakage current through the EPR of the dielectric membrane. Furthermore, the displacement overshoot error in the experimental results of Jung et al. for DEA operating at relatively high actuation frequencies suggest it is necessary to specifically account for significant charging/discharging current through the DEA and current due to the capacitance of the DEA changing rapidly. This has not been addressed in any of the
DEA self-sensing systems cited. The results of Toth and Goldenberg and Keplinger et al. also highlight how interdependent the electrical parameters of a DEA are, particularly with regard to how important it is to measure the resistance of the electrodes in order to obtain a reliable estimate of capacitance.

Examples of capacitive sensing have focused solely on superimposing a sinusoidal AC signal on the actuation signal and measuring the gain of the circuit to determine the complex impedance of the DEA. Only Keplinger et al. have extended this technique to measure the phase delay of this signal, a novel aspect that allows the instantaneous ESR of the electrodes to be estimated during operation. This is particularly relevant given the current state of compliant electrodes for DEA; it has clearly been shown that time and repeated cycling each contribute to changes in the overall resistance of the electrodes. If the resistance of the electrodes cannot be updated online, the accuracy of a DEA self-sensing system will degrade with time.

Real-time sensing of leakage current through the EPR of the dielectric membrane and current induced due to the capacitance of the DEA changing rapidly have been ignored in all of the DEA self-sensing systems reviewed. The combined influence of these currents can influence the transfer function of a DEA circuit, particularly if the sum of these currents is of a similar to the magnitude to that of the current induced in the circuit due to the AC sensory signal. This influence can be greatly reduced by increasing the frequency of the sensor signal. This serves to increase the magnitude of the complex current through the DEA, effectively ‘drowning out’ the leakage current and current due to the capacitance changing. For portable systems however this has practical implications: common DC-DC converter circuit designs have rectified outputs and are not well suited to sinking current, making faithful reproduction of high frequency signals problematic. Furthermore the ‘harder’ a power supply has to work to generate the sensing signal, the less current capacity is available for charging the DEA, limiting actuation bandwidth.

A further constraint of using an AC signal to sense the capacitance of a DEA is that in all of the examples cited in this section, each self-sensing system necessarily couples the DEA to the power supply. A single power supply can therefore only generate a combined actuation/sensing signal for a single degree-of-freedom. Consider a portable application such as a realistic prosthetic hand: 20+ degrees of freedom are required to mimic the form and function of a real hand, many of which will require small, but very finely controlled actuators. Actuation will be intermittent, and it is unlikely that all of the degrees-of-freedom will be required to actuate
simultaneously. All of these factors suggest a dedicated power supply for each degree of freedom would be an inefficient use of volume and weight.

Resistive sensing, particularly DES, shows great promise as a means of detecting the position of a DEA. In the long term, DES also offer the enticing possibility of integrated position sensing, logic, and driver elements on a single DEA, paving the way for soft computing. Resistive sensing alone however is limited in its ability to be used in a health monitoring capacity. It is undoubtedly useful for estimating stretch and would be well suited to preventing tensile failure. Furthermore its ability to render a DEA mecano-sensitive with virtually no computational overhead is particularly attractive for the integration of built in ‘reflex’ actions to a DEA based device. For other modes of failure such as dielectric breakdown and electromechanical instability however resistive sensing is less effective.

2.2.4. Conclusions

In reviewing the prior art, several gaps in the literature have been identified:

1. DEA have three key electrical parameters: electrode resistance, capacitance, and leakage current through the dielectric membrane, however, there are no examples of self-sensing where all three have been estimated online in real-time. In fact, only one self-sensing system has demonstrated the simultaneous estimation of more than one parameter.

2. Capacitance has shown great promise as an indicator of the mechanical state of the DEA, but the techniques that have been used to simultaneously actuate a DEA and measure its capacitance are not well suited to low power driving electronics.

3. Experimental results suggest significant charging/discharging current or a high rate of change of the capacitance of a DEA affect the accuracy of capacitance estimations, however, these effects have not been accounted for in any of the self-sensing examples.

4. There is only one example of self-sensing (O’Brien et al.) where the feedback has been used to modify the output of the DEA, and in this example the DEA only responds to mechanical disturbances. In other examples of self-sensing, feedback has only been used to monitor the behaviour of the DEA as it is subjected to an arbitrary actuation signal or an external mechanical disturbance.

5. There are no examples where self-sensing has been used to prevent failure in DEA.
In the remainder of this thesis, a self-sensing system will be developed that seeks to address the issues identified above. More specifically, a self-sensing system that is capable of measuring all three key electrical parameters of a DEA simultaneously will be described. This system has been designed from the ground up with the capabilities and limitations of low power driving electronics suitable for DEA applications in mind. The algorithm used to estimate the parameters of a DEA is well suited to implementation in an embedded system such as a microcontroller or an FPGA. Furthermore, this self-sensing system will be experimentally validated. Importantly, it will be used to demonstrate advanced DEA functions such as position and stiffness control that have not been reported previously, and its feasibility as a part of a system for monitoring the health of a DEA will be shown.

2.3. Chapter Summary

DEA have exhibited great promise as muscle-like actuators. To expand beyond the laboratory however they must be applied to real-world applications. In practical applications, predictable behaviour and reliability are essential. In the simplest sense this can be achieved by tightly constraining the DEA and applying a large safety factor with regard to the maximum applied electric field, but DEA are capable of significantly greater performance than this approach allows. Feedback directly from the DEA is critical to expanding the scope of what is possible using DEA in a way that does not unnecessarily constraining the DEA with additional sensors and support structures.

The capacitance of a DEA, the ESR of its electrodes, and leakage current through the EPR of the dielectric membrane are all linked to its mechanical state and its health. By monitoring each of these parameters, in real-time, there is significant potential for considerably greater control of the mechanical behaviour of the DEA and improved reliability. Several attempts have been made to sense the various electrical parameters of a DEA whilst it is being actuated, but none have combined real-time sensing of all three key electrical parameters. Furthermore, with the exception of Toth and Goldenberg, there has been limited thought regarding the implementation of self-sensing as part of a compact, portable system. DEA are lightweight, fundamentally scale invariant devices, thus the lower bound of the overall size of a device is heavily dependent on the scale of the driving electronics. For smart DEA devices to be untethered from bench-top power supplies and desktop computers it is necessary to incorporate the capabilities and limitations of compact driver electronics into the design criteria of a self-sensing system.
Self-sensing for DEA

The capacitance of a DEA, the ESR of its electrodes, and leakage current through the EPR of the dielectric membrane have been identified as key parameters that will provide valuable information regarding the mechanical state and health of a DEA. Acquiring this information is a fundamental step towards enabling greater control of the electromechanical behaviour of a DEA. In the prior art, no example of a system that can reliably estimate all three of these parameters in real-time whilst applying a driving voltage has been presented.

In this chapter the development of a novel self-sensing system for DEA specifically targeted for portable devices will be discussed. In a departure from the prior art, Pulse Width Modulation (PWM) was used to simultaneously generate a large scale DC offset to control the level of actuation and a small scale electrical oscillation to facilitate sensing the electrical parameters. This chapter specifically addresses the first objective of this thesis: an algorithm for estimating the key electrical parameters of DEA during both static and transient operating conditions that is suitable for a portable device is derived.

3.1. Pulse Width Modulation applied to DEA

Sensing the capacitance of a DEA requires the application of a periodic electrical disturbance. In the prior art this was achieved by superimposing a high frequency, low amplitude AC voltage signal onto the DEA actuation signal. This necessarily requires a tone generator, and as discussed in Chapter 2 is not well suited to the capabilities of low-power, high-gain DC-DC converters. As demonstrated in the examples presented in Chapter 2 it also couples the dynamics of the DEA to the dynamic behaviour of the power supply, and prevents the power supply from being used to control multiple DEA independently.
In a departure from the prior art, PWM has been chosen as the method for controlling the voltage across the DEA. A PWM signal is a square wave with a fixed frequency and an adjustable duty cycle, where the duty cycle is the ratio of the time the signal is high to the period of the signal (see Figure 3-1). By making the period, \( T \), of the PWM signal sufficiently small relative to the electrical and mechanical time constants of the DEA, controlling the duty cycle of the signal \( t/T \) controls the average voltage across the DEA, which governs the degree of actuation. At the same time, the rapid switching of the PWM signal introduces small scale oscillations to this voltage, and it will be shown in this chapter that this is can be used to sense the electrical parameters of the DEA.

**Figure 3-1**: Schematic diagram of a PWM waveform. The period of the PWM signal is equal to \( T \), and the duty cycle of the PWM signal is equal to \( t/T \).

PWM control is achieved by connecting the DEA to a power supply via a high speed switch. There are several advantages to this configuration:

1. PWM is a digital technique that is readily compatible with microcontroller architectures. Microcontrollers are ideal for portable devices: they provide considerable computational power in an inexpensive, compact, low-power form, and many have dedicated on-chip hardware for generating a PWM signal.

2. PWM is a simple method for controlling an analogue device with a digital signal. The DEA acts as a low pass filter to the PWM signal, effectively converting the digital signal to an analogue voltage proportional to the duty cycle.
3. The oscillation in voltage across the DEA due to the rapid switching of the PWM signal eliminates the need for an additional tone generator.

4. The power supply can be set to a fixed voltage. Rather than controlling the voltage across the DEA by changing the output voltage of the power supply, switches connecting the DEA to the power supply regulate the charging current to the DEA and therefore the actuation voltage of the DEA. This effectively decouples the dynamics of the DEA from the dynamics of the power supply, shifting this function to the switches instead.

5. The power supply can be connected to multiple DEA simultaneously. The output voltage of the power supply is effectively independent of the voltage across the DEA, therefore multiple DEA can be connected to a single power supply, and they can be controlled independently.

In normal operation the voltage across the DEA will always be less than or equal to the voltage of the power source*. The power supply therefore is acting purely as a current source and is not required to sink current. This is particularly well suited to power supplies with a rectified output. Such a configuration however necessitates an alternative discharge path for the DEA. This can be achieved by passive or active means e.g. a resistor connected in parallel with the DEA or a second switch dedicated to discharging the DEA.

3.2. A circuit for acquiring raw feedback for DEA self-sensing

Sensing the electrical parameters of a DEA requires measuring the voltage across the DEA and the series current through the DEA. It is informative to consider the model of a DEA as part of a functionally complete circuit in order to better understand its behaviour (Figure 3-2, with the DEA shown enclosed in the blue rectangle). The power supply is based upon a compact, low power DC-DC converter connected to the DEA via a high speed, high voltage opto-coupler (OC100HG, Voltage Multipliers, Inc.)†. The output current of the opto-coupler, i.e., the current that flows from the DC-DC converter to the DEA, is proportional to the input current through the low voltage LEDs of the opto-coupler. By using a PWM signal to turn on and off the current

* A special case exists where an external mechanical disturbance is driving the deformation of the DEA: in this situation it is possible the DEA will enter a generator mode and the voltage across the DEA could grow to exceed the voltage of the power supply.

† The opto-coupler uses light to transmit electrical signals between two circuits whilst maintaining a high level of electrical isolation between the circuits. This enables the high voltage output of the DC-DC converter to be controlled using a low voltage signal from, for example, a microcontroller.
3.3 Fundamental equations for self-sensing

through the input LEDs of the opto-coupler, the DC-DC converter and opto-coupler combined act as a PWM current source ($I_{\text{source}}$).

![Diagram of DEA circuit](image)

**Figure 3-2**: A simple functionally complete DEA circuit that enables the capacitance of the DEA, the ESR of the electrodes, and leakage current through the EPR of the dielectric membrane to be measured.

A voltage divider is connected between the positive terminal of the DEA and ground ($R_{P1}$, $R_{P2}$), simultaneously providing a passive discharge path and a means for measuring the voltage at the positive terminal of the DEA. A fixed resistor is connected in series between the negative terminal of the DEA and ground ($R_S$). Together, $V_1$ and $V_2$ can be used to estimate the voltage difference between the positive and negative terminal of the DEA (Equation 3.1) and the series current ($i_{\text{series}}$) through the DEA (Equation 3.2).

\[
V_{DEA} = V_2 \frac{R_{P1} + R_{P2}}{R_{P2}} - V_1 \quad 3.1
\]

\[
i_{\text{series}} = \frac{V_1}{R_S} \quad 3.2
\]

### 3.3. Fundamental equations for self-sensing

Estimating the electrical parameters of a DEA requires acquiring and interpreting measureable electrical signals from a circuit containing a DEA. With reference to Figure 3-2, these measureable signals are the series current through the DEA ($i_{\text{series}}$) and the voltage difference between the terminals of the DEA ($V_{DEA}$). It is important however to consider what these signals represent.
Using Kirchhoff’s Current Law, the series current is the sum of the current through $C_{DEA}$ and the leakage current through $R_{EPR}$. Current is equivalent to the rate of change of charge with respect to time, and the charge on a capacitor is the product of its capacitance ($C_{DEA}$) and voltage ($V_C$). The current through $C_{DEA}$ is therefore the first derivative with respect to time of $C_{DEA}V_C$, taking care to note both $C_{DEA}$ and $V_C$ potentially have non-zero derivatives. Thus the series current through the DEA is the sum of three components: the current that is charging the DEA ($C_{DEA}dV_C/dt$), the current induced due to the rate of change of the capacitance ($V_CdC_{DEA}/dt$) and leakage current through $R_{EPR}$ ($i_{EPR}$) (Equation 3.3).

$$i_{series} = C_{DEA} \frac{dV_C}{dt} + V_C \frac{dC_{DEA}}{dt} + i_{EPR} \quad 3.3$$

Using Kirchhoff’s Voltage Law, the voltage across Circuit A (red box, Figure 3-2), is equivalent to $V_C$. The voltage difference between the terminals of the DEA ($V_{DEA}$) is therefore equal to the sum of the voltage across the electrodes and $V_C$. To go one step further, the voltage across the electrodes can be expressed as the product of the series current and the resistance of the electrodes ($R_{ESR}$), thus $V_{DEA}$ can be expressed in the form of Equation 3.4.

$$V_{DEA} = i_{series}R_{ESR} + V_C \quad 3.4$$

Equations 3.3 and 3.4 form the foundation upon which the self-sensing algorithm is based. It is clear however that there are 2 equations but 6 unknowns ($C_{DEA}$, $dC_{DEA}/dt$, $V_C$, $dV_C/dt$, $i_{EPR}$, and $R_{ESR}$). Additional steps are required to reduce this system to one that is solvable.

3.4. Evolution of a DEA self-sensing algorithm

The details of the final design of the self-sensing algorithm for DEA that was developed for this thesis are presented in Section 3.5, however it is informative to briefly summarise previous versions of the algorithm to provide context for the final design.

3.4.1. Self-sensing for DEA – Iteration #1

The first iteration of the DEA self-sensing algorithm focused on estimating the capacitance of the DEA [105]. With reference to Figure 3-2, the DEA was simplified to be a variable capacitor, i.e., $R_{ESR}=0$, $R_{EPR}=\infty$, and $V_C=V_{DEA}$. By selecting the frequency of the PWM signal to be much greater than that which can be reproduced mechanically by the DEA to be sensed, it
3.4 Evolution of a DEA self-sensing algorithm

could be assumed that the mean capacitance of the DEA was not affected by the oscillatory component of the actuation waveform.

If the capacitance is assumed to be constant for a single cycle of the PWM signal, i.e., a zero-order approximation, and leakage current is assumed to be negligible, the second and third terms on the right hand side of Equation 3.3 disappear. Thus the capacitance of the DEA could be determined from the slope of the voltage across the DEA during the “off” portion of the PWM input signal when the DEA was discharging (Equation 3.5). Where the period of the PWM signal was much shorter than the RC time constant of the DEA circuit*, the DEA voltage waveform was approximately linear for this period, and could be estimated by applying a linear least squares fit to the acquired voltage data.

\[ C_{DEA} = \frac{i_{series}}{\left(\frac{dV_{DEA}}{dt}\right)} \quad 3.5 \]

The first iteration of the self-sensing algorithm was limited in that it did not account for the resistance of the electrodes, leakage current, or the current induced due to the rate of change of the capacitance of the DEA. In particular, a sudden change in the capacitance of the DEA initially resulted in the estimated capacitance changing in the opposite direction to the actual capacitance (see Figure 3-3). Furthermore, leakage current and the voltage drop across the resistance of the electrodes affected \( i_{series} \) and \( dV_{DEA}/dt \) such that an estimation of \( C_{DEA} \) would be offset from its true value. Nevertheless, it was simple and was well suited to applications where the relative steady state capacitance was important and leakage current was negligible. O’Brien successfully implemented Iteration #1 of the self-sensing algorithm in several biomimetic arrays, including a linear array of 4 mechano-sensitive bending DEA elements that were made to actuate when they detected a small perturbation from their equilibrium position [106], an oscillating ball-on-rails system that used diaphragm DEA to autonomously propel a ball around a circular track [107], and to demonstrate autonomous travelling waves in planar and inflated DEA [108].

* Where \( R \) is the resistance of the discharge path of the DEA, i.e., \( R = R_s + R_{P1} + R_{P2} \).
3.4.2. Self-sensing for DEA – Iteration #2

The second iteration of the self-sensing system sought to address some of the shortfalls of the first. Clearly current due to the rate of change of the capacitance would need to be accounted for to improve the dynamic response of the self-sensing. Furthermore, it was necessary to compensate for the effects of leakage current at high electric fields. The first step therefore was to revisit the simplifications that were made of Equation 3.3, and determine a method for incorporating the effects of the second and third terms from the right hand side into the self-sensing process.

To enable the second and third terms of Equation 3.3 to be grouped together, leakage current was expressed in terms of the voltage across the capacitance of the DEA and $R_{EPR}$. Thus Equation 3.3 became Equation 3.6.

$$i_{\text{series}} = C_{\text{DEA}} \frac{dV_c}{dt} + V_c \left( \frac{dC_{\text{DEA}}}{dt} + \frac{1}{R_{EPR}} \right)$$

Equation 3.6 could be further simplified by evaluating the parameters at a point in time where $dV_c/dt = 0$, thus eliminating the first term on the right hand side. At this point in time, it is therefore possible to combine the effects of the rate of change of capacitance and leakage current into a single error term $K$ (Equation 3.7). By assuming $K$ remains constant for a short
3.4 Evolution of a DEA self-sensing algorithm

period after it has been calculated, $C_{DEA}$ can be estimated using Equation 3.8 for any point in time where $dV_C/dt \neq 0$. Furthermore, once $C_{DEA}$ is known, finite differences can be used to calculate $dC_{DEA}/dt$. This can be substituted back into Equation 3.7 to enable the calculation of $R_{EPR}$, and thus leakage current.

$$\frac{i_{series}}{V_C} = \left(\frac{dC_{DEA}}{dt} + \frac{1}{R_{EPR}}\right) = K \quad \text{3.7}$$

$$C_{DEA} = \frac{i_{series} - V_C K}{(dV_C/dt)} \quad \text{3.8}$$

The point in time at which $dV_C/dt = 0$ occurs is during the period when the PWM signal is transitioning from ‘on’ to ‘off’, or vice versa. For a conventional PWM signal with a very high slew rate, i.e., where the transition between ‘on’ and ‘off’ is effectively instantaneous, it is entirely impractical to evaluate the state of the circuit the point in time when $dV_C/dt = 0$. To improve this situation the slew rate of the PWM signal used for self-sensing was capped, i.e., the rising and falling edges of the PWM waveform became ramps rather than step changes. This expanded the period of time over which the transition between the on and off states occurred and made it feasible to determine the point in time when $dV_C/dt = 0$ (Figure 3-4).

![Figure 3-4: Schematic representation of the voltage across the capacitance of a DEA (dash-dot green line, top) and the series current through the DEA (solid red line, middle) when a PWM input current signal with a limited slew rate (dashed blue line, bottom) is supplied to the DEA circuit](image)

At $t = t_0$:

$\rightarrow dV/\text{dt} = 0$

$\rightarrow i_k/V_k = K$
Equations 3.7 and 3.8 enabled capacitance and leakage current to be determined provided the voltage across the capacitance of the DEA, $V_C$, was known. Recalling Equation 3.4 however, it was necessary to account for the resistance of the electrodes before capacitance and leakage current could be estimated. Figure 3-5 illustrates the influence of $R_{ESR}$ on $V_{DEA}$ (top) for a short period of time centred on the point in time that a PWM input current signal transitions from the ‘off’ to the ‘on’ state (bottom). Note for both $V_{DEA}$ waveforms shown in the top plot of Figure 3-5, $V_C$ is the same. However, for the dashed blue line $R_{ESR}=0$, thus $V_{DEA} = V_C$, while for the solid red line $R_{ESR}=500 \, k\Omega$, thus $V_{DEA}$ has a current dependent term. This is reflected by the difference between the two lines. Most notably however, when $R_{ESR}$ is significant, ‘corners’ appear in the $V_{DEA}$ waveform as the PWM signal changes state (see $V_{DEA}$ for $R_{ESR}=500 \, k\Omega$ at $t=t_{ref}$ and $t=t_f$ from Figure 3-5). This feature provides a mechanism that can be used to evaluate $R_{ESR}$. By rearranging Equation 3.4 to be in terms of $V_C$ (Equation 3.9), the correct value for $R_{ESR}$ will transform the solid red line from the top graph of Figure 3-5 to the dashed blue line, thereby eliminating the corners.

![Figure 3-5: A schematic representation of the influence of $R_{ESR}$ on the waveform of $V_{DEA}$ (top) when the series current through the DEA (bottom) is controlled using a PWM input current signal with a limited slew rate. Note the data corresponds to a period of time less than the period of the PWM signal, and is centred on the start of a cycle of the PWM signal.](image-url)
3.4 Evolution of a DEA self-sensing algorithm

\[ V_C = V_{DEA} - i_{series} R_{ESR} \]  

3.9

With reference to Figure 3-5, the necessary information to determine \( R_{ESR} \) can be obtained by using regression to fit straight lines to the voltage data and the series current data from Part 1, and the series current data from Part 2, and fitting a parabola to the voltage data from Part 2 (Equations 3.10-3.13). By substituting \( V_{DEA(Part \ 1)} \) and \( i_{\text{series}(Part \ 1)} \) into one expression for \( V_C \), and \( V_{DEA(Part \ 2)} \) and \( i_{\text{series}(Part \ 2)} \) into second expression for \( V_C \), the correct value for \( R_{ESR} \) will make the slope of each expression for \( V_C \) equal at \( t=t_{\text{ref}} \). Thus \( R_{ESR} \) can be found using simple algebra (Equation 3.14).

\[ V_{DEA(Part \ 1)} = m_{V1} t + c_{V1} \]  

3.10

\[ i_{\text{series}(Part \ 1)} = m_{i1} t + c_{i1} \]  

3.11

\[ V_{DEA(Part \ 2)} = a_2 t^2 + a_1 t + a_0 \]  

3.12

\[ i_{\text{series}(Part \ 2)} = m_{i2} t + c_{i2} \]  

3.13

\[ R_{ESR} = \frac{m_{V1} - 2a_2 t - a_1}{m_{i1} - m_{i2}} \]  

3.14

The accuracy of this self-sensing algorithm was verified using a numerical simulation created in MATLAB (R2008a, The Mathworks, Inc., Appendix 1). Based on the results of the numerical simulation, the second iteration of the self-sensing algorithm addressed all of the shortfalls of the first iteration. The resistance of the electrodes was accounted for, and accurate estimations of capacitance and leakage current were possible for static and dynamic operating conditions. Attempts to implement this system in a practical system however were only moderately successful. Accurate estimations of the electrode resistance were possible. Estimations of capacitance and leakage current had the correct nominal value, however, they were very noisy. In particular, calculating \( K \) (Equation 3.7) was highly sensitive to noise in the feedback signal, which translated to noise in the estimated parameters of the DEA. Further work was required to reduce the sensitivity of the self-sensing algorithm to noise in the raw feedback.
3.4.3. Self-sensing for DEA – Iteration #3

A simple but powerful breakthrough in the development of the self-sensing algorithm was the realisation that the derivative terms of the Equation 3.3 could be approximated using terms based on finite differences. This meant that rather than attempting to quantify the derivative of an inherently noisy feedback signal for a specific instant in time, the derivatives could be approximated using multiple data points spanning a short period of time. By using multiple data points to estimate average values for the parameters of interest, the influence of noise can be greatly attenuated. The system of equations used for self-sensing therefore become Equations 3.15-3.17*.

\[ i_{series} = C_{DEA} \frac{\Delta V_c}{\Delta t} + V_c \left( \frac{\Delta C_{DEA}}{\Delta t} + \frac{1}{R_{EPR}} \right) \]  

\[ \frac{i_{series}}{V_c} = \left( \frac{\Delta C_{DEA}}{\Delta t} + \frac{1}{R_{EPR}} \right) = K \]  

\[ C_{DEA} = \frac{i_{series} - V_c K}{\left( \frac{\Delta V_c}{\Delta t} \right)} \]  

Drawing a line of equal voltage across \( V_c \), such that it intersects \( V_c \) at two points, defines a period of time, \( \Delta t \), over which \( \Delta V_c = 0 \) (Figure 3-6). Thus \( K \) can be estimated by measuring the average of \( i_{series} \) for \( \Delta t \), and dividing it by amplitude of the line of equal voltage. Capacitance can then be estimated using the average \( i_{series} \) and the average \( V_c \) for any short period where \( \Delta V_c \neq 0 \). When implemented in a physical system, this new approach greatly reduced the noise in the estimated capacitance and leakage current. There was still room for improvement however. In particular, additional circuitry was required to impose the limited slew rate on the PWM signal. Furthermore, imposing a horizontal line on \( V_c \) in order to calculate \( K \) resulted in a significant improvement over Iteration #2 of the self-sensing algorithm when tested experimentally, but it still did not use all of the available data. It also required additional computation because it was necessary to ensure the line crossed \( V_c \) at two points in time. These issues were addressed in the next and current iteration of the self-sensing algorithm, which is discussed in the following section.

*Note \( i_{series}, C_{DEA}, V_c, \) and \( R_{EPR} \) now represent mean values over a period defined by \( \Delta t \)
3.5 3D DEA self-sensing

3.5.1 Sensing electrode resistance

In order to measure the capacitance of the DEA it is necessary to calculate the voltage waveform with respect to time across the capacitive element of the DEA. This can be found by subtracting the voltage drop across $R_{ESR}$ from the voltage drop across the DEA. In many respects this is convenient; measuring $R_{ESR}$ also provides information regarding the stretch state of the DEA.

The same principle that was used to estimate the resistance of the electrodes in Iteration #2 and Iteration #3 of the self-sensing algorithm has been used, only it has been adapted to work with a conventional PWM signal that does not have a limited slew rate. $R_{ESR}$ can be estimated at the points in time where the PWM signal is transitioning between the high and low states. For example, when the PWM signal is high the DEA is being charged and the current through the series resistance is positive, creating a positive voltage drop across the electrodes. When the PWM signal is low the DEA is discharging and the current through the series resistance is reversed, creating a negative voltage drop across the electrode resistance. A step change in the series current through the DEA when the PWM signal transitions therefore results in a step change in the voltage across the DEA because the voltage across a capacitor cannot change instantaneously (see Figure 3-7). This step change can be attributed to the voltage drop across
the electrodes. $R_{ESR}$ is the magnitude of the step change in the voltage across the DEA divided by the magnitude of the step change in the series current through the DEA at the transition of the PWM signal (Equation 3.18). By recording the time-history of the resistance values calculated, an $n$th-order approximation of resistance with respect to time can be used to estimate the electrode resistance at points in time between PWM transitions.

$$R_{ESR} = \frac{V_x - V_y}{I_x - I_y} \quad 3.18$$

### 3.5.2. Sensing capacitance and leakage current

At any instant in time the voltage across the capacitive component of a DEA is equal to the instantaneous electrical charge stored on the DEA divided by its capacitance, and the rate of change of the electrical charge is equivalent to the net current through the capacitive component. Thus the DEA capacitance, electrical charge, voltage, and time exhibit an interdependent relationship. This relationship can be exploited to determine the capacitance of the DEA and the leakage current through the dielectric membrane.

If the electrical charge stored on a DEA, the voltage across its capacitance, and time are plotted on orthogonal axes of a 3D graph for some period of time, the resultant cloud of unique datum...
3.5 3D DEA self-sensing

points describes a surface in 3D space. The partial derivatives of this surface at each of the datum points, i.e., \( \frac{\partial Q}{\partial V} \) and \( \frac{\partial Q}{\partial t} \), are related to the instantaneous capacitance and leakage current respectively. However, from a practical perspective it is computationally intensive to fit an arbitrary surface to a cloud of data. For a DEA we can greatly simplify this process by making the period of time short relative to the electrical and mechanical time constants of the DEA and linearizing the DEA over this short period. If we assume the behaviour of the capacitance of the DEA and the electrical charge lost to leakage current is approximately linear, the data points all fall substantially on a single 2D plane (shown schematically in Figure 3-8). The partial derivatives of the surface are therefore the same at each datum point, and thus all of the data points can be used to determine the characteristic equation of the surface using straightforward regression. Capacitance and leakage current can be estimated from the coefficients of this characteristic equation. This plane fitting process is effectively an extension of the line fitting process used in Iteration #3 of the self-sensing algorithm.

![Diagram of 3D plot with time (t), voltage (V), and charge (Q) as axes](image)

Figure 3-8: A schematic representation of the 3D plot with time (t) voltage (V), and charge (Q) as the three orthogonal axes. Example data points are shown as blue circles. Also shown is a plane fitted to the data points.

The plane fitting process can be described mathematically using the foundation equations (Equations 3.3 and 3.4). Building on these two relationships, a window of feedback data within which the series current through the DEA changes significantly can be used to determine \( C_{DEA} \) and \( i_{EPR} \). It is convenient, but not essential, to set the width of this window to correspond with the period of the PWM signal. The time \( t \) and the electrical charge stored on the DEA \( (Q_{C}) \) is defined to be zero at the beginning of the window. Where \( t_a \) is some point in time within the window, the integral with respect to time of \( i_{series} \) between \( t=0 \) and \( t=t_a \) is the total electrical charge that has passed through the DEA \( (Q_{input}(t_a)) \). The total electrical charge that has passed

56
through the DEA is equal to the sum of the integral with respect to time of the current through \( C_{DEA} \), and \( Q_{\text{leakage}}(t_a) \), the integral with respect to time of the leakage current (Equation 3.19, Equation 3.20).

\[
\int_{0}^{t_a} i_{\text{series}} \, dt = \int_{0}^{t_a} i_c \, dt + \int_{0}^{t_a} i_{EPR} \, dt
\]

\[
Q_{\text{input}}(t_a) = Q_c(t_a) - Q_c(0) + Q_{\text{leakage}}(t_a)
\]

When the period of the PWM signal is short relative to the electrical and mechanical time constants of the DEA, \( C_{DEA} \) can be modelled using a first order approximation i.e. \( dC_{DEA}/dt \) is assumed to be constant. Similarly, if the peak-to-peak amplitude of \( V_C \) for the period of the window is small relative to the absolute mean of \( V_C \), the leakage current through \( R_{EPR} \), i.e., \( dQ_{\text{leakage}}/dt \), can be assumed to be constant. Applying these assumptions to Equation 3.20 and expressing the charge in terms of \( C_{DEA} \) and \( V_C \) results in Equation 3.21. If \( t, V_C, \) and \( Q_{\text{input}} \) are then plotted on the \( x, y, \) and \( z \) axes respectively of a 3D plot, the points will all fall substantially on a single 2D plane (see Figure 3-8).

\[
Q_{\text{input}}(t_a) = C_{DEA}(t_a)V_C(t_a) - C_{DEA}(0)V_C(0) \frac{dQ_{\text{leakage}}}{dt} t_a
\]

The coefficients of the plane formed by the \( t, V_C, \) and \( Q_{\text{input}} \) data are equivalent to the partial derivatives with respect to \( t \) and \( V_C \) of \( Q_{\text{input}} \). That is, the partial derivative with respect to \( V_C \) of \( Q_{\text{input}} \) is capacitance \( (C_{DEA}) \) (Equation 3.22, time indices have been omitted for clarity). Note the \( C_{DEA}(0)V_C(0) \) term from Equation 3.21 is a constant thus does not appear in the partial derivative. The partial derivative with respect to time of \( Q_{\text{input}} \) is the combined effect of the rate of change of the capacitance \( (V_C \partial C_{DEA}/\partial t) \), and the leakage current through the dielectric membrane \( (\partial Q_{\text{leakage}}/\partial t) \) (Equation 3.23, time indices have been omitted for clarity).

\[
\frac{\partial Q_{\text{input}}}{\partial V_C} = C_{DEA}
\]

\[
\frac{\partial Q_{\text{input}}}{\partial t} = \frac{\partial C_{DEA}}{\partial t} V_C + \frac{\partial Q_{\text{leakage}}}{\partial t}
\]

\* i.e., \( Q(t_a) \), the charge on the capacitor at \( t=t_a \), minus \( Q(0) \), the charge at \( t=0 \)
3.5 3D DEA self-sensing

An estimate of $C_{DEA}$ can thus be derived directly from the slope of the plane of best fit along the direction of the voltage axis. Finite differences can then be used to evaluate $\partial C_{DEA}/\partial t$, and this can be substituted back into Equation 3.23 to separate the current induced due to the capacitance changing and the leakage current. Leakage current can thus be derived from the slope of the plane of best fit along the time axis.

The plane that best fits the available data in the least squares sense can be found using regression. The plane equation is of the form $f(x,y) = a_1x + a_2y + a_3$, where $t$, $V_C$ and $Q_{input}$ represent $x$, $y$, and $f(x,y)$ respectively. Thus, in the general case, the values for $a_1$, $a_2$, and $a_3$ that define the least squares solution can be found by solving the set of linear equations in (Equation 3.24).

$$Ma = b$$

Where:

$$M = \begin{bmatrix}
\sum_{j=1}^{n} t_j^2 & \sum_{j=1}^{n} t_j V_{C_j} & \sum_{j=1}^{n} t_j \\
\sum_{j=1}^{n} t_j V_{C_j} & \sum_{j=1}^{n} V_{C_j}^2 & \sum_{j=1}^{n} V_{C_j} \\
\sum_{j=1}^{n} t_j & \sum_{j=1}^{n} V_{C_j} & \sum_{j=1}^{n} 1 
\end{bmatrix},
a = \begin{bmatrix}
a_1 \\
a_2 \\
a_3 
\end{bmatrix},
b = \begin{bmatrix}
\sum_{j=1}^{n} t_j Q_{input_j} \\
\sum_{j=1}^{n} V_{C_j} Q_{input_j} \\
\sum_{j=1}^{n} Q_{input_j}
\end{bmatrix}$$

For a set of three equations with three unknowns, this set of linear equations can be solved in a straightforward manner by applying Cramer’s rule. Where $i = \{1, 2, 3\}$, the unknown variable $a_i$ can be found using Equation 3.25, where $M_i$ is the matrix formed by substituting the $i$th column of $M$ with the column vector $b$.

$$a_i = \frac{\det(M_i)}{\det(M)}$$

An important part of successfully fitting a plane to the available data points is the oscillations in the voltage across the DEA. Without these oscillations the $Q_{input}$, $V_C$, and $t$ data would collapse into a line in 3D space. It would therefore be impossible to find a unique plane that passed through all of the data points because the system of equations would be under-determined and the plane fitting process will fail. With the oscillations the raw data no longer forms a line, and therefore a unique plane can be fitted to the available data points.
3.5.3. Key advantages of the self-sensing method

The overwhelming advantages of this self-sensing method is that $C_{DEA}$ is obtained directly from fitting the plane to the available data, and it has an inherent mechanism for attenuating noise in the feedback signal. This is apparent at multiple levels of the parameter estimation process.

1. By making the period of the PWM signal short relative to the electrical time constant of the DEA, the voltage and series current data can each be separated into the charging and discharging portions of the PWM cycle and linearized with minimal loss of information. Estimating the resistance of the electrodes using the step change in the series current and the step change in the voltage across the DEA when the PWM signal transitions therefore becomes a simple exercise in solving simultaneous equations.

2. Integrating the series current acts as a means of low pass filtering the series current feedback data. Where noise has a mean value of zero, integrating acts to attenuate the noise component from the signal.

3. Using regression to fit a plane to the available data uses all of the data available. It does not rely on datum points from any one instant in time hence the influence of spurious data points on the estimated parameters are minimised.

Using a least squares regression process also provides a mechanism for evaluating the validity of the constant $dC_{DEA}/dt$ and $dQ_{leakage}/dt$ assumptions. Where the assumptions are valid, the residual of the regression process will be small. A large residual however indicates that one or both of the assumptions are not satisfied.

3.5.4. Limitations of the self-sensing method

The primary limitation of the DEA self-sensing system presented in this chapter is that it is a two stage process. The ESR of the electrodes must be calculated first, and the estimated value must be used to modify the raw feedback data in order to estimate capacitance and leakage current. The self-sensing system also makes use of regression to fit a plane to a cloud of feedback data. For a short period of time, the DEA is linearized about an operating point and feedback data spread over this period is interpreted according to this approximation. The accuracy of this approach relies on two assumptions: that $dC_{DEA}/dt$ is constant for the period of the feedback; and that the average leakage current through the dielectric membrane is constant for the period of the feedback. Where one or both of these criteria are not met the data cloud
will describe a curved rather than a flat surface. For example, if the DEA was being driven at audio frequencies the second derivative of capacitance may be significant, or if the rate of charging or discharging is so great the voltage changes significantly over the period of the feedback window the leakage current may also change significantly. The goodness of fit of the fitted plane will degrade. This will effectively introduce a phase delay between the electrical parameters of the DEA as estimated using the fitted plane and their true values. This can be addressed by shortening the period of the feedback window, thereby improving the linear approximation of the plane fitted to the feedback data. However, this requires either the number of feedback data points acquired to be reduced, thus potentially increasing the influence of noise; or the feedback sampling rate to be increased.

3.6 Visualisation of the 3D self-sensing process

It is convenient to demonstrate the influence of the electrical parameters of the DEA on the self-sensing method using 3D graphs. This makes it easy to understand how the behaviour of each of the three key electrical parameters affects the plane fitting process. A numerical simulation of the simple circuit from Figure 3-2 was created in MATLAB (R2008a, The Mathworks, Inc.). This simulation demonstrated the influence of the electrical parameters of the DEA on the characteristic equation of the fitted plane (see Appendix 1). The numerical simulation allowed the input current waveform, the feedback resistors, $C_{DEA}$, $R_{ESR}$, and the $R_{EPR}$ from Figure 3-2 to be selectively manipulated. For a range of operating conditions, the voltages at the $V_1$ and $V_2$ nodes of the circuit were generated by the simulation and used to determine the electrical parameters of the DEA using the methods described in Sections 3.3 and 3.5.2.

Figure 3-9 displays the influence of capacitance on the fitted plane. Leakage current and $dC_{DEA}/dt$ were set to zero, and DEA capacitances of 500pF, 1000pF, and 1500pF were simulated (Figure 3-9 (a)-(c), respectively). Clearly increasing capacitance serves to increase the slope of the fitted plane along the direction of the voltage axis. The effect of a non-zero $dC/dt$ is shown in Figure 3-10. Leakage current was set to zero. The initial capacitance was fixed at 1000pF and the circuit was allowed to reach a steady state before a constant $dC_{DEA}/dt$ was applied. The values of $dC/dt$ shown correspond to the capacitance changing at a rate equivalent to (a) -625%/s, (b) 0%/s, and (c) 625%/s, which is equivalent to the area stretch of the DEA changing at a rate of 250%/s or approximately 5 times the peak strain rate of mammalian skeletal muscle as reported in [33]. In Figure 3-11 the impact of leakage current is demonstrated. The capacitance was fixed at 1000pF and the circuit was allowed to reach a
steady state before an $R_{EPR}$ of 250MΩ was connected across the capacitor. Starting from the same initial conditions, data for (a) a DEA circuit with $R_{EPR}=\infty$, and (b) with $R_{EPR}=250M\Omega$ are shown side-by-side as a comparison. Figure 3-12 shows the combined influence of leakage current and $dC_{DEA}/dt$. Starting from the same initial conditions, Figure 3-12 shows (a) the fitted plane for a DEA with a value for $dC_{DEA}/dt$ corresponding to -625%/s and $R_{EPR}=\infty$, and (b) the combined influence of a value for $dC/dt$ corresponding to -625%/s and an $R_{EPR}=250M\Omega$. Similarly in Figure 3-13 (a) the fitted plane for a DEA with a value for $dC_{DEA}/dt$ corresponding to 625%/s and $R_{EPR}=\infty$ is shown next to (b) the combined influence of a value for $dC_{DEA}/dt$ corresponding to 625%/s and $R_{EPR}=250M\Omega$. Both a non-zero value for $dC_{DEA}/dt$ and leakage current affect the slope of the fitted plane along the time axis.

![Figure 3-9: Simulation results demonstrating the influence of capacitance on the plane of best fit for (a) 500pF capacitance, (b) 1000pF capacitance, and (c) 1500pF capacitance. Note $R_{EPR}=\infty$ and $dC_{DEA}/dt=0$.](image)

![Figure 3-10: Simulation results demonstrating the influence of $dC_{DEA}/dt$ on the plane of best fit for capacitance changing at a rate equivalent to (a) -625%/s, (b) 0%/s, and (c) +625%/s. Note $R_{EPR}=\infty$ and $C_{initial}=1000pF$.](image)
3.6 Visualisation of the 3D self-sensing process

Figure 3-11: Simulation results demonstrating the influence of leakage current on the plane of best fit: (a) a DEA with $R_{EPR}=\infty$, and (b) a DEA with $R_{EPR}=250\, \text{M}\Omega$. Note $dC_{DEA}/dt=0$ and $C_{initial}=1000\, \text{pF}$.

Figure 3-12: Simulation results demonstrating the combined influence of $dC_{DEA}/dt<0$ and leakage current on the plane of best fit: (a) the capacitance of the DEA changing at a rate of $-625\%$/s with $R_{EPR}=\infty$, and (b) the capacitance of the DEA changing at a rate of $-625\%$/s with $R_{EPR}=250\, \text{M}\Omega$.

Figure 3-13: Simulation results demonstrating the combined influence of $dC_{DEA}/dt>0$ and leakage current on the plane of best fit: (a) the capacitance of the DEA changing at a rate of $+625\%$/s with $R_{EPR}=\infty$, and (b) the capacitance of the DEA changing at a rate of $+625\%$/s with $R_{EPR}=250\, \text{M}\Omega$.
3.7. Chapter Summary

In this chapter a novel method for sensing the capacitance of the DEA, the ESR of its electrodes, and leakage current through the EPR of the dielectric membrane whilst it is being actuated has been presented. This is the first example of self-sensing where all three key electrical parameters of a DEA are estimated in real-time, and it is the first to specifically account for current induced due to the capacitance of the DEA changing at a significant rate. This system uses a PWM signal that takes advantage of the capacitive nature of the DEA to generate a waveform with both a large DC offset used for actuation and a small amplitude oscillation used for sensing the electrical parameters of the DEA. The system presented has low sensitivity to noise in the feedback signals, and it is the first that has been designed to be readily compatible with microcontroller architectures and the current sourcing abilities of compact DC-DC converters. The self-sensing method presented also promotes a smaller overall system by enabling the possibility of using a single power supply that is set to a fixed voltage to power multiple independent DEA simultaneously.
**Experimental validation of DEA self-sensing**

To be truly useful artificial muscles, it must be possible to implement DEA self-sensing in a practical device. This is required to verify the theoretical developments outlined in Chapter 3 translate into real world benefits. This chapter contains the details of the experimental validation process for the self-sensing method. It begins with the design of the circuit used to obtain the necessary feedback information. Several mock DEA circuits, consisting of a high voltage capacitor and a range of resistors representing the ESR and EPR of a DEA, were used to validate the real-time sensing of the ESR and the leakage current. The accuracy of the real-time sensing of capacitance was then evaluated using three simple expanding dot DEA. This chapter specifically addresses the second objective of this thesis: the implementation of DEA self-sensing in a system suited to portable applications.

**4.1. Introduction**

The parameter estimations produced by the DEA self-sensing process presented in Chapter 3 must be validated against an independent estimation for the same parameters, for the same operating conditions. For a planar DEA configuration, capacitance can be estimated using video extensometry to measure the change in area of the electrodes. However, it is difficult to independently validate the ESR of the electrodes and the leakage current through the EPR of the dielectric membrane during actuation. Instead, the effectiveness of the self-sensing process at estimating these two parameters was evaluated using a mock DEA circuit consisting of a fixed capacitor and a range of fixed resistors. The chapter therefore is a collection of several experiments, each of which has been specifically designed to test different aspects of the DEA self-sensing system. The experiments were controlled using a custom built LabVIEW (2009, National Instruments) interface, the details of which can be found in Appendix 1.
4.2 Self-sensing feedback circuit design

Good quality feedback signals are required for the self-sensing system to accurately estimate the electrical parameters of the DEA. The system is designed to operate in a high voltage, low current regime. With any voltage driven device such as this, the acquired feedback is particularly susceptible to noise. Good circuit design is essential; minimising the length of circuit tracks and buffering signals where possible greatly improves noise rejection. Hardware and software filtering are also useful, but great care must be taken to ensure that the filters do not interfere with the circuit’s ability to capture the characteristic features of the signals of interest.

A prototype circuit was designed and fabricated to implement the self-sensing method (see Figure 4-1 for the circuit schematic). For the experiments conducted in this chapter, the circuit was connected to a desktop PC via a National Instruments Data Acquisition Card (DAQ) and controlled via LabVIEW, however, the circuit was specifically designed with the typical characteristics of standard microcontrollers in mind. That is, special care was taken to ensure the voltages on any signal line that interfaced directly with the DAQ fell within the range of 0-5V, and that the current sinking/sourcing requirements of any signal line running too or from the DAQ fell within the range of 0-5mA. This ensured that in the future, a microcontroller could be directly substituted for the desktop PC and DAQ card without requiring the circuit to be redesigned.

Figure 4-1: A prototype circuit designed to drive a DEA and provide feedback for the self-sensing system described in Chapter 3
An OC100G 10kV opto-coupler (Voltage Multipliers, Inc) driven by a PWM signal regulated the current flow from the high voltage supply to the load. A 100MΩ:120kΩ voltage divider between the positive terminal of the load (Node1) and the circuit ground was used to step down the voltage at the positive terminal for measurement. The negative terminal of the load (Node2) was connected to a 1.2V reference voltage rail via a 30kΩ resistor. Having a positive reference rail enabled the circuit to be designed such that $V_2$ remained positive relative to the ground potential for the full range of expected series currents through the load, whether the series current through the load was positive or negative. This eliminated the need to create a power rail with a negative potential, and shifts the voltage of the signal to a range that is suited to the Analogue-to-Digital Converter (ADC) inputs of a microcontroller.

The signals of interest were the voltage across the 30kΩ resistor ($V_2-V_{ref}$) and the voltage across the 120kΩ resistor ($V_1$). A quad package rail-to-rail operational amplifier (OPA-4344, Texas Instruments) placed as close as possible to the sense resistors was used to buffer each of the signals. The very small bias current at the input terminals of the OPA-4344 ensures the act of measuring the signals has a negligible impact on the behaviour of the system (max. ±10pA [109]). Each signal was filtered using a simple single pole, low pass RC filter before being buffered by a second OPA-4344 prior to being transmitted to an ADC (shown schematically on the right hand side of Figure 4-1). The active nature of the outputs of the amplifiers act to reject noise picked up by the transmission path between the amplifier and the ADC.

In all of the experiments conducted, a 200Hz PWM signal was used to control the input of the opto-coupler. The current source was configured to supply 90μA when the PWM signal was high and ~0μA when the PWM signal was low.

### 4.3. ESR and leakage current validation

The ESR and leakage current through the dielectric of hand fabricated DEA can vary widely even when produced with the same overall dimensions. Furthermore, both parameters can vary in a non-linear and time-dependent manner. Estimating both whilst a DEA is being actuated is a primary objective of this thesis that has not been addressed in the prior art. Thus several mock DEA circuits were constructed using nominally fixed value components to validate this aspect of self-sensing. This enabled the circuit to be broken down into its constituent parts so that they could easily be independently tested. The circuits consisted of a high voltage capacitor and a
4.3 ESR and leakage current validation

range of resistors representing the ESR and EPR of the DEA, and the self-sensing system was used to estimate these values.

4.3.1. Materials and methods

Every combination of four values for $R_{ESR}$ (no resistance, 225kΩ, 447kΩ, and 675kΩ) and three values for $R_{EPR}$ (no resistance, 300MΩ, and 150MΩ) was tested to evaluate the $R_{ESR}$ and leakage current estimation capabilities of the system. Each mock circuit was subjected to duty cycles corresponding to average voltages across the mock DEA of 500-2500V in 500V steps. A high voltage multilayer ceramic capacitor with a rated capacitance of 2.2nF was used in the mock circuit (ECKD3J222MDU, Panasonic).

The voltage and frequency dependent characteristics of the high voltage multilayer ceramic capacitor were unknown, thus a simple calibration routine was used to eliminate the effects of these phenomena on the feedback data for the $R_{ESR}$ and leakage current validation process. With just the high voltage capacitor connected between Node1 and Node2 (see Figure 4-1), duty cycles that resulted in voltages across the capacitor of 500-3000V in 500V steps were applied. The estimated $R_{ESR}$ and leakage current for the test cycle were plotted against duty cycle and the resultant fitted curves were defined as the “Zero ESR” and “Zero Leakage Current” curves respectively. In subsequent experiments with the mock DEA circuits, the applied duty cycle was used to calculate the “zero value” for each parameter. The zero value was then subtracted from the raw estimated value for each parameter to determine the true ESR and leakage current.

4.3.2. Results

Figure 4-2 shows raw data used to determine the Zero ESR curve (red crosses), and the resultant first order approximation of that data (dashed blue line, Equation 4.1). Figure 4-3 shows the raw data used to determine the Zero Leakage Current curve (red crosses), and the resultant first order approximation of that data (dashed blue line, Equation 4.2).
Chapter 4. Experimental validation of self-sensing for DEA

Figure 4-2: The "Zero ESR" curve obtained from the calibration of the self-sensing driver/feedback circuit

\[
ESR_{\text{zero}} = 733.7 \times \text{duty} - 1607.3
\]  

4.1

Figure 4-3: The "Zero Leakage Current" curve obtained from the calibration of the self-sensing driver/feedback circuit

\[
\text{Leakage}_{\text{zero}} = 0.832 \times 10^{-9} \times \text{duty} - 54.988 \times 10^{-9}
\]  

4.2

Figure 4-4 shows the experimental validation of the ESR estimation. The lines indicate the true values of \( R_{\text{ESR}} \), and the data points indicate the estimated value for \( R_{\text{ESR}} \). There are three sets of data for each value of \( R_{\text{ESR}} \): one for each of the three values of \( R_{\text{EPR}} \). Figure 4-5 shows the experimental validation of the leakage current estimation. The lines indicate the predicted leakage current based on the voltage across the capacitive element of the mock DEA circuit and the value of \( R_{\text{EPR}} \). There are four sets of data for each value of \( R_{\text{EPR}} \): one for each of the four values of \( R_{\text{ESR}} \).
4.3 ESR and leakage current validation

Figure 4-4: $R_{ESR}$ of the mock DEA circuit as estimated using the self-sensing system (marked with data points) versus the actual $R_{ESR}$ (marked with lines) for a range of values of $R_{ESR}$ and $R_{EPR}$.

Figure 4-5: The leakage current through $R_{EPR}$ as estimated using the self-sensing system (marked with data points) versus the leakage current as predicted based on the voltage across $R_{EPR}$ of the mock DEA circuit and the $R_{EPR}$ (marked with lines) for a range of values of $R_{ESR}$ and $R_{EPR}$.

4.3.3. Discussion

The performance of the $R_{ESR}$ and leakage current sensing is excellent. $R_{ESR}$ is consistently estimated to within ±10kΩ for a wide range of voltages series resistance values. Leakage current through the EPR of the mock DEA circuit is accurate to less than 100nA for all of the conditions tested. It is difficult however to compare this performance to examples from literature because limited information is available. Keplinger et al. [102] were the only example of DEA self-sensing where capacitive and resistive sensing were combined, however the work they presented was very much a proof of concept. No information was provided that confirmed the accuracy of the resistive sensing. Similarly the resistive feedback in the system presented by O’Brien et al. [48] was used to generate training data for a position controller, thus it was not
necessary to use an independent method to confirm the absolute accuracy of the estimated electrode resistance. Furthermore, with regard to sensing leakage current through the membrane of the DEA there are no examples from the prior art with which to compare. Nevertheless, accurate estimates of both $R_{ESR}$ and leakage current were achieved using the DEA self-sensing system described in Chapter 3 after a simple calibration routine was run. These results were achieved in spite of the fact the high voltage capacitor used in the mock DEA circuits had a capacitance with an unknown voltage dependence. Estimations for $R_{ESR}$ exhibited negligible voltage dependence for a range of voltages representative of those likely to be applied to a DEA (Figure 4-4). Furthermore, the estimated $R_{ESR}$ exhibited no notable dependence on the magnitude of the leakage current. Leakage current itself was accurately estimated for a range of values of $R_{EPR}$ over a range of applied voltages (Figure 4-5). This reinforces the accuracy of the estimation of $R_{ESR}$; estimation of leakage current requires an accurate estimation of the voltage across the $R_{ESR}$.

4.4. Capacitive sensing verification

The voltage dependence of the high voltage multi-layer ceramic capacitor used in the mock DEA circuits was unknown, thus it was not used to verify the capacitive self sensing. Instead, an expanding dot DEA fabricated from a VHB4905 membrane was used to achieve this task. Using video extensometry, the ‘rest’ capacitance* of the DEA and the ratio of the instantaneous area of the electrodes of an expanding dot DEA to their ‘rest’ area can be used to estimate its capacitance (Equation 2.1). Before this experiment could be undertaken however, the fabrication of several expanding dot DEA, the design of a capacitance meter to measure the rest capacitance of each DEA, and the design of experimental apparatus for measuring the instantaneous area stretch using video feedback was required.

4.4.1. DEA fabrication

Three expanding dot DEA were used to verify the capacitive sensing component of the self-sensing process. Each DEA consisted of a 3M VHB4905 membrane stretched equibiaxially in its planar directions and bonded to a rigid support frame (Figure 4-6). The rigid support frame had a circular internal aperture with a diameter of 120mm. In the centre of the stretched membrane a silicone mask was used to apply concentric circular electrodes of diameter 45mm.

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* i.e. the capacitance of the DEA when there are no mechanical disturbances applied to it and when the applied voltage is 0 V.
4.4 Capacitive sensing verification

to opposing sides of the membrane using Nyogel 756 electrically conductive grease. Nyogel 756 tracks were also applied radially out from the electrode area to the points on the edge of the support frame that could be connected to external circuitry. Upon application of an activation voltage, the area of the DEA electrodes expanded radially. A second, independent DEA was patterned around the perimeter of the VHB membrane for the purpose of applying a disturbance. Activation of the second DEA relaxed the radial tension in the membrane around the perimeter of the expanding dot, causing it to contract until a new equilibrium between the electrostatic and mechanical forces was found.

Figure 4-6: An expanding dot DEA used to validate the capacitive sensing component of the self-sensing system

To ensure a spread of DEA capacitances were tested each of the three DEA had different planar stretch ratios: DEA #1 had an area stretch ratio of 6.25, DEA #2 an area stretch ratio of 12.5, and DEA #3 an area stretch ratio of 25. Thus because the area of the electrodes for all three DEA is constant, the rest capacitance of DEA #2 is approximately double that of DEA #1, and the rest capacitance of DEA #3 is approximately double that of DEA #2.

4.4.2. Rest capacitance meter

It is important to understand the frequency dependence of the capacitance of each of the DEA because a PWM signal is the sum of an infinite series of cosine waveforms with harmonic frequencies at multiples of the base PWM frequency. That is, for the 200Hz PWM signal used in these experiments, the harmonics are at 200Hz, 400Hz, 600Hz, and so on. The magnitude of
each harmonic is a function of the order of the harmonic and the duty cycle of the PWM signal. Thus it is possible that if the capacitance of the DEA is different for the higher harmonics of the PWM signal, the capacitance as estimated using self-sensing may deviate from the capacitance as estimated using video extensometry, which assumes a constant scalar value for the rest capacitance. Therefore, it is prudent to evaluate the rest capacitance of the DEA not only at the frequency of the PWM signal, but also at multiples of the PWM frequency.

A secondary circuit was designed and built for the purpose of evaluating the rest capacitance of each DEA (Figure 4-7). A 68.7kΩ resistor was connected between the negative terminal of the DEA and 2.5V reference voltage, and a sinusoidal voltage (2V amplitude, 2.5V DC offset) was applied to the positive terminal of the DEA. A range of frequencies from 100Hz to 3200Hz were tested to evaluate the frequency dependence of the capacitance of the DEA. Two unity gain op-amp buffer circuits (OPA-4344, Texas Instruments) placed close to the DEA were used to transmit the voltages at both the positive and negative terminals of the DEA and the voltage of the reference rail to a PC running LabVIEW 8.6 (National Instruments) via a PCI-6529 Data Acquisition (DAQ) card. The rest capacitance of the DEA was calculated by evaluating Equation 4.3, where \( I_{RMS} \) is the Root Mean Square (RMS) value of the current through the 68.7kΩ resistor, \( V_{RMS} \) is the RMS value of the sinusoidal input voltage, \( \omega \) is the frequency of the sinusoidal input voltage in radians per second, and \( \phi \) is the phase delay between the input voltage waveform and the voltage waveform as measured at the negative terminal of the DEA.

\[
C = \frac{I_{RMS}}{V_{RMS}\omega\sin(\phi)} \tag{4.3}
\]
4.4 Capacitive sensing verification

Figure 4-7: The low voltage capacitance sensor used to measure the rest capacitance of the DEA.

Figure 4-8 shows the frequency dependence of the capacitance of DEA #1, DEA #2, and DEA #3, respectively, for sinusoidal excitation frequencies ranging from 100Hz to 3200Hz.

Figure 4-8: The low voltage capacitance of the expanding dot DEA for a range of frequencies from 100Hz to 3200Hz.

4.4.3. Video extensometry apparatus

A USB camera (Quickcam, Logitech) running at 5 frames per second was used to measure the area of the expanding dot DEA as it was being actuated. Video extensometry was selected
because it is a non-contact process that does not affect the mechanical behaviour of the DEA, and because it provides a straightforward method of measuring strain in 2 dimensions. The camera was mounted on a purpose built jig that ensured the centre of the expanding dot DEA was aligned with the centre of the field of view of the camera, and that the plane of each DEA was positioned at the same fixed distance from the camera (Figure 4-9). The video feedback was calibrated to account for distortion near the edges of the image due to the perspective of the camera lens. A series of circular black discs of with diameters ranging from 20mm to 90mm in 10mm steps were placed in the centre of the field of view at the same distance from the camera as the plane of the DEA membrane. The area in pixels of each of the reference discs were correlated with the true area of the disc based on its physical dimensions, and a transformation function converting the number of pixels to a physical area was defined. The results of this calibration are shown in Figure 4-10, and the equation of the fitted curve is defined by Equation 4.4*.

* For reference, based on Figure 4-10 the mean area per pixel ranged from $131 \times 10^{-9}\, \text{m}^2$ for the 20mm disc, to $123 \times 10^{-9}\, \text{m}^2$ for the 90mm disc.
4.4 Capacitive sensing verification

![Figure 4-10: The area of the calibration discs in pixels plotted against the actual area of the calibration discs, with a 2nd order fitted curve.](image)

\[A_{true} = -8.3937 \times 10^{-14} A_{pixels}^2 + 1.2638 \times 10^{-7} A_{pixels} + 2.0221 \times 10^{-5}\]

4.4.4. Capacitive sensing materials and methods

The self-sensing circuit, the video feedback apparatus, and a 4-channel EAP Controller (Generation 2, Biomimetics Laboratory) were used to perform the capacitive sensing experiments (Figure 4-11). The EAP Controller was controlled using LabVIEW via a USB connection (connection to PC not shown). One output channel of the EAP Controller was used to control the voltage to the disturbance DEA, while a second output channel was used to provide a high voltage DC input of 4kV to the self-sensing circuit. The self-sensing circuit operated on battery power (6.6V Li-Po, Hyperion) and had on-board voltage regulation and signal amplifiers. Signals were sent to and from the PC via a cable connected to the DAQ card connector (cable not shown).
The initial area of each DEA was measured using video feedback without any actuation voltage to provide a reference area for determining the area stretch ratio of the DEA during high voltage testing. An initial duty cycle of 5% was then applied to the DEA for 20 seconds. This provided the voltage oscillations for the self-sensing algorithm to work, yet it only resulted in a mean actuation voltage of approximately 450V being applied to the DEA. For each DEA this resulted in only a very small deformation relative to the rest state of the DEA. After 20 seconds the duty cycle was then incremented by 1% every 10 seconds until the DEA had spent 10 seconds at a duty cycle of 30%. A duty cycle of 30% resulted in the mean actuation voltage reaching approximately 2800V, a limit imposed to prevent the DEA from failing due to dielectric breakdown. Also after the first 20 seconds of the test cycle, a sinusoidal voltage with a frequency of 0.25Hz was applied to the second DEA patterned around the perimeter of the DEA membrane to generate an external disturbance. This sinusoidal voltage had an amplitude and a DC offset of 1250V, 1000V, and 875V for DEA #1, DEA #2, and DEA #3, respectively. The disturbance was applied to ensure the self-sensing system was robust to changes to the load acting on the DEA. Feedback data, was written to file for post-processing using a custom MATLAB script (The Mathworks, Inc) (see Appendix 1).
The MATLAB script was used to analyse the video of the experiment to measure the area of the electrodes of the DEA on a frame-by-frame basis. The area of the electrodes was then used to estimate the capacitance of the DEA based on its physical dimensions for the duration of the experiment using Equation 2.1. The capacitance based on the change in area was then synchronised with the capacitance as estimated by the self-sensing process. For all three DEA the rest capacitance, $C_0$, used to estimate the capacitance of the DEA was the capacitance as evaluated using a 200Hz low voltage, sinusoidal excitation (see Section 4.4.2). The MATLAB script also used the area stretch of the DEA to estimate the electric field within the dielectric membrane. The thickness of the membrane was estimated to be the initial thickness of the VHB4905 (500µm) divided by the product of the prestretch of each membrane* and the area stretch as estimated using video extensometry. The electric field was the ratio of the instantaneous voltage across the capacitive component of the DEA, as recorded during the experiment, to the estimated thickness of the membrane.

4.4.5. Capacitive sensing results

Figure 4-12 shows a comparison of the capacitance of DEA #1 as estimated by the self-sensing process (solid blue line) and as estimated based on the change in the area of the electrodes (dash-dot red line) versus time for the capacitance verification cycle. Figure 4-13 shows the capacitance of DEA #1 as estimated by the self-sensing system plotted directly against the capacitance of DEA #1 as estimated using video extensometry (blue line), with a linear fit (dashed red line, Equation 4.6). Figure 4-14 shows the difference between the capacitance of DEA #1 as estimated using self-sensing and as estimated using video extensometry relative to the capacitance as estimated using video extensometry, which was calculated using Equation 4.5. Figure 4-15 to Figure 4-17 and Equation 4.7 show the equivalent information for DEA #2, and Figure 4-18 to Figure 4-20 and Equation 4.8 show the equivalent information for DEA #3. In Figure 4-21 the relationship between the applied electric field and the absolute area stretch of the membrane, and the relationship between the applied electric field and the error between the self-sensing capacitance and the video feedback capacitance is shown for each DEA.

\[
\text{Difference} = 100 \times \frac{(C_{SS} - C_{video})}{C_{video}} \quad \text{4.5}
\]

* i.e., 6.25 for DEA #1, 12.5 for DEA #2, and 25 for DEA #3.
Chapter 4. Experimental validation of self-sensing for DEA

Figure 4-12: Comparison between the capacitance of DEA #1 as estimated using the self-sensing system (blue line), and as estimated using video extensometry (red line).

Figure 4-13: The capacitance of DEA #1 as estimated by the self-sensing system, plotted directly against the capacitance of DEA #1 as estimated using video extensometry (blue line), with a linear fit (dashed red line).

\[ C_{\text{video}} = 0.9722C_{\text{SS}} + 0.0179 \]  

Figure 4-14: The difference between the capacitance of DEA #1 as estimated by the self-sensing system and as estimated using video extensometry.
4.4 Capacitive sensing verification

Figure 4-15: Comparison between the capacitance of DEA #2 as estimated using the self-sensing system (blue line), and as estimated using video extensometry (red line).

Figure 4-16: The capacitance of DEA #2 as estimated by the self-sensing system plotted directly against the capacitance of DEA #1 as estimated using video extensometry (blue line), with a linear fit (dashed red line).

\[ C_{video} = 0.9599C_{SS} + 0.0494 \]  

4.7

Figure 4-17: The difference between the capacitance of DEA #2 as estimated by the self-sensing system and as estimated using video extensometry.
Chapter 4. Experimental validation of self-sensing for DEA

Figure 4-18: Comparison between the capacitance of DEA #3 as estimated using the self-sensing system (blue line), and as estimated using video extensometry (red line).

Figure 4-19: The capacitance of DEA #3 as estimated by the self-sensing system plotted directly against the capacitance of DEA #1 as estimated using video extensometry (blue line), with a linear fit (dashed red line).

\[ C_{\text{video}} = 0.8118C_{\text{SS}} + 0.5239 \]  \hspace{1cm} 4.8

Figure 4-20: The difference between the capacitance of DEA #3 as estimated by the self-sensing system and as estimated using video extensometry.
4.4 Capacitive sensing verification

Figure 4-21: The applied electric field versus the absolute area stretch (left), and the applied electric field versus the difference between the capacitance as estimated using self-sensing and the capacitance as estimated based on the area of the electrodes (right) for DEA #1 (top row, blue), DEA #2 (middle row, red), and DEA #3 (bottom row, green).
4.4.6. Discussion

There is excellent agreement between the shapes of the capacitance as estimated by the self-sensing process versus the capacitance as predicted by the change in the area of the electrodes for all three DEA (Figure 4-12, Figure 4-15, Figure 4-18). In all three cases the capacitance as estimated using the self-sensing system at the initial duty cycle of 5% is very closely matched to the capacitance as estimated using the low voltage sinusoidal wave and the area stretch of the DEA. Due to the noticeable decrease in the capacitance of each DEA for excitation frequencies $>1$kHz (Figure 4-8), this indicates that the capacitance of the DEA as estimated by the self-sensing system is primarily a function of the first 5 harmonics of the PWM signal. Most importantly however the relationship between the capacitance as estimated using self-sensing and as estimated using video extensometry was found to be linear (Figure 4-13, Figure 4-16, Figure 4-19). From a control perspective this is ideal. For the planar DEA configuration tested, this enables the area of the electrodes to be determined from capacitance.

Of the three DEA, the results for DEA #3 are notably different from the other two DEA. For DEA #1 and DEA #2 the self-sensing capacitance matches the capacitance as estimated using video extensometry to $<2\%$ for the entire range of motion tested with no need for any form of calibration, and was substantially unaffected by the disturbance acting on the DEA. DEA #1 was subjected to the lowest electric fields during the experiment, and the difference between the two capacitances is primarily a function of noise. For DEA #2 and DEA #3 however the maximum electric field applied was much greater. At high electric fields the capacitance as estimated using the self-sensing exceeds the capacitance as predicted based on the change in electrode area. For DEA #2 this contributes to a relatively small difference between the two estimations of capacitance near the upper limits of the range of motion tested. However, the apparent over-estimation of the capacitance of the DEA by the self-sensing process is much more pronounced for DEA #3. This indicates the relative permittivity of VHB4905 does not remain constant under certain conditions. Nevertheless, when comparing the ratio of the two capacitances for DEA #2 (Figure 4-15) and DEA #3 (Figure 4-18), the relationship between each remains linear. Ultimately this indicates a simple calibration routine could reconcile the two estimations, however further research is required to identify the cause of this behaviour.

To explore the difference between the two capacitance estimations for DEA #3 in particular it is informative to consider the influence of electric field. Looking to Figure 4-21, it is clear that all three DEA exhibited the typical approximately quadratic relationship between electric field and
4.4 Capacitive sensing verification

area stretch for the range of conditions tested (see Equation 1.1). What is most significant however is that the results for DEA #2 and DEA #3 indicate that the relationship between the capacitance difference and electric field is approximately linear. Initially it was thought parasitic capacitance due to induced charging of the high voltage carbon grease track that acted as the electrical connection between the DEA and the edge of the support frame contributed to a greater sensed capacitance. However, for DEA #3, very similar results were achieved when the carbon grease traces connecting the expanding dot to the edge of the support frame were removed and replaced with a fine copper trace adhered to the DEA using the viscosity of the grease of the electrodes (Figure 4-22). Similarly, the error is not proportional to the voltage, suggesting it is not the result of errors in the feedback signal stemming from the behaviour of the self-sensing hardware. Furthermore, a review of the value of $dQ/dt$ recorded for DEA #3 during the experiment showed it exhibited a non-linear relationship with electric field, indicating this was not the source of the error either (Figure 4-23).

![Figure 4-22: Schematic diagram of DEA #3 where the carbon grease tracks connecting the expanding dot to the edge of the support frame have been replaced by fine copper traces.](image)

![Figure 4-23: Electric field versus $dQ/dt$ for DEA #3 during the capacitance validation test cycle.](image)
The results for DEA #2 and DEA #3 suggest the dielectric constant of VHB4905 has a weakly positive relationship with the electric field. Limited information regarding the high electric field dependence of the dielectric constant of VHB4905 is available in the literature, however this weakly positive relationship echoes the results of McKay et al. [69] where based on blocked force experiments, the dielectric constant of VHB4905 increased with increasing electric field. Similarly, in the self-sensing system presented by Keplinger et al. [102], the capacitance proportionally overestimated the change in area of an expanding dot DEA at electric fields below that which caused the DEA to transition into a buckled state. This is in contrast with the generally observed weakly negative relationship between dielectric constant and stretch for VHB4905 DEA. Where good contact is ensured between the electrodes and the dielectric membrane, low voltage testing of VHB4905 DEA has demonstrated the dielectric constant decreases by approximately 5-7% as the absolute area stretch increases from 1 to 25 [67, 69]. These results indicate competing mechanisms are at work on the dielectric constant of VHB4905. Clearly the self-sensing system represents a method for exploring these behaviours further.

4.5. Integrated self-sensing of DEA

4.5.1. Materials and methods

In a final experiment, the ability of the self-sensing system to respond to a dynamic actuation profile was tested. DEA #2 was subjected to a pseudo-random actuation signal whilst a sinusoidal voltage waveform with a frequency of 0.25Hz, and an amplitude and a DC offset of 1000V was applied to the perimeter DEA to generate a disturbance. The capacitance of DEA #2, the ESR of the electrodes, and the estimated value for \( dQ/dt \) were recorded.

4.5.2. Results

The estimated electric field applied to DEA #2 for the pseudo-random actuation cycle is shown in Figure 4-24. Also shown are the estimated capacitance of DEA #2 (Figure 4-25), the capacitance difference (Figure 4-26, calculated using Equation 4.5), the estimated ESR of the electrodes (Figure 4-27), and the estimated value for \( dQ/dt \) for the actuation cycle (Figure 4-28).
4.5 Integrated self-sensing of DEA

Figure 4-24: The electric field applied to DEA #2 for the duration of the pseudo-random actuation cycle.

Figure 4-25: The capacitance of DEA #2 as estimated using the self-sensing system (blue line) and as estimated using video extensometry (red line) versus time for a pseudo-random actuation cycle.

Figure 4-26: The difference between the capacitance as estimated using self-sensing and as estimated using the change in electrode area for DEA #2 for the duration of the pseudo-random actuation cycle.
4.5.3. Discussion

In the final experiment conducted for this chapter the capacitance of DEA #2, the ESR of the electrodes, and $dQ/dt$ were estimated for a pseudo-random actuation cycle. This pseudo random actuation cycle demonstrated the accuracy of the estimation of the capacitance of the DEA is not limited to quasi-static operating conditions, and remains accurate during transient conditions. It is also of significant note that the ESR of the electrodes does not display a monotonic relationship with the capacitance of the DEA. For the DEA configuration tested, this indicates that the ESR of the electrodes could be a function of both the geometry of the electrodes and percolation effects related to the change in the density of the conducting particles within the electrodes as they stretch. Furthermore this illustrates how, for carbon grease, the resistance of the electrodes drifts over time and exhibits complex transient behaviour when sudden changes in displacement are made, and highlights the need for real-time monitoring of the resistance of the electrodes.
4.6 Conclusions

Whilst this thesis is primarily focused on the use of DEA in closed loop control systems, it is readily apparent from the results of the experiments conducted that this self-sensing system will be a powerful tool for characterising the properties and the behaviour of DEA in situ and at high electric fields. The properties of new materials can be characterised experimentally for a range of operating conditions. Furthermore, the accuracy of the system is not limited to quasi-static operating conditions thus these properties can be evaluated in dynamic situations. In particular it also allows the relationship between the ESR of the electrodes and their stretch state to be characterised. Exploring this relationship will potentially enable the progression from using the estimation of the ESR simply as a step towards estimating capacitance, to using the ESR as a feedback variable in its own right to provide information regarding the stretch state of the DEA. Importantly, combining this information with the nominal electrode area and membrane thickness obtained from the capacitance of the DEA may enable the area stretch to be decomposed into stretches along orthogonal planar axes, which will be a valuable feature for DEA configurations more complex than the expanding dots used in these experiments.

4.6. Conclusions

In this chapter a method for estimating the equivalent series resistance of the electrodes, the capacitance of a DEA, and the leakage current through the dielectric membrane whilst the DEA is being actuated was experimentally validated. This system uses a PWM signal that takes advantage of the capacitive nature of the DEA to generate a waveform with both a large DC offset used for actuation and a small amplitude oscillation used for sensing the electrical parameters of the DEA. The experimental results demonstrate that accurate estimates of all three electrical parameters of interest can be made simultaneously for a wide range of operating conditions including when external mechanical disturbances are being applied to the DEA. Furthermore, the results presented clearly highlight the potential for the self-sensing system to be employed to characterise the performance and behaviour of DEA in situ, while they are being actuated, particularly at very high electric fields. This will be a powerful tool for quantitatively evaluating the performance of DEA materials, thus providing a mechanism for comparing them with each other.
4.7. Chapter Summary

Muscles are ‘smart’, that is, they act as both actuators and sensors. The feedback they provide is essential to their function. In this chapter it was demonstrated experimentally that actuation and sensing can be integrated into a single DEA element. Furthermore, this was achieved using a circuit design that can easily be implemented in a portable, battery operated device with minimal, if any, modification. This is an essential step towards creating true artificial muscles using DEA, and satisfies the second research objective of this thesis identified in Chapter 1.
Position and stiffness control of DEA

Muscle is incredibly versatile because both position and stiffness can be controlled. In Chapter 4 it was demonstrated that the self-sensing system is capable of accurately estimating the electrical parameters of DEA over a wide range of operating conditions. This represents a significant advancement of the current state of the art. The next step is to use self-sensing feedback to control the behaviour of DEA. This is important: in the prior art not related to this thesis, there has only been one example where self-sensing feedback has been used as part of a closed loop controller. In every other example self-sensing has only been used to monitor the properties of a DEA when it is subjected to an arbitrary disturbance or actuation voltage. It was demonstrated in the previous chapter that the capacitance of an expanding dot DEA enables its area to be determined. Furthermore, capacitance enables the electrical charge on the DEA to be estimated. In this chapter it will be demonstrated that capacitance and charge can be used to control area and the effective stiffness of the dot. This chapter specifically addresses the third and fourth research objectives of this thesis: to demonstrate a closed loop controller that uses feedback from the self-sensing system to achieve muscle-like control of position and stiffness of the DEA.

5.1. Introduction

For DEA ‘position control’ is a general term that warrants clarification. Relating the estimated electrical parameters of a DEA to its position is entirely dependent on the type of DEA that is used and the mechanism by which it is coupled to a load. Thus ‘position’ will have many different meanings depending on the DEA configuration used. For the purposes of this chapter, expanding dot DEA were used and the position of the DEA was defined to be equivalent to the area of the dot.
5.1 Introduction

In Chapter 4 it was demonstrated that the instantaneous area of an expanding dot DEA made from VHB4905 could be determined from its capacitance. Capacitance therefore forms the basis for the position and stiffness controller. The genesis of these controllers is straightforward: the mechanical output of the DEA is governed by the equilibrium between the force exerted by the load coupled to the output of the DEA, the passive stiffness of the DEA, and the electrostatic pressure generated by the actuation voltage. In the general case, the force exerted by the load should be treated as unknown and variable over time, and the passive stiffness of the DEA is a complex non-linear material property that cannot be changed. Thus controlling the equilibrium of these forces requires controlling the electrostatic pressure.

The electrostatic pressure and thus the mechanical behaviour of the DEA can be manipulated by charging or discharging the DEA. Using capacitance as a proxy for position, if the capacitance of the DEA is greater than the capacitance setpoint, reducing the electrostatic pressure will effectively increase the stiffness of the DEA and result in a net increase in the force acting against the load. All else being constant, the capacitance of the DEA will decrease as it contracts to a new equilibrium position. Reducing the electrostatic pressure requires a negative current through the capacitive component of the DEA to discharge it. The reverse is true if the capacitance of the DEA is below the capacitance setpoint: positive current through the capacitive component of the DEA charges the DEA and increases the electrostatic pressure, increasing the forces acting to enlarge the capacitance. Therefore, by controlling the charging/discharging current, the capacitance of the DEA can be driven to achieve a desired response.

The current through the capacitive component of the DEA \( (i_C) \) is equal to the total input current to the self-sensing circuit \( (i_{in}) \) minus the sum of leakage current \( (i_L) \) and the current through the parallel voltage divider \( (i_P) \) (Equation 5.1). Using feedback from the self-sensing circuit, \( i_L \) and \( i_P \) can be measured, and \( i_{in} \) can be controlled using the duty cycle of the PWM signal, thus \( i_C \) can be controlled. A position controller has been developed to control \( i_C \) to drive the DEA to a desired capacitance setpoint. Using the same basic structure, a separate controller capable of modifying the effective stiffness of the DEA controls \( i_C \) to drive the charge on the DEA to a desired setpoint. In this chapter, these controllers are demonstrated using the experimental setup from Chapter 4, including the self-sensing circuit, the test fixture, the USB webcam and the LabVIEW PC interface. DEA #2 from Chapter 4 was used as a test subject. Note while the expanding dot DEA does not couple to an external load, ultimately any form of position and stiffness control requires controlling the thickness compression and/or the areal expansion of
the DEA in some manner. The expanding dot DEA with a second independent DEA patterned around its perimeter provides a simple setup that enables an electronically controlled mechanical disturbance to be applied to the expanding dot DEA whilst it is being actuated. Importantly, this setup also enables the mechanical deformation of the expanding dot DEA to be measured in a straightforward manner using video extensometry without influencing the behaviour of the DEA.

\[ i_C = i_{in} - i_L - i_p \]  

5.2. Design and tuning of a position controller for an expanding dot DEA

5.2.1. Position controller design

In Chapter 4 the excellent agreement between the capacitance of DEA #2 as estimated using the self-sensing system and the capacitance as estimated using video extensometry clearly demonstrated that capacitance provides an accurate estimate of the area of the DEA. For convenience therefore capacitance is used as a proxy for area in the development of a position controller.

A proportional controller (P-controller) with a nested feedback loop has been developed to demonstrate the feasibility of closed loop control the capacitance of a DEA using self-sensing (Figure 5-1). The P-controller used the product of the error between capacitance setpoint \( C_{SP} \) and the actual capacitance of the DEA \( C_A \) (Equation 5.2), and a scalar gain coefficient, \( K_p \), to determine the desired value for the current through the capacitive component of the DEA, \( i_C \). The nested feedback loop evaluated the current required to compensate for leakage current through the dielectric membrane and the current through the parallel voltage divider used to measure the voltage across the DEA \( (i_L + i_P) \). All three currents were summed, and the ratio of this total current to the maximum amplitude of the input current waveform, a parameter that was also measured using feedback, was equivalent to the desired duty cycle to be applied to the DEA (Equation 5.3).

\[ C_{\text{error}} = C_{SP} - C_A \]  
\[ \text{Duty cycle} = \frac{K_p C_{\text{error}} + i_P + i_L}{i_{in,\text{max}}} \]
5.2 Design and tuning of a position controller for an expanding dot DEA

Figure 5-1: Schematic diagram of the controller used to control the capacitance and therefore the position of the expanding dot DEA.

A key advantage of the control structure is that it only has one parameter to be tuned, yet it ensures the capacitor will continue to be charged or discharged until the capacitance setpoint is reached. It is particularly powerful because the controller does not require explicit knowledge of the mechanical strain energy function of the DEA, or the magnitude of any loads or disturbances. The relative rather than absolute electrostatic pressure is controlled. This makes the controller inherently robust to time-dependent effects such as stress relaxation and creep. This is achieved by the inclusion of the nested feedback loop. Without it, a stand-alone P-controller acting on $C_{error}$ would result in steady state error between the capacitance setpoint and the actual capacitance*. This is a well-established characteristic of P-controllers, and the magnitude of this offset is equal to Equation 5.4 [110]. Clearly this error can be reduced by increasing the gain, $K_p$. However, $K_p$ cannot be increased indefinitely. In any closed loop controller, there is a time delay associated with the time it takes to process the feedback data, the time it takes to update the output of the controller, and the time it takes for the actuator to respond to the controller. If the state of the DEA changes significantly during this delay period, the output of the controller may be out-of-date by the time it is applied to the DEA and the stability of the system can be compromised. In the specific application presented in this chapter, this would typically result in the actual capacitance of the DEA oscillating about the capacitance setpoint.

* That is, once the transient response of the DEA has decayed and the DEA has reached an equilibrium state, the actual capacitance would be offset from the setpoint.
Note in Figure 5-1, the desired duty cycle that is calculated based on the self-sensing feedback is conditioned using a saturation block. The duty cycle was coerced to fall within the range of 5-35%. In this specific implementation of self-sensing, the driver and feedback circuit used in this experiment rely on a passive voltage divider to discharge the DEA, thus the duty cycle must be greater than zero at all times to generate voltage oscillations that enable the self-sensing algorithm to work. The lower bound of 5% was selected because, in the absence of a disturbance, a duty cycle of 5% resulted in negligible change in the capacitance of the DEA from its rest state. An upper bound of 35% limited the maximum voltage that could be applied to the DEA to be approximately 3.25kV. In a more advanced system these upper and lower bounds can be expanded. In particular, if the circuit was modified to have two switches, one that controlled the charging of the DEA from the power supply, and another that controlled the discharging of the DEA, the duty cycle could be allowed to span positive and negative values. A ‘positive’ duty cycle would correspond to the charging switch being active while the discharging switch remained off, while a ‘negative’ duty cycle would correspond to the charging switch remaining off while the discharging switch was active. This will serve to increase the speed of the transient response of the DEA.

**5.2.2. Position controller parameter tuning**

Before the position control experiments could be executed, it was necessary to tune the gain of the controller, $K_p$. The gain of the controller, with units of Amps per Farad, was manually tuned using the response of the DEA to a step change in the capacitance setpoint. The capacitance setpoint was toggled between two values: 1500pF, corresponding to an area stretch of approximately 7.5%; and 2000pF, corresponding to an area stretch of 24%. These values were chosen because they correspond to a large change in area, but are still within the bounds of the maximum and minimum capacitance the DEA could achieve. For low values for $K_p$, the controller would take a relatively long time to drive the capacitance of the DEA to the new setpoint when the setpoint was toggled. This was because a low $K_p$ leads to a low current $i_C$, and slow charging. Increasing $K_p$ resulted in higher values for $i_C$, thus the DEA charged faster and the settling time reduced. However, as identified in Section 5.2.1, $K_p$ could not be increased indefinitely. Starting from a value of 10 A/F, $K_p$ was gradually increased until the settling time of the DEA began increasing due to incipient oscillation. Increasing $K_p$ beyond $1 \times 10^5$ A/F
resulted in the settling time increasing, therefore $K_p = 1 \times 10^5 \, \text{A/F}$ was used as the gain for all three position control experiments.

### 5.3. Position control experimental methods and results

Several key dynamic behaviours were experimentally tested using the position controller developed in this section. It is important to ensure that together, the controller and the system are robust to a range of potential inputs. The experiments presented in this section reflect a range of common actuation profiles that are used to demonstrate the performance of a closed loop control system. The experimental apparatus from Figure 4-11 was reused for these experiments. In each experiment, the capacitance as estimated using the self-sensing system was correlated with the capacitance as estimated using video extensometry and the capacitance setpoint.

#### 5.3.1. Disturbance rejection

In the first experiment the ability of the position controller to reject disturbances was tested. This was important because it demonstrated that the position controller was robust to variations in the load acting on the DEA. The entire test cycle lasted approximately 62 seconds. At the start of the cycle, a DC voltage of 1414V was applied to the disturbance DEA patterned around the perimeter of the dielectric membrane*, and the DEA was driven to a capacitance setpoint of 1800pF. The DEA was maintained at the setpoint for 30 seconds to allow creep effects to substantially decay. Between 30 and 46 seconds, the capacitance controller was disabled, and a sinusoidal voltage waveform with a frequency of 0.25Hz, an amplitude and a DC offset of 1000V, and a phase delay of 45° was applied to the disturbance DEA†. The capacitance controller was re-enabled starting at 46 seconds. The entire cycle was repeated a second time except a square wave disturbance voltage was substituted for the sinusoidal disturbance voltage used in the first cycle.

The results of the controller acting to reject a sinusoidal and a square wave disturbance applied to the DEA patterned around the perimeter of DEA #2 are shown in Figure 5-2 and Figure 5-3

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* The electrostatic pressure is approximately proportional to the voltage squared, thus for a voltage waveform with a peak value of 2000V, 1414V represents an approximate midpoint for the pressure applied to the disturbance DEA. This ensured that when the disturbance waveform began oscillated it would both act to stretch and compress the DEA from its setpoint, thus causing $C_{true}$ to span both positive and negative values.

† The phase delay was chosen so that the initial value of the sinusoidal waveform was 1414V. This ensured there was not a step change in the disturbance voltage when it began to oscillate.
respectively. Note the initialisation period of the DEA has been truncated to focus on the dynamic aspects of each experiment.

Figure 5-2: The position controller acting to reject a sinusoidal disturbance. Note the position controller is deactivated between 8sec < time < 24sec.

Figure 5-3: The position controller acting to reject a square-wave disturbance. Note the position controller is deactivated for 8sec < time < 24sec.

Figure 5-2 and Figure 5-3 demonstrate the position controller is acting to reject the applied disturbance to the DEA. For the sinusoidal disturbance, there is a variation in the area of the DEA due to the disturbance was reduced by almost 80% when the controller was enabled. The range of motion of the DEA is reduced from a capacitance change of approximately 140pF, corresponding to a change in area of 3.8%, when the position controller is disabled, to approximately 30pF when it is enabled, corresponding to change in area of 0.8%.

Looking specifically at the region where both the controller and the disturbance were enabled (time > 24sec), there is a small difference between the capacitance as estimated using self-sensing and using video extensometry of approximately 20pF. In Chapter 4 it was demonstrated that the dielectric constant of VHB4905 appeared to have a minor dependence on electric field,
and the electric field would necessarily change in order to maintain a constant capacitance setpoint under the influence of varying disturbances. Alternatively this may simply be an artefact of the video feedback process. When the disturbance is applied, the design of DEA #2 leads to the expanding dot DEA becoming slightly elliptical, however the video feedback was calibrated to transform the area of the DEA to a physical area for circular shapes only. Nevertheless, from Equation 2.1, this corresponds to an error* in the predicted area of the DEA of less than 0.6%.

For the square wave disturbance, the influence of the disturbance is reduced by more than 90% when the controller is active. The range of motion is reduced from a capacitance change of approximately 170pF, corresponding to a change in area of 4.7%, to approximately 20pF, corresponding to an area change of 0.3%, when considering the capacitance as estimated using video feedback. Similar to the sinusoidal disturbance, there is a small difference observed between the self-sensing capacitance and the video feedback capacitance when both the disturbance and the controller are active. The transient response of the DEA also appears to deviate further from the setpoint when the controller is enabled when compared to the period when the controller is disabled. However, this can be explained by the behaviour of the controller. When the disturbance voltage is at its peak, the duty cycle required to sustain the setpoint is greater than if the disturbance was not present. When the disturbance transitions to 0V, the higher pressure due to the higher duty cycle drives the DEA above the setpoint before the controller can respond to counteract the disturbance. The reverse is true when the disturbance transitions from 0V to 2000V. The observed spike is therefore due to controller lag. Importantly, the transient response of the DEA is present in both the self-sensing data and the data from the video feedback. The transient response therefore is not a limitation of the self-sensing feedback but rather the inherent time constant of the specific system used in this experiment.

5.3.2. Setpoint tracking

In the second position control experiment, the ability of the controller to track a variety of capacitance setpoint waveforms was tested. The controller was used to track a sine wave, a square wave and a triangle wave, each oscillating between 1500pF and 2000pF at 0.25Hz. The range of capacitances corresponded to a change in the area of the DEA of approximately 16.5%.

\[ \text{error} = 100 \times \frac{(C_{\text{video}} - C_{\text{self-sensing}})}{C_{\text{video}}} \]

* Where error = $100 \times \frac{(C_{\text{video}} - C_{\text{self-sensing}})}{C_{\text{video}}}$
The frequency of actuation was chosen to demonstrate the dynamic response of the controller, but also to reflect the restrictions placed on the input power supplied to the DEA by the high voltage source, which were imposed during the experimental process to ensure the DEA did not fail.

For each waveform, the DEA was initially driven to a capacitance setpoint of 1500pF. After approximately 10 seconds, the capacitance setpoint began to oscillate according to the desired waveform. This was important because it demonstrated that the output of the DEA could be controlled over a large change in area. In the prior art, self-sensing has been used to monitor the parameters of a DEA where it is subjected to an arbitrary disturbance or voltage waveform, or, in the case of O’Brien et al., it has been used to respond to external mechanical stimuli. However, self-sensing has not been used in a system that will track a parameter setpoint, e.g., capacitance or resistance, that is independent of external disturbances.

The position controller is shown tracking a 0.25Hz sinusoidal setpoint in Figure 5-4, a 0.25Hz square-wave setpoint in Figure 5-5, and a 0.25Hz triangle-wave setpoint in Figure 5-6. Note the initialisation period of the DEA has been truncated to focus on the dynamic aspects of each experiment.

![Figure 5-4: The position controller tracking a sinusoidal setpoint oscillating between 1500pF and 2000pF at 0.25Hz.](image-url)
5.3 Position control experimental methods and results

Figure 5-5: The position controller tracking a square-wave setpoint oscillating between 1500pF and 2000pF at 0.25Hz.

Figure 5-6: The position controller tracking a triangle-wave setpoint oscillating between 1500pF and 2000pF at 0.25Hz.

As a general observation there is excellent agreement between the capacitance as estimated using self-sensing and as estimated using video extensometry, with the difference typically falling within a range of ±30pF for both steady state and transient conditions. In the 3 figures presented, there is a slight phase delay between the self-sensing capacitance and the video feedback capacitance. However, this is constant across all variations in the setpoint waveform, so is attributed to a systematic discrepancy between the timestamp of each frame of the video and the timestamp of the self-sensing capacitance data, which were collected using two separate processes. Furthermore, for specific times when the area of the DEA is changing rapidly, it is possible there was minor smearing or distortion* of the individual video frames. Taking this into account, the difference between the two capacitance estimates was remarkably small.

* In digital imaging, smearing and distortion occurs when objects in the field of view of the camera moving while the image is taken. Smearing can occur if the level of light an individual pixel is exposed to changes during the time the shutter is open, and results in a blurry image. Distortion can occur because not all of the pixels of an image are acquired at the same instant in time. Considering a digital image as a 2D array of pixels, images are commonly acquired by reading the pixel data one row at a time, from top to bottom. Distortion occurs if the position of the
In Figure 5-4, Figure 5-5, and Figure 5-6 the controller accurately tracks a sinusoidal, square wave, and triangle wave setpoint respectively. Of note in Figure 5-5 however, the controller exhibits overshoot when the setpoint transitions from 1500pF to 2000pF. This is primarily due to the viscoelasticity of the VHB4905 membrane, i.e., the change in area lags behind the change in electrostatic pressure, thus for periods of relatively rapid charging the area of the DEA will continue to increase for a short period after it has stopped charging. This could be improved by using a less viscous polymer for the dielectric membrane of the DEA, or, like the results of the disturbance rejection tests, it could be improved with more advanced controller design. There is also a slight asymmetry between the rising and falling edges of the capacitance waveform. The reduced slew rate of the falling edge rate is the result of relying on a passive voltage divider to discharge the DEA. Incorporating an active discharge path would rectify this.

5.3.3. Frequency response

In a final experiment, the frequency response of the DEA system was tested. The controller was also used to drive the DEA to track a sinusoidal capacitance setpoint waveform oscillating between 1500pF and 2000pF at 0.05Hz, 0.5Hz, and 1.0Hz. For each waveform the DEA was initially driven to a capacitance setpoint of 1500pF, and after approximately 10 seconds, the capacitance setpoint began to oscillate. The maximum actuation frequency that could realistically be achieved was limited by the capabilities the specific platform used in these experiments. The low output power capabilities of the driving circuit, the reliance on a passive discharge mechanism for the DEA, the limited frame rate at which video feedback could be acquired, and the viscosity of the VHB4905 DEA prevented higher frequencies from being tested. Nevertheless, a majority of the movements made by a human hand, for example, fall within the range of several Hertz [58], thus the frequencies tested are at least of a comparable magnitude to what is observed in muscles.

The results of the position controller tracking a 0.05Hz sinusoidal setpoint, a 0.5Hz sinusoidal setpoint, and a 1.0Hz sinusoidal setpoint are shown in Figure 5-7, Figure 5-8, and Figure 5-9 respectively. Note the initialisation period of the DEA has been truncated to focus on the dynamic aspects of each experiment.
5.3 Position control experimental methods and results

Figure 5-7: The position controller tracking a sinusoidal setpoint oscillating between 1500pF and 2000pF at 0.05Hz

Figure 5-8: The position controller tracking a sinusoidal setpoint oscillating between 1500pF and 2000pF at 0.5Hz

Figure 5-9: The position controller tracking a sinusoidal setpoint oscillating between 1500pF and 2000pF at 1.0Hz

In addition to Figure 5-4 from the previous section, Figure 5-7, Figure 5-8, and Figure 5-9 demonstrate the frequency response of the controller for a range of actuation frequencies. Clearly as the actuation frequency increases, the phase delay between the capacitance setpoint and the actual capacitance becomes larger. However, there is still excellent agreement between
the self-sensing capacitance and the video feedback for all of the frequencies tested, thus the issue is with power limitations of the driver circuit and the time constant of the entire system. Importantly, the self-sensing capacitance feedback remained accurate for all of the frequencies tested.

Experimentation at frequencies greater than 1Hz could not be conducted due to hardware limitations specific to the experimental platform used, but this should not be viewed as a limitation of the underlying self-sensing. In these experiments, the maximum frequency was limited by the driving circuit: the maximum charging rate of the DEA was limited by the cap placed on the maximum duty cycle; and the rate at which the DEA could be discharged was limited by the passive discharge resistor. In contrast, the plane fitting process operated at the same frequency as the PWM signal, i.e., 200Hz. It is desirable to acquire feedback from an actuator at a sampling frequency at least an order of magnitude greater than the maximum frequency of the actuator, thus with a more powerful driving circuit the self-sensing system could be applied to a DEA that had a maximum frequency of approximately 20Hz without modification. In general however, the maximum frequency at which a self-sensing DEA can operate is an application dependent optimisation problem influenced by several mechanical, electrical, and computational factors:

1. **The mechanical properties of the DEA:** Viscoelasticity in the DEA materials mechanically damps its motion and will ultimately define the absolute maximum speed of operation.

2. **The capabilities of the driving circuit:** The DEA cannot be driven faster than the rate at which it can be electrically charged and discharged.

3. **The size of the DEA:** For a given driving circuit, DEA with larger capacitances will take longer to charge or discharge.

4. **The length of the period over which the DEA is linearized for self-sensing:** It is desirable for the plane fitting process to be executed at a frequency at least an order of magnitude greater than the maximum actuation frequency of the DEA. This will be governed by the capabilities of the computational hardware.

5. **The number of raw data points used in the plane fitting process:** For a given linearization period, more data points can result in greater accuracy of the sensed parameters, but requires faster sampling of the raw data.
5.4 Design and tuning of a stiffness controller for an expanding dot DEA

5.4.1. Stiffness controller design

Controlling the relative electrostatic pressure applied to a DEA is ideal for pure position control, however this presents a challenge when extending the controller to incorporate control of the stiffness of the DEA. The objective of the capacitance controller is to drive the capacitance error to zero. Effectively this generates an infinite stiffness controller, i.e., irrespective of any changes in loading, the controller will ultimately attempt to drive the net change in displacement to zero. Control of the stiffness of the DEA however requires that when the system is perturbed from its equilibrium position by a constant disturbance for example, the DEA will settle at a new equilibrium where $C_{error} \neq 0$. Controlling the true stiffness of the DEA therefore requires knowledge of its mechanical strain energy function or the parameters of the load. Without this information it is only possible to control the relative stiffness of the DEA, i.e., for a given mechanical input the DEA can be made ‘more stiff’ or ‘less stiff’. However, it is only my intention to demonstrate that the relative stiffness of the DEA can be modified in a controlled manner using self-sensing feedback. Future work will include more advanced control strategies such as integrating a mechanical material model into an observer that is part of the control loop in order to control the true stiffness of the DEA.

To control the relative stiffness of the DEA, the controller from Section 5.2.1 has been modified to control the instantaneous charge on the DEA (Figure 5-10). This can be achieved by controlling the charge on the DEA relative to the position, i.e., the capacitance of the DEA. This therefore requires a total of 4 input parameters: a capacitance setpoint ($C_{sp}$); a capacitance gain ($G$), with units of Coulombs per Farad; a charge offset ($Q_0$); and a charge gain ($K_p$) with units of Amps per Coulomb. In the ideal case, $Q_0$ is the charge required to maintain a stable equilibrium at $C_{sp}$ when no disturbance is acting on the DEA. To control the stiffness, it is necessary to define the desired charge setpoint ($Q_{sp}$) to be a function of $Q_0$, $G$, and $C_{error}$ (Equation 5.5). That is, if a disturbance acts to displace the capacitance of the DEA from the setpoint, $Q_{sp}$ will increase, decrease, or stay the same depending on $G$. In turn, the error ($Q_{error}$) between $Q_{sp}$ and the actual charge on the DEA ($Q_A$) will control whether or not the DEA is charged or discharged (Equation 5.6). This will modify the effective stiffness of the DEA.

$$Q_{sp} = Q_0 + GC_{error} \quad \text{(5.5)}$$
Figure 5-10: Schematic diagram of the controller used to control the electrical charge on the expanding dot DEA in order to control its relative stiffness.

By modifying $G$, the relative stiffness of the expanding dot DEA can be modified. When $G=0$, the desired electrostatic charge remains constant. Where constant charge is maintained, the volumetric incompressibility of the membrane means any deformation will result in the density of charge on the DEA changing. This will result in the electrostatic pressure inherently acting to retard the motion of the deformation, i.e., the electrostatic pressure will increase if the actual capacitance of the DEA drops below the capacitance setpoint, and decrease if the actual capacitance of the DEA is greater than the capacitance setpoint. By modifying $G$ we can enhance or suppress this inherent response. For $G<0$ the desired electrostatic charge will decrease if the actual capacitance of the DEA is less than the capacitance setpoint, and increase if the actual capacitance of the DEA is greater than the capacitance setpoint. This has the net effect of decreasing the relative stiffness of the DEA. For $G>0$ the electrostatic charge will decrease if the actual capacitance exceeds the capacitance setpoint, and increase if the actual capacitance is less than the capacitance setpoint. This has the net effect of increasing the relative stiffness of the DEA.

In this section, there is a specific focus on tuning $G$ to ensure the stiffness controller remains stable for the range of experimental conditions tested. The limits of the values $G$ can assume are bounded by the behaviour of the DEA for two special cases that occur when the absolute value of $G$ becomes large. Outside of these bounds, the controller becomes unstable. This is not
5.4 Design and tuning of a stiffness controller for an expanding dot DEA

necessarily a negative effect, and this instability can be used to achieve desirable behaviours. However, it is important to consider the effects of these unstable regimes so they may be avoided for the experiments in this section.

As $G$ tends towards negative infinity, the response of the controller will become self-reinforcing. That is, where a disturbance acts to drive the capacitance below the setpoint, so much charge will be removed from the DEA that the electrostatic pressure will act to reinforce the disturbance. This will in turn cause the capacitance to drop further below the setpoint, thus forming a positive feedback loop. The DEA will therefore be driven to the minimum possible charge and become locked there. Similarly, if the disturbance acts to drive the capacitance above the setpoint, the charge added to the DEA will result in the capacitance being driven further above the setpoint, and the DEA will be driven to the maximum possible charge and become locked there. However, this is not necessarily an unwanted behaviour. In effect, this causes the DEA to behave as a mechanical comparator, i.e., it effectively becomes a bi-stable element with an adjustable tipping point. A disturbance that pushes the DEA past the tipping point will cause it to toggle states, and it will remain in that state even if the disturbance is removed.

As $G$ tends towards positive infinity, the reverse is true. If $G$ is large and positive and the capacitance deviates from the setpoint, the controller will apply maximum effort to drive the capacitance back to the setpoint. The controller therefore becomes a ‘bang-bang’ controller, i.e., it is effectively either ‘on’ or ‘off’. Issues arise if, in driving the capacitance back to the setpoint, the output of the controller is not updated fast enough to prevent the capacitance from overshooting the setpoint. This will cause the controller to oscillate around the setpoint without ever settling, a phenomenon known as ‘chattering’.

5.4.2. Stiffness controller parameter tuning

At the heart of the stiffness controller is a control loop that controls the charge on the DEA. This initially required $K_p$ to be tuned to track a charge setpoint. Tuning was manually carried out in the same manner as for the position controller as described in Section 5.2.2. Instead of toggling between two capacitance setpoints, $K_p$ was tuned by reducing the settling time when toggling between two charge setpoints: 1.5µC and 3.0µC. This resulted in a value for $K_p$ of 25 A/C.
5.5. Stiffness control of an expanding dot DEA

5.5.1. Experimental methods

The experimental apparatus from Figure 4-11 was reused in these experiments. VHB4905 is a highly viscoelastic material that exhibits significant time-dependent creep behaviour. Without a mechanical model of VHB4905, it was not possible to pre-define a relationship between charge and capacitance for the DEA. This therefore required the charge setpoint, $Q_{SP}$, and the capacitance setpoint, $C_{SP}$, used in the stiffness controller to be set independently. This was achieved by driving the DEA to a charge setpoint and allowing it to reach an equilibrium state. The capacitance of the DEA in this equilibrium state then became $C_{SP}$. The stiffness test then began, and the capacitance setpoint was used to evaluate $C_{error}$, which was then used to calculate the $Q_{sp}$ and the desired duty cycle using Equation 5.6.

The effective stiffness of the DEA was modified by changing the parameter $G$. A range of constant values for $G$ were tested. Each stiffness test was separated into two stages: in the first stage, the charge was driven to a setpoint of 3µC, and $G$ was set to zero, thus creating a constant charge controller. This state was held for 30 seconds to allow the effects of creep to substantially decay. At the end of 30 seconds, the capacitance of the DEA was recorded and used as the capacitance setpoint, and $G$ was set to a constant scalar value. At the same time, a sinusoidal voltage waveform with a frequency of 0.25Hz, and an amplitude and a DC offset of 1000V was applied to the disturbance DEA, and the test was allowed to continue for a further 20 seconds. The capacitance as estimated using the self-sensing system, and the capacitance as estimated using video extensometry were recorded.

5.5.2. Results

The experimental cycle was executed for several values of $G$ ranging from 7500 to -3000. Values of $G$ greater than 7500 resulted in the controller exhibiting signs of chattering. Values of $G$ less than -3000 resulted in the capacitance of the DEA not returning to the capacitance setpoint when the disturbance was removed, i.e., the controller behaved like a bi-stable element. Note, the viscoelasticity of VHB4905 resulted in the capacitance setpoint for each cycle being slightly different. The capacitance values recorded during each cycle were therefore normalised to the capacitance setpoint for that cycle to simplify the presentation of the results.
5.5 Stiffness control of an expanding dot DEA

In Figure 5-11, the capacitance of the DEA as estimated using self-sensing (lines) and as estimated using video extensometry (plusses) when a sinusoidal voltage waveform with a frequency of 0.25Hz, and an amplitude and DC offset of 1000V is applied to the disturbance DEA is shown for several values of \( G \). In Figure 5-12, the corresponding electrical charge on the DEA for each test cycle is displayed.

![Figure 5-11: The capacitance of the DEA as estimated using self-sensing (lines), and as estimated using video extensometry (plusses) while the stiffness controller was running for several values of \( G \).](image)

![Figure 5-12: The electrical charge on the DEA while the stiffness controller was running for several values of \( G \).](image)

5.5.3. Discussion

It has been demonstrated that by modifying the stiffness of a DEA, the level of mechanical deformation it undergoes in response to an external disturbance can be controlled. In Figure 5-11, the peak reduction in the capacitance, and thus the peak reduction in the area of the DEA, is markedly different depending on the relationship between the instantaneous charge on the DEA and capacitance. For \( G=7500 \), charge was added to the expanding dot DEA as it was compressed by the disturbance (Figure 5-12, red line). Under the influence of the disturbance
the capacitance of the expanding dot DEA was reduced by approximately 3%, corresponding to an area change of 1.5%. For $G=-3000$, charge was removed from the expanding dot DEA as it was compressed by the disturbance (Figure 5-12, black line). Under the influence of the disturbance the capacitance of the expanding dot DEA was reduced by approximately 12%, corresponding to a change in area of 6.2%. Intermediate values of $G$ achieved intermediate levels of reduction of the capacitance of the DEA.

The change in the stiffness of the DEA can be estimated by interpreting the results using a simple neo-Hookean model. For equibiaxial extension of an incompressible solid, the stress in each of the planar directions, $\sigma_{11}$, can be found using Equation 5.7, where $\mu$ is the shear modulus of the material, and $\lambda_A$ is the area stretch [62]. By assuming $\sigma_{11}$ is the same for both the case where the area compressed by 6.2% and the case where it compressed by 1.5%, it is possible to solve for the ratio of the shear modulus for each case using Equation 5.8. For the neo-Hookean model, the Young’s modulus is 3 times the shear modulus, thus the ratio of the shear modulus in Equation 5.8 is equivalent to the ratio of the stiffness of the DEA for each case. Based on this approximation, the stiffness of the DEA was 4.3 times higher for $G=7500$ than it was for $G=-3000$.

$$\sigma_{11} = \mu \left( \lambda_A - \frac{1}{\lambda_A^2} \right)$$  

$$\frac{\mu_{3\%}}{\mu_{12\%}} = \frac{\left( \lambda_{A_{6.2\%}} - \frac{1}{\lambda_{A_{6.2\%}}^2} \right)}{\left( \lambda_{A_{1.5\%}} - \frac{1}{\lambda_{A_{1.5\%}}^2} \right)} = \frac{(0.938 - \frac{1}{0.938^2})}{(0.985 - \frac{1}{0.985^2})} = 4.3$$  

While it provides a useful approximation, it is important to note that the estimated change in the relative stiffness obtained using Equation 5.8 will overestimate the actual change in stiffness because the pressure $\sigma_{11}$ is not equal for both cases. This is because the change in the area of the DEA is actually a combination of two effects for the experimental setup used. The change in the charge density on the expanding dot DEA affects the relative electrostatic pressure acting on it as it is deformed, however the level of deformation also affects the electrostatic pressure acting on the disturbance DEA. For example, where the charge on the expanding dot DEA is made to increase as the capacitance drops below the capacitance setpoint, the increase in the relative electrostatic pressure on the expanding dot DEA will act to retard the expansion of the
disturbance DEA. This limits the amount the thickness of the disturbance DEA will compress by. For the same voltage waveform, this will therefore reduce the maximum electrostatic pressure acting on the disturbance DEA. Thus the value calculated using Equation 5.8 overestimates the relative change in actual stiffness of the DEA. Nevertheless, Figure 5-11 and Figure 5-12 clearly demonstrate that the relative stiffness of the DEA can be modified by controlling the charge on the DEA. Furthermore, the data for $G=0$ is the first reported example of a constant charge controller for DEA.

5.6. Conclusions

In this chapter real-time feedback from the DEA self-sensing system has been used to control the position and the relative stiffness of an expanding dot DEA. A simple position controller has been developed that has demonstrated the ability to reject disturbances, and to track a range of setpoint waveforms at a range of frequencies. The controller explicitly uses the capacitance of the DEA to control its area, and is the first known example of a closed loop feedback controller for DEA to do so. It is also the first controller to explicitly account for changes in the resistance of the electrodes, significant charging and discharging current through the DEA, leakage current, and current due to the rate of change of capacitance. Also presented is a second controller that uses DEA self-sensing feedback to control the electrostatic charge on the DEA. This controller has been demonstrated to modify the effective stiffness of the DEA. By varying the desired charge setpoint according to the capacitance of the DEA, the mechanical behaviour of the DEA under the influence of an external mechanical disturbance can be modified.

Separate controllers based on the same core structure were developed to control position and stiffness. This is a limitation of not incorporating a mechanical material model into the observer of the control structure. For pure position control, the lack of a mechanical material model is highly advantageous as the controller is effectively independent of the DEA material, and it is inherently robust to non-linear and time dependent mechanical behaviour. However, to properly integrate stiffness and position control it is necessary to include a mechanical model of the material in the controller observer. By doing so both position and the true stiffness of the DEA can be controlled using a single process.

5.7. Chapter summary

Control of both position and stiffness is a core function of muscle that enables them to be adapted to a wide range of applications. Control of position is essential for co-ordination and
the execution of movements where positional accuracy is important. Tuneable stiffness greatly simplifies the control of applied forces, naturally damps disturbances, and enables muscles to perform in a highly efficient manner relative to pure position control. In this chapter it was demonstrated that by using feedback from the DEA self-sensing system (described in Chapters 3 and 4), both the position and stiffness of a DEA could be modified in a controllable manner. These are two of the three key abilities stemming from self-sensing that an artificial muscle must possess.
The maximum active pressure a DEA can generate is limited by the electric field at which the membrane undergoes dielectric breakdown. Excessive localised leakage current through the dielectric membrane as a result of dielectric breakdown results in irreversible damage to the membrane and often leads to catastrophic failure of the DEA. The point at which breakdown occurs however varies between DEA. This is the result of inherent variability in the microstructure of DEA membranes; microscopic defects are unavoidable. Rather than compensating for these defects by applying a blanket safety factor to all DEA of a given configuration, the performance of individual DEA can be improved greatly if a means to predict, and ultimately prevent, dielectric breakdown can be found. Effectively this involves developing a parameter akin to what humans and animals know as pain. This chapter seeks to address the final research objective of this thesis: to develop a mechanism based on self-sensing feedback that replicates the function of pain in muscle.

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6.1. Introduction

DEA have exhibited great promise in laboratory conditions, achieving active strains of several hundred per cent and active pressures of several megapascals [33]. However, there is a significant gap between the impressive peak performance that a DEA can achieve without consideration for its longevity, and what is repeatable over millions of cycles. This is because localized weak points in the DEA compromise its overall reliability. Failure must only occur in one specific region of the DEA for the entire DEA to be rendered inoperable. To compensate
6.2 Characterisation of leakage current

for this, a common remedy is to apply a blanket safety factor the rated capabilities of the DEA. This safety factor must account for any degradation in the performance of the DEA over its expected operating life, thus it potentially imposes performance penalties on a majority of DEA for the sake of a few.

To prevent failure, and create an analogue to pain for DEA artificial muscles, it is necessary to determine how the effects of localized failure modes such as electromechanical instability, thermal runaway, and partial discharge events affect the mean electrical parameters of the DEA as measured in real-time using the DEA self-sensing system described in Chapters 3 and 4. Clearly dielectric breakdown is linked to the leakage current through the dielectric membrane, thus there will be a particular focus on this parameter. This first step however is to explore the relationship between electric field, leakage current, and dielectric breakdown in a simple system not including DEA self-sensing.

In the first part of this chapter, the relationship between electric field, leakage current, and dielectric breakdown was investigated for several simple VHB4905-based DEA using a custom-built sensor apparatus designed specifically to measure leakage current. Particular focus was placed on the identifying characteristic features of the leakage current signal leading up to full dielectric breakdown. In the second part of this chapter the DEA self-sensing system was used to estimate the mean electrical parameters of several VHB4905-based DEA that were tested to the point of dielectric breakdown, and the results were interpreted using knowledge obtained from the initial leakage current experiments.

6.2. Characterisation of leakage current

In practice, dielectric breakdown within a DEA is a localized phenomenon. In particular, there are two types of “high risk” regions within a dielectric: those where leakage current is greater than the mean leakage current in the surrounding membrane; and regions containing physical defects such as voids or contaminant particles. Regions with high local leakage current, whether due to spatial variations in the resistivity of the membrane or due to local minima in the membrane thickness, can lead to localized softening and ultimately thermal runaway or electromechanical instability. These effects potentially manifest as an increase in the mean leakage current through the DEA. Regions with defects typically provide sites for partial discharge events to occur. These events are also expected to have an impact on the mean leakage current through the DEA in the form of short-lived spikes.
In this section, the characteristic behaviour of the mean leakage current through the DEA is investigated for several DEA that are driven to failure. A custom built apparatus was designed and built specifically for measuring the current through the DEA at a high sampling rate. Using expanding dot DEA, this apparatus made it possible to measure the total current through the DEA and to estimate the capacitance of the DEA using video extensometry. Thus the current contributing to the charging of the capacitance and the current induced due to the rate of change of the capacitance could be subtracted from the total current to isolate the leakage current in post-processing.

6.2.1. Materials and methods

There is notable variability in the maximum electric field a DEA can sustain before failing, even when the DEA are fabricated to the same initial specifications. This variability is primarily due to two factors: the density of defects in the dielectric membrane, which is an artefact of the membrane manufacturing process; and how the membrane is handled during DEA fabrication and application of the electrodes. These factors are magnified when manual fabrication processes are employed to produce small batches of DEA for laboratory experiments. It is important therefore to investigate the characteristic behaviour of leakage current through several DEA to ensure a spread of data is obtained.

Nine expanding dot DEA (Samples A-I) were fabricated from sheets of 3M VHB4905. The membranes were stretched equibiaxially to 16 times their original area and bonded to a rigid circular support frame (Figure 6-1). The frame had an internal aperture with a diameter of 100mm. In the centre of the stretched membrane a circular electrode of diameter 24mm was applied to opposing sides of the membrane using Nyogel 756 electrically conductive carbon loaded grease. Nyogel 756 tracks approximately 6mm wide were also applied radially out from the electrode area to the points on the edge of the support frame that could be connected to external circuitry.
6.2 Characterisation of leakage current

It is necessary to know the instantaneous capacitance of the DEA throughout the experimental procedure so that leakage current could be isolated from the total current through the DEA. Recalling Equation 2.1, this can be achieved using the rest capacitance of the DEA and its instantaneous area stretch. The area of the DEA was measured using the apparatus depicted in Figure 4-9. It was not possible however to obtain a stable capacitance reading when a Fluke RCL meter was used to measure the rest capacitance of the test DEA. This was most likely a result of the high impedance of the Nyogel 756 carbon grease coupled with the small amplitude of the excitation signal outputted by the RCL meter. Instead, a custom capacitance sensor was designed and built for this task. The custom capacitance sensor supplied a 2Hz, 20V peak-to-peak triangle wave voltage signal to the positive electrode of the DEA and the current through a 10MΩ series resistor connected between the negative terminal of the DEA and ground was measured using LabVIEW via a PCIe-6259 DAQ card (National Instruments) (Figure 6-2). Capacitance was calculated using the ratio of the instantaneous current \(i\) to the rate of change of the voltage \(dV/dt\) (Equation 6.1). The accuracy of the custom capacitance sensor was verified by comparing the capacitance of three different commercially available capacitors as estimated using the Fluke RCL Meter with the capacitance as estimated by the custom capacitance sensor.

![Expanding dot DEA and supporting frame.](imageURL)
Driving a DEA to dielectric breakdown requires a high voltage power source. In order to examine the relationship between the leakage current and level of actuation during high voltage tests a second circuit was designed and built (Figure 6-3). The positive terminal of the DEA was connected to the output of a high voltage DC-DC converter (T-3005, AM Power Systems). The series current through the DEA was measured using a 30kΩ resistor connected between the negative terminal of the DEA and electrical ground. The voltage across the DEA was measured using a parallel voltage divider (100MΩ:120kΩ) connected between the output of the DC-DC converter and ground. Unity gain buffer circuits transmitted the voltage across the 30kΩ and 120kΩ resistors to a PC running LabVIEW via the DAQ card.
6.2 Characterisation of leakage current

Figure 6-3: Schematic diagram of the system used for characterising the leakage current through the DEA when subjected to high actuation voltages.

During testing, each DEA was subjected to an identical voltage waveform. The DEA was initially driven to a voltage of 500V*, which was maintained for 30 seconds to ensure the DEA had reached a stable equilibrium before the voltage began to increase. After 30 seconds, the voltage was increased linearly at a rate of 5V/s to 3000V† or until the DEA failed, whichever came first. A relatively slow rate of increase of the voltage was chosen to minimise the influence of viscoelastic effects on the mechanical behaviour of the DEA. All high voltage experiments were conducted in a single session in a temperature controlled, air conditioned environment. This test procedure was initially performed without a DEA connected to the circuit in order to calibrate the voltage dependency of the feedback circuit and create a “Zero Current Curve”. In post-processing the Zero Current Curve was subtracted from the recorded series current to get the true series current measurements.

The video feedback apparatus and analysis software described in Chapter 4 was used to record changes in the area of the electrodes of the DEA while they were being actuated. The area stretch (\(\lambda_A\)) was used to approximate the capacitance of the DEA (Equation 6.2) and estimate the thickness of the dielectric in order to calculate the mean electric field. Leakage current (\(i_{leakage}\)) was calculated by subtracting the current due to the DEA being charged (\(CdV/dt\)), and the current due to the rate of change of the capacitance of the DEA (\(VdC/dt\)) from the calibrated series current through the DEA (\(i_{series}\)) (Equation 6.3). The mean leakage current and the

---

* A minimum voltage was specified because the DC-DC converter had a minimum turn on voltage.
† The rated limit of the DC-DC converter.
magnitude and frequency of partial discharge events were extracted from the leakage current data.

\[ C = C_0 \lambda^2 \]  

6.2

\[ i_{leakage} = i_{series} - C \frac{dV}{dt} - V \frac{dC}{dt} \]  

6.3

6.2.2. Results

The results of the calibration test for the custom capacitance sensor used to measure the rest capacitance of each DEA are shown in Table 1. Note the error term in the final column was calculated using Equation 6.4. The rest capacitances of each of the test DEA are shown in Table 2.

Table 1: Calibration of DEA rest capacitance meter circuit

<table>
<thead>
<tr>
<th>Capacitor</th>
<th>Fluke RCL Meter Reading</th>
<th>Custom PCB Capacitance Meter Readings</th>
<th>Average Reading</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reading 1</td>
<td>Reading 2</td>
<td>Reading 3</td>
<td>Average</td>
</tr>
<tr>
<td>1</td>
<td>225pF</td>
<td>225pF</td>
<td>227pF</td>
<td>226pF</td>
</tr>
<tr>
<td>2</td>
<td>446pF</td>
<td>446pF</td>
<td>450pF</td>
<td>448pF</td>
</tr>
<tr>
<td>3</td>
<td>661pF</td>
<td>666pF</td>
<td>670pF</td>
<td>668pF</td>
</tr>
</tbody>
</table>

\[ Error = 100 \times \left( \frac{C_{average} - C_{fluke}}{C_{fluke}} \right) \]  

6.4
6.2 Characterisation of leakage current

Table 2: Rest capacitance and rest equivalent series resistance of test DEA

<table>
<thead>
<tr>
<th>DEA</th>
<th>Rest Capacitance (rounded to nearest picofarad)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reading 1</td>
</tr>
<tr>
<td>A</td>
<td>301pF</td>
</tr>
<tr>
<td>B</td>
<td>290pF</td>
</tr>
<tr>
<td>C</td>
<td>290pF</td>
</tr>
<tr>
<td>D</td>
<td>336pF</td>
</tr>
<tr>
<td>E</td>
<td>287pF</td>
</tr>
<tr>
<td>F</td>
<td>286pF</td>
</tr>
<tr>
<td>G</td>
<td>302pF</td>
</tr>
<tr>
<td>H</td>
<td>293pF</td>
</tr>
<tr>
<td>I</td>
<td>288pF</td>
</tr>
</tbody>
</table>

During the high voltage test, 6 of the 9 actuators failed. In the following figures, these DEA are denoted with solid lines. The 3 DEA that did not fail are denoted with dashed lines in the same figures.

The electric field within the DEA versus the area stretch ratio is shown in Figure 6-4. Electric field versus the mean leakage current, calculated using Equation 6.3, is shown in Figure 6-5. Note in both Figure 6-4 and Figure 6-5 the data has been downsampled to improve readability.

![Figure 6-4: The mean electric field within the dielectric of each DEA versus the area stretch ratio of the DEA.](image)

120
Figure 6-5: The mean electric field within the dielectric versus the leakage current through the dielectric.

The leakage current data was also analysed to identify the frequency of discharges due to partial breakdowns in relation to the electric field. A typical leakage current plot for a single test is shown in Figure 6-6. Note the clean shape of the underside of characteristic leakage current curve indicates that these spikes correspond to partial discharges and are not artefacts as a result of noise in the feedback circuit. The rate of partial discharge events was measured and cross-correlated with the mean electric field within the dielectric, and a third order polynomial was fit to the resultant data using Matlab’s ‘polyfit’ function (Figure 6-7). The difference between the peak current during the partial discharge event and the mean leakage current through the DEA was also cross-correlated with the electric field within the dielectric membrane. This data is displayed in Figure 6-8 for the 6 DEA that did fail during testing, and Figure 6-9 for the 3 DEA that did not fail during testing.

Figure 6-6: A typical leakage current waveform for the high voltage leakage current test.
### 6.2 Characterisation of leakage current

**Figure 6-7:** The rate of partial discharge events for each DEA, cross correlated against the mean electric field within the dielectric.

**Figure 6-8:** The difference between the peak current during a partial discharge event and the mean leakage current through the DEA cross-correlated with the mean electric field within the dielectric membrane for the DEA that failed prematurely during testing.

**Figure 6-9:** The difference between the peak current during a partial discharge event and the mean leakage current through the DEA cross-correlated with the mean electric field within the dielectric membrane for the DEA that did not fail during testing.
6.2.3. Discussion

From Figure 6-4 it is very clear there is a strong correlation between the electric field and the area stretch ratio as the DEA is activated. This highlights the fundamental mechanical repeatability of DEA despite the fact that each of the DEA was fabricated by hand and subject to inconsistencies due to human variability. This consistent behaviour however masks what is happening below the surface. From the other results it can be seen that despite the consistent mechanical behaviour there is significant variability between DEA with regard to leakage current and partial breakdown events.

Full dielectric breakdown is a rapid event. For the DEA that failed, the measured leakage current exhibited a sharp increase at the point of dielectric breakdown that typically occurred over a time period of 100-200μs (Figure 6-6). However, there was little to distinguish the initial stages of a partial breakdown event and full dielectric breakdown. In a real system this severely constricts the time available to take corrective action upon its detection, thus limiting its usefulness as a standalone parameter for detecting and preventing dielectric breakdown.

There is a relatively large variation in the leakage current measured through the dielectric membrane at high electric fields as shown in Figure 6-5. The most likely explanation for this is a variable density of inconsistencies or defects such as microscopic voids or foreign particles within the membrane or localised variations in the thickness of the membrane. These inconsistencies act as weak points in the dielectric strength of the membrane. This is where the pain parameter shows the most promise. The harder a DEA has to work to achieve a given displacement, the closer it is to its limits and the more ‘pain’ it is in. It can be seen from Figure 6-5 that 5 of the 6 DEA that failed catastrophically during testing exhibited significantly higher leakage currents for a given electric field than the 3 DEA that did not fail during testing. Furthermore, this relationship is evident even at moderate electric fields, indicating that the mean leakage current provides an excellent indicator of the quality of the DEA.

The most interesting result however is that 5 of the 6 DEA that failed early exhibited a much higher frequency of partial breakdown events as the electric field increased than the 3 DEA that did not fail (Figure 6-7). It can also be seen when considering Figure 6-7, Figure 6-8, and Figure 6-9 that DEA that did fail were typically characterised by frequent, relatively small partial discharge events, while DEA that did not fail exhibited a lower partial discharge rate, albeit with relatively large discharge magnitudes. However, when considering the data for all 9 DEA a trend emerges: at relatively low electric fields, the magnitude of the partial discharge
6.2 Characterisation of leakage current

events and relatively large and they occur infrequently, but as the electric field increases, magnitude decreases and frequency increases. For the DEA that failed this occurred at lower electric fields when compared to the DEA that did not fail.

The observed trend in the frequency and magnitude of the partial discharge events may be able to be explained by the size of the defect and the magnitude of the leakage current. Consider a void in an otherwise defect-free dielectric membrane simplified into a lumped circuit model (Figure 6-10, adapted from [111]). The void is represented by a capacitance and a spark gap across which partial discharges occur. Where leakage current is small, i.e., $R_m$ is very large, the equivalent circuit behaves predominantly as two capacitors in series. The ratio of the local electric field within the void to the electric field within the dielectric membrane material is equivalent to the ratio of the relative permittivity of the membrane to the relative permittivity of the void (Equation 6.5). Thus because the void will typically have a much lower relative permittivity compared to the membrane material, the local electric field within the void is higher it is within the membrane material.

![Figure 6-10: Schematic diagram of a void within a dielectric membrane, and the equivalent circuit model of the void region (adapted from [111]).](image)

\[
\frac{E_{\text{void}}}{E_{\text{membrane}}} = \frac{\varepsilon_{\text{membrane}}}{\varepsilon_{\text{void}}}
\]

6.5

The increase in the frequency or partial discharge events is likely related to the magnitude of the leakage current through the dielectric membrane. When the breakdown field of the void is reached, $C_v$ is discharged through the spark gap until the local electric field is sufficiently reduced that the conduction path cannot be maintained and the breakdown event ceases. After a partial discharge, $C_v$ will initially be charged via $C_m$ until the sum of the voltage across $C_v$ and
$C_m$ is equivalent to the voltage across the surrounding membrane. This will increase the charge on $C_m$ and thus its voltage. This will prevent $C_v$ from immediately reaching the same voltage it had prior to the partial discharge. After this initial charging however, $C_v$ is recharged charged via $R_m$. $R_m$ is large, resulting in a relatively long time constant that limits the rate at which $C_v$ can recharge to the point that another partial discharge event will occur. Assuming in the first instance that the ratio of $C_v$ to $C_m$ is relative constant, increased leakage current through $R_m$ will reduce the time it takes for $C_v$ to recharge, thus leading to increased frequency of discharges. This scenario is consistent with the observations made during this experiment.

The magnitude of the discharge events is likely to be linked to the size of the defect. Looking to the cross-section of the dielectric membrane shown in Figure 6-10, if we assume the effective area of $C_m$ and $C_v$ are equivalent, a small value for the ratio $x/d$ will correspond to relatively large values for $C_v$ and $R_m$. When partial breakdown is initiated, more charge must be discharged to reduce the local electric field to the point that breakdown ceases, and the time constant $C_vR_m$ is large. Thus we expect the partial discharge events to be less frequent and have a longer duration. More energy is being released in the partial discharge event, hence we also expect larger discharge magnitudes. Again as leakage current increases, this recharge rate will increase leading to increased partial discharge rate. This too is consistent with the experimental data and suggests the DEA that did not fail were superior due to the presence of smaller defects.

The increased frequency and reduced magnitude of the partial discharge events at high electric fields may also provide an indicator of damage occurring to the dielectric. A void may act as a mechanical stress riser in the dielectric, resulting in localised thinning of the membrane when it is stretched and thereby acting to increase the ratio $x/d$. This would reduce $C_v$ and $R_m$, resulting in more frequent partial discharges with a smaller magnitude. A similar result would occur if the partial discharges resulted in damage to the dielectric, thus acting to increase $x/d$ by making the void bigger. The high frequency of partial discharges could also serve to raise the equilibrium temperature of the membrane by not allowing it to cool down between discharges, thereby facilitating the onset of electromechanical instability or thermal runaway.

The results of this initial investigation indicate that a combination of leakage current and the characteristics of partial discharge events show great promise as the foundation for a pain parameter for DEA. As a general trend, inferior DEA exhibited greater leakage current for a given electric field, and exhibited smaller and more frequent partial discharge events as the electric field within the dielectric approached the electrical breakdown strength. This is
consistent with what is expected based on the analysis of a simple lumped circuit model of an imperfect dielectric membrane. However, it is not yet clear how this information could be condensed into a general purpose, quantifiable cyber-pain parameter. Considered individually, leakage current and the magnitude and frequency of partial discharge events do not provide a general purpose indicator of impending dielectric breakdown. A promising avenue of future research is investigating how the relationship between all three phenomena changes near the point of dielectric breakdown, and in particular identifying whether the observed behaviour of the partial discharges is the result of physical damage to the dielectric or whether the defect facilitates the onset of other electromechanical failure modes through reversible effects such as stress concentrations and localized heating.

6.3. Real-time estimation of leakage current using DEA self-sensing

Leakage current and the characteristic features of partial discharge events will play an important role in detecting imminent breakdown. However, the 3D plane fitting algorithm used in the DEA self-sensing system described in Chapters 3 and 4 necessarily uses a regression process that effectively low-pass filters the series current data. This is a double edged sword: the inherent filtering helps to reduce the influence of noise when estimating the mean values of the electrical parameters of the DEA, but without augmenting the self-sensing system with a separate process to analyse the series current data to identify partial discharge events, the short time scale of the partial discharges means their influence on the estimated electrical parameters of the DEA is significantly attenuated. In this section, the DEA self-sensing system is used to estimate the electrical parameters of the DEA when they are tested to the point of dielectric breakdown. In particular, the influence of partial discharge events on the estimated mean leakage current will be investigated.

6.3.1. Materials and methods

Five expanding dot DEA (Samples A-E) fabricated from sheets of 3M VHB4905 to the same specifications as described in Section 6.2.1 were used to characterise leakage current using the DEA self-sensing system. The experimental apparatus from Figure 4-11 were used to test the sample DEA. A 4kV DC signal was applied to the HV terminal of the self-sensing circuit using a Generation 2 Biomimetics Laboratory EAP Controller. A PWM signal with an initial duty cycle of 10% was applied to the DEA. The duty cycle was then increased in 1% increments every 10 seconds until the DEA failed. During this period, the mean voltage across the DEA,
Chapter 6. Cyber-pain for DEA

the capacitance of the DEA, the nominal leakage current through the DEA, and the amplitude of
the noise in the nominal leakage current were estimated using the self-sensing system. Note the
current due to the rate of change of the capacitance is sufficiently small for the test conditions
that it can be ignored. All high voltage experiments were conducted in a single session in a
temperature controlled, air conditioned environment.

6.3.2. Results

Similar to the previous results, the relationship between the electric field applied to the DEA
and the area stretch was highly consistent between the 5 DEA (Figure 6-11). The 5 DEA also
showed exceptional resilience when subjected to high actuation voltages. At very high strains
however cracks appeared in the electrode and it ceased to be a continuous layer (see Figure
6-12).

Figure 6-11: The electric field dependent area stretch of each DEA
6.3 Real-time estimation of leakage current using DEA self-sensing

Figure 6-12: A close up photo of the cracks beginning to appear in the DEA electrode at high active strains. For each cycle of the PWM signal, the mean voltage across the DEA was measured. In Figure 6-13 a close up of the mean voltage with respect to time of the latter portion of the test cycle is shown. The mean voltage drops away sharply when full dielectric breakdown occurs. Note the mean voltage is asymptotic because the maximum input current is restricted to ~120µA whilst the discharge current during the off portion of the PWM cycle is proportional to the voltage across the DEA.

Figure 6-13: A close up view of the mean voltage across the DEA for V>2600

Figure 6-14 displays the capacitance as measured by the self-sensing process. Note the vertical lines at the end of each curve represent breakdown conditions. In Figure 6-15 the measured leakage current with respect to the electric field within the DEA is presented. The amplitude of the noise in the leakage current measurements is shown in Figure 6-16.
Figure 6-14: The capacitance of each DEA as estimated using the DEA self-sensing system for the duration of each breakdown test.

Figure 6-15: The estimated mean leakage current through the dielectric membrane of each DEA for the duration of each breakdown test.
6.3 Real-time estimation of leakage current using DEA self-sensing

![Figure 6-16: The amplitude of the noise in the mean leakage current as estimated using DEA self-sensing for the duration of each breakdown test.](image)

6.3.3. Discussion

It is clear from Figure 6-11 and Figure 6-15 that electric field, area stretch and the estimated leakage current reached much higher magnitudes prior to failure when compared with the data presented in Section 6.2. This could be the result of effects such as variations in the ambient temperature or the fact that each set of DEA was fabricated using a VHB4905 from a different batch. Personal experience suggests that improvements in the fabrication process could have also contributed to this improvement. For the DEA used in the experiments in Section 6.2, a fine hair paint brush was used to apply the carbon grease. The hairs are highly flexible however it is possible for tips of the hairs to damage the surface of the membrane, creating a weak point in the dielectric membrane, or for the hairs to break off and be left within the grease. The tips of any fibre-like particles left behind act to concentrate the electric field, creating a local region where that is more susceptible to dielectric breakdown. For the DEA used in this section, the grease was applied using a rubber-tipped colour shaper, thus avoiding these issues.

The 5 test DEA used in these experiments significantly outperformed the DEA fabricated for the experiments presented in Section 6.2. In the current experiments, the peak area strain ranged from 140-180% for the 5 test DEA, whereas in Section 6.2 peak area strains were limited to 95-140% for the 9 DEA tested. This impressive active strain brought to light issues with regard to the electrode material. At very high strains the surface of the electrode began to crack up and form islands of conductive material (see Figure 6-12). This creates non-uniformity in the resistance of the electrodes. In extreme cases it may result in portions of the electrode becoming electrically isolated. This likely explains the variations observed in the measured capacitance of
the DEA (Figure 6-14, 200-350 seconds). As the DEA expands, small local regions that have effectively become isolated no longer contribute to additional expansion or contribute in a reduced capacity as the mean voltage is increased. Furthermore, when compounded with the initial prestretch, the large area stretches indicate the DEA are close to their tensile limits.

In line with previous experiments, partial discharges appear to be a notable indicator of impending dielectric failure. Significant partial discharges resulted in clear drops in the mean voltage across the DEA for Samples A, B, and C (Figure 6-13). These significant partial discharges occur several seconds before full dielectric breakdown is initiated. Furthermore, when correlated with the measured capacitance (Figure 6-14), these precursors to breakdown occur after the DEA is substantially at its maximum active strain but before dielectric breakdown occurs. Samples D and E however do not exhibit the hallmarks of significant partial discharge events in the period leading up to full breakdown, but like Samples A-C, the measured capacitance for Samples D and E are substantially at their maximum when breakdown occurs (Figure 6-14).

While significant partial discharge events are clearly evident in the mean voltage across the DEA, small partial discharge events do not have a significant impact on the DEA voltage, and are attenuated by the signal conditioning filters on the feedback signals. However, whilst attenuated, they will effectively reduce the goodness of fit of the self-sensing plane. If we assume some deviation occurs in the magnitude and frequency of the small partial discharge events between cycles of the PWM input signal, this will manifest as noise in the estimated leakage current. This is demonstrated in Figure 6-16. Despite each of the 5 test DEA failing at different voltages, times, and capacitances, the noise in the estimation of the leakage current at breakdown was similar for all five. Each failed when the amplitude of the noise in the estimated mean leakage current reached approximately 2-2.5µA. This is a very encouraging result. Potentially, owing to the apparent improvement in the quality of these DEA when compared with the previous experiments, this suggests that the characteristic behaviour of partial discharge events in particular become more uniform as quality improves. Thus its effectiveness as part of a cyber-pain parameter will also improve.

The results of these experiments indicate that feedback from the DEA self-sensing system can be used to generate practical pain signal. Quantifying such a signal requires consideration of multiple measureable electrical parameters, in particular the mean voltage across the DEA; the capacitance of the DEA; and the magnitude and noise in the mean leakage current through the
dielectric of the DEA. For all 5 DEA, the estimated capacitance had effectively reached a plateau, and in 2 cases had begun to decrease by the point of dielectric breakdown. This could indicate the DEA had undergone significant strain hardening and were near their tensile limits, or that the electrodes had undergone significant fragmentation. Nevertheless even in this constrained state, the parameters of the leakage current exhibited behaviour consistent with that observed in the results presented in Section 6.2. Significant partial discharge events had a noticeable effect on the mean voltage, and in 3 of the 5 actuators tested they were observed several seconds before full dielectric breakdown occurred, indicating they provide ample warning that breakdown is imminent. Furthermore, numerous, smaller partial discharges had a notable effect on the noise of the estimated mean leakage current for all 5 DEA tested.

6.4. Conclusions

The first steps towards a pain parameter for DEA have been made. From Chapter 4 and the results in Section 6.3, capacitive sensing can give an indication of the physical deformation of the DEA, and will play an important role in determining when the DEA is being overstressed mechanically. However, capacitive sensing alone is not enough and it is clear that any pain parameter will be the result of the combined behaviour of several phenomena. Monitoring the behaviour of the leakage current shows great promise as a core component of a pain parameter enabling better monitoring of the performance of the electrical sub-system of the DEA. The leakage current, the magnitude of partial discharges through the membrane and the frequency at which they occur, are correlated with the point of catastrophic failure. Importantly, it was demonstrated that these phenomena had a measurable influence on the electrical parameters of the DEA as estimated using the DEA self-sensing system, despite the self-sensing process acting to attenuate individual partial discharge events. A specific relationship quantifying a pain parameter in terms of leakage current and the characteristics of partial discharge events has yet to be defined, but the general trend of increased leakage current and high frequency low amplitude partial discharge events near the point of failure observed in the experimental data agrees with theoretical predictions. An important avenue of future research will be focused on investigating and developing this relationship in greater detail. It will also be important to expand the experimental characterisation of dielectric breakdown using the self-sensing process to DEA that are subjected to external disturbances. In practice “pain” is not necessarily limited to cases where the DEA is at its maximum extension. External loads affect the equilibrium
position of the DEA, thus it is necessary to examine their influence on the parameters of interest we have identified.

6.5. **Chapter summary**

In muscle, pain plays an important role in governing mechanical output and preventing permanent damage from occurring due to the muscle being overstressed. In this chapter the foundation was established for a pain parameter for artificial muscles based on the feedback from the DEA self-sensing system developed in this thesis. Such a parameter is an important development for DEA artificial muscles. A blanket safety factor applied to all DEA of a given configuration ultimately results in many DEA not being used to their full potential. Furthermore, in any device, the properties of a moving part will change over time, thus an adequate safety factor applied at the time of manufacture is constrained not by its capabilities as when brand new, but by the likely properties the device will possess at the end of its operating life. A pain parameter will potentially enable both of these issues to be addressed. At a basic level, pain would enable the health of the DEA to be determined and this information could be used to schedule maintenance and repairs. As the pain parameter becomes more sophisticated not only is there the potential for the reliability of the device to be improved, but it also means each DEA can be used at levels closer to their maximum potential throughout their entire operating life, even if their peak performance changes over time.
Conclusions and future work

This thesis has advanced the state of the art of Dielectric Elastomer Actuators (DEA) by creating a self-sensing system that enables the key electrical parameters of DEA to be accurately estimated online whilst they are being actuated. Using this self-sensing, it has been shown experimentally that DEA can replicate the core functions that make muscle such a versatile actuator. DEA can now truly be called ‘artificial muscles’. Furthermore, this self-sensing unlocks two major areas of research in the field of dielectric elastomer devices: it enables the behaviour and electrical properties of dielectric elastomer devices to be characterised in situ at high electric fields; and it enables new control strategies founded on closed loop feedback to be developed for DEA devices. In this chapter a brief summary of this thesis and its contributions to the field of DEA is given as well as potential applications for this technology and directions for future research.

7.1. Thesis summary

To develop robots capable of functioning in the real world, the safety of the robot, the environment, and most importantly of people are paramount. Self-sensing, compliant actuators inspired by muscle not only provide an inherent mechanical safeguard against inadvertent damage due to mechanical shock, but also potentially enable greater control of applied forces, increased stability and robustness, reduced sensitivity to vibrations, and reduced energy consumption. DEA have long been referred to as artificial muscles because like muscle they are inherently soft and lightweight, yet they are capable of outperforming muscle in terms of active strain, speed, pressure, and energy density. As identified in Chapter 1 however, to truly earn the moniker of “artificial muscles” they must be more than simply soft actuators. DEA must be made smart and robust with the ability to provide position feedback, have a tuneable stiffness,
and feel pain. Self-sensing is required to achieve these capabilities. By integrating actuation and sensing a true engineering analogue to muscle can be created from a single soft element.

The key electrical parameters of a DEA are its capacitance, the resistance of its electrodes, and leakage current through its dielectric membrane. By being able to estimate these parameters during actuation, inferences can be made regarding the mechanical state and the health of the DEA. In Chapter 2 a critical review of previous examples of self-sensing systems for DEA has been presented. No example from the prior art was capable of estimating all three electrical parameters of interest in real-time, and in particular none accounted for leakage current through the dielectric membrane or the current induced in the DEA due to the capacitance of the DEA changing at a significant rate. Furthermore, with specific reference to capacitive sensing, the self-sensing techniques employed in the prior art were developed without consideration for their practical implementation. In particular, these techniques required relatively bulky, high powered electrical hardware that was at odds with the compact, low-power form factor of the DEA. Thus there was a gap in the literature not only for a method for estimating all three of the major electrical parameters of a DEA, but also for the development a scalable system for controlling DEA that was suited to portable applications.

In Chapter 3 a novel DEA self-sensing system based on Pulse Width Modulation (PWM) was described. The system enabled the capacitance of a DEA, the resistance of its electrodes, and leakage current through the dielectric membrane to be estimated in real-time and it specifically accounts for the influence of current induced due to the capacitance of the DEA changing at a significant rate. The algorithm employed has low sensitivity to electrical noise in the raw feedback, and it is readily compatible with microcontroller architectures. Furthermore it has been designed to work well with the capabilities and limitations of compact high voltage power supplies, and enables multiple independent DEA to be driven from a single power supply.

In Chapter 4, the DEA self-sensing system was implemented in a physical device. A self-sensing circuit that was capable of running on battery power was designed and built. Experimental data was presented that used a combination of several mock DEA circuits and simple, equibiaxially prestretched expanding dot DEA to demonstrate that accurate estimations of all three key electrical parameters of a DEA could be made in real-time, for a wide range of operating conditions.

In Chapter 5, self-sensing feedback was used to achieve basic position and stiffness control of a DEA, thus replicating core functions of muscle. Capacitance feedback was used to control the
area of an expanding dot DEA to match a variety of setpoint waveforms whilst under the influence of external mechanical disturbances. Also in Chapter 5 it was demonstrated that the effective stiffness of the DEA could be modified by controlling electrical charge. The results of Chapter 5 are the first reported examples of mechanical disturbance rejection, using feedback to track a changing setpoint, control of the electrical charge on a DEA, and control of the stiffness of the DEA.

In Chapter 6, the foundations were established for an analogue to pain for DEA. When driven to failure, characteristic trends were observed in the mean voltage across the DEA, the capacitance of the DEA, leakage current and the frequency and magnitude of partial discharge events. Furthermore, it was demonstrated these phenomena had distinct, measureable effects on the feedback from the DEA self-sensing system. This provided sufficient evidence to suggest further development would benefit DEA with regards to both health monitoring and quality control.

### 7.2. Contributions of this thesis

- **A DEA self-sensing system was developed that enables the capacitance of the DEA, the equivalent series resistance of the electrodes, and leakage current to be estimated in real time whilst a DEA is being actuated.** This is the first DEA self-sensing system that enables all three parameters to be estimated in real-time, and the first to specifically account for current induced due to leakage mechanisms and due to the rate of change of the capacitance.

- **A DEA self-sensing system was developed that was specifically designed to be scalable to portable devices.** The system specifically accounted for the typical characteristics of low-power driving electronics, and the self-sensing algorithm is well suited to implementation in an embedded system. Furthermore, a self-sensing circuit that ran on battery power was designed and built and used successfully in experiments.

- **The DEA self-sensing system has been experimentally validated.** Experimental data has been presented demonstrating accurate estimations of all three key electrical parameters of a DEA could be made in real-time, for a wide range of operating conditions.
7.3 Applications of self-sensing

- **Using feedback, closed loop control of the position of an equibiaxially prestretched expanding dot DEA was demonstrated.** This is the first example of closed loop control where capacitance has explicitly been used as the control variable. This is also the first time a controller for a DEA has used self-sensing feedback to reject the effect of external mechanical disturbances, and the first time a controller for a DEA has used self-sensing feedback to track a position setpoint.

- **Using feedback, it was demonstrated that the effective stiffness of an equibiaxially prestretched expanding dot DEA could be modified using closed loop control of electrical charge.** This is the first example of closed loop control where self-sensing feedback has been used to control the charge on a DEA. This is also the first time self-sensing feedback has been used to control the effective stiffness of a DEA.

- A foundation has been established for a ‘cyber-pain’ parameter for DEA. The mean voltage across a DEA, its capacitance, leakage current through the dielectric, and the frequency and magnitude of partial discharge events were found to exhibit characteristic behaviours as the DEA were electrically and mechanically overstressed. Furthermore it was demonstrated that these characteristic behaviours had a measurable influence on the self-sensing feedback.

### 7.3. Applications of self-sensing

Self-sensing for DEA is an enabling technology. DEA are clearly capable of impressive performance as actuators, and now self-sensing enables significantly greater control of their output. As this capability is further developed, it makes DEA a viable actuation technology for implementation in practical devices that must be capable of responding to external mechanical stimuli or where positional accuracy and robustness are important. Furthermore, self-sensing enables realisation of the inherent and unique benefits of DEA, i.e., it enables the creation of a muscle-like actuator that is simple, inexpensive, lightweight, capable of high strains, operates silently, is mechanically resilient, and can operate in a wide range of environments.

An active element with a tuneable stiffness will potentially benefit a wide range of applications where the dynamics of a device’s mechanical response is important. In Chapter 1 it was clearly identified that in humanoid robots for example, significant reductions in energy consumption can be achieved by combining position and stiffness control. This has implications for all robotic devices: stiffness control could potentially lead to devices that can operate for longer on
a single charge, or that can function with smaller batteries and thus less weight. However, this is only a small subset of the potential applications. In many industrial processes, vibrations are an unavoidable by-product of having moving parts. Tuneable stiffness can act to amplify or attenuate the mechanical response of the system in a manner that is inherently robust to changes in the plant parameters. Stiffness control could also be a powerful addition to many materials handling applications. Motion paths could be simplified as the risk of damage from inadvertent collisions is reduced, and variable stiffness devices would be well suited to handling objects that are soft themselves, or that are delicate or have irregular shapes. Furthermore, by intentionally tuning the stiffness to make it unstable, the DEA can be made to behave as a mechanical comparator with a tuneable tipping point, thus they could be used for a wide range of mechano-sensitive switching applications.

The results of Chapter 6 indicate the estimated electrical parameters of a DEA, particularly leakage current, are related to the quality of the DEA. The experimental evidence clearly indicates that when subjected to a given electric field, leakage current and the rate of partial discharge events will be higher for an inferior DEA. This effect is readily apparent even at electric fields well below the breakdown strength of the material. Whilst a general purpose pain parameter has yet to be formulated, the self-sensing system could already easily be incorporated into a fast, simple quality control process for evaluating DEA. Furthermore, as the concept of pain for DEA becomes better understood, it is entirely feasible that self-sensing feedback will become part of an online health monitoring process that will greatly improve DEA reliability.

The main focus of this thesis is the integration of actuation and sensing in a single element, but this is not the limit of its application. The self-sensing system has been designed to withstand high voltages, but it is does not require them. The resistive, capacitive and leakage current sensing are equally applicable to low voltage applications. This enables the creation of very low elastic modulus, large strain sensors. Conventional strain sensors are low stain, high stiffness devices, thus they are of limited use for flexible structures. However, DEA sensors could be integrated into flexible structures or textiles without unnecessarily stiffening the host structure. In particular this would be beneficial for health monitoring of composite materials designed to have a combination of flexibility and strength. On a more advanced level, the rapid growth of capacitance-based touch sensitive technology in consumer electronics such as smart-phones and mobile media centres could be enhanced through a soft and compliant physical interface.
7.4 Future work

The DEA self-sensing system enables the electrical properties of dielectric elastomer devices to be characterised at high electric fields. Importantly this allows the properties of the device to be monitored whilst it is in operation. For example, from the capacitive sensing results in Chapter 4 it appeared that the dielectric constant of VHB4905 exhibited a weakly positive relationship with electric field. Phenomena like this can be explored in greater depth. Most importantly self-sensing will allow the performance of different materials used for dielectric membranes or for compliant electrodes to be compared in a quantifiable way. This will be particularly useful for evaluating the properties of new, yet-to-be-developed membrane materials, especially where these materials are multiphase composites.

7.4. Future work

The self-sensing system has demonstrated excellent performance over a range of conditions; nevertheless, it would be advantageous if the self-sensing process could be streamlined from two stages to one. Presently, for a given set of raw feedback data, the resistance of the electrodes must be estimated, and this value must be used to condition the data before the plane fitting process can be used to estimate capacitance and leakage current. This necessarily requires feedback to be acquired in a batch rather than a continuous process and introduces a time delay in the feedback path.

The regression process used to fit the plane that enables capacitance and leakage current to be determined is straightforward, but it is not yet known how the computational requirements will scale if the self-sensing process is sped up. In designing a control system for a DEA, it is desirable to estimate electrical parameters of the DEA at a rate much greater than the maximum frequency at which the DEA will actuate. For example, for a DEA designed to operate at 10Hz it is desirable to acquire position feedback at 100Hz or more. Further investigation, through experimentation and optimisation, is required in order to determine what the practical limits of this self-sensing algorithm are.

While the experiments conducted for this thesis all used VHB4905 as the dielectric membrane material and carbon loaded grease for the flexible electrodes, the self-sensing methods are designed to be independent of the material used for the membrane and the electrodes. Different membrane materials will have different stretch, temperature, humidity, and electric field dependent properties and the self-sensing methods developed will provide a powerful tool for characterising these properties for a range of DE configurations. However it is important this is
verified experimentally using a variety of electrode materials and soft polymer dielectrics. An especially relevant avenue of future work will be in testing dielectric membranes that have lower mechanical losses than VHB4905, e.g., silicones. Less viscous materials may respond mechanically to the oscillations in the actuation signal introduced in order to enable self-sensing, causing the DEA to vibrate at the frequency of the oscillation, which may affect the accuracy of the self-sensed electrical parameters.

Further work on the cyber-pain parameter is required. In Chapter 6, it was shown experimentally that the characteristic behaviour of several key electrical parameters changed as the DEA neared failure. General trends were observed, however not enough is yet known to be able to use these parameters to define a general-purpose pain parameter. Furthermore, currently only one DEA material (VHB4905) and one DEA configuration (an expanding dot DEA with an equibiaxial prestretch of 16) in a temperature controlled, air conditioned environment has been investigated. However, different materials will have different electromechanical properties and may have different characteristic behaviours. Furthermore, it is not yet known exactly how changes to the ambient environment, particularly changes in temperature and humidity, will affect the characteristics of leakage current through a DEA. It will be important therefore to investigate the relationship between temperature, humidity, leakage current, partial discharges, and dielectric breakdown in comparison to the behaviours observed in the experiments conducted in Chapter 6.

More work is required to develop control strategies for self-sensing DEA. Based on the prior art, self-sensing techniques for DEA had a number of limitations and it was not straightforward to implement them in a practical system. For this reason little work has been done to determine how best to use self-sensing in a closed loop controller. The self-sensing presented in this thesis is both practical and robust, thus further exploration of the advantages and disadvantages of different control theories can now be undertaken, e.g., PID, adaptive control, state space, or gain scheduling. In particular, integrating the position and stiffness controllers will be a significant advantage for DEA-based devices.

Exploring different control strategies also raises the issue of observability. In control theory, a system is said to be observable if the state of the DEA can be fully determined using the measured feedback parameters. In the experiments conducted in this thesis, the simple expanding dot DEA was observable because the capacitance enabled the area of the electrodes to be determined. For more advanced DEA configurations however, capacitance alone may not
be enough to fully determine the mechanical output of the DEA. In particular, capacitance sensing alone does not enable the differentiation of stretches in each of the planar directions of a DEA. Furthermore, new materials for dielectric membranes, especially composite materials, may for example exhibit hysteresis in the relationship between capacitance and stretch, or it may not be accurate to regard them as volumetrically incompressible. More advanced control strategies will integrate the other self-sensing feedback parameters into a controller.

Another enticing prospect for self-sensing is the concept of integrating self-sensing with other flexible electronic technologies, thus paving the way for fully compliant active devices. In particular, Dielectric Elastomer Switch (DES) technology is a promising candidate. At the most basic level, DES could be used as part of a stretch sensitive feedback mechanism, however it has already been demonstrated that this technology also has application in high voltage driving circuitry and soft logic elements. As this technology develops, power circuitry and perhaps even computing could be integrated into the membrane of the DEA itself, thus reducing the number of ‘hard’ elements in a DEA device whilst retaining their artificial muscle status.

It will also be important to evaluate how well the self-sensing scales to systems with multiple degrees-of-freedom. The basic configuration developed enables a single power supply, set to a fixed voltage, to be connected to several DEA that can each be controlled independently. This was demonstrated experimentally for the Iteration #1 of the self-sensing algorithm in a system of four bending DEA in [106]. However, there are many aspects of this general structure yet to be explored. In particular devising a way of co-ordinating multiple degrees-of-freedom and controlling the distribution of power to achieve a desired response will be important future developments.

Within individual degrees-of-freedom in a DEA device, multiple active elements offer potential advantages with regard to efficiency and robustness to partial failure, and it will be valuable to explore how this configuration might affect a self-sensing system. As discussed in Section 1.2.4, staged recruitment of individual motor units within natural muscle enables control of overall force and stiffness, key features that contribute to muscle’s versatility and efficiency. Smart DEA have an advantage over natural muscle in that control of force and stiffness can be achieved using a single element, but the recruitment process is also a mechanism that enables individual motor units to be rested during muscle activation, and makes natural muscle robust to partial failure. In contrast, failure of a DEA is typically catastrophic and prevents further actuation. By subdividing a large DEA into multiple smaller DEA however, the failure of a
single element has a reduced impact on the overall performance. Alternatively special self-healing electrodes, where dielectric breakdown electrically isolates the defective region by causing the surrounding electrode material to be burnt away, could also be used to achieve the same effect. Further work is required to investigate what effects partial failure of a DEA device will have on the self-sensing process.

7.5. Related Publications

7.5.1. Book chapters


7.5.2. Conference papers

Papers on which I have been primary author:


In the following papers, O’Brien implemented Iteration #1 of the self-sensing algorithm in several practical demonstrations of biomimetic actuator arrays with my help:


7.5 Related Publications

7.5.3. Patents

- Inventor on the PCT patent application entitled “System and Method for Dynamic Self-Sensing of Dielectric Elastomer Actuators” (Serial No. PCT/NZ2010/000025, filed 18 Feb, 2010) covering the second iteration of the self-sensing method described in Section 3.4 of this thesis.

- Inventor on the provisional patent application entitled “Self-Sensing Dielectric Elastomer Actuator” (Application No. 588641, filed 18 Oct, 2010) covering the 3D self-sensing method for DEA described in Section 3.5 of this thesis.


Supplementary DVD

The appendices of this thesis are provided on a supplementary DVD. On the DVD is a collection of the MATLAB m-files that were used to simulate a DEA system, evaluate the performance of the various iterations of the self-sensing algorithm, and to analyse the video feedback recorded during each of the experiments performed for this thesis. Also included are the LabVIEW virtual instruments that were used to control the self-sensing experiments from Chapters 4-6. A selection of the raw videos from the self-sensing experiments is also provided.

A1.1. MATLAB m-files

The MATLAB m-files included on the DVD are:

1. **dea_simulator.m**: a numerical simulation of the circuit presented in Figure 3-2 was created as a design tool for evaluating the performance of the self-sensing algorithms from Chapter 3. This simulation enabled the influence of each of the electrical parameters on a DEA to be selectively manipulated, and generated the time history of the voltages at nodes $V_1$ and $V_2$. This information could then be used as raw data input for any of the self-sensing algorithms. This simulation was validated using experimental data obtained in producing my 2008 SPIE EAPAD conference paper [105].

2. **plane_fitting_visualisation.m**: this m-file applied the DEA self-sensing algorithm presented in Section 3.5 to a range of data sets generated using dea_simulator.m. This m-file was used to generate the figures presented in Section 3.6.

3. **video_analysis.m**: For each experiment presented in this thesis that involved an expanding dot DEA, the area of the DEA was measured using video extensometry. This
A1.1 MATLAB m-files

particular MATLAB script was used to analyse the videos from the capacitive sensing verification experiments conducted in Section 4.4 – Capacitive sensing verification. Variations of this code were used to analyse data for the other experiments presented in this thesis.

A1.2. LabVIEW virtual instruments

Several virtual instruments (VIs) were created in LabVIEW 8.6, and later LabVIEW 2009, for controlling the experiments presented in this thesis. Included on the supplementary DVD is a LabVIEW VI and its associated sub-VIs that were used to control all of the experiments. Minor variations of this LabVIEW file were employed for each of the experiments conducted for this thesis. The files included are:

1. **3D self-sensing position controller for setpoint tracking.vi**: This LabVIEW file is the main program that was used to control the experiments conducted in this thesis. The file acquired images from the USB camera, controlled the EAP Controller high voltage power supply via USB, acquired data from the self-sensing circuit, executed the self-sensing algorithm, executed the control law, updated the duty cycle, and recorded all of the experimental data to file. Minor variations of this file were used in each of the experiments presented in this thesis.

2. **Self-sensing raw data conditioning (SubVI).vi**: This algorithm took the raw data from the self-sensing circuit, calculated $R_{ESR}$, and used this value to transform $V_{DEA}$ into $V_C$.

3. **Self-sensing plane fitting using Cramers rule.vi**: This algorithm took the output data from the **Self-sensing raw data conditioning** sub-VI and fitted a plane to the cloud of data. The outputs were the coefficients of the fitted plane.

A1.3. Video Files

A selection of the raw video files used in Chapters 4-6 is included on the supplementary DVD. From Chapter 4, the videos for the capacitance validation experiments have been included. From Chapter 5, the videos for the disturbance rejection experiments, the setpoint tracking experiments, and the frequency response experiments have been included. From Chapter 6, the videos from each dielectric breakdown test were very similar, therefore only a single video of an expanding dot DEA being driven to the point of dielectric breakdown has been included.