

Novel Actuation for Jumping Space Robotics

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Abstract

Chapter 1

Introduction

Robots are generally defined by autonomy. While simpler automata-like machines can carry out well defined, easily repeatable tasks, a robot is capable of complex action under its own autonomy. Robots are computer programmable, in general, able to follow out complex instructions. Crucially, however, they are distinguished from simpler machines by their ability to sense what is around them, adapting to stimuli to mould to a situation^[8]. Applications of these machines are numerous and exceptionally promising.

Classic examples are robotic arms seeing use in manufacturing industries. These robots are multi-axis handling and transfer devices, able to handle a multitude of different workpieces and tools. When compared to traditional human-involved methods of manufacturing they see great improvements on speed and efficiency when deployed^[3]. While having fewer Degrees of Freedom (DoF) than human arms, they can move through greater angles. The International Federation of Robotics^[46] computed the operational stock of industrial robots at 2,722,077 units in 2020. In the period 2014-2019, trends towards automation saw an 11% increase of robotic installations each year. While these numbers have dipped in 2019, the COVID-19 pandemic is expected to see a medium term growth of the industry as more companies use the opportunity to further push automation.

In medical fields, robotics are seeing rapid progress. The precision, accuracy and repeatability of movement allows delicate operations to

be performed to greater efficiency and effectiveness. Robotics in this field have facilitated improvements in quality of life for both patient and surgeon. Reductions in scarring, surgery time and hospitalisation time for patients^[60;95] have been reported: As early as 2000, with the robotic-assisted surgery da-Vinci systems. Over 3400 da-Vinci units are in use around the world (as of 2015) and clearance has been granted for numerous procedures including cardiological and head surgeries^[78]. By interaction with a master console, a surgeon can manipulate four, 3-DoF arms as well as a proprietary wrist-like device, granting seven extra DoF. The da-Vinci system is designed as an extension of the surgeon's abilities, assisting in the delicate operations. This deviates from the standard definition of robotics. However the autonomy here is seen in the robot's interpretation of the surgeon's instructions, translating them into actions. Other surgical platforms, such as Senhance have built upon the da-Vinci system, offering haptic feedback and more ergonomic visualisation^[78]. Robots such as the FreeHand system use articulating arms to manipulate a camera for surgical investigation. Again, this system is human controlled and robotically enhanced. Full autonomy in this sector presents high risk interactions between robot and the delicate biology of humans^[9]. Though many autonomous surgical robots are being developed for relatively simple operations^[92], human observation is still required.

Urban farming, forestry and agricultural sectors are also seeing robotic integration. Incited by advancements in GPS systems, laser detection, ranging technologies, and actuators, this field has begun to make use of intelligent, autonomous technologies^[17;4]. Precision weed control and fertiliser allows reductions in costs, crop losses and the environmental impact of blanket spraying. Systems such as the Ladybird robot RIPPA (Robot for Intelligent Perception and Precision Application)^[17] allow for the precision application of agrochemicals. Robotic applications are also seeing research in harvesting. Traditionally labour intensive, advances in machine learning based vision and gripper technologies

are making the automation of this process more feasible. Though these advances are still challenged by the high variability of the shape, size and colour of different crops and the role these factors play in the decision to harvest^[23]. Advances in sensing may also facilitate autonomous detection of plant diseases with non-destructive methods^[4].

Autonomous systems have seen interest and success for fielding in applications that provide significant risk to human health. MiMRee from Catapult intends to use a fully autonomous system of boats and Unmanned Aerial Vehicles (UAVs) to carry out repair and maintenance operations on off-shore wind turbine blades^[69;13]. This would mitigate the dangers faced to human engineers when carrying out routine maintenance by performing preventative maintenance on the blades themselves. This reduces the amount of callouts for human engineers for minor repairs. Operating on turbine blades is notoriously unsafe. Increasing safety and reducing economic costs for wind turbines can provide the wind energy sector additional viability for replacing tradition power production methods^[93;103].

Nuclear Decommissioning is an area which thrives on the rapid deployment and reduction of human health risk robots facilitate, and has seen increases in recent years. Fukushima Daiichi has been undergoing decommissioning since the disaster in 2011. There, environments are highly radioactive and especially unsafe for humans^[71]. Applications for these robots are tricky, with many failures due to robots becoming stuck, entangled or failing due to radiation^[73]. Characterising environments submerged in radioactive water to locate fuel debris and nuclear waste are of great interest, especially in Fukushima Daiichi's case where flooding is prevalent and explosions have scattered radioactive debris^[72]. The University of Manchester's AVEXIS and MALLARD robots^[72;35], Toshiba's "Little Sunfish" and a swimming robot from Hitachi have all been developed or adapted to tackle this task.

However impressive the research commitment and practical success, robots are limited. The robots of the manufacturing world exist in a tailored environment: vast, flat and controlled

warehouses constitute their operational universe. Within this they can achieve great success, but they lack adaptability and faced with novelty, their efficacy reduces to an infinitesimal shadow. Robotic systems that do face the novel environment face hurdles of complexity due to the unpredictability of our universe. The natural world is a complex, highly coupled chaotic system. Natural organisms have only managed to operate within it by virtue of being part of it, growing with it. UAVs and underwater robotics, though facing numerous challenges not faced by their limited, somewhat ignorant cousins in the factories, exist in 3 dimensional continua that - placing the discussions of complex fluid mechanics aside - they can move about freely within. The obstacles are not physically solid barriers, and while the complex dynamics of fluid pose considerable challenge to this day, they can still venture through such fluidic entities without being physically blocked. These systems face other drawbacks: the power appetite required to fly; the nature of pressure underwater; the stability of a control system; and the payloads they can carry to name but a few. Humanity exists in a pseudo-three dimensional realm, we are constrained by gravity in most part. We are limited in our motions by mountains, rocks, trees and these complex environments create considerable obstruction. Even as we make moves to explore bodies other than our own in space, these challenges remain present. The bodies are still rocky, they are still mountainous and they are still unpredictable. Humans conquer such obstacles, but other challenges of these environments mean we can not set foot there without considerable and costly effort. As such, Humans send machines as ambassadors to these unforgiving worlds, they do not need air or food in traditional senses and so boast much higher odds of success for their tasks. As we have mentioned however, our machines are still not up for most of their tasks and, while extremely impressive, they fail frequently.

Research and success in the field of soft robotics has lead to a surge of interest. Soft robotics are compliant and adaptive robots that make heavy use of biomimetics. Some advances

in soft robotics are however rather more detached from macroscale biology, actuating themselves with light, magnetism and heat.

It is not new in any sense to seek nature as an inspiration for creation and the skilful use of such a muse has lead to many of science's greatest achievements. Awe inspiring feats of engineering and mastery of physics are presented to us daily within nature, the product of millions of years of brutal and random mutation. Humans themselves are part of such lineage. Animals find minimal impedance within such complex environments which they are part of. Birds ride the unpredictable dynamics of air with grace, Goats scale near-shear cliff faces with ease and Monkeys leap across branches of complex interwoven forests. It is difficult to avoid notions of 'Design' and 'Purpose' in discussions of nature, despite knowing it does neither of these things. However, nature appears to have designed it's machines in a way that addresses the environment and asks 'What is exploitable?' and 'What must be mitigated against?'. Sadly, it is not yet conceivable that humanity can match nature's beautiful creations, but we can capture their abstractions. What allows an entity of nature to operate so gracefully as part of it's environment? We benefit from heuristic and hindsight which - in combination with the inspiring success of science, mathematics and engineering - allows us to distil such abstractions and compare them to our own technologies to see where our gaps lie. This is the approach behind this work. What is the environment? What is our task within this environment? What must be mitigated? What is exploitable? These questions are asked with a backdrop of compliance, adaptability and integration crucial to nature's success, that comes tied with an observation and distillation of the principles facilitating such concepts.

A particular field of robotics that carries significant interest for ground based environment navigation is that of saltatorial locomotion and, more specifically, jumping. Animals that utilise this locomotion mode are extremely capable at navigating complex environments. Animals using jumping are as small as fleas or as large as monkeys. Many robotic systems have attempted

to use this mode to varying levels of success. Challenges exist that make this locomotion difficult, mainly concerning the mechanism of actuation, the complexity of the individual movement and the control for path planning, landing and stability leading to repeated jumps. More recently, jumping has begun to see interest for the application for space exploration. Currently robotic rovers and, recently, UAVs have been deployed on mars the moon and in some capacity an asteroid but as mentioned face problems of navigation. With the reduced gravity of these bodies, saltatorial locomotion is endowed even further validity for environmental navigation.

This project's intention is to develop a soft robotic actuator for saltatorial motion to tackle the challenge of rugged terrain of the Moon and Mars. Taking on board the philosophy mentioned in prior paragraphs of 'environment first' - in this case space - in design and being followed by the distillation and application of biomimetic principles from analysis of nature, before being adapting these principles to the extra-terrestrial environments.

This writing explores first the literature of Space (§2) asking questions of environment, what allowed the success of our robots in these environments and where yet are advances to be made? This frames the next chapter §3 which introduces soft-robotics, expressing interest in actuators within the field and exploring in further detail the Peano-HASEL actuator (the focus of this project). Explorations and comparisons of actuator mechanisms, capabilities and disadvantages are discussed. Then, in chapter §4, the actuators are compared to that of nature's creations, with a lens of saltatorial locomotion, to distil concepts that will inform the actuators expansion and application to jumping robotics. Then explored is the full summary of the potential of the actuator in application via a feasibility discussion (§6). This will provide a high-level view of what concepts need to be addressed in making progress towards jumping locomotion in space robotics. §7 lays out the aims and objectives of this project alongside presenting current results and future avenues of research.

Chapter 2

Space Robotics

2.1 Space as an Environment

The project at hand intends to develop a jumping robot with the intention of exploring extra-terrestrial bodies. Two major operational environments are intended for this project: The Moon and Mars. Both are considerably rocky, making navigation with wheels cumbersome. Both have very little atmosphere. Mars' atmospheric pressure is 6.1mbar near the surface, 0.61% of Earth's. The moon is basically vacuum. These conditions pose difficulty for aerodynamics of UAV flights which are currently generally rotor powered to allow electronic charging. The *Ingenuity* Martian helicopter must spin its rotors in excess of 2400rpm in order to fly, requiring considerable power draw. This gives the UAV a range of 300m with 5m of altitude, for a flight time of 90-seconds per Martian day^[74]. The engineering to facilitate this is no less impressive given the technical specifications of this proof of concept, but it highlights the considerable hurdles faced by UAV flight in extra-terrestrial environments. The UAV would simply not work on the moon for lack of atmosphere.

Extra-terrestrial environments also pose hazards that are not present or mitigated on Earth. Our Sun's influence extends across the solar system. This so called *Space Weather* consists of the solar system scale effects that the highly-energetic celestial ball of plasma creates. Space Weather loosely follows the 11-year solar activity cycle in which the sun oscillates from low

to high activity. Plasma consists of high energy ions in a constant state of collective flux^[47] involving mechanical, nuclear and electromagnetic interactions in droves. This can cause erratic and unpredictable behaviour. Solar flares, Coronal Mass Ejections and Solar Proton Events are all characteristic of solar activity, sporadically emergent from these intricate, smaller scale dynamics. Coronal Mass Ejections are considered the solar systems most powerful phenomena other than the Sun itself. The propagate across space at speeds in excess of 1000kms^{-1} and pose considerable risk to electronic structures. High energy ions are also released. These events are of particular note for their high risk potential but are difficult to design against due to the intensity of such phenomena. Radiation from both the sun and sources beyond the heliosphere require attention. Terrestrially, these effects are highly mitigated by the Earth's atmosphere and the magnetosphere, however this safety cushion is lacking on the Moon and Mars.

Solar Energetic Particles (SEPs) consisting of high energy particles in the region of KeV \rightarrow GeV can be dangerous forms of solar weather^[91]. These particles are ejected from the high-energy environment of the sun and pose considerable threat to robots, affecting material integrity and interfering with electronic systems. They are sporadic with onset times on the order of minutes and durations on the order of days^[41].

Galactic Cosmic Rays (GCRs) also require consideration. GCRs are dominated by protons, but also contain a significant portion of helium ions. A non-negligible amount of heavier nuclei (1%) are also present. These originate from interstellar sources. The energy of these particles far exceeds its solar, but is, but is highly chronic and therefore predicatable. Single particles of 10^{20}eV ^[65], with a more common energy range of $100 \rightarrow 10000\text{MeV}$ ^[104;97], can enter the solar system from interstellar sources and affect biological life and electronic systems. GCRs are also anti-correlated with the cycle of sun activity, being modulated by solar winds. The mechanism of modulation is the magnetic field embedded within the winds and such is lowest at periods of low solar activity^[104;97]. It is very difficult to

shield against GCRs. Typical aluminium shields read career limits of exposure in roughly 3 years of GCR exposure. Other estimates cite an unrealistic shielding of 15m of lead^[65].

When one begins to consider the radiation on the surface of bodies, more factors come into play. The Mars surface radiation environment is dependant on the atmospheric properties. Given that the atmosphere of Mars is $< 1\%$ of terrestrial, only lower energy particles are effectively filtered^[104;41]. The surface material also contributes when considering the neutron environment. Interactions of both GCRs and SEPs with the surface produce neutrons and γ -rays, further populating the radiation environment^[41]. The *Curiosity* Rover took measurements of the radiation environment. GCR doseages were between $180 \rightarrow 225 \mu\text{Gy/day}$ with variance attributed to the atmospheric pressure, Martian seasonal variations and heliospheric structure variability due to solar activity^[7]. These values were measured near the maximum of Solar Cycle 24 and as such GCR modulation was near peak. SEPs were

2.2 Robots in Space

The hostile environment presented to humans^[40] in vacuum and on other extra-terrestrial bodies means space is a realm mainly populated by robots. This section explores in more depth previous and current robotic exploration platforms.

Valuable and extensive research, often beyond original operational scope, has been carried out by rovers on the surface of the Moon, Mars and other operational theatres^[6;25]. The *Yutu* robot, due to mechanical failure, ended its mission a month and a half after landing on the Moon. However a month later it was reanimated to collect data, record videos and communicate signals for some time, despite lacking locomotion; a demonstration of the value of even erroneous robotics missions. While rovers on missions exploring the moon and mars have lead to improved understanding of the bodies, challenges and failures are abundant.

Perhaps one of the most inspirational tales of extra-terrestrial inspiration is NASA's *Opportunity*

rover. Currently holding the record for longest distance travelled on another body, *Opportunity* travelled 45.16km and exceeded it's design lifespan by more than 14.12 years. The rover's mission was deemed complete after a planet wide dust storm caused it to lose communication.

Mateo Sanguino^[25] in their comprehensive review evaluates over 100 mobile exploration robots between 1959 to 2016 and performed a bibliographic analysis investigating the different types of robots seeing interest in research. Their conclusions show that 93% percent of the vehicles are low speed, with 76% having basic suspension systems. Rover masses range up to 120kg. Suggestions for improvements based on this analysis are concluded, including but not limited to: "more simple and effective locomotion" and novel approaches to exploring extreme terrains to reduce failure rates. Issues such as CPU designs, Multi-Mission Radioisotope Thermoelectric Generator efficiencies and safer batteries which recharge faster, have higher density ratios and life cycle. The review also concludes that interest in research for rovers has moved to regions with higher scientific return, such as robotic manipulators, Unmanned Aerial Vehicles (UAVs) and humanoid robots. Though one could see this as a lack of interest in exploration, the average trends of contributions on robotic exploration vehicles by region shows that the field still exists having held gains. One may consider the branching scientific implications of the mentioned alternatives, having impacts across multiple applications of robotics^[89]. For instance, the field of robotic grippers, and robotic actuation in general, can benefit a large number of applications, including space exploration robotics. This suggests that research efforts may be better spent in the development of more general technologies that can be adapted to space robotics, rather than a specific focus and subsequent technological diffusions to other fields.

Aerial Robots, such as UAVs, have seen significant spikes in interest in the period 2000-2015, while rovers have plateaued over the same period, dipping in 2015. This may be due to the failures associated in navigating terrain and the

allure of reducing failure rates by simply avoiding terrain navigation, for the most part with UAVs and other aerial robotics. However fig.7 in Matteo Sanguino's review paper shows that all parts of the world have seen rises in contributions on robotic exploration vehicles in the same period, levelling out at an elevated average.

While the mentioned UAV systems are viable for exploration, when flying over obstacles, flight times are limited to 90 seconds. This limitation is imposed by the high RPM of the rotor required for martian atmosphere, and the reliance of solar charging of a battery for power^[56;79]. Aerodynamics and low gravity also pose challenges to the operation of UAVs on extra terrestrial bodies with atmospheres, inciting challenging aerodynamics such as vortex shedding. High propulsion efficiency and low mass are also paramount, so large loads cannot be lifted as yet. On those bodies without atmosphere, the propeller simply would not function. However for short range scouting missions and sample movement they could prove extremely useful.

2.3 The future of Space Operations

A recent explosion of space activity thanks to private companies inciting competition looks to see space industries expand rapidly. Since the cold war era space race, new players have entered from both national agencies such as India, China and Japan, as well as the well know surge in private industry, offering a variety of scales for launch platforms^[89]. This level of competition is potentiating explosive growth in the industry, with private companies investing heavily in research and development^[101].

Sights of public and private sectors are being set on asteroid mining for rare Earth minerals^[25], payload delivery and construction into/in Low Earth Orbit and human colonisation of extra terrestrial bodies^[14]. Rare Earth materials are crucial for a number of technologies required for the move away from fossil fuels and many other technologies we have come to rely on such as

high-capacity batteries, solar cells fuels cells and catalyzers^[25]. Many proposed systems for extra-terrestrial resource attainment rely on robotics for prospecting and extraction operations, requiring small, cheap and mass-producible spacecraft to be economically viable. These technologies are immature, despite significant progress in recent years. Pena-Ramos et. al.^[77] suggests the most important technologies are those designed to detect which materials are present in asteroids, as well as those designed to harvest them. Missions such as the ESA Rosetta/Philae have made headway into landing on asteroids and performing (somewhat unorthodox given its landing situation) research into the physical makeup and behaviour of asteroids^[98].

With the competition provided by private sector industries, payload prices have begun dropping on average, approaching single digits per kg^[51], with some as low as $1.4\$/\text{kg}^{-1}$. The validity and economic viability of space missions decreases with payload costs, making these trends promising for beginning larger space operations^[99]. Missions using lighter payloads are more frequently deployed in all orbit theatres. This demonstrates that, although costs are decreasing, preference towards smaller payloads remains. 1000kg payloads saw beyond double launch frequency than 2000kg payloads in 2000-2013^[18], though this may have decreased considerably since then. This is further supported by the percentage of launch vehicle decisions by cost effective ranking, which sees rapid decay as this rank decreases.

Chapter 3

Soft-Robots

3.1 Traditional Actuation

To understand the reasoning behind moving away from hard robotics to soft, it is important to understand the status quo. Traditional actuation for robotics, and the current norm, utilise predominately motors. Motors have experienced significant development and research. Their mechanics are widely understood, they are tractable and common place in a myriad of systems, robotic or not of varying scales. Motors produce rotational torque by exploiting the effects of electromagnetic force. For these reasons, motors are a powerful tool in modern systems and not one soft robotic actuators will replace in all fields, at least in the near term. Traditional actuation however does have some disadvantages. For one, motors have a commonly understood theoretical limit, imposed by a sharp rise in effective magnetic reluctance imposed by material choice and operating magnetic flux density. Operating at a high enough flux density, a significant amount of Magnetomotive Force (MMF), the mechanism from which a motor produces force, is used in driving flux through the magnetic circuit. This imposes fundamental limits onto the motor. However, this is not necessarily an issue as many motors are competently designed to mitigate such problems for given applications. There is also a radial force which pulls the stator pole towards the body of the rotor, a by product of the . This total radial flux can be rather large, on the order of 1000N

in some cases. Motors mitigate this in design by equally spacing poles around the rotor with equal flux density. However, small discrepancies cause inconsistencies in field strength, and can contribute to untimely wear.

In order to provide comparative metrics later in this writing, it is important to define the mathematical nature of these metrics in motors. Firstly, power is an important property in actuation. The motors power output $P[W]$ is given by:

$$P = T\omega = \frac{\pi}{2}D^2L(\bar{B}\bar{A})\omega \quad (3.1)$$

where $T[Nm]$ is the Torque , $\omega[rads^{-1}]$ is Angular Velocity, $\bar{B}[Tm^{-1}]$ is the Specific Magnetic Loading, $\bar{A}[Am^{-1}]$ is the Specific Electric Loading and $D[m]$ and $L[m]$ are the Rotor Diameter and Length respectively. From this equation, via the D^2L term one observes that the power output is dependant on the rotor geometry. Thus the torque output and subsequently, power output of a motor is proportional to these dimensions. However, rotational velocity carries as much weight in the equation as torque. Larger, low speed motors appear more costly than high-speed smaller motors, often therefore belts and gears are required to reduce speeds. Perhaps a more important quantity is that of *specific* power output. In conversations about mobile robotics, the notion of specifics is important as weight is at a premium. This is exasperated by the attention to a space application. Specific Power in this writing is defined as the power per unit weight $p = \frac{P}{M_m}[Wkg^{-1}]$.

3.2 Soft-Robotic Actuation

A critical component of a robot is its ability to interact and locomote in and about an environment. The ultimate goal of robotic design is to achieve (and, potentially supersede) the organisms developed by natural selection. Natural selection allows organisms to adapt and mould to their environment, exploiting aspects they can and compensating for those they can't. Crucially, evolution produces 'machines' that can

comply with an environment. Currently, traditional, hard actuation struggles with this later point in that complying to novel applications, environments and actions is a significant challenge for rigid materials and the control that moves them. Compliant actuation is therefore a field of significant research. Compliant here can be taken to mean an adaption to novelty in environment and task. The combination of a compliant body and a compliant mind is what allows nature to achieve it's efficacy. The compliant body will be the focus of this section, more specifically the recent research in soft robotic actuators, which show promise as a step towards the natural ideal.

El-Atab et al. (2020)^[29] provide a comprehensive breakdown of the various types of soft-actuators currently in development. Soft-Actuators make use of polymers, gels fluids and papers .etc, that exhibit the sought after properties of soft-robotics. Materials vary between actuation and sensing methodology.

The review groups actuators by their actuation stimuli: Electrically Responsive, Magnetically Responsive, Thermally Responsive, Photo-Responsive, Pressure-Driven and Explosive; an example that shall be followed in this writing. Comparisons with alternative stimuli and discussions of Electrically Responsive actuators are given in detail in later sections, being the major topic of this report.

3.2.1 Shape Memory Alloy

3.2.2 Magnetically Responsive

Magnetically Responsive actuators apply an external magnetic field to stimulate actuation. The fields interact with magnetic fillers embedded in soft compounds. Varying directions and magnitudes of applied fields allows control of actuators^[75]. Small areas may see independent creation of fields and its spatial gradients to allow multiple actuation modes, facilitating more complex movements^[27]. Response times are fast, with 100Hz responses reported. Drawbacks to this actuation method are the complexity and cost of manufacturing involved with integrating magnetic components into the actuators, though

work is being done to mitigate this^[29]. Another challenge is that magnetically responsive actuators are not yet able to restore their original shape in the absence of applied fields, likely leading to decreases in per movement efficiency as control expenditure is raised in restoring resting shape.

3.2.3 Thermally Responsive

Thermally Responsive actuators are stimulated by infra-red, near infra-red, thermal radiation or Joule heating^[29]. These methods are safer than electric fields or Ultra Violet (UV) light, but are less efficient, some as low as 1.32%^[37], and slower than other methods. They also suffer from Hysteresis which impacts control. Shape memory alloy and polymer smart materials can deform under stimulus and return to their original pre-deformation state passively. This is achieved through crystal structure properties that vary with Young's modulus. Liquid Crystal Elastomers (LCE) are another material used, which are useful for stimulus response applications. LCE hinges can be actuated at a variety of temperatures and showed large, reversible bending. However, their torque output is low^[57]. Synthetic Hydrogels consisting of 3D polymer networks containing up to 99 wt% water are capable of shrinking when influenced by a range of stimuli, including temperature. These materials are deployed with a number of strategies for different applications, showing particular promise for biomedical applications (i.e drug delivery, tissue engineering)^[29].

3.2.4 Photo-Responsive

Photo-Responsive actuators are wireless and able to be miniaturised. Materials in Photo-Responsive actuators use optical signals to modify their properties and perform actuation. Optical stimulations range from visible light actuation to near infra-red. Visible light robotics bear the advantage that they can operate in natural environments without applying additional energy. However as sunlight is consistent, there

needs to be introduced periodicity for certain methods of actuation.

Near infra-red actuation is appealing as it can penetrate biomaterials with low losses^[29]. Issues of low actuation and degraded mechanical characteristics are prevalent in both ranges of wavelengths, though this is credited to poor fabrication techniques. Both methods require high intensities of light for relatively limited deformation possibilities. The materials involved are also sophisticated, consisting of polarised molecular arrays of high order, adding to the ease of manufacturing.

3.2.5 Pressure-Driven

Pressure-driven actuation is nothing new, being the premise behind examples of hard actuators. Research of miniaturised pressure driven soft actuators has seen interest, performing well in force intensity at small scales. The focus of this research looks into simplification of manufacturing process for inflatable chambers, accuracy of locomotion and increasing force intensity. Pneumatic actuators actuate with air, making them efficient and safe sources of actuation. A significant downside with regards to autonomy is the requirement of pumps to actuate. These may be large and rigid. The necessity to be connected to rigid control and power supplies to achieve adequate forces is cumbersome. Applications currently are fluid movement process valves in chemical and process industries. Hydraulic actuators use fluid pressure. These actuators suffer from the added weight and energy consumption in pumping due to the viscosity of fluids. Rigid power and control is still an issues as in pneumatics.

3.2.6 Explosive

Research has been conducted investigating actuation based on explosive chemical reactions. One example uses hydrocarbons introduced to electrical spark generating an explosion, causing the robot to jump. However, directional control is challenging here. Force production is high, with a 2.1kg robot from Loeffe et al.^[62] jumping 7.5

times its height in 20s. Attempts to control the direction integrate pneumatic actuation to tilt the robot prior to a jump. While this is a copious amount of force, Loeffe et al. report that the robot landing on its back causes immobilisation. Viability of explosive actuation is limited. Having to replenish chemical materials reduces their long term remote operation potential. Materials also need to be strong to contain the explosive work. Scalability is a challenge and combined finally with the lack of stable control, these actuators require much more research to be applicable^[29].

3.3 Peano-HASEL Actuators

Another class of soft robotic actuators of importance to this project are electrically responsive, transducing electrical energy into mechanical. Electric signals allow relatively precise actuation responses and these devices are easily compatible with existing electronic devices. El-Atab et al. boldly claim the application potential to be “unlimited”^[29]; including micro-fluidic, micro-scale object manipulation, micro-locomotion^[49] and artificial muscles^[1;55;44].

3.3.1 Dielectric Elastomer Actuators

Dielectric Elastomer Actuators (DEAs) are the precursor to HASEL actuators and an alternative employed by many. By exploiting the Coulombic attraction^[45]; establishing a potential difference between two electrodes and them pulling together through the electrostatic forces of attraction. These electrodes are located on opposing faces of a compressible membrane so that the membrane is deformed as the electrodes experience said force. Typical elastomers employed are “Acrylic, Silicones, Polyurethanes (PU) and Rubber.”^[29]. Attributes and disadvantages vary by material and are application specific. For example, silicone and PU elastomers are mouldable to a number of shapes and degrees of softness, do not often require pre-stretching and have fast response times. Though strain production is relatively lower and reduced permittivity of silicones

requires higher voltage stimuli, reducing the autonomy of a system. Research on these actuators reports high strains ($> 100\%$), high efficiencies ($> 80\%$), energy densities and self-sensing. Combination effects of multiple actuators and integrations with frames can improve force output. Models for simulation have been demonstrated to be accurate and applications in artificial muscles are shown. Though these attributes are promising, DEAs require large voltages in the kV range and suffer from leakage currents, which can cause electrical breakdown in the dielectric^[19]. This damages the dielectric and has deleterious performance effects^[29;1]. Stacked actuators require large areas of dielectric, prone to electrical failure according to Weibull distributions for dielectric breakdowns^[59;105]. Silicone sponges swollen with silicone oil showed continued operation post breakdown, but strains were below 5%^[44;1]. Research has been conducted in low voltage DEAs which have shown functional actuation at 450V with strain values up to 25%^[49].

3.3.2 Hydraulically Amplified Self-Healing Electrostatic Actuators

DEAs are attractive actuators, but they suffer from senescence. High electric fields and breakdowns can exhibit aging or sudden failure. To overcome this, Hydraulically Amplified Self-Healing ElectroStatic (HASEL) actuators have been developed that address the problems of both soft fluidic and electrostatic actuators, while utilising their strengths. A notable amount of outstanding and detailed work for HASEL actuators has been carried out by the Keplinger Research Group at the University of Colorado. HASEL actuators use liquid dielectrics to facilitate self-healing^[1], opposed to the solid dielectric in DEAs. When a dielectric breakdown occurs between electrodes, material in the path is destroyed as the voltage exceeds the dielectric strength of the material. In solid dielectric, this creates a channel that remains in the dielectric, reducing performance or inciting failure from short-circuiting. In solid

dielectrics the path of the breakdown leaves a cavity which affects performance detrimentally. Liquid dielectrics will flow to fill voids left by breakdowns, thus self-healing^[1;55]. Elastomer shells do not self-heal; but do self-seal^[87], this means that breakdown events still have a deleterious impact, be it substantially mitigated by liquid dielectrics. Suggestions for improvements are made by Rothermund et al. proposing incorporation of mechanically self-healing and/or gas-permeable elastomers that would allow bubbles to escape from the actuator. Acome et al in experiments showed breakdown events where observed at an average voltage of 23.8kV, with a minimum of 18kV. Over 50 breakdown events, the first and last breakdown events occurred within 0.3kV of one another (1st : 29.0kV/50th : 29.3kV). However, liquid dielectrics are not immortal. Cavities such as bubbles form after a breakdown, which have low breakdown strength. These will lead to a small but non-negligible increase in breakdown occurrence. In fig.1F^[1], it would appear that later breakdowns were more biased to be below average, with a high density of occurrence around the 20kV region. Arguably, the average in the 35 \rightarrow 50 event range would be significantly lower than when viewed holistically.

HASEL actuators make use of Maxwell stresses to induce Maxwellian pressures^[1;87;45]. These are stresses that come about in matter as a result of electric fields, shown by the Maxwell Equations of electromagnetism^[45]. By coating the elastomer shell partly in electrodes, then establishing a potential difference which generates electric fields within the dielectric, the dielectric is forced elsewhere by the mechanism of Maxwell pressures, as the volume between the electrodes is reduced by motion of electrode attraction. The fluid moves to other volumes within the elastomer shell, exerting hydraulic pressure and causing deformation as the density of the fluid increases. Influence is exerted by the deformation pushing or pulling on the intended actuation object, and designs are customisable for a variety of actuation modes. In a HASEL actuator, at a particular voltage, the Maxwell stresses exceed the restoration forces imposed by the elastomer; at this point the electrodes pull together

abruptly. This voltage threshold is called the “pull in voltage”.

The Maxwell stress (and, therefore, the Maxwell Pressure) is proportional to the dielectric permittivity (ϵ) and the magnitude of the electric field (E) and the relationship is given by (3.2)^[45;106]:

$$P \propto \epsilon E^2 \quad (3.2)$$

HASEL actuators, like DEAs, exhibit self-sensing. HASSEL actuators are essentially deformable capacitors. By passing a low amplitude AC voltage, superimposed on the high-amplitude actuation voltage, the impedance can be analysed to provide sensing of deformation^[1;55;87]. This is possible as the capacitance of an actuator is a function of its geometric properties, and thus strain: $C \propto \frac{A}{d}$ where C is capacitance, A is electrode area and d is the inter-electrode distance. Kellaris et al.^[55] compared optical to capacitive datasets against position data for a peano-HASEL (PH) actuator under a varying voltage stimulus. By using a constant scaling factor, they observed reasonable agreement between the datasets. Discrepancies were observed, implying a non-linear strain/capacitance relationship. Being electrically stimulated, precise and responsive actuation is possible in HASSEL-like actuators.

HASELs, like soft-hydraulic actuators, allow design and actuation-mode freedoms. However, HASSEL actuators generate their pressure locally by electrostatic forces^[1;87]. This removes the need for bulky equipment like compressors, fluid reservoirs, pumps etc, seen on other fluidic actuators, making them light weight and easily integrated.

Average specific power values range from $80Wkg^{-1}$ (High Strain-PH) to $180Wkg^{-1}$ (PH), with $337Wkg^{-1}$ recorded at resonance for planar HASSELs. For comparison, Mammalian skeletal muscle has an average specific power of $50Wkg^{-1}$. Linear strains up to 124% have been reported for planar HASSELs at resonance and quadrant donut HASSELs have shown 118% linear strains. Robustness tests from Acome et al.^[1] of these actuators have shown negligible deterioration after 1 million cycles (with strains

of 15%). Stacks of donut HASSEL actuators have been used for robotic grippers and planar HASSELs can displace 4kg objects with strain values of 69% when applied in parallel^[1].

In experiments comparing HASSEL to DE actuators, Acome et al. showed that under 11kV voltage stimulus, HASSEL actuators saw almost a 4 fold increase in area strain compared to DEAs ($\frac{46\%}{12\%}$). The rate of area strain with voltage stimuli was much steeper for HASSEL than DEA. Divergence was observed around 3kV. This demonstrates that HASSEL actuators not only address the problems of DEAs but outperform them, with experimental control for dielectric thickness and elastomer material (Ecoflex 00-30). It should be noted that these strains were achieved way below the dielectric breakdown voltage average and below the minimum value (from the experiments in Acome et al.^[1]).

High voltage stimulus requirements still remain an issue with HASSEL actuators. Acome et al. recognise this in their paper, citing the thick elastomer shell as a source of the required high actuation voltages. They do provide a potential solution, proposing the use of higher permittivity dielectric layers, which from equation (3.2) would increase Maxwell Pressures, and advanced fabrication techniques to produce high-resolution dielectric structural features.

3.3.3 Peano-HASEL Actuators

HASEL actuators require stretchable materials. This contributes towards manufacturing complexity and cost as electrodes and dielectrics must be compliant to this stretch. Stretchable material variations are also limited. Peano-HASEL (PH) actuators address this, instead using inextensible but flexible shells^[55]. PH actuators combine HASSEL actuators with Peano fluidic actuators^[76], to create a linearly contracting actuator. To generate pressure, again the Maxwell pressure is used to create zipping between two electrodes. The electrodes start at one edge of the pouch and progress inwards towards the middle. As the electrode zips, the liquid dielectric is forced into the unzipped, free region of the actuator. As the containing film is de-

formable but inextensible, the increased density in a decreasing volume causes a change in the pouch cross section from the resultant pressure. It is this deformation which provides the contraction. The linear contraction and electronic stimulation provide comparison to natural muscle, which also uses electric control signals via motoneurons and achieves linear contraction.

Due to the pressure being generated locally via electrostatic forces, Peano-HASEL are more versatile and applicable to autonomous systems, removing the extra equipment for traditional hydraulic actuation and are renewable, relying on electrical stimulation rather than compressed air. However, this does leave the actuators performance and applicability in part at the mercy of the energy-density of the power source. This is particularly troublesome with the high actuation voltages present, on the order of kV, though this may be mitigated with material choices for dielectric and shell. The distinct advantages of PH actuators over traditional HASEL are the versatility of materials, due to flexible materials being more numerous than stretchable; and they allow for fabrication compatible with existing industrial methods, reducing cost and increasing versatility. Kellaris et al. (2018) report their actuators cost \$0.10 in materials, using biaxially orientated polypropylene as a film material, conductive hydrogel as electrodes and Envirotrop FR3 vegetable based transformer oil as dielectric^[55]. They also note that in large scale manufacturing this cost would significantly decrease. Due to the inextensible nature of the shell, PH actuators removed the instability observed in HASEL actuators and provide smoother, progressive zipping, avoiding the pull in voltage threshold standard HASELs exhibit. Once the activation voltage is exceeded, electrodes zip controllably and in accordance to applied voltage^[87]. PH actuators suffer from observed complex motion modes when wrinkling occurs in the film shell. This traps fluid and causes inhomogeneous out-of-plane deformations near the zipping regions of the actuator, reducing the possible strain output but also affects the roll off frequency. However, Kellaris et al. (2019) observed that under high loads, their actuators performed

better than theoretical models. They attributed this to these instabilities, noting that rotation was also observed about the free end of the actuators, simultaneous with contraction^[54]. Thus zipping areas are larger for the same actuation strain, increasing force output as a result. Wang et al. (2020) replaced BOPP shells with thermoplastic polyurethane (TPU) for High-Strain Peano-Hasel (HS-PH) actuators, which are more compliant^[102]. TPU shells had three times the relative permittivity compared to BOPP; however the shell was twice as thick, so similar load-strain characteristics were expected. TPU could achieve 1.71 ($\frac{16.03\%}{9.36\%}$) times the strain of BOPP at 10kV lifting a 0.2N load. However, there is no information that shows the voltage strain characteristics, which would be an insightful observation. TPU lifted lower loads in low strain regions than BOPP. Wang et al. attribute this to liquid dielectric trapped by buckling traces in regions of the shell, which prevented uniform electrode zipping.

While the simplicity, cost, ease of manufacturing, relatively high specific power, responsive and controllable actuation are all promising attributes of PH actuators, there are still a number of issues that need addressing. There is considerable trade off between force output and strain inversely proportional to the latter. High-Strain-Peano-HASEL (HS-PH)^[102] are an attempt to address this. Rather than covering the entire width of the shell with the electrode, aligned with the contraction direction, HS-PH instead place the electrodes orthogonally to the loading direction. In a standard PH actuator, the electrode contributes to the initial length but not to the contraction, affecting strain output. HS-PH actuators remove this. Theoretical limits of strain are therefore increased from 24%^[54] to 36%^[102]. Experimentally, achieved strains were $\approx 24\%$ with a load of 0.2N. A trade off for this increased strain was a significant reduction in blocking force, from 65N to 18N and a reduction in force generation in low strain actuation^[102].

An interesting property of the PH actuator is the direct link between geometry and actuation performance. Kellaris et. al (2019) developed an analytical model which provided considerable

agreement with their experimental results. Using a free energy approach, they were able to indentify four scaling predictions for the PH actuator:

1. The force produced by the actuator is independent of the pouch length.

Despite promising initial results, HASEL technology is still in its infancy, many of the geometric, material and fabrication combinations still remain largely unexplored.

Sensing

Sensory feedback for control can be a challenge with soft robotics. It is necessary for a robot to not only have a sense of environment, but also a sense of self. This gives it a reference to then manipulate and manoeuvre within an environment relative to it. Hysteretic properties and high resistivity associated with the operational nature of soft robotics, when subject to high stretch, hinders active sensor use^[80]. Methods of sensing, therefore, are often related to capacitance and impedance monitoring, as these properties change with deformation^[1;29], providing insights on the current state of an actuator. Highly extensible elastomers doped with additives that are electrically conductive are common in passive capacitance monitoring. Adding Carbon black, metal nanoparticles, carbon nanotubes or graphene are valid methods, as well as confining liquid metals in microchannels within the device. However, these methods can increase manufacturing complexity, stiffen the actuator and can be costly to implement. This begins to reduce the advantages using soft robotics which thrive on their cost, manufacturing ease and soft interactions. Hysteric effects of embedded sensing catalysts are also still present.

Electrically conductive Hydrogels can be used for sensing mediums to some success. They are easy and cost effective to manufacture, with the additional benefit of being bio friendly and optically transparent^[80;55;102]. However, ionic migration and electro-chemical breakdowns can occur at relatively low voltages, which can have

deleterious impacts of actuator and sensing performance.

Magnetic sensing through custom made magnetic curvature sensors can sense the closed 3D magnetic curves formed by the pose of magnetic elements embedde in the elastomers. These curves vary continuously and so provide continuous feedback for motion control, with potential in sensing force and axial deformations with minimal variations in implementation strategies^[80].

Some of the actuators currently undergoing research display inherent kinaesthesia^[55;86;1]. This proprioception can allow for high control accuracy prospects and is potentially computationally inexpensive, relying on simple relationships^[55;1]. Methods of kinesthetic sensing vary from actuator to actuator. DEA and HASEL actuators utilise capacitance sensing, which will allow relationships between actuator geometry and capacitance, though the relationship is yet unknown.

Geometry and Scaling

So far, much of the research mentioned has looked into the 2D geometric variance of PH actuators. 3D movement has been achieved through variations in in voltage applied to combinations of 2D actuators creating asymmetric actuation^[70]. Geometry of the electrodes for PH actuators has been shown to be a factor of consideration^[102]. Notched electrodes demonstrated more consistent scaling in actuator number in series than rectangular counterparts, with slight improvements in low loading regions of the Load-strain relationships. Four-unit HS-PH actuators under a 10kV stimulus achieved a 4% strain increase when compared to rectangular electrodes. Furthermore, analytical models of PH actuators have demonstrated that force-strain characteristics of PH actuators are independent of their pouch length^[87;54]. Therefore a single pouch will have the same force-strain properties as a number of smaller pouches of the same overall length, with a reduction in mass. The reduction in mass follows a $1/n$ rule where n is the number of actuators in series. As the size of a single actuator cell decreases, the ra-

dius follows suit. This facilitates increasing of packing density of actuators in parallel arrays, which increases energy density and actuation stress by increasing the force output specific to cross-sectional area. Mass specific energy and power is also increased as the length of a single pouch reduces, as less dielectric is required to fill a pouch. However this is limited by the bending stiffness of the pouch film, which is dependant on pouch thickness^[54]. Thinner shells require a lower stimulus voltage; however the pouch length must be reduced to maintain specific energy values. Rothmund et al.^[88] in their analysis showed geometric consideration can improve actuation speeds of Peano-HASEL actuators, identified by their theoretical models.

Stacked PH actuators have also been demonstrated by Mitchell et al. (2019) to create a modular actuator^[70]. Actuators were constructed in sheets and then folded to layer the actuators one above the other. Not only was this simple to manufacture, allowing rapid prototyping and experimental variation, but also demonstrated strain values of 110% for 8 actuators and a maximum force of 33N with stimulus of 8kV constructed from BOPP and Carbon Ink electrodes. Mitchell et al. also note that the stack/folding method is not limited to the module design they used, citing the quadrant donut shape explored in the same paper as an applicable module. These donut actuators build on designs presented for HASEL actuators by Acome et al. (2018)^[1]. The donut actuator was initially dimpled to instigate zipping, then made into a quadrant actuator to reduce inhomogeneous dielectric distributions during zipping, also improving initiation of zipping. While the dimpled donut had higher strain rates in the 8 → 10kV range when alone, with peak strains of $\approx 58\%$ for dimpled and $\approx 40\%$ for quadrant (at 10kV), in a stack of 3, the quadrant donut far outperformed a similar stack of dimples by a significant margin. Quadrant stacks showed strains of $\approx 72\%$ at 10kV, compared to $\approx 20\%$ for dimpled designs.

Stacks of actuators in parallel have been demonstrated allowing 3D continuum control with a human operated maze game solved by actuating stacks of HASEL with varying voltage

stimulus for each stack, controlled by joystick^[70]. 3 stacks of 5 HASELs were used. The same stack configuration was given a robotic gripper that showed reliable soft-grip, as well as object manipulation. The gripper was adapted from a scorpion tail proof of concept for curling HASEL actuators and placed on top of the stack.

Geometry optimisation also has impacts on the problem of requiring large electric fields for actuation^[55], which, though not exclusively, is a geometric problem. Alternative geometries and dielectric thickness are cited as possibilities for decreasing the needed actuation voltage.

The size of the design space for not only individual actuator cell designs but the combinations of modules presents a vast array of possible applications. Further research could apply current models and rapid prototyping to experiment within this variable space and create application specific geometries. 3D structures of actuators, arrays of small cells, allow the actuators to generate significant force outputs and high specific energies when in large numbers.

With existing models, tools could be developed to computationally optimise values of benefit, such as vertical force impulse for the application for Jumping Space Robotics. This would be achieved by creating a hyperspace, using the mathematical models already developed, to generate a cost function that is optimised for desired effects. This can be constrained to be realistic, such as providing geometric, manufacturing constraints, materials, etc. These tools, however, would not be limited to a single application, with the constraints and desired outputs tuneable for a given application. By simulating modules as single elements, it may be possible to computationally generate 3D arrays of actuators that minimise a given cost function by generating 3D structures of these elements. This would require characterising the behaviour of a module and then determining what an interaction between modules would look like. The computer program then generates a cost function and iterates through combinations of elements to optimise this to desired effect. The low cost and simplicity of manufacturing these actuators can allow computationally generated geometries and

arrays to be tested quickly and inexpensively, providing valuable data and experience to tune models.

Materials

From the discussion, another evident point of further research is the selection of materials. Maxwell stress, the driving mechanism behind HASEL actuators, is a function of electrical permittivity of the materials. This is particularly true of the dielectric. Breakdown voltage is also a material specific variable^[102;70;55;54]. The change in force-strain characteristics and efficiencies when Wang et al.^[102] made the switch from BOPP to TPU also demonstrate the potential in carefully selected materials for improving performance of actuators. Rothmund et al. in their review of HASEL actuators suggest that materials with higher dielectric constants and breakdown strengths would increase specific energy^[87]. Suggestions for materials such as PVDF-Terpolymer, with $\epsilon_r = 50$ and breakdown strength $E = 600V\mu m^{-1}$, could raise specific energies for PH actuators up to $20000Jkg^{-1}$, based on a model from Kellaris et al.^[54]. For reference, skeletal muscle achieves $40Jkg^{-1}$. While exciting, these models are primitive, first principles models which neglect many important effects in actuators such as dielectric viscosity which has significant effects on actuation frequency response, speed and efficiency.

Material properties are also linked to the required voltage stimulus. As the Maxwell Stress is proportional to $\epsilon_r E^2$, an increase in dielectric permittivity would decrease the required field strength, and thus the voltage stimuli.

The challenge is finding the balance of material properties that meets the optimal configuration. For this application, the actuator will be operating over a wide temperate range, subject to radiation and in the case of the moon, exposed to very near vacuum. The impacts of these environmental factors are significant and diligence must be paid to them when selecting materials.

Control

One of the most appealing attributes of HASEL actuators is the proprioception they exhibit. The ability to glean information about a system state from an inherent attribute is attractive for closed-loop control. The peano-HASEL actuator shows a direct relationship between the amount of zipped electrode and it's stroke. As the amount of zipped electrode can be inferred via the capacitance kinaesthesia, so too can the stroke.

While proportional-integral-differential (PID) controllers have been applied in conditions where HASEL actuators showed second order linearity^[90;50;87], results show that in regions where strain-load relationships behave like linear mass-spring-damper systems - identified with static load tests used by Schunk et al.^[90] - "acceptable" control performance was achieved in the well-defined strain regions. This was achieved with a PI controller, omitting the derivative component. Also the only sensory feedback was the kinaesthetic self-sensing inherent to the actuators. Johnson et al.^[50] implemented a PID control onto foldable planar HASEL actuators. These behave as non-linear time-varying systems. Several assumptions were used, such as that actuators behave as time-invariant in time scales of 180ms, noting that charge retention was less than 5% in that duration. Using external sensors such as elastometric strain sensors, they achieved real-time closed loop control under loads of 25.5g (64.7% actuator mass). While these results are promising, they are performed under idealised experimental settings. Online control will need to adaptable and operating beyond these time scales and assumptions, probably in the form of non-linear systems. Methods of developing non-linear control are taxing on time and situation dependant.

Methods have been developed that utilise data-driven control generation to computationally define non-linear systems and develop control laws for them. Two promising methods, especially in combination, are Sparse Identification of Nonlinear Dynamics with control (SINDYc) and genetic programming.

SINDYc is a mathematical tool developed by Kaiser et al.^[53] building on the work done by Brunton et al.^[21]. By developing a library of potential functions and integrating this with data gathered through experimental methods, SINDY allows sparse regression to be carried out to identify significant governing terms in a system from the data alone. This allows a best fit system to be developed removing negligible dimensions, saving computational expenditure and reducing control law complexity, but also allows the capturing of non-linear dynamics. SINDYc expands upon this to include the actuation control signal into the system model. The ease and inexpensive nature of experiments on HASEL-like actuators makes experimental testing and data-collection relatively trivial for a non-linear system. This system of regression modelling has been shown to address many of the weaknesses of other data-driven control development techniques such as Neural Networks (NN) and Dynamic Mode Decomposition with control (DMDc), and are fast, suitable for strongly non-linear systems, resistant to noise, fast in training and execution and provide excellent control performance [Table 2. *Kiaser et al.*]^[53], even in low data amounts. Applications thus far are the classic Lorentz system^[22], turbulence control^[20], epidemic modelling and chaotic electroconvection^[36]. This method could be incredibly effective with HASEL actuators which display non-linear dynamics. SINDy has a python package developed by the creators of the method that allows standardised easy use of the method^[24]. SINDy is compatible with a number of Machine Learning techniques and adaptable to situations. it should be noted that although SINY was chosen in these applications, DMD and NN also have their places, with a bi-linear adaption of DMD being used on quantum systems, for example^[33].

Although this system may be over zealous for the actuator application, it may allow insights into the dynamics at play within actuators. For example, by including dielectric viscosity in SINDYc’s library, the tool would use the data to find relationships between this and other aspects of actuators. This can facilitate needed improvements in the models of HASEL

actuators^[87]. By testing geometries and experimenting with actuators, data will be farmed from these experiments regardless of developing control in tandem. Also, Rothmund et al (2020) find in their paper two identifiable dynamic regimes: inertial and viscous^[88]. In the inertial regime, they identify an undershoot and oscillation from the inertia of the load, and note that an “appropriate control strategy” may address this in applications. The control signals for actuators are voltage signals, which Rothmund et al. also identify as a key component in the viscous regimes.

Chapter 4

Saltatorial Locomotion in Nature

Jumping and Hopping as a locomotive modes allow three-dimensional movement in difficult terrains is employed heavily in vertebrates and many invertebrates that find themselves in these environments. The advantages of jumping are the sudden and often unpredictable impulse, providing animals with a key tool to escape predators, attack prey or begin flight, providing crucial early acceleration^[48]. Marsh et al.^[66] paraphrased in James et al's review^[48] suggest the "ecological importance of jump performance in many species is likely to be related to predator avoidance and/or prey capture success", highlighting the advantages seen in this movement. Quadrupedal rodents were preyed upon at higher rates than the sympatric bipedal hopping counterparts, and see better metabolic efficiencies in larger hopping species^[67]. This is attributed to the unpredictability of jumping trajectory, as well as the speed of the movement. The environmental evolutionary pressures that see the origination of bipedal hoppers is often structurally complex forest environments, alluding to the benefits of this locomotion mode as a means to navigate unpredictable and unfavourable terrain effectively. Hopping also see's high use by Macropods in desert environments where resource scarcity promotes adaption to en-

ergy efficiency.

The term jumping is distinguished from hopping by implying a standing start or a single movement, whereas hopping involves multiple, successive jumping movements in series. Hopping is prevalent mainly in mammalian species and is considered highly specialised. The *Jaculus jaculus*, commonly called the lesser Egyptian Jerboa, uses hopping to great effect making hopping it's "fastest mode of steady-state locomotion" ^[67].

Many species (for example: frogs, macropods, locust) have found such success in Saltatorial movement that it has become their primary locomotive mode. These species, with a higher tendency to jump, maximise jump performance by exhibiting certain morphological and physiological traits. It is important, from an engineering perspective, to appreciate what these traits are and exactly how they lead to this maximisation of performance and understand the factors that influence the adaptations. James et. al^[48] note that there is considerable discussion on the most important factor contributing to jumping performance, but suggests that it is unlikely one variable would be a key determinant encompassing all systemic groups and ecological settings. As is well known, natural selection as a 'design' process allows dominant survival strategies to thrive, due to the brutal 'methodology' of the selection. The use of this from an engineering perspective is that it provides insight into mechanics, material properties and geometry, fine tuned over millions of iterations, which are impeccably optimised for their use (though not perfect). This chapter explores an overview of important factors seen to affect saltatorial motion in nature, as well as investigating a few examples in an effort to better understand the mechanics, materials and geometry involved, as well as some of the control strategies utilised. The intention is to provide a foundational understanding of the potential of saltatorial motion and allow design specification to be formulated to develop biomimetic jumping in robots.

4.1 Take-off velocity

Jumping performance is partly a function of take-off velocity. James et al.^[48] use a simple ballistic equation:

$$d = \frac{\sin(2\alpha)}{g} v^2 \quad (4.1)$$

Where: $d[\text{m}]$ is distance jumped, $v[\text{ms}^{-1}]$ is take-off velocity, $\alpha[\text{deg}]$ is take-off angle and $g[\text{ms}^{-2}]$ is the gravitational acceleration ($\approx 9.81\text{ms}^{-2}$ on Earth). This equation is cited as demonstrating the dominance of the velocity term, which we can see is highly proportional to jump distance, by virtue of being a squared term. Assumptions made are the neglect of air resistance and that forces as well as acceleration are constant throughout the jump. It should also be noted that this equation does not take into consideration the location of the applied force in relation to the centre of mass, something that will be explored with detail in a section forthcoming. The review also acknowledges this, communicating that the kinematics become insensitive to take-off angle when this is considered, causing higher sensitivity to variations in take-off velocity and height. Equation (4.1) is expanded^[66;48] to consider the variations in acceleration and location of force application:

$$d = \frac{\sin(2\alpha)}{g} \left[\frac{\bar{P}L}{M_b} \right]^{\frac{2}{3}} \quad (4.2)$$

Replacing v^2 with a ratio of $\bar{P}[\text{W}]$, the total average power utilised in the jump; $L[\text{m}]$, the distance between the most distal part of the limb and the centre of mass; and $M_b[\text{kg}]$, the body mass. In this equation, we see the potential for adaptations that increase jump distance. Firstly, while power must be provided by skeletal muscles, the introduction of elastic potential energy storage mechanisms could allow energy to be released that is stored prior to or during the jump, enhancing jump distance by increasing \bar{P} . Secondly, L can be increased through the use of relatively long legs. The power required for a jump is directly proportional to the available acceleration distance, which manifests here

in leg length^[2]. Having a larger body mass is also shown to be a detrimental property regarding jump distance, demonstrating the value of a high specific energy actuation strategy. Locomotive parameters that govern jumping ability are predicted to adapt with increasing body-size to compensate for increase in weight-related muscular skeletal forces by the theory of dynamic similarity. This theory has been shown to have great predictive ability in a number of factors^[15;68]. Subsequent sections will explore the factors that influence this equation, as well as other factors also impacting the quality of a jump.

4.2 Skeletal Muscle Operation Mechanisms

An obviously important factor of consideration in saltatorial, or indeed any locomotion, is the nature of the actuator. All animals use some variation of skeletal muscle. In most jumping animals, skeletal muscle is not just utilised in jumping locomotion. Ideally, during jumping, muscles that act as extensors would rapidly shorten, producing high power, maximising acceleration and thus take-off velocity^[48]. However, by having muscles carry out different mechanical tasks, their properties are not tuned for this ideal in almost all animals. The composition of the muscle demonstrates this multi-function trade off. There are also considerable mechanical factors that influence the type of muscle and its use, including fatigue, optimisation of force/shortening velocity characteristics, metabolic efficiency and so on. This section explores the underlying dynamics of mammalian muscle which bare similarities across phylums.

Mammalian skeletal muscles are made of *Fascicles*, bundles fibres bound together by connective tissue. Within these fibres, *myofibrils* are wrapped in binding membrane called *Sarcolemma*. Myofibrils are made of functional units called *Sarcomeres*, which facilitate contraction and are arranged in series within the Myofibril. Sarcomeres are separated from one another by dense protein *Z discs*, made of α -actinin. The

so called *M-Line* divides the Sarcomere, made of *Myomesin* protein. This is not the end of the complexity and at smaller scales the Sarcomere's constituent parts reveal themselves. Sarcomeres are made of contractile proteins, regulatory proteins and structural proteins. Three plentiful proteins: *Myosin*, *Actin* and *Titin* form the majority of the Sarcomere structure and their interactions for the majority of the mechanism that allows muscle actuation^[94].

Myosin builds *thick filaments*, the major contractile mechanism of the Sarcomere, twisting around itself like a helical rope with two "golf club" Myosin heads. There are roughly 300 hundred Myosin molecules in a single filament. Neighbouring Myosin threads lie parallel along the length of the Sarcomere, creating the thick filaments. The heads protrude outwards, reaching for the six *thin filaments* that surround each thick filament^[94].

Actin molecules join together to form actin filaments, twisted into a helix forming the major construction of the thin filament. The thin filament is anchored at the Z-Disc. Actin molecules have Myosin binding sites for the attachment of the Myosin heads. The thin filament structure also contains the regulatory proteins *Tropomyosin*, which block binding sights in relaxation, and *Troponin*, acting on the former during muscle activation, allowing access to binding sights^[94].

Titin are structural proteins. A single Titin molecule spans half the length of a Sarcomere, binding to the Z disc and stretching to the M-Line. Titin acts as a restoration element, returning the Sarcomere to its rest state post-deformation. The molecule is very elastic, able to achieve strains of 300% with no plastic deformation and it generously lends its elasticity and extensibility to the Myofibril at large^[94].

These elements combine in a beautiful synergy of biological mechanics. Contraction occurs as the Myosin heads, binding to the sites on the Actin chain, pull filaments towards the central M-line. This sliding brings the Z-discs closer together as the thin filaments are anchored to them, shortening the Sarcomere. Ascending up the spatial scales, the combined contractions of

Sarcomeres shortens the muscle fibres, causing muscle contraction holistically.

The reason for exploring these aspects of muscles internal working is that they provide valuable insight from a design perspective. The mechanical and geometric properties displayed by the distinct elements of the Sarcomere and how they interact to allow the versatile movement seen from skeletal muscle will be invaluable when we later explore the design requirements of a biomimetic soft-robotic actuator.

Fibre Types and Their Functions

There are three classifications of skeletal muscle fibre **in mammals**: Type 1 (Slow Oxidative), Type 2A (Fast Oxidative-Glycolytic) and Type 2B (Fast Glycolytic). Muscle fibre types are generally categorised by the speed at which the fibres produce and hydrolyse Adenosine Triphosphate (ATP) to generate mechanical work: with Type 1 as "Slow Twitch", alluding to its relatively slow production and subsequent hydrolysis of ATP; and Type 2 being "Fast Twitch", performing both relatively faster^[94]. The contraction velocity is directly related to the proportion of these fibre types within a bundle.

Type 1 fibres generate ATP via aerobic respiration, hence "oxidative". They take 100–200ms to contract with peak tension, taking relatively longer than their Type 2 counterparts. These fibres exhibit high resistance to fatigue and can produce sustained contractions for many hours. As a result, these fibres are heavily utilised in posture maintenance and endurance locomotion.

In contrast, the Type 2 fibres make use of anaerobic glycolysis for ATP generation. This allows faster ATP production and hydrolysis. Type 2A fibres utilise both methods of ATP production, providing a "best of both worlds" approach to contraction. ATP is hydrolysed 3 - 5 times faster than in Type 1 fibres, increasing their contraction speed and allowing faster times to reach peak tension. They are commonly associated with walking and sprinting modes of locomotion. The trade-off is in the brevity of the contraction duration, lasting less than $100 \times 10^{-3}\text{s}$ ^[94].

Type 2B fibres mainly generate ATP through glycolysis. Their ability to rapidly hydrolyse ATP means their contractions are rapid and strong. While allowing intense anaerobic exercises such as weight-lifting and sprinting. However, the duration is very short and fatigue is prevalent.

Skeletal muscles are a mixture of these fibres, and the proportion depends on the muscles function and frequency of use. In humans, posture maintenance muscles will have a high proportion of Type 1 fibres, while muscles in, for example, the shoulders not constantly active favour Type 2.

The structure of muscle demonstrates something of interest for a biomimetic process. Looking at the output of a single PH actuator in section, one observes that it does not output a particularly high force or strain. A single actuator is therefore an infeasible candidate to create jumping power requirements. However, when one observes the sarcomere, one would not expect the sarcomere to act alone and indeed it does not. The muscle is a deep array structure, building from the low output sarcomere into a higher output fibril into a fibre into a muscle. The single PH actuator can therefore be considered analogous to the sarcomere, rather than the muscle in entirety and indeed the literature on peano-HASEL actuators demonstrates this scaling behaviour^[54]. With this view, the biomimetic principle of combinatory action lends validity to the Peano-HASEL actuation strategy.

4.2.1 Muscle Activation in *Rana Pipens* During Jumping

Within *Rana Pipens*, a type of Frog, faster fibres were found to consist of 89 – 90% of the hindlimb extensor muscles¹. The remaining 10% was made of the second fastest fibre types and fibres consisting of a mixture of the two^[85;64]. This demonstrates the dominance of this locomotion mode in frogs as the fibre type is almost homogenous. Lutz et al.^[63] identified three con-

ditions for a frog jumping muscle to generate maximum mechanical power:

1. Operate where maximum force is generated on the sarcomere length (SL)-tension curve.
2. Operate at an appropriate ratio of shortening velocity to max shortening velocity ($\frac{V}{V_{max}}$).
3. Be maximally activated.

This approach allows the maximum power to be generated during a jump, which maximises equation 4.2 for a given L and M_b . Condition 1 was shown by their experiments to be met as their empirical data fit well onto "the standard frog SL-tension curve". The muscles shortened in the Sarcomere length plateau region, never dropping below 90% of the optimal force generation^[63]. Similarly, with condition 2, their data was plotted onto typical force/velocity and power/velocity curve. Their empirical data showed that the mean velocity of jumping (3.43MLs^{-1} [*Muscle Lengths per second*]) occurred at the point 99% of the maximum power was generated, giving $\frac{V}{V_{max}} = 0.33$ with $V_{max} = 10.35 \pm 0.2\text{MLs}^{-1}$. This "gearing ratio" shows that the frog does not fully utilise the maximum shortening velocity of its fibres. For condition 3, the results of the previous experiments were compared to *in vivo* from jumping, with the hypothesis being that should the muscle generate a similar force as with the experiments in condition 2, the muscle is maximally activated. They found that the force generated was greater or equal to this force, demonstrating maximal activation.

These results indicate the optimisation potential of the evolutionary process. The frog met the ideals expected. Operating in regions of non-linear curves that allowed maximisation of power. This also demonstrates that optimisation is not necessarily found in the fastest muscle fibres or largest muscles, but may require a more

¹It should be noted that the literature refers to these as *Type 1* fibres. The nomenclature for amphibian fibre types differs from mammalian.

nuanced approach to the control and morphology employed by the creature.

4.3 Energy Storage Systems (ESS)

It appears common among jumping animals to employ a method of energy storage, though the strategy is not unique to jumpers. Extending beyond obviously high impulse gaits, elastic elements are common in animals across phylums. Evolution provides a great filtering of ineffective strategies for survival. This cross-phylum evolution is therefore interesting as it demonstrates convergence in evolution. Three major roles for elastic elements in locomotion are identified by Roberts & Azizi (2011)^[83]:

1. Energy Conservation: Recycling of energy due to gravitational work into kinetic work to improve metabolic economy.
2. Power Amplification (Modulation): Power Production enhancing acceleration type movements (i.e. jumping).
3. Power Attenuation: Absorbing energy with the intention of stopping motion, such as in landing.

All three are advantageous to animals adapted to saltatorial locomotion. Considerable interest is warranted to the power amplification in this discussion as it is the most important for the application to soft-robotic actuators, however attenuation will also be important. Energy conservation also initially appears relevant, but upon consideration of the application to extra terrestrial bodies, gravity will play a reduced role in the locomotion, especially on the Moon or small asteroids if the hopping frequency is high. It is important when undertaking a biomimetic study to maintain the perception that these adaptations are a product of selection to fit an environment. The application environment for the Peano-HASEL actuators is alien, and such the adaptations utilised in these animals must be considered and adapted on that basis.

More recent studies make note of the misnomer of the word “Amplification”, citing its use in electronics to add energy. These systems do not act in this way. Haldane et. al instead use the term “Modulation”, semantics better suited to describe the timing of energy use for kinetic work in this mechanism, an example substitution made in discussion henceforth^[38;83]. As power is the ratio of work over time, muscular power is limited by the rate limits of its processes. Elastic elements are purely passive and their function purely defined by their structure. This allows the relatively slow muscle contraction to be modulated into a much faster release, thus increasing the transient power output of the system.

Observations of jumping animals show that the power output required for them to achieve their seemingly remarkable jump height far surpasses the power output of the muscle^[12;2]. The jump of the *Galago senegalensis*, weighing 0.25kg, produced a peak centroid power of 200W. The highest specific power output available instantaneously in a vertebrate was identified in *Rana Pipens* by Lutz & Rome (1994) to be 371Wkg⁻¹^[63]. This means the aforementioned Galago’s muscle mass to power such a jump would need to be 0.539kg, over double its weight. The impact of this observation is enhanced by the fact that the Galago’s extensor muscles are roughly 25% of its body mass, requiring the muscle to achieve 9 times the *Rana Pipens* output^[2].

By considering the performance of mammalian muscle, it is evident that these animals employ power modulation. Elastic elements allow an animal to pre-load energy into elastic elements preceding a jump, quickly expending the energy along with muscle actuation to maximise power output. This power modulation behaviour appears consistently in literature, showing minimal release of power and low jump movement in the early half of the jump before a large release in the later half.

Temperature effects on muscle are well documented^[48] and show further utilisation of elastic elements. This adaption is one that enhances the nature of jumping as a sudden and abrupt movement, allowing unpredictability and speed,

as well as compensation for adverse environmental conditions. Many animals find optimal jumping at a temperature that best represents their historical environment. This is seen in *anurans*, which see their jumping performance deteriorate at extremes of their relative thermal spectrums. As a result, many animals in an effort to maintain locomotion, should they find themselves in unfavourable temperate conditions, employ elastic strain energy mechanisms. Ectotherms, for example, who rely on external sources of heat, find advantages of high force output at low environmental temperatures by employing these energy storage mechanisms. In fact, the jump distance of a cold locust was recorded to be the same as those in ideal temperatures, the only disadvantages arising from the time to load the elastic elements increasing. Also, for a minimal weight addition, increases in take-off velocity can be achieved, already seen to be a cost-effective benefit to this locomotive mode^[32;10;48].

4.3.1 Jumping Insects

Insects especially see the use of energy storage mechanisms, not just as compensation for temperature as mentioned, but to enhance jumping. Many insects use a catch mechanism to allow the build up of elastic potential without premature kinetic conversion. Equation 4.2 also shows that smaller animals, with a shorter acceleration distance (impacting the influence of the term L) due to smaller limbs, can utilise elastic energy elements to instead increase peak power and higher maximum muscle shortening velocities to maintain take-off velocity. Further restraints are imposed on smaller animals as drag effects begin to become notable with decreasing body size, bolstering the case for achieving higher muscle power outputs, though this only becomes notable at the scale of small insects^[48]. Fleas^[11], click beetles^[30;31] and locust^[10;32;100] are all particularly studied, with varying mechanisms of energy storage, but all following a fairly common theme. All of these animals use power modulation, making the timely release of stored energy possible by use of various catch mechanisms. The nature of this is rather like a catapult, releasing the en-

ergy suddenly with high impulse. Muscle output energy can be stored within the elastic elements and then released at take-off to enhance power outputs via the timely elastic recoil. This allows slow muscular contraction prior to a jump to contribute to the high impulse jumping motion.

Flea

In the flea, energy is stored in a resilin pad, loaded by depression of the metathoracic femur. The pad is located between the notum and pleuron and the depressor muscle of the femur originates from the notum. The tendon from this muscle to the femur runs through the centre of the trochanter-femoral joint (the major active joint in jumping). This means the resilin pad and femur depressor have near no mechanical advantage, and joint articulation can not occur, thus energy from muscular contraction is stored in the pad. A second muscle pulls this tendon away from the centre, releasing the energy in the resilin pad and allowing the tendon to articulate the femur^[11]. Species with larger resilin pads are observed to be better jumpers, providing evidence towards the advantage of increasing power modulation.

Click Beetle

The click beetle is unusual among jumping insects, as it does not use legs to jump. Instead the click beetle lies on its back, and makes a sharp flexion around a hinge in the middle of its body, rapidly jack-knifing. The beetle has a peg-like extension which provides a frictional latch, preventing rotation about the hinge. Evans (1972) removed the peg, observing that in its absence, the beetle could not jump. When a beetle sets the peg, it spends sometime before making the jump, about 0.4s. In this time, the major jump muscle in the beetle builds energy into the muscles series elastic elements and its proposed that some is stored in cuticle deformation. This occurs until the friction is overcome at the peg, causing a rapid release of energy and the transient release of the stored energy, causing the jack-knife and

jump^[30]. A beetle weighing 40mg produced a velocity of 2.4ms^{-1} and 2.26ms^{-1} in its first and second jumps respectively. For the former jump, the necessary power output of the jumping muscle was calculated by Evans (1973) to be either 84Wg^{-1} or 177Wg^{-1} , depending on the method of energy budget calculation employed, which either involved a vibrational analysis of a lightly damped oscillator for the later or an analysis of the energy budget required for the whole body translations for the former^[31]. These values vary considerably, being the highest and lowest estimates of jumping energy, however both are far larger than the potential output of the muscle by virtue of the time taken for the violent movement after the peg slips. It appears common in early literature for muscle power estimates to be taken from other species of insect, which can make the actual power output of muscles confusing. Nevertheless, the mechanism employed by the click beetle is one of energy storage. This mechanism was shown to be extremely ineffective. 50-60% of the energy expended actually goes towards movement. When the beetle jumps, its body rotates considerably about the central hinge and a large amount of energy is expended here, this will be touched on in further discussions of morphology.

Locust

In their 1975 paper, Bennet-Clark performs an extensive study of the locust leg mechanism and its properties. Locust are efficacious jumpers. They're long legs are well adapted for the locomotion mode and achieve jumping through expeditious extension of the tibiae. Their peak power output during a jump is 75W, producing an a peak acceleration of 180ms^{-2} and a peak velocity of 3.2ms^{-1} ^[10;100]. They show that the locust *Schistocerca Gregaria* stores the energy of 70mg of muscle in stores weighing 4mg per leg. The system of stored energy in the locust increases power 1.5 times the muscles production capabilities, leading to a power modulation of 10 times. This is achieved with only a 5% weight penalty^[10].

The catch mechanism employed by the locust

is called "Heitler's lump". The lump acts as a pivot for the flexor tendon in the femur, making its contact point with the lump the effective origin of the tendon. At full flexion of the tibia, the flexor tendon is exerting maximum leverage as Heitler's lump allows an angle of approximately 90degrees between the line of action of the flexor tendon and its insertion to the pivot in the leg. In contrast, the extensor tendon experiences a mechanical disadvantage, having an equivalent angle of 6 degrees. Heitler calculates this to be a lever ratio of 260 : 1 between the distal tibia and the extensor muscle. As the extension of the tibia progresses, the angles of action decrease and increase respectively. The extensor at maximum angle shows a gear ratio of 35 : 1, before decreasing again as the tibia reaches full extension^[42]. The change in this gear ratio as the leg extends is what allows the power modulation of the muscles, greatly increasing power output.

Bennet-Clark (1975) identifies two functions associated with the catch mechanisms observed across insects. Firstly, the catch allows substantial storage of energy in elastic elements, as discussed. Secondly, it allows any antagonists to the jumping motion to be relaxed prior to energy release, so that they do not see damage from the high impulse. Interestingly, Bennet-Clark observes that the locusts without the lump operational were still able to jump, though the absence of the catch was deleterious to jump performance. This serves to highlight that this evolutionary adaptation was not necessary for allowing the jumping locomotion mode, but is crucial in optimisation of its performance.

The locust leg stores energy in a variety of different structures, however in Bennet-Clark's (1975) study, two are given prominence, storing the majority of the energy. Firstly, the *Semilunar Process* is a non-linear spring, named for its crescent shape. Each leg has one semilunar process located in the distal region of the femur. It is connected to the tibiae extensor muscle and loaded when Heitler's lump prevents articulation of the tibia. An adult male locust requires 9mJ to jump, while a large female requires 11mJ. Each semilunar process stores 4mJ energy at the 15N maximal force of the exten-

sor tibiae, in fully elastic deformation^[10]. The second structure is the apodeme of the extensor tibiae itself. Apodeme are the attachment points for a muscle to the insects exoskeleton.

4.3.2 Jumping Vertebrates

Larger Animals also make use of energy storage mechanisms, primarily in the form of tendons. Larger animals also see increased jump performance relative to their insect counterparts, with higher jump frequency, speed and height. The comparison here is fair. Bennet-Clark (1976) posits that the energy - mass ratio of an animal is the deciding factor in jump height^[12]. The highest reported jump of a bushbaby saw a centre of mass displacement 6 body lengths in magnitude: a 0.250kg animal leaping 2.25m, but as previously mentioned, the muscle power output is not nearly enough to meet the power demands of such a jump. Unlike insects, no distinct clutch is observed, however energy storage is clearly needed. This is explored in section (ref) as it is achieved through limb morphology, but utilises a similar mechanism of mechanical advantage.

Tendons, along with the materially similar aponeurosis, play a vital role in many acceleration based locomotion modes, passively storing energy from the body's motion under gravity, such as in steady state motion, storing the work done by muscle fibre shortening or absorbing impacts^[83;10;12;5;34;82]. In human jumpers it was shown that series elastic components of the ankle extensors increased jump distance by allowing the muscle to achieve higher work outputs and operate over lower shortening velocities on average^[16]. The large molecular spring *titin* is an example of an interfibrillar elastic component in the Sarcomere. Elastic compliant components act either in series or parallel, depending on where the compliance acts in relation to the force-producer. *Titin* and connective tissues that bind fascicles and fibres are examples of parallel components. Tendons are series elastic.

Experiments have show that the importance of tendon elasticity predominates in many muscle structures. Intrafibrillar structures have lim-

ited extension ranges and so a minimal capacity for energy storage. Values of compliance vary based on the muscle-tendon complexes function, although the properties of the tissue vary little between species. 'Fixed-End Contraction' allows the importance of the tendon in external power generation to be shown. By fixing both ends of the muscle-tendon complex, stimulating the muscle to maximal tetanic force, the shortening of muscle fibres can be overserved only if the tendon (or other external elastic element) is stretched. By observing the fascicle length in this contraction, along with muscle force, a measure of tendon compliance can be generated^[82;34]. This produces a metric know as 'fixed-end compliance' (FEC), which expresses the potential influence on muscle fibre shortening as a result of the tendons compliance. The strain in muscle fibres as the force rises from rest to peak tetanic is dependant on the tendon's compliance, the ability of the muscle to generate force and the fibre length of the muscle. Muscles with high values of FEC will expend a large portion of their shortening capacity in deforming the tendon over creating skeletal displacements, loading them with elastic energy for recoil release. The maximum output distal limb muscles, with highly pennate, short fibre construction usually exhibit high fixed end compliance. Tendons here are long and relatively thin, generating high forces^[82].

Interestingly, Lieber et. al (1991) in studies of the *Rana Pipen's* semitendinosus (ST) muscle observed that the tendon in series with this muscle was short in comparison to the Achilles tendon in line with the gastrocnemius. The ratios of muscle to tendon length respectively: $Ratio_{ST} = 1.5$ | $Ratio_{Gastro} = 11$ ^[61;96]. The difference between these complexes is their function, the ST being involved in flexion and the gastrocnemius in extension. As the frog is a jumping animal, its likely what is seen here is an indication to the function specific deployment of the tendon: the extensors being heavily involved in power generation for movements of the whole body against gravity requiring significantly more power than the flexing of a limb. This is also noted by Leiber et. al. Investigations into the

role of the Achilles tendon in *Rana Pipens* also demonstrated that the muscle lengths between the gastrocnemius and the ST varied by only 8mm, while the tendons varied by 5mm and the aponeurosis by 15mm, in favour of the gastrocnemius^[96]. The tendon and the distal aponeurosis region were considered a single functional unit by Trestik et.al. (1993) due to negligible differences in strain between the two. The gastrocnemius was identified as the more compliant complex of the two by comparing tendon length/fibre length ratios, though it should be noted that tendon length includes all connective tissue in series with the muscle fibres, including tendon and aponeurosis. The gastrocnemius ratio was observed as 3.30 ± 0.42 against the ST's 1.01 ± 0.19 . The values seen in the ST may be a function adaption, as the knee extensors are suggested to actively extend the ST during hopping, which would be impacted deleterious to function with a long tendon. Variation is also seen in the YM at peak tetanic tension (P_0) of these tendons (1548 ± 683 | 188 ± 21 MPa), although the P_0 of the gastrocnemius was 20times that of the ST^[96].

Muscles in series with shorter, stiffer, tendons are key in jumping, being best suited to output high power. This is seen in the human Achilles tendon, with the distal part being much stiffer and having higher cross-section area than the proximal. It is also a smaller portion of the overall tendon^[81;96]. Tendons not only vary between complexes but also vary in themselves. Young's modulus (YM) values vary significantly along lengths of tendons^[61;96]. In *Rana Pipens*, the YM at maximum tetanic tension of the relatively thinner, proximal tendon was over double the thick, distal region (1548 ± 683 | 632 ± 280 MPa)^[96].

Reeves et. al (2017) in a study of the human Achilles tendon found as the cross-sectional area along the tendon would vary, different sections of the tendon would experience different forces, stiffness, stress and have differing Poisson's ratio. The proximal region to the gastrocnemius was seen to be significantly longer than the distal region, and experienced 60% lower force, 30% lower stiffness and 70% lower stress in com-

parison. They concluded that the proximal region acts as a buffer, protecting the stiffer distal component from injury^[81]. Muscles also absorb mechanical power, such as in landing. This variation in length is also seen in *Rana Pipens*, exhibiting three-fold variation along its length, with a significantly thicker region towards the heel^[96].

Tendons are readily accepted to exhibit two distinct regions of their stress strain curves. A compliant 'Toe' region and a linear region following that. Lieber et. al (1991) showed through analysis of the *Rana Pipens* that tendons operate exclusively in the toe region of this curve^[61].

Studies into the Bushbaby showed that the internal connective tissue sheets found in the vastus muscle store the elastic strain energy in the preparatory crouching. This is not released until late in the take-off with energy still being stored in the early phases of knee extension^[2]. In countermovement jumps: those involving a crouch contrary to the direction of motion, before leaping, enhancing a jump by stretching the active muscle; storing energy in series tendons and adding time for extensor muscles to reach high forces prior to shortening^[48].

4.3.3 Non-jumping movements of interest

4.4 Physiology and Morphology

One of the most obvious distinctive features of specialised jumpers is seen in their limb morphology. Legs that are employed in jumping are often very long, and this adaption is observed across phylogenetic branches and across the spectrum of organism sizes. Equation 4.2 alludes to what the advantage of this development would be for a jumper, bolstering the L term, relating to the distal limb elements which finds a mechanical basis in the principle of moments. There is also the advantage of the amount of acceleration time available with increasing distance. More time spent accelerating leads to a higher take-off ve-

locity, which from equation 4.1 correlates positively with jump distance. An obvious example of this is the locust, which is known for its extremely long hind legs. One sees the antiphase of this principle in the click beetle. In fairness, the click beetle does not use jumping as a primary locomotion mode, but as a last resort escape mechanism. However, the presence of longer limbs does not necessarily indicate a good jumper, with long limbs find use in running and climbing.

Interindividual differences are observed in exactly which part of the leg is made long. *Indriids* have been described as “long-thighed” and “thigh-powered” jumpers, whereas *Tarsiers* and *Galagos* are described as “long-tarsal jumpers”^[26]. The foot of the Indriid is more adapted for gripping than enhancing jumping, therefore the femur-length compensates. Increases in limb length are also seen as body size increases and this obviously increases acceleration time.

However, many benefits of limb morphology are not so immediately obvious.

4.4.1 Dynamic (Inertial) Clutch

Firstly, many jumping animals without distinct clutch mechanisms make use of a “dynamic clutch”^[5] or “Inertial Catch”^[84;43]. Effectively exploiting moments about limbs and ground reaction forces to load series-elastic elements prior to take-off. It is necessary that the tension in the elastic element develops before joint movement, to avoid the premature release of stored energy and develop the prerequisite for the large power release seen in the last half of the jump. In invertebrates such as the Locust and Flea, this is achieved through a distinct clutch mechanism, as discussed, but in many vertebrates the careful design of the limbs morphology allows this to occur. Astley et al explored the development of preloading in the plantaris ankle extensor in *Rana Pipens*. They give a simple equation that captures this mechanism:

$$F_m = F_R \frac{R}{r} \quad (4.3)$$

This equation equates the force of the muscle (F_m [N]) to the ground reaction force (F_R [N]), scaled by the ratio of the out-moment arm, R [m] and the in or anatomical moment arm, (r [m]). A high value of this ratio gives a poor mechanical advantage for the plantaris against the centre of mass, allowing the development of force within its series elastic without the movement of limbs. This mechanical advantage is not static, evolving throughout the stance phase of jumping. As the muscle actuates and loads the elastic element, there is minor joint movement. Eventually there is a runaway gain in mechanical advantage, the joint begins to move, allowing the stored energy to be released. This ratio is a direct result of the design of limb morphology and is the cause of the power modulation that many animals without distinct clutch mechanisms use to great effect^[5;43]. The dynamic clutch is primarily a property of the limb morphology and the movement ranges it facilitates. The advantage of a dynamic clutch when compared to distinct clutches such as though found in insects appears to be the repeatability of jumps. For a locust to jump it must set itself against the clutch and this takes relatively more time than landing and crouching into the dynamic clutch.

4.5 The Importance of Control

Chapter 5

Saltatorial Locomotion in Robots

Alluded to in the introduction section of this writing, jumping robotics have been a goal of many researchers for some time. Along the way there have been substantial developments and insights, culminating in the current exemplar of the field: SALTO-1P produced by Haldane et.al (2017)^[39]. To best compare these robots and provide performance benchmarks, this work will incorporate a number of key metrics. These are given in table ??.

The first metric is rather obvious: “Jump height”. For this work, jump height is defined as the maximum vertical displacement of the centre of mass of a system from the initial height obtained in a neutral stance prior to the particular jump.

Naturally a second metric emerges by considering the horizontal element of a jump: “Jump distance”. This is defined as the horizontal displacement of the centre of mass of the system from the position

A metric comes from Haldane et.al (2016) allows a combination of all the above metrics. In their paper and follow up works, they define the “agility metric”, which aims to capture the jumping ability of a system, be it biological or mechanical, from purely uninvasive measures, building on previous work of standardised per-

formance metrics for comparison^[28]. “vertical jumping agility to be the height that a system can reach with a single jump in Earth gravity, multiplied by the frequency at which that jump can be made”^[38]. The vertical jumping agility (VJA [ms^{-1}]) is expressed mathematically as:

$$\frac{h}{t_{\text{stance}} + t_{\text{apogee}}} \quad (5.1)$$

where $h[\text{m}]$ is the max height of a jump, t_{stance} and $t_{\text{apogee}}[\text{s}]$ measure the time spent in stance from actuation onset and the time from lift-off to jump apogee. This expresses the systems agility as a dimensional quantity; an expression of the average climb rate in a gravitational field with repeated jumps. As the quantity has dimensions, Haldane et. al point out that this will be limited by the power-weight ratio of the system. The use of a dimensional quantity is warranted as the relative size of the terrain does not affect the required jump height to conquer said terrain. This is similar to the claim made by Bennet-Clark (1976) when comparing mammalian jumps to insects^[12]. Jump apogee is the point of zero-velocity. With this, jumps can be seen to terminate at the apogee, and so a ballistic limit is defined as:

$$h \leq \frac{g}{2\omega^2} \quad (5.2)$$

Where $g[\text{ms}^{-2}]$ is the gravitational constant and $\omega[\text{Hz}]$ is the jump frequency, capturing the limit as the time in stance approaches 0.

Jumping locomotion requires directional control but also the ability to upright after landing to then jump again. Kovac et al. (2010)^[58] created an 18cm robot that could jump up to 62cm. From a take-off angle of 75° , it could recover and orient itself. The robot had a mass of 14g. The passive up-righting structure comprised of a cage wrapped around the robot which rolled it upright upon landing. This robot showed great potential but Kovac et al. note that the limitations lie in payload, citing significant losses in jump height, though most sensing and camera equipment is fairly lightweight. The robot is also fairly complex, with many moving parts and connections. Actuation was achieved with a

torsion spring that imparted energy into a four bar leg system. A DC motor powers a eccentric cam through a 4-stage gearbox, which charges two springs. Arguably this would reduce the robustness of the design, as each additional part is an added point of failure. It is also

Jung et al. (2016) demonstrated a robot with a mass of 59.4g that could jump 1.62m at a size of 10cm^[52]. This robot could also crawl, demonstrating multi-modal locomotion. Again; the jumping mechanism is complex and has numerous parts. A DC motor is attached to and drives a pulley. The pulley contracts a four-bar, diamond-shaped which charges spring elements strung across the interior of the diamond. The triggering mechanism consists of a planet gear that sits between the DC motor driven gear and the pulley gear. When the rotation of the drive gear is clockwise, the pulley is driven. In anti-clockwise motion, the planet gear detaches, allowing free rotation of the pulley. This allows the release of the potential stored in spring elements and, thus, the robot jumps. While multi-modal locomotion is useful, the paper makes no mention of the robots self-righting capacity.

One particularly interesting robot that utilises saltatorial locomotion is the SALTO robot which, along with its successor: SALTO-1P, achieves extremely effective and impressive jumping, allowing continous jumps to great height. As well as designing SALTO, Haldane et. al (2016)^[38] also investigated the biological principles that facilitate jumping, taking inspiration from many of the concepts discussed in the previous chapter and particularly paying interest to power modulation and mechanical advantage.

Using their agility metric, the Galago achieved a vertical jumping agility of 2.2ms⁻¹ and, impressively, the SALTO robot achieved 1.7ms⁻¹. As noted in the previous chapter, Haldane et. al identify the prominence of compliant enabled power modulation utilised by animals for their jumps. They point out that this allows animal systems to achieve greater jumping ability than robots that have higher power density.

SALTO exemplifies the use of elastic elements. Identifying the importance of mechanical advantage for power modulation and energy

increases utilised by animals, they produced a robot which applies these principles to great effect. It is no surprise that the success of their platform was derived in part by their attention to the principles of Galago jumping, attempting to match or better them. SALTO is a monopedal hopper, and leg extension was fixed to be the same as the Galago, as was mass. The intention of the SALTO platform was to experimentally demonstrate the differences between rigid, parallel-elastic, series-elastic and series-elastic with mechanical-advantage actuation (SE-MA) strategies. The SE-MA strategy utilised the dynamic clutch method, starting with a low mechanical advantage to allow loading of elastic elements with minimal limb movement, moving to a high advantage later in the stance to allow release of this energy.

Optimisation was undertaken across all free parameters of vertical jumping agility for two power densities: 10Wkg⁻¹ and 100Wkg⁻¹. The later is close to the the Galago's specific power of 93Wkg⁻¹ Using a rigid actuator, the Galago model experienced a height reduction of 60% and a vertical agility of 1.7ms⁻¹. Both series elastic actuators surpassed this for a given power density. Their model also showed that increasing the ratio of mechanical advantage at the beginning and end of the stance-phase increases jump height. In the case of 10Wkg⁻¹ specific power, this increase in jump height did not lead to an increase in agility, as the frequency of the jump diminished in turn. This is due to the relationship $Power = Force \times Velocity$ which imposes a limit of $\frac{10W}{1kg \times 9.81ms^{-2}} \approx 1ms^{-1}$ on the jumping agility. However, the 100Wkg⁻¹ did see increases to jumping agility.

Chapter 6

Peano-HASEL Actuators for Saltatorial Locomotion in Space

6.1

6.2

Within this section, I will explore the reasons behind applying the Peano-HASEL actuator to a jumping robot, with the intention of deploying that robot onto the Moon or Mars. I will also discuss the challenges and outlying research that needs to be addressed in order to approach this aim.

Firstly, HASELs are incredibly lightweight. As previously discussed, high specific energies are traits soft-actuators revel in. When observing existing jumping robots, as well as jumpers found in the natural world, it is evident and somewhat obvious that an increase in specific energy from an actuator will attribute itself to improved jump performance. Given the discussion on payload weights for rocket launches, it seems obvious that an increase in specific ener-

gies of actuators increases dramatically the viability of a robotic mission. Monetary, fuel and spatial occupation are all reduced as less massive actuators can be equipped to a robot for the same energy output. Other actuators in the soft-robotics family also share this trait.

Secondly, the cost of the actuators from a manufacturing standpoint is very low. This allows not only experimental research to be cheap, but also manufacturing for a given application. Material and manufacturing costs naturally will increase for space applications as special considerations need to be observed due to the environmental extremes (as will be discussed shortly). Naturally this will incur additional manufacturing complexity also; however, starting from a lower base cost can only be beneficial.

Peano-HASEL actuators have demonstrated good continuous control with 3D movement achieved^[70]. This can allow a jumping robot to lean or orientate itself to jump in a specific direction, as well as allowing self righting actuation modes that are smooth and reliable. The continuum actuation exhibited by the muscle also allows compliance to novel terrains, complimenting the compliance already exhibited by the material construction of the actuator. The ability to orientate without additional actuators is invaluable for this form of locomotion. Firm footing is essential to prevent slipping and take off angle impacts both jump direction and velocity. Furthermore, all mechanisms of jumping require that the jumping limb flex, so as to allow sufficient acceleration times. If the robot is limited in movement possibilities, this will have a detrimental impact on its ability to achieve this flexion.

The robustness and compliance of these actuators means that long term missions can adapt better in-situ. Terrain can be navigated that usually would stunt traditional robotics, by jumping and complying to unpredictable obstacle topologies. This allows high mission adaptation potential which in frontier environments would be invaluable. Actuators for grippers also allow sample handling that can comply with unusual structure, without damage to a sample. These grippers can be added with minimal

weight consideration as the actuators are so low in weight, though it should be noted additional weight may come in the form of a power supply that can handle kV order potential differences.

Actuators have been shown, even in this infant state of development, to be reliable up to a million actuation cycles^[87]. Reliability is crucial in a space application, where autonomy is key and there is minimal to no hope of repair.

On the topic of autonomy, the self-sensing capabilities of the actuators further reduce the complexity due to the inherent kinaesthesia, and with that, the number of potential failure points. The actuators themselves are not overly complex in structure, further reducing failure potential. This is valuable for reliability and control applications.

6.3

Chapter 7

Current Research

7.1 Peano-HASEL Series Elastic Actuators

Evidently, the process of creating a jumping machine is complex. The matter becomes yet more onerous when one considers the application to extra-terrestrial environments. It is tempting to consider all possibilities: the morphology of the leg, the shape of the foot, the mind of the robot. However, the time frame of a PhD is limited. With this fact in hand, the research within which this writing is contained will be limited to the exploration and development of actuators for compliant, jumping robotics, with adaptations to extra-terrestrial environments.

The philosophy behind such work will be one heavily focused on biomimetics, taking abstractions of nature's innovations and mimicking them with the hope of capturing some of the mastery in those designs. Peano-HASEL actuators and the work done by the Keplinger research group have already pushed this off the ground. The linear contraction, inherent kinaesthesia, high specific energies are all traits exhibited by natural muscle, and pose exciting possibilities for expansion. Something of note from literature is the dominance of power modulation in jumping animals. This innovation permeates across phyla, seen in amphibians, insects, mammals, reptiles and birds. Given the mindless brutality of natural selection, these adaptations would not be seen in such abundance were

they not effective in their task. Particularly, the series elastic elements of muscles in the form of tendons are extremely effective at achieving not just power modulation, but providing other properties of compliance such as impact protection and gravitational energy return. This is not a unique observation; many robotic designs have capitalised on these observations; like the Kovac locust and the impressive SALTO-1P. However, none of these designs have featured soft actuators.

This research then will focus on the development of a Peano-HASEL Series Elastic Actuator (PH-SEA). Intended to capture the power modulation seen in nature's jumpers. The PH-SEA would feature a series elastic element (SEE) in tandem with the contractile element of the Peano-HASEL actuator.

A brief note here on nomenclature. In order to distinguish better between the levels of the PH-SEA, a single pouch of a PH actuator will be referred to as a *PH-Sarcomere*, in recognition of the similarity of the muscles smallest contractile element. A series of PH-Sarcomeres will be called a *PH-Fibre*, while the parallel array of such PH-fibres will be called a *PH-Muscle*. This facilitates fluid discussion of all the components.

7.1.1 PH-Sarcomere Investigations

In order to maximise the potential of the actuator, it is necessary to further explore its capabilities. Initial investigations will focus on the PH-Sarcomere initially. Optimising the PH-Sarcomere should make the scaling to fibres then muscles far simpler and a thorough understanding of the mechanics will allow control development of the actuator. Investigations will focus on mitigation of the high voltage needs of the PH-Sarcomere and increasing specific energies, both of which are likely to be achieved through clever materials choice. As the film's relative permittivity is directly linked to the strength of the electric field it permits, which in turn is directly related to the production of Maxwell Pressure, a higher relative permittivity is clearly beneficial.

The viscosity of the dielectric oil is also im-

portant for time-dependant mechanics of the actuator, as higher viscosity oils will take longer to move under the influence of zipping. Viscosity will also affect the efficiency of the system. An increase in viscosity would increase the friction within the fluid and wall interactions with the fluid. This leads to an increase in heat dissipation from the system, decreasing efficiency. Its possible the impact of this effect will be negligible, but it should be considered none the less.

Furthermore, investigations of actuator geometry will be of significant interest. It has been seen from analytical models that reductions in pouch lengths maintains the force output of a PH-Sarcomere^[54]. The same paper also demonstrated that bending stiffness also impacts the actuator below a particular ratio of pouch length to thickness. Another aspect of geometry to explore is the electrode placement in relation to the deformation direction. Wang et.al (2020) have already show this to be a factor of consideration with their High-Strain Peano-HASELs, with a change in electrode placement and distribution on the actuator leading to an increase in low-load region strains, but reducing the force in low strain regions^[102].

7.1.2 PH-Fibres and PH-Muscles

Once the PH-Sarcomere has been refined, the exploration of series and parallel combinations of PH-Sarcomeres into PH-Fibres and PH-Muscles respectively can be explored. With regards to the fibres, an interesting investigation would be differential pouch geometries across the series. Balcheva (2020) in their undergraduate dissertation explored this somewhat. They found that a triangular shaped series, with varying width, trapezial PH-Sarcomeres and electrode coverage varying on each PH-Sarcomere^[7]. Their model pointed towards increases in force output and potential energy however the COVID-19 crisis prevented experimental validation. Their model also assumed that PH-fibres linearly scale effects PH-Sarcomeres within them, which has been shown to not be the case empirically, at least in the case of High-Strain Peano-HASELs^[102]. Experimental validation of these results, insights

into the behaviour of series scaling, with the addition of different PH-Fibre shapes would be an insightful and valuable set of investigations before stacking these in parallel to create PH-Muscles. As the PH-Muscle will be an array of many actuators at the same voltage, it is expected the power appetite will scale proportionally. The degree of this power appetite is an exceptionally important consideration when considering both robotic deployment and the operation theatre of extra-terrestrial bodies, where robustness and longevity reign supreme.

Another important and exciting investigation will be the relationship between the capacitance and the deformation. The effects of parallel scaling are not discussed in literature, and would be an important consideration for the control of the actuator, which shows promise for a streamlined and simple control scheme.

7.1.3 Control

On the topic of control, an important takeaway of biological systems analysis is that intelligence is key. This is not a new statement, but its profoundly important. An actuator on an autonomous system is useless without effective control, and an efficient and well designed controller can reduce power expenditure, increase efficiency and permit adaptability. Once the actuator mechanics are well understood, and the system has been optimised, control will be a major factor of consideration. An exciting prospect is given through the aforementioned kinaesthesia, which combined with continuum control and recent developments in machine learning control can allow the compliant potential of soft robotics to truly be utilised in novel environments. This is however no small undertaking.

- 7.1.4 Linear and Non-linear Springs
- 7.2 Discussion of Design Requirements
- 7.3 Aims
- 7.4 Objectives
- 7.5 Methods
- 7.6 Results
- 7.7 Discussion
- 7.8 Conclusions
- 7.9 Future Work

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