Soft-Actuation for Jumping Space Robotics: Preliminary Literature Review and Research Proposal

Harrison McAleese

Lead Supervisor: Dr Andrew Weightman.
Co-Supervisor: Dr Alejandro Macario Rojas
Co-Supervisor: Dr Vidyadhar Peesapati

Abstract

This report conducts a brief literature review; investigated topics include: robotics industries, soft-robotics, soft-actuators, electrically responsive actuators, and particularly Hydraulically Amplified Self-Healing Electrostatic (HASEL) actuators. The case for applying HASEL actuators for jumping locomotion modes for space exploration robotics is made by comparing the situational applicability of HASEL actuators against other methods of actuation and highlighting advantages and disadvantages of the technology. Research into the field is then suggested based on the understanding of challenges facing the use of HASEL actuators such as: geometric implications for design and combinations of actuators; modelling and design methodology; materials and manufacturing; control, using novel data based regression approaches. Implications of such research, both directly related to space robotics and indirectly to other fields, are also highlighted.

1 Introduction

2 Robotics Applications

2.1 Current Robotic Applications and Fields: Some Examples

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[5]. 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[2]. While having fewer Degrees of Freedom (DoF) than human arms, they can move through greater angles. The International Federation of Robotics[31] 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[45;70] 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[57]. 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 visulisation[57]. 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 [6]. Though many autonomous surgical robots are being developed for relatively simple operations [66], 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 [9;3]. Precision weed control and fertiliser allows reductions in costs, crop loses and the environmental impact of blanket spraying. Systems such as the Ladybird robot RIPPA (Robot for Intelligent Perception and Precision Application) [9] 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 [15]. Advances in sensing may also facilitate autonomous detection of plant diseases with non-destructive methods [3].

2.2 Robots in Extremes

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 [48;7]. 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 [69;76].

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 [50]. Applications for these robots are tricky, with many failures due to robots becoming stuck, entangled or failing due to radiation [52]. 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 [51]. The University of Manchester's AVEXIS and MallARD robots [51;25], Toshiba's "Little Sunfish" and a swimming robot from Hitachi have all been developed or adapted to tackle this task.

2.2.1 Space

Space operations are also seeing further expansion. The hostile environment presented to humans [28]in vacuum and on other extraterrestrial bodies means this is a realm mainly touched by robots.

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 [64]. This level of competition is potentiating explosive growth in the industry, with private companies investing heavily in research and development [74].

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 [4;17]. 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.

Sights of public and private sectors are being set on asteroid mining for rare Earth minerals[17], payload delivery and construction into/in Low Earth Orbit and human colinisation of extra terrestrial bodies[8]. With the competition provided by private sector industries, payload prices have begun dropping on average, approaching single digits per kg[34], with some as low as 1.4$\$$kg^{-1}. The validity and economic viability of space missions decreases with payload costs, making these trends promising for beginning larger space operations[72]. 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[10], though this may have decreased considerably since then. This is further supported by the percentage of launch vehicle decisions by cost effective ranking[10], which sees rapid decay as this rank decreases.

Development and competition appears bottle-necked by a renewed return to research, and further growth in some branches of the industry is awaiting the proof of new, novel concepts. Mateo Sanguino[17] in their comprehensive review evaluates over 100 mobile exploration robots between 1959 to 2016. 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 recharger 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[64]. For instance, the field of robotic grippers, and robotic actuation in general, can benefit a large number of applications, including space exploration robotics.

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[17]. Many proposed systems 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.[56] 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[71].

While rovers on missions exploring the moon and mars have lead to improved understanding of the bodies, challenges and failures are abundant. Mateo Sanguino[17] performed a bibliographic analysis investigating the different types of robots seeing interest in research. 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 Mateo 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.

2.3 Jumping Space Robotics

A solution to the issue of terrain navigation faced by ground-based vehicles is to jump over obstacles. Nature sees many examples of animals that can leap to navigate: frogs, fleas, beetles and locusts, for example. Nature is often an Engineer's muse and inspiration has been taken here also. The smaller the navigator, the more difficult terrain navigation becomes as the relative size of an obstacle increases; this is called the "Size Grain Hypothesis" [37]. This method of locomotion could be extremely effective in space appliciations. Many planetary bodies are less massive than Earth, thus exerting less gravitational influence. Jumping therefore is more viable as smaller impulses can generate greater accelerations. Additionally, some bodies have atmospheres less dense than Earth's, reducing drag and further increasing the input/output returns for locomotion. The Philae lander operated on comet 67P/Churyumov-Gerasimenko had gravitational potentials at the surface in the range of $-0.45 \rightarrow -0.27\text{Nmkg}^{-1}$ [67]. The moon has no atmosphere and gravitational acceleration is 1.62ms^{-2} which is roughly 16.5% of Earth's. Mars' own gravitational acceleration is 3.711ms^{-2} (37.8% Earth's). All of these bodies have been targeted for human exploration and expansion. This not only reduces the amount of energy required to launch a system, but also reduces the impact forces experienced when landing under free fall.

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 [40;59]. 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.

Jumping locomotion requires directional control but also the ability to upright after landing to then jump again. Kovac et al. [43] 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 man 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. Jung et al. [35] demonstrated a robot with a mass of 59.4g that could jump 1.62m at a size of 10cm. 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 exciting, the paper makes no mention of the robots self-righting capacity.

3 Soft-Robots

3.1 In General

Soft robots are a momentum gaining field that seeks to generate compliant robotics. Polygerinos et al[60] in their 2017 review of the field define a soft robot as one which will deform before damaging objects, when applying stresses to objects it was designed for. El-Atab et al[23] in their own 2020 review describe the field of "compliant, continuum and configurable robotics". Both of these definitions do well to capture the design principles of soft robotics. Advances in micro-electro-mechanical systems (MEMS)[58] lead to the possible integrations of printed circuit boards with sensors and actuators. Able to be batch fabricated, these MEMS elements include "cantilevers, diaphragms, plates, joints, springs, grippers, switches, gears, rotary motors and resonators"[23]. They also boast "compatibility, sensitivity and performance" characteristics that are attractive for robotics. Development times and costs are increased, however, by the need for clean room fabrication. Being naturally rigged, they pose challenges for deployment on unconventional surfaces. This was one of the initial stimuli for the growth of soft-robotics.

Compliance is a core principle of soft-robotics. As such, research has moved to actuators that utilise soft, flexible, stretchable and active materials such as polymers, rubbers, elastomers, liquids. These materials are also highly manufacturable; many can be 3D printed, allowing rapid prototyping and design adaptation, along with complex features[23;55;62]. Some can be manufactured using highly economically inexpensive materials, such as vegetable based dielectric[39].

Due to these features, these actuators lend themselves a number of applications, such as the implantable technology, manipulators for the grasping of objects with variable geometries and navigation of unpredictable terrain[60;23]. Interactions with humans and delicates has been challenging with so called hard robotics, provoking considerable risk of damage. In agriculture, soft robotic grippers would be able to handle the unpredictable geometries of crops without causing damage[15]. Soft robotic locomotion allows terrain navigation with minimal damage to crops due to their low weight and soft interactions. It also allows robotic farming to be deployed in less developed farming scenarios, which are seeing interest for sustainable farming, as they are compliant and therefore can handle the unstructured environment[68]. Removing the need for tracks to navigate fields[9;3] could lead to greater crop yields by increases in growing area, also increasing the viability of robotic farming for smaller nations or organisations where space is at a premium. Reductions in cost help poorer communities feel the benefits of automated agriculture. Ease of manufacturing and material acquisition further allow robots to be more affordable as the techniques used are often without specialist equipment[62].

Soft robotics show potential for medical robotics, intrinsically allowing interactions with delicate tissues found in humans[23]. More invasive procedures can see robotic introduction as risks of collateral damage are reduced significantly. In mental health, human like robots are being trialed for a number of applications such as companionship for Alzheimers patients[42]. Soft robotics can help make these robots more appealing and natural. Soft robotic actuation may also help towards greater degrees of autonomy for medical robot systems, reducing the risks involved in granting human interaction systems such freedom when wielding hard, traditional actuators. With advances in machine learning control also surfacing, this is a realistic aim for these tasks.

Delicate repair operations would also see beneficial influence from soft robotics research. In the MiMRee project there is a non-negligible potential to cause damage to the delicate surfaces of turbine blades. Scratching can occur from hard interactions which have deleterious effects of turbine blade aerodynamics. Weight limits of the UAVs are also a challenge, requiring additional legislation to operate beyond certain masses and contributing to the potential of damage to the turbine blade. Soft robotics being lightweight addresses this issue, as well as mitigating the damaging interaction potential of contacting a turbine blade[7].

Weight reductions in the space sector, with regard to payload costs, are also beneficial. despite recent progress. Soft-robotics have potential to be extremely lightweight, with high specific energies[62;23;60]. Exploration of extra terrestrial bodies has been affected by a lack of effective terrain navigation and detrimental complexity of locomotion methods, discussed in section 2.3. Soft robotics may have a number of implications, allowing for more economical operations, facilitating larger scale, more ambitious missions. They also see potential to reduce failure rates associated with poor terrain and systems failures by facilitating the navigation through simple, robust actuator designs.

3.2 Soft-Robotic Actuation

A critical component of a robot is its ability to interact and locomote in and about an environment. Actuation is therefore a field of significant research. El-Atab et al[23] provide a comprehensive breakdown of the various types of actuators currently in development. Actuators make use of polymers, gels fluids and papers .etc, that show the sought after properties of soft-robotics. Materials vary between actuation and sensing methodology.

For summary[1], 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 section 4.

3.2.1 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[53]. Small areas may see independent creation of fields and its spatial gradients to allow multiple actuation modes, facilitating more complex movements[18]. 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 down to mitigate this[23]. 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.

3.2.2 Thermally Responsive

Thermally Responsive actuators are stimulated by infra-red, near infra-red, thermal radiation or Joule heating[23]. These methods are safer than electric fields or Ultra Violet (UV) light, but are less efficient, some as low as 1.32%[27], 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[41]. 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)[23].

3.2.3 Photo-Responsive

Photo-Responsive actuators are wireless and able to be miniaturised. Materials in Photo-

[1]The full review paper is extensive and competent. Discussion here is kept to a summary for brevity and it is encouraged that more information of the various form of soft actuators be sought from the review paper itself. Tables 1 and 2 in the review are also invaluable resources of actuator comparison.

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 [23]. 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.

3.2.4 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.

3.2.5 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 Loepfe et al. [46] 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 extensive amount of force, Loepfe 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 [23].

3.3 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 [60]. Methods of sensing, therefore, are often related to capacitance and impedance monitoring, as these properties change with deformation [1;23], 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 of 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 [60;39;75]. 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 embedded 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 [60].

Some of the actuators currently undergoing research display inherent kinaethesia [39;61;1]. This proprioception can allow for high control accuracy potential and is often computationally inexpensive, relying on simple relationships [39;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.

4 HASEL Actuation for Jumping Space Robotics (JSR)

4.1 HASEL Actuators

Omitted from the previous summary were Electrically responsive actuators. Flexible, stretchable and soft materials capable of transforming electrical to mechanical energy are numerous. 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" [23]; including micro-fluidic, micro-scale object manipulation, micro-locomotion [32] and artificial muscles [1;39;29].

4.1.1 Dielectric Elastomer Actuators

Dielectric Elastomer Actuators (DEAs) are the precursor and an alternative actuator. By exploiting the Coulombic attraction [30]; establishing a potential difference between two electrodes and them pulling together through the laws of electromagnetism. These electrodes are located on either end of a compressible membrane. Typical elastomers employed are "Acrylic, Silicones, Polyurethanes (PU) and Rubber." [23]. 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. 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 [11]. This damages the dielectric and has deleterious performance effects [23;1]. Stacked actuators require large areas of dielectric, prone to electrical failure according to Weibull distributions for dielectiric breakdowns [44;77]. Silicone sponges swollen with silicone oil showed continued operation post breakdown, but strains were below 5% [29;1]. Research has been conducted in low voltage DEAs which have shown functional actuation at 450V with strain values up to 25% [32].

4.1.2 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;39]. Elastomer shells do not self-heal; but do self-seal [62], 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 occured 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;62;30]. These are stresses that come about in matter as a result of electric fields, shown by the Maxwell Equations of electromagnetism [30]. By coating the elastomer shell partly in electrodes, then establishing a potential difference which generates electric fields within the dielectric, the dilectric 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 is 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 (1) [30;78]:

$$P \propto \epsilon E^2 \tag{1}$$

HASEL actuators, like DEAs, exhibit self-sensing. HASEL 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;39;62]. 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. [39] 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 HASEL-like actuators.

HASELs, like soft-hydraulic actuators, allow design and actuation-mode freedoms. However, HASEL actuators generate their pressure locally by electrostatic forces [1;62]. 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 HASELs. For comparison, Mammalian skeletal muscle has an average specific power of $50Wkg^{-1}$. Linear strains up to 124% have been reported for planar HASELs at resonance and quadrant donut HASELs 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 HASEL actuators have been used for robotic grippers and planar HASELs can displace 4kg objects with strain values of 69% when applied in parallel [1].

In experiments comparing HASEL to DE actuators, Acome et al. showed that under $11kV$ voltage stimulus, HASEL 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 HASEL than DEA. Divergence was observed around $3kV$. This demonstrates that HASEL 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 HASEL 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 (1) would increase Maxwell Pressures, and advanced fabrication techniques to produce high-resolution dielectric structural features.

4.1.3 Peano-HASEL Actuators

HASEL actuator's 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. PH actuators [*Fig.* 1] combine HASEL actuators with Peano fluidic actuators [54], but due to the pressure being generated locally via electrostatic forces, are more versatile and applicable to autonomous systems, removing the extra equipment for traditional hydraulic actuation. 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. [39] report their actuators cost \$0.10 in materials, using biaxially orientated polypropylene as a film material, conductive hydrogel as electrodes and Envirotemp FR3 vegetable based transformer oil as dielectric. 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 [62]. 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. [38] observed that under high loads, their actuators performed better than theoretical models. They

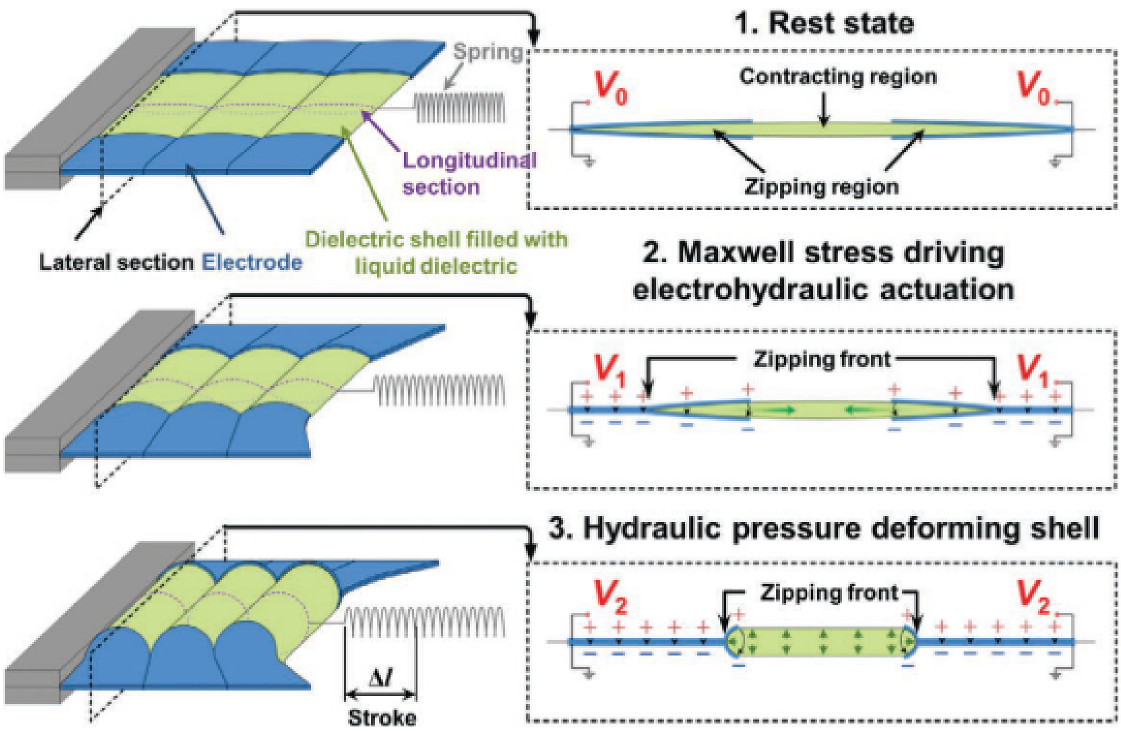

Figure 1: Basic operation of a High-Strain Peano-HASEL actuator. The operation of electrode zipping is the same as in all PH actuators, only the placement of the electrode is changed in HS-PH.[75;62]

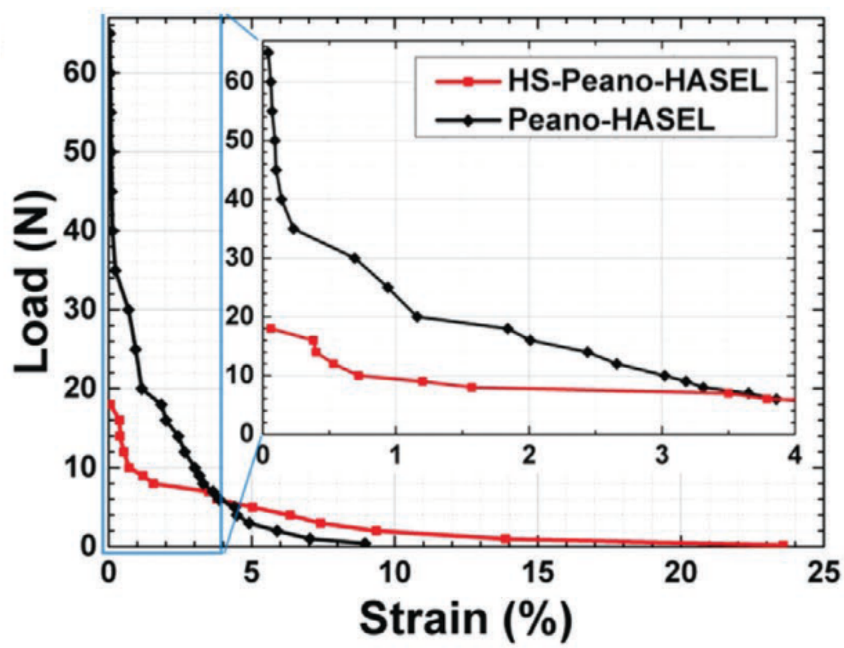

Figure 2: Load-Strain characteristics of two types of Peano-HASEL actuator compared. Until 4% strain, standard PH actuators could lift higher loads than their Hig-Strain counterparts[75].

attributed this to these instabilities, noting that rotation was also observed about the free end of the actuators, simultaneous with contraction. Thus zipping areas are larger for the same actuation strain, increasing force output as a result. Wang et al.[75] replaced BOPP shells with thermoplastic polyurethane (TPU) for High-Strain Peano-Hasel (HS-PH) actuators, which is more compliant. 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 171% ($\frac{16.03\%}{9.36\%}$) 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 [*Fig.* 2], the former being inversely proportional to the latter. HS-Peano-HASEL (HS-PH)[75] 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%[38] to 36%[75]. 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 $18N$[75].

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

4.2 Jumping Space Robotic Application

Application to Jumping Space Robotics is the intention of this research, but by no means the only potential application. By developing these actuators, other applications may see use of the PH-VSSEA with minimal adapation. Locomotion and compliant interaction are both problems addressed by soft actuators and, while many problems will still need resolving beyond this research, some which may be fatal, peano-HASEL actuators approach the right tool for the job. While the technology is still infant, it shows great promise and the theoretical models show that research thus far has only scratched the surface of this potential. In this section the validity of applying these actuators in JSR will be explored, along with some opportunities the unique environment of space presents, as well as some of the challenges and their potential solutions.

4.2.1 Validity

Firstly, HASELs are incredibly lightweight. As previously discussed, high specific energies are traits soft-actuators revel in. Given the discussion on payload weights for rocket launches in section 2.2.1, it seems obvious that an increase in specific energies increases dramatically the viablity of a robotic mission. Moentary, fuel and spatial occupation are all reduced as less massive acutators can be equipped to a robot for the same energy output.

Secondly, the cost of the actuators from a manufacturing standpoint is very low. This allows not only experimental research to be cheap, but also maufacturing 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 costs; however, starting from a lower base cost can only be beneficial.

HASEL actuators have demonstrated good continuous control with 3D movement achieved [Fig. 3] through combinations of actuators[49].

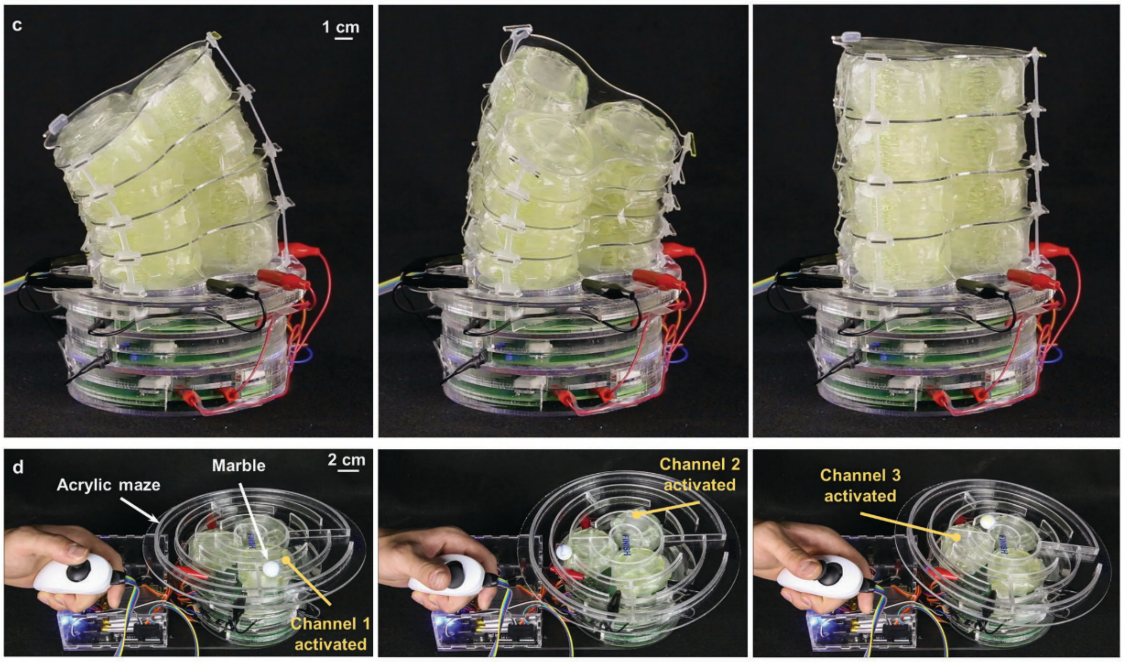

Figure 3: Mitchell et al.'s demonstration of an array of donut hasel actuators orientating itself in 3-Dimensions.[49]

This can allow a jumping robot to lean or orientate itself to jump in a specific direction or, on an intra-PH-Muscle scale, single PH-Sarcs to interact with tendons asyncronously for added control possibilities.

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 geometries. This allows high mission adaptation potential, reducing failure probability, which in frontier environments would be invaluable. Acutators 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.

PH-Actuators have been shown, even in this infant state of development, to be reliable up to a million actuation cycles[62]. Reliability is crucial in a space application, where autonomy is key and there is minimal to no hope of repair.

The actuators themselves are not overly complex in structure, and require minimal mechanical interfaces, such as those between gears, which may wear with time, further reducing failure potential. This is valuable for reliablity and control applicaitons.

On the topic of autonomy, the self-sensing capabilites of the actuators further reduce the complexity due to the inherent kinaethesia, and with that, the number of potential failure points. The ability to infer the majority of the Peano-HASEL component's state variables through the actuation signal reduces the need for sensors and means that, in most cases, if the actuator can be stimulated, it can be sensed in some part.

Despite Peano-HASEL actuators currently displaying relatively low force output in comparison to their harder counterparts, the operating theatres associated with vacuum or extraterrestrial bodies mitigate the impact of this. For instance, operating in vacuum, any small acceleration is non-negligible as there is no gravitational or aerodynamic resistance, meaning that a smaller force can lead to a much larger displacement of mass realtive to Earth. This also extends to the surfaces of many extraterrestrial bodies, as shown in section 2.3 two major targets for exploration and intended operating environments for these robots (The Moon and Mars) have significantly less gravitational pull than Earth. As Newtonian physics describes the gravitational potential as $E_{gp} = mgh$ where m =Mass, g = Gravitational Constant of the Body in a Uniform Gravitational Field and h = Height, a reduction in g drastically reduces the needed energy to gain height in a jump. Additionally, this lowers the impact velocity of falling objects, reducing damage to the robots. It should also be noted that the *mass specific* force and energy outputs of the peano-HASEL acutators are considerable, which gives more output for a given weight.

4.2.2 Challenges with PH Application in Space

Extraterrestrial operation environments present a considerable amount of unique challenges; temperature on the surface of Mars, for example, can drop to $173K$[59]. The moon can approach $140K$ at lunar night. Material selection is impacted heavily by this, as the properties of materials vary considerably with temperature. Elastomers exhibit a glass transition temperature that creates considerably more brittle properties. As soft actuators rely on the elastic shell, this is a factor of consideration. Either the material must perform under these temperatures, or a method of thermodynamic regulation must be added to a system, which can add weight and reduce battery to actuation energy efficiency. Due to the effects of temperature on oriental polarisation, dielectrics display an increase in dielectric constant (or relative permittivity), until at a certain temperature, the dielectric permittivity drops rapidly, as the material loses its ability to polarise[19]. The effects of temperature on the operation of HASEL-like actuators will therefore need to be understood as a major factor of consideration for such choices.

The Mars Helicopter design has had to account for the effects on thermal management. Permittivity drops rapidly as the material loses its ability to polarise[19]. Excess heat is primarily adibiatically stored, caused by the low atmospheric density[59].

Radiation is another consideration. As most extraterrestrial bodies of interest have little to no atmosphere, radiation exposure is undettered. Two categories of radiation exposure are identified in deep space: chronic and acute. Chronic exposure involves high-energy atomic nuclei with fluxes of $10GeVnucleon^{-1} \rightarrow TeVnucleon^{-1}$ from mainly galactic cosmic rays. Acute is radiation ranging from $0.1GeVnucleon^{-1} \rightarrow 10GeVnucleon^{-1}$ caused by solar particles[47]. Radiation exposure is a geometric function in part, as the exposed area and the angle of incidence for the radiation on the surface are factors for the overall exposure. TPU shows significant decay in Ultimate Tensile Stregnth (UTS) when exposed to only $2.6MGy$ of radiation[73]. $1Gy$ is the absorbtion $1Jkg^{-1}$. $1TeV$ is equal to $1.6 \times 10^{-10}J$ which means to reach the $2.6MGy$ of deterioration, 1.625×10^{16} chronic irradiation events need to occur per kg of material. While this number seems large, given the size of nucleons and the speeds at which they move, this can occur rapidly. TPU experiences chain scission of C-H bonds when exposed to irradiation, but C-O-CN crosslinking occurs which compete with the scissions. This changes the solubility of TPU, but it maintains its elasticity. The UTS of TPU experiences a monotonic decrease as radiation increases.

5 Suggested Research Topics

5.1 Research Aims and Objectives

5.1.1 Aim

The aim of this research is to investigate the applicability of applying HASEL technology to allow jumping locomotion for non-biological systems in extraterrestrial environments, and improve the technology in general.

5.1.2 Objectives

- Amalgamate existing research on HASEL actuators and space technology to understand identified dynamics to date and define accurately the challenges with achieving the aim.
- Define a design specification to address challenges.
- Explore the implications of actuator geometry to define a geometry that optimises the dynamics of controlled varaibles (such as material properties).
- Explore combinations of actuators, the geometries of these arrays and the proportion of types of actuators within.
- Assess the viablity of materials that optimise a particular geometry. This will involve investigating material properties, manufacturing techniques to facilitate geometry and material combinations.
- Using data gathered from experimental testing, use data driven regression techniques to identify variable relationships to improve models.
- Use models and data driven non-liner computationally assisted control design techniques to define control laws to facilitate effective and reliable autonomous locomotion.

5.2 Geometry

So far, much of the research mentioned has looked into the 2D geometric variance of actuators. 3D movement has been achieved through variations in in voltage applied to combinations of these 2D actuators[49]. Geometry of the electrodes for PH actuators has been shown to be a factor of consideration[75]. 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[62]. Therefore a single pouch will have the same force-strain properties as a number of smaller pouches of the same overall length. This facilitates the increasing of packing density of pouches in modular matrixes, 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. Thinner shells require a lower stimulus voltage; however the pouch length must be reduced to maintain specific energy values. Rothemund et al.[63] in their analysis showed geometric consideration can improve acutation speeds of Peano-HASEL acutators, identified by their theoretical models.

Stacked PH actuators have also been demonstrated by Mitchell et al.[49] to create a modular actuator. 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.[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 $8 \rightarrow 10kV$ 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 [49]. 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 [39], which, though not exclusively, is a geometric problem. Alternative geometries and dielectric thickness are cited in Kellaris et. al (2018) as possibilities for decreasing the needed actuation voltage. Computational geometry generation can allow unexpected geometries to be explored that may have effects on this problem, though this is dependant on the accuracy of a model.

The sheer amount of customisablity for not only individual module design 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 modules, could generate significant force outputs and high specific energies.

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 variable 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 minimse 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 valubale data and experience to tune models.

5.3 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. While proportional-integral-differential (PID) controllers have been applied in conditions where HASEL actuators showed second order linearity [65;33;62], Results show that in regions where strain-loads relationships behave like linear mass-spring-damper - identified with static load tests used by Schunk et al. [65] - “acceptable” control performance was achieved in the well-defined srain regions. This was achieved with a PI controller, omitting the derivative component. Also the only sensory feedback was the kinesthetic self-sensing inherent to the actuators. Johnson et al. [33] 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 180s, 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 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 promosing 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.[36] building on the work done by Brunton et al.[13]. 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 [*Fig.*4]. 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 realtively 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, suitible for strongly non-linear systems, resistant to noise, fast in training and execution and provide excellent control performance [*Table 2. Kiaser et al.*][36], even in low data amounts. Applications thus far are the classic Lorentz system[14], turbulence control[12], epidemic modelling and chaotic electroconvection[26]. 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 standarised easy use of the method[16]. 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 bilinear adaption of DMD being used on quantum systems, for example[24].

To generate control laws, one approach is to apply genetic programing techniques. Genetic programming utilises genetic algorithms to create control laws from an identified set of variables, in this case from the SINDYc system model. It achieves this by selecting and combining variables with a pool of mathematical operations $(+, -, \times, \div, sin, cos^2 etc.)$, including non-linear operators, then optimising this via exploration and exploitation of complex cost function spaces[20;22]. The advantage of genetic programming is that any local optimisiations are exploited in the cost space through genetic programming opeartions such as "Elitism" and "Replication", but through operations such as "Mutation" and "Crossover", the global optimum may be found and then explotied. Valuable work in this area for control by Duriez et al.[21] has proven genetic programming to be effective and efficient when applied to systems with highly non-linear dynamics such as turblent flow mixing control. In these tests online genetic programming control allowed similar flow mixing to open loop control, with significantly less control expenditure, which is useful for limited power supplies for onboard electronics. This was done simply with data feedback from sensors and no control law was established intially, nor was a model used.

Although this system may be over zealous for the actuator application, it may allow insights into the dynamics at play within acutators. 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[62]. By testing geometries and experimenting with actuators, data will be farmed from these experiments regardless of developing control in tandem. Also, as Rothemund et al.[63] find in their paper two identifiable dynamic regimes: inertial and viscous. In the intertial regime, they identify an undershoot and oscilaltion from the intertia of the load, and note that an "appropriate control strategy" may address this in applciations. The control signals for actuators are voltage signals, which Rothermund et al. also identify as a key component in the viscous regimes.

5.4 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[75;49;39;38]. The change in force-strain characteristics and efficiencies when Wang et al.[75] made the switch from BOPP to TPU also demonstrate the potential in carefully selected materials for improving performance of actuators. Rothemund et al. in their review of HASEL actuators suggest that materials with higher dielectric constants and breakdown strengths would increase specific energy[62]. Suggestions for materials such as PVDF, 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[38]. For reference, skeletal muscle achieves $40Jkg^{-1}$. While exciting, these models are primative, 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 ϵE^2, an increase in dielectiric 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. As the actuator will be operating in an evironment that affects its properties, via mechanisms of temperature or radiation, for example, the optimisiation has to occur in the interplay between all considerable variables. Material variables can be put into the library of SINDyc and thus through regression carried out on data, extract the dynamics between these variables. These can then be optimised for a particular property, for example strain by using an optimisation method to computationally find a point in this space where strain is optimised.

Combining material effects with geometric models, then performing similar optimisation iterations could allow convergence on an ideal actuator (for an application) within the accuracy of the model and material dataset. This can then be experimentally tested, compared with the model. Improvements can be made to the model from this comparison.

6 Conclusion

While there are many issues with HASEL-like actuators, it is an infant technology with great promise shown from experimental and theoretical investigation. Research into geometry can help define specialised actuators and exploit as much as possible from the shape of both actuator and arrray combinations. Materials research may lead to more reliable actuators by mitigating dielectric breakdown potentials, with higher specific energies while lowering activation stimuli needs, as well as environmental operating feasability for space operations. Investigations and experiments needed for control design can reveal relationships between variables associated with actuators, and models can be improved from this understanding. This can be achieved while making progress towards defining control laws.

The ease of experimental manufacturing, as well as the low cost involved means that potential for rapid development is high; existing models can be emperically explored as soon as manufacturing is set up.

The suggested research should allow a greater understanding of actutors to be formed, allowing the applicaiton to Jumping Space Robotics, while in addition furthering the actuator technology in general, which has branching influence to other robotics applications.

References

[1] E Acome, S K Mitchell, T G Morrissey, M B Emmett, C Benjamin, M King, M Radakovitz, and C Keplinger. Hydraulically amplified self-healing electrostatic actuators with muscle-like performance. 65(January):61–65, 2018.

[2] Haider A.F. Almurib, Haidar Fadhil Al-Qrimli, and Nandha Kumar. A review of application industrial robotic design. *International Conference on ICT and Knowledge Engineering*, pages 105–112, 2011.

[3] Yiannis Ampatzidis, Luigi De Bellis, and Andrea Luvisi. iPathology: Robotic applications and management of plants and plant diseases. *Sustainability (Switzerland)*, 9(6):1–14, 2017.

[4] Max Bajracharya, Mark W. Maimone, and Daniel Helmick. Autonomy for Mars Rovers: Past, present, and future. *Computer*, 41(12):44–50, 2008.

[5] Mordechai Ben-Ari and Francesco Mondada. *Elements of Robotics (Robots and Their Applications)*. 2017.

[6] Mordechai Ben-Ari and Francesco Mondada. *Elements of Robotics (Robots and Their Applications)*. 2017.

[7] Sara Bernardini, Ferdian Jovan, Zhengyi Jiang, Simon Watson, Peiman Moradi, Tom Richardson, Rasoul Sadeghian, and Sina Sareh. A Multi-Robot Platform for the Autonomous Operation and Maintenance of Offshore Wind Farms. *Aamas*, pages 1696–1700, 2020.

[8] Matt Rydin Bettina Inclán. NASA Publishes Artemis Plan to Land First Woman, Next Man on Moon — NASA.

[9] Robert Bogue. Robots poised to revolutionise agriculture. *Industrial Robot*, 43(5):450–456, 2016.

[10] Tom R. Boone and David P. Miller. Capability and Cost-Effectiveness of Launch Vehicles. *New Space*, 4(3):168–189, 2016.

[11] Paul Brochu and Qibing Pei. Advances in dielectric elastomers for actuators and artificial muscles. *Macromolecular Rapid Communications*, 31(1):10–36, 2010.

[12] Steven L. Brunton, Bernd R. Noack, and Petros Koumoutsakos. Machine Learning for Fluid Mechanics. *arXiv*, 2019.

[13] Steven L. Brunton, Joshua L. Proctor, J. Nathan Kutz, and William Bialek. Discovering governing equations from data by sparse identification of nonlinear dynamical systems. *Proceedings of the National Academy of Sciences of the United States of America*, 113(15):3932–3937, 2016.

[14] Kathleen Champion, Bethany Lusch, J. Nathan Kutz, and Steven L. Brunton. Data-driven discovery of coordinates and governing equations. *Proceedings of the National Academy of Sciences of the United States of America*, 116(45):22445–22451, 2019.

[15] Nikolaus Correll, Nikos Arechiga, Adrienne Bolger, Mario Bollini, Ben Charrow, Adam Clayton, Felipe Dominguez, Kenneth Donahue, Samuel Dyar, Luke Johnson, Huan Liu, Alexander Patrikalakis, Timothy Robertson, Jeremy Smith, Daniel Soltero, Melissa Tanner, Lauren White, and Daniela Rus. Indoor robot gardening: Design and implementation. *Intelligent Service Robotics*, 3(4):219–232, 2010.

[16] Brian M. de Silva, Kathleen Champion, Markus Quade, Jean Christophe Loiseau, J. Nathan Kutz, and Steven L. Brunton. PySINDy: A python package for the sparse identification of nonlinear dynamics from data. *arXiv*, 5:3–6, 2020.

[17] Tomás de J Mateo Sanguino. 50 years of rovers for planetary exploration: A retrospective review for future directions. *Robotics and Autonomous Systems*, 94:172–185, 2017.

[18] Eric Diller, Joshua Giltinan, Guo Zhan Lum, Zhou Ye, and Metin Sitti. Six-degree-of-freedom magnetic actuation for wireless microrobotics. *International Journal of Robotics Research*, 35(1-3):114–128, 2016.

[19] DoITPoMS. DoITPoMS - TLP Library Dielectric materials - Effect of temperature on the dielectric constant.

[20] D. C. Dracopoulos and S. Kent. Genetic programming for prediction and control. *Neural Computing and Applications*, 6(4):214–228, 1997.

[21] Thomas Duriez and Steven L Brunton. *Machine Learning Control – Taming Nonlinear Dynamics and Turbulence*. Springer, 2017.

[22] Thomas Duriez, Steven L. Brunton, and Bernd R. Noack. Chapter 7 - MLC tactics and strategy. *Machine Learning Control – Taming Nonlinear Dynamics and Turbulence*, 116(Mlc):155–170, 2017.

[23] Nazek El-Atab, Rishabh B Mishra, Fhad Al-Modaf, Lana Joharji, Aljohara A Alsharif, Haneen Alamoudi, Marlon Diaz, Nadeem Qaiser, and Muhammad Mustafa Hussain. Soft Actuators for Soft Robotic Applications: A Review. *Advanced Intelligent Systems*, 2000128:2000128, 2020.

[24] Andy Goldschmidt, Eurika Kaiser, Jonathan L. Dubois, Steven L. Brunton, and J. Nathan Kutz. Bilinear dynamic mode decomposition for quantum control. (November), 2020.

[25] Keir Groves, Andrew West, Konrad Gornicki, Simon Watson, Joaquin Carrasco, and Barry Lennox. MallARD: An autonomous aquatic surface vehicle for inspection and monitoring of wet nuclear storage facilities. *Robotics*, 8(2), 2019.

[26] Yifei Guan, Steven L Brunton, and Igor Novosselov. Sparse nonlinear models of chaotic electroconvection arXiv : 2009 . 11862v1 [physics . comp-ph] 24 Sep 2020. pages 1–14.

[27] Carter S. Haines, Márcio D. Lima, Na Li, Geoffrey M. Spinks, Javad Foroughi, John D.W. Madden, Shi Hyeong Kim, Shaoli Fang, Mônica Jung De Andrade, Fatma Göktepe, Özer Göktepe, Seyed M. Mirvakili, Sina Naficy, Xavier Lepró, Jiyoung Oh, Mikhail E. Kozlov, Seon Jeong Kim, Xiuru Xu, Benjamin J. Swedlove, Gordon G. Wallace, and Ray H. Baughman. Artificial muscles from fishing line and sewing thread. *Science*, 343(6173):868–872, 2014.

[28] Kurt Harris. Where No One Can Hear You Scream: Regulating the Commercial Space Industry to Ensure Human Safety. *Health Matrix: The Journal of Law-Medicine*, 30(1):375, 2020.

[29] Stacy Hunt, Thomas G. McKay, and Iain A. Anderson. A self-healing dielectric elastomer actuator. *Applied Physics Letters*, 104(11):2012–2015, 2014.

[30] Paul G. Huray. *Maxwell ' s Equations*. Number 915. John Wiley & Sons, Inc, 2015.

[31] IFR International Federation of Robotics. Executive Summary World Robotics 2020 Industrial Robots. *World Robotic Report*, pages 15–24, 2020.

[32] Xiaobin Ji, Xinchang Liu, Vito Cacucciolo, Matthias Imboden, Yoan Civet, Alae El Haitami, Sophie Cantin, Yves Perriard, and Herbert Shea. An autonomous untethered fast soft robotic insect driven by low-voltage dielectric

elastomer actuators. *Science Robotics*, 4(37), 2019.

[33] Brian K. Johnson, Vani Sundaram, Mantas Naris, Eric Acome, Khoi Ly, Nikolaus Correll, Christoph Keplinger, James Sean Humbert, and Mark E. Rentschler. Identification and Control of a Nonlinear Soft Actuator and Sensor System. *IEEE Robotics and Automation Letters*, 5(3):3783–3790, 2020.

[34] Harry W Jones. The Recent Large Reduction in Space Launch Cost. *48th International Conference on Environmental Systems*, (July 2018):81, 2018.

[35] Gwang Pil Jung, Carlos S. Casarez, Sun Pill Jung, Ronald S. Fearing, and Kyu Jin Cho. An integrated jumping-crawling robot using height-adjustable jumping module. *Proceedings - IEEE International Conference on Robotics and Automation*, 2016-June:4680–4685, 2016.

[36] E. Kaiser, J. N. Kutz, and S. L. Brunton. Sparse identification of nonlinear dynamics for model predictive control in the low-data limit. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 474(2219), 2018.

[37] M. Kaspari and M. D. Weiser. The size-grain hypothesis and interspecific scaling in ants. *Functional Ecology*, 13(4):530–538, 1999.

[38] Nicholas Kellaris, Vidyacharan Gopaluni Venkata, Philipp Rothemund, and Christoph Keplinger. An analytical model for the design of Peano-HASEL actuators with drastically improved performance. *Extreme Mechanics Letters*, 29:100449, 2019.

[39] Nicholas Kellaris, Vidyacharan Gopaluni Venkata, Garrett M. Smith, Shane K. Mitchell, and Christoph Keplinger. Peano-HASEL actuators: Muscle-mimetic, electrohydraulic transducers that linearly contract on activation. *Science Robotics*, 3(14):1–11, 2018.

[40] Witold J.F. Koning, Wayne Johnson, and Håvard F. Grip. Improved mars helicopter aerodynamic rotor model for comprehensive analyses. *AIAA Journal*, 57(9):3969–3979, 2019.

[41] Arda Kotikian, Connor McMahan, Emily C. Davidson, Jalilah M. Muhammad, Robert D. Weeks, Chiara Daraio, and Jennifer A. Lewis. Untethered soft robotic matter with passive control of shape morphing and propulsion. *Science Robotics*, 4(33):1–11, 2019.

[42] Dimitrios Koutentakis, Alexander Pilozzi, and Xudong Huang. Designing Socially Assistive Robots for Alzheimer's Disease and Related Dementia Patients and Their Caregivers: Where We Are and Where We Are Headed. *Healthcare*, 8(2):73, 2020.

[43] Mirko Kovač, Manuel Schlegel, Jean Christophe Zufferey, and Dario Floreano. Steerable miniature jumping robot. *Autonomous Robots*, 28(3):295–306, 2010.

[44] G. Kovacs, L. Düring, S. Michel, and G. Terrasi. Stacked dielectric elastomer actuator for tensile force transmission. *Sensors and Actuators, A: Physical*, 155(2):299–307, 2009.

[45] Anand Kumar, Nirma Yadav, Shipra Singh, and Neha Chauhan. Minimally invasive (endoscopic-computer assisted) surgery: Technique and review. *Annals of Maxillofacial Surgery*, 6(2):159, 2016.

[46] Michael Loepfe, Christoph M. Schumacher, Urs B. Lustenberger, and Wendelin J. Stark. An untethered, jumping roly-poly soft robot driven by combustion. *Soft Robotics*, 2(1):33–41, 2015.

[47] Bryan Manning and Robert Singleterry. Radiation engineering analysis of shielding materials to assess their ability to protect astronauts

in deep space from energetic particle radiation. *Acta Astronautica*, 171(January):23–30, 2020.

[48] MiMRee. Multi-Platform Inspection, Maintenance and Repair in Extreme Environments (MIMRee) — Project — ORE Catapult, 2019.

[49] Shane K. Mitchell, Xingrui Wang, Eric Acome, Trent Martin, Khoi Ly, Nicholas Kellaris, Vidyacharan Gopaluni Venkata, and Christoph Keplinger. An Easy-to-Implement Toolkit to Create Versatile and High-Performance HASEL Actuators for Untethered Soft Robots. *Advanced Science*, 6(14), 2019.

[50] Keiji Nagatani, Seiga Kiribayashi, Yoshito Okada, Kazuki Otake, Kazuya Yoshida, Satoshi Tadokoro, Takeshi Nishimura, Tomoaki Yoshida, Eiji Koyanagi, Mineo Fukushima, and Shinji Kawatsuma. Emergency response to the nuclear accident at the Fukushima Daiichi Nuclear Power Plants using mobile rescue robots. *Journal of Field Robotics*, 30(1):44–63, 2013.

[51] M. Nancekievill, A. R. Jones, M. J. Joyce, B. Lennox, S. Watson, J. Katakura, K. Okumura, S. Kamada, M. Katoh, and K. Nishimura. Development of a Radiological Characterization Submersible ROV for Use at Fukushima Daiichi. *IEEE Transactions on Nuclear Science*, 65(9):2565–2572, 2018.

[52] Matthew Nancekievill, Jose Espinosa, Simon Watson, Barry Lennox, Ashley Jones, Malcolm J. Joyce, Jun Ichi Katakura, Keisuke Okumura, So Kamada, Michio Katoh, and Kazuya Nishimura. Detection of simulated fukushima daichii fuel debris using a remotely operated vehicle at the naraha test facility. *Sensors (Switzerland)*, 19(20), 2019.

[53] Nam Trung Nguyen. Special issue on magnetic-based microfluidics. *Microfluidics and Nanofluidics*, 13(4):527–528, 2012.

[54] Ryuma Niiyama, Daniela Rus, and Sangbae Kim. Pouch Motors: Printable/inflatable soft actuators for robotics. *Proceedings - IEEE International Conference on Robotics and Automation*, pages 6332–6337, 2014.

[55] Maura R. O'Neill, Eric Acome, Shannon Bakarich, Shane K. Mitchell, Julia Timko, Christoph Keplinger, and Robert F. Shepherd. Rapid 3D Printing of Electrohydraulic (HASEL) Tentacle Actuators. *Advanced Functional Materials*, 30(40), 2020.

[56] José Antonio Peña-Ramos and Fernando Rafael Ramírez de Luis. Resources in space and asteroid mining: Where we are and which challenges should be expected. *International Journal of Technology Management*, 82(3-4):197–205, 2020.

[57] Brian S. Peters, Priscila R. Armijo, Crystal Krause, Songita A. Choudhury, and Dmitry Oleynikov. Review of emerging surgical robotic technology. *Surgical Endoscopy*, 32(4):1636–1655, 2018.

[58] Kurt E. Petersen. Silicon as a mechanical material. *Micromechanics and MEMS: Classic and Seminal Papers to 1990*, 70(5):58–95, 1982.

[59] Benjamin T. Pipenberg, Matthew T. Keennon, Jeremy D. Tyler, Sara A. Langberg, Bart Hibbs, J. (Bob) Balaram, Håvard F. Grip, and Jack Pempejian. Design and fabrication of the mars helicopter rotor, airframe, and landing gear systems. *AIAA Scitech 2019 Forum*, (January 2019), 2019.

[60] Panagiotis Polygerinos, Nikolaus Correll, Stephen A. Morin, Bobak Mosadegh, Cagdas D. Onal, Kirstin Petersen, Matteo Cianchetti, Michael T. Tolley, and Robert F. Shepherd. Soft Robotics: Review of Fluid-Driven Intrinsically Soft Devices; Manufacturing, Sensing, Control, and Applications in Human-Robot

Interaction. *Advanced Engineering Materials*, 19(12), 2017.

[61] Philipp Rothemund, Nicholas Kellaris, and Christoph Keplinger. How inhomogeneous zipping increases the force output of Peano-HASEL actuators. *Extreme Mechanics Letters*, 31:100542, 2019.

[62] Philipp Rothemund, Nicholas Kellaris, Shane K Mitchell, Eric Acome, and Christoph Keplinger. HASEL Artificial Muscles for a New Generation of Lifelike Robots — Recent Progress and Future Opportunities. 2003375:1–28, 2020.

[63] Philipp Rothemund, Sophie Kirkman, and Christoph Keplinger. Dynamics of electrohydraulic soft actuators. *Proceedings of the National Academy of Sciences of the United States of America*, 117(28):16207–16213, 2020.

[64] Luigi Scatteia. Main trends and challenges in the space sector. *PwC trend report*, (June), 2019.

[65] Cosima Schunk, Levi Pearson, Eric Acome, Timothy G. Morrissey, Nikolaus Correll, Christoph Keplinger, Mark E. Rentschler, and J. Sean Humbert. System Identification and Closed-Loop Control of a Hydraulically Amplified Self-Healing Electrostatic (HASEL) Actuator. *IEEE International Conference on Intelligent Robots and Systems*, pages 6417–6423, 2018.

[66] Azad Shademan, Ryan S Decker, Justin D Opfermann, Simon Leonard, Axel Krieger, and Peter C W Kim. Supervised autonomous robotic soft tissue surgery. Technical report.

[67] Holger Sierks, Cesare Barbieri, Philippe L. Lamy, Rafael Rodrigo, Detlef Koschny, Hans Rickman, Horst Uwe Keller, Jessica Agarwal, Michael F. A'Hearn, Francesco Angrilli, Anne Therese Auger, M. Antonella Barucci, Jean Loup Bertaux, Ivano Bertini, Sebastien Besse, Dennis Bodewits, Claire Capanna, Gabriele Cremonese, Vania Da Deppo, Bjö Davidsson, Stefano Debei, Mariolino De Cecco, Francesca Ferri, Sonia Fornasier, Marco Fulle, Robert Gaskell, Lorenza Giacomini, Olivier Groussin, Pablo Gutierrez-Marques, Pedro J. Gutiérrez, Carsten Güttler, Nick Hoekzema, Stubbe F. Hviid, Wing Huen Ip, Laurent Jorda, Jörg Knollenberg, Gabor Kovacs, J. Rainer Kramm, Ekkehard Kührt, Michael Küppers, Fiorangela La Forgia, Luisa M. Lara, Monica Lazzarin, Cédric Leyrat, Josè J. Lopez Moreno, Sara Magrin, Simone Marchi, Francesco Marzari, Matteo Massironi, Harald Michalik, Richard Moissl, Stefano Mottola, Giampiero Naletto, Nilda Oklay, Maurizio Pajola, Marco Pertile, Frank Preusker, Lola Sabau, Frank Scholten, Colin Snodgrass, Nicolas Thomas, Cecilia Tubiana, Jean Baptiste Vincent, Klaus Peter Wenzel, Mirco Zaccariotto, and Martin Pätzold. On the nucleus structure and activity of comet 67P/Churyumov-Gerasimenko. *Science*, 347(6220):1–6, 2015.

[68] Robert Sparrow and Mark Howard. Robots in agriculture: prospects, impacts, ethics, and policy. *Precision Agriculture*, (September), 2020.

[69] Martin Stokkeland, Kristian Klausen, and Tor A. Johansen. Autonomous visual navigation of Unmanned Aerial Vehicle for wind turbine inspection. *2015 International Conference on Unmanned Aircraft Systems, ICUAS 2015*, pages 998–1007, 2015.

[70] Hanh Tran. Robotic Single-Port Hernia Surgery. 2011.

[71] Stephan Ulamec, Laurence O'Rourke, Jens Biele, Björn Grieger, Rafael Andrés, Sylvain Lodiot, Pablo Muñoz, Antoine Charpentier, Stefano Mottola, Jörg Knollenberg, Martin Knapmeyer, Ekkehard Kührt, Frank Scholten, Koen Geurts, Michael Maibaum, Cinzia

Fantinati, Oliver Küchemann, Valentina Lommatsch, Cedric Delmas, Eric Jurado, Romain Garmier, and Thierry Martin. Rosetta Lander - Philae: Operations on comet 67P/Churyumov-Gerasimenko, analysis of wake-up activities and final state. *Acta Astronautica*, 137(February):38–43, 2017.

[72] Merel Vergaaij and Colin Mcinnes. Vergaaij , M ., McInnes , C . and Ceriotti , M . (2019) Influence of launcher cost and payload capacity on asteroid mining profitability . Journal of the This is t he author ' s final accepted version . There may be differences between this version and . 72(April):435–444, 2020.

[73] Paul Wady, Alex Wasilewski, Lucy Brock, Ruth Edge, Aliaksandr Baidak, Connor McBride, Laura Leay, Arron Griffiths, and Cristina Vallés. Effect of ionising radiation on the mechanical and structural properties of 3D printed plastics. *Additive Manufacturing*, 31(April 2019):100907, 2020.

[74] Brian Wang. The Next Fifteen Years With SpaceX, Mars and Space — NextBigFuture.com, 2018.

[75] Xingrui Wang, Shane K. Mitchell, Ellen H. Rumley, Philipp Rothemund, and Christoph Keplinger. High-Strain Peano-HASEL Actuators. *Advanced Functional Materials*, 30(7):1–9, 2020.

[76] M Wilkinson, F Spianto, and M Knowles. Towards the zero maintenance wind turbine. *41st International Universities Power Engineering Conference, UPEC 2006, Conference Proceedings*, 1:74–78, 2006.

[77] Ernest Y. Wu, J. Suñé, and W. Lai. On the weibull shape factor of intrinsic breakdown of dielectric films and its accurate experimental determination-Part II: Experimental results and the effects of stress conditions. *IEEE Transactions on Electron Devices*, 49(12):2141–2150, 2002.

[78] Zhigang Suo. THEORY OF DIELECTRIC ELASTOMERS Zhigang Suo * School of Engineering and Applied Sciences, Kavli Institute for Nanobio Science and Technology, Harvard University, Cambridge, MA 02138. *October*, pages 1–55.

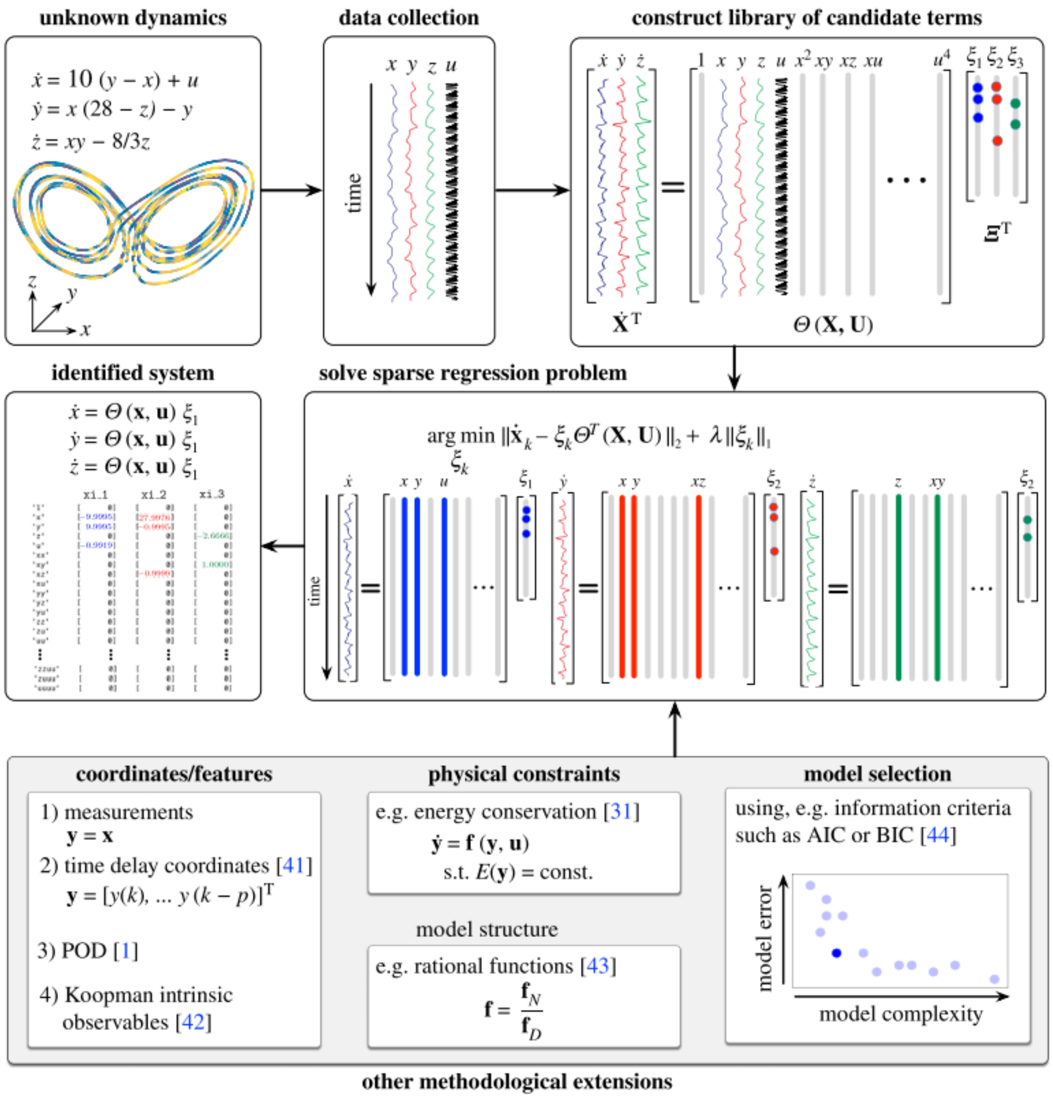

Figure 4: Schematic operation of the SINDyc algorithm on an example Lorentz system [36]. Note that references in the figure are not the same as those in this writing.