Energy-based Approach to Develop Soft Robots

Ho-Tak Derek Chun

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Abstract

Soft robotic systems offer advantages against rigid robot systems in applications that involve physical robot-human interactions, unstructured or extreme environments, and manipulating delicate objects. Soft robots can offer inherently safe operation and adapt to unknown geometry of the environment or object. The current soft robot development approach is an empirical approach starting from a type of soft actuation technology, whereas the development of rigid robots can start from a top-level task in a System Engineering framework. The rigid robot developer can select from well-defined components to construct the task-orientated system. Soft robots are relatively novel systems compared with rigid robots and do not have well-defined components due to a wide range of soft actuation technologies. The initial choice of soft actuation technology places constraints on the system to perform the task. Soft robotic systems are not widely used despite the advantages compared to rigid robots.

In this thesis, I study an abstraction approach to enable a System Engineering framework to develop soft robotic systems. My research focus is on an energy-based approach that encompasses the multi-domain nature of soft robotic systems. The impact on the final system from the energy transfer characteristics of the initial choice of the soft actuator has not been fully explored in the literature. I study how energy, and rate of energy transfer (power), can describe different components of each type of soft actuation and how the total energy can model the top-level system. This thesis includes (i) a literature review of soft robots; (ii) an abstraction approach based on bond-graph theory applied to soft actuation technologies; (iii) a port-Hamiltonian theory to describe the top-level soft robotic system, and (iv) an experimental application of the approach on a type of soft actuation technology.

In summary, I explore how energy and rate of energy transfer can provide the abstraction approach and in time provide the well-defined components necessary for task-orientated design approaches in a System Engineering framework. In particular, I applied the approach to soft pneumatic systems for additional insights relevant to the development of future task-orientated soft robotic systems.

Declaration of Authorship

I, Ho-Tak Derek CHUN, declare that this dissertation titled, 'Energy-based Approach to Develop Soft Robots'is my own original work that is being submitted to Heriot-Watt University, Scotland in partial of the Degree of Doctorate of Science in Robotics and Autonomous Systems. This work is submitted for the first time and has never been submitted to any university or institution of higher learning. My contribution and those of colleagues to collaborative work have been explicitly indicated below. I confirm that appropriate credit has been given within this thesis where reference has been made to the work of others.

The work presented in Ch. 4 on 'Port-Hamiltonian Reformulation to Develop Energy Efficient Soft Pneumatic Actuators", was assisted by Jamie O. Roberts, Mohammed E. Sayed, and Simona Aracri on the experimental preparation. I was responsible for all the experimental and analytical work and the interpretation of the results. I was responsible for all the experimental design and interpretation of the results.

Ho-Tak Derek Chun,
Edinburgh, United Kingdom May 2022

Signed electronically: Derek Chun

Date: 02/05/2022

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I benefited from being a member of the Soft Systems group and thank Mohammed E. Sayed for working with me on interfacing the instrumentation; Jamie Roberts, Ross McKenzie and Simona Aracri for the experiment preparation.

During the course of my PhD, I also had the opportunity to win the John Moyse Lessells Travel Scholarship from the Royal Society of Edinburgh to visit Osaka University, for which I owe my sincere gratitude to Koh Hosoda Sensei for the opportunity. I would like to thank Hayato Inoue for his help in performing the experiment in Japan.

Finally, I must express my very deep appreciation to my wife and son for providing me with enduring support and continuous encouragement throughout my study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

Ho-Tak Derek Chun

Research Thesis Submission

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Chapter 1

Introduction

1.1 Soft robotic systems

Robots are useful machines that enhance our everyday lives. The traditional robots are rigid and made from hard materials like steel, which are hazardous in physical robot-human interaction applications. Soft robotics is an emerging research area, where the soft robot is typically made from soft materials that are comparable to biological tissues and are partially soft or wholly soft [1]. Soft robots open opportunities in physical robot-human interaction applications, where the system can be inherently safe.

The promise of soft robotic systems to enhance our everyday lives has not been fulfilled. The scope of the soft robotic research continued to expand to different actuation technologies across different physical domains with biomimetic or bioinspired control. The application that is synonymous with soft robotic systems is still undefined. The current development approach is focused on the actuator at a component level. The potential performance of the system is constrained by the choice of the actuator. A System Engineering approach enables the top-level requirements to flow from a system-level down into a component level. A rigid robot developer can select from a list of well-defined components based on the requirements to construct a task-orientated system. A system Engineering approach for soft robotic systems will create more task-orientated soft robotic systems and a step towards identifying the application that will be synonymous with soft robots.

Soft robots can perform an array of tasks, such as locomotion, manipulation and grasping. The soft actuation technologies encompass a wide selection of domains from; pneumatic, fluidic, thermal, chemical, electrical, electromagnetic and mechanical. Figure 1.1 shows a montage of different soft robotic systems doing a range of tasks.

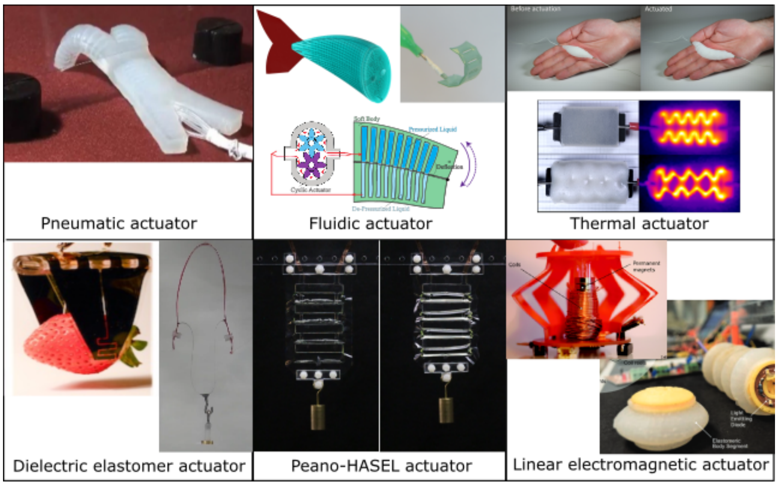

FIGURE 1.1: A range of soft robotic systems covering different soft actuation technologies and tasks. Clockwise from the top left-hand side. Pneumatic actuator example is the Multigait Robot by Shepherd et al. [2], Fluidic actuator examples are Fish robot by Katzschmann et al. [3] and (inset) Thin soft actuator by Mosadegh et al. [4], Thermal actuators by Miriyev et al. [5], Dielectric elastomer actuators (left) Shintake et al. [6], and (right) by [7], Peano-HASEL actuator by Kellaris et al. [8], Electromagnetic actuator by Mckenzie et al. [9] and Wormbot by Nemitz et al. [10].)

Soft robots are machines and are either partially or wholly soft. A machine converts energy from one form into another and eventually into useful work done. The multi-domain nature of soft robotic systems makes analysis complex. Energy is the 'Lingua Franca' of engineering [11]. The law of conservation of energy states that energy can neither be created nor destroyed. The energy only changes from one form to another or transforms from one object to another. The law of conservation of energy lays the foundation of the energy-based approach.

Energy-based approaches already exist through bond-graph theory and port-Hamiltonian approach. In 1962, Henry Paynter invented bond-graph theory to graphically represent the energy transfer through a system [12]. The graphical output looked like bonds connecting elements together from a chemist's point of view. Bond graph theory was extended into the port-Hamiltonian approach in subsequent years [11]. The Hamiltonian denotes the total energy of the system. The total energy of the system is made up of internal and external energy interactions. The 'port' aspect is the power connection port that links the energy interactions. In this thesis, I applied bond graph theory and the port-Hamiltonian approach to soft robotic systems to see how a System Engineering design approach is feasible for soft robotic systems.

The soft robot research community, Robosoft, defined soft robots or devices as 'soft robots/devices that can actively interact with the environment and can undergo large deformations relying on inherent or structural compliance.' [13]. The two defining features are the active interaction with the environment, which is the energy transferred between the robot and the environment and the large deformation, which is the strain energy stored as denoted by the area under the stress-strain curve. The thesis looks at how the two features fit in the energy interactions of the port-Hamiltonian approach and how bond-graph theory can be used to express the essential energy transfer characteristics. The energy-based description is applied to soft robotic systems on a system level and a component level and how the energy-based abstraction enables the transition between the two levels in a Systems Engineering framework to develop task-orientated systems.

1.2 Motivation and problem definition

The last decade has seen the rapid emergence of the field of soft robotics [14]. The inherent softness offers advantages over traditional rigid robots in certain applications. For example, Soft Robotics Inc. [15] demonstrated the suitability of soft robotic systems in the manipulation of delicate objects. However, the everyday physical human-robot application of soft robotic systems is still not widely available. The energy interchange between the human and the robot in physical human-robot interaction provides opportunities to look at the applicability of soft robotic systems in physical human-robot interaction.

This thesis aims to use energy and the rate of energy transferred, power, to bridge the top-level requirements with the component level of the soft actuation technologies. Bond graph theory and port-Hamiltonian theory can be combined into an energy-based approach to describe or reformulate a system in terms of energy. The large deformation and active external interaction with the environment are the two key energy interactions that define soft robotic systems. An energy-based approach can enable System Engineering of soft robotic systems.

Therefore, the soft robot developer can change the question from, 'What the soft actuator can potentially do?' to 'How the task can be performed by a soft robotic system?'. The SE design process provides a top-down approach from a system-level to an component-level and the energy-based approach generalises the different soft actuation technologies. The approach provides additional questions:-

1. What does an energy-based approach to soft robotic system design in a Systems Engineering framework look like?
2. Can we model different soft actuation technologies by energy on a component level?
3. What impacts do the top-level requirements have on the physical design of the soft robot?
4. What are the key energetic characteristics of a soft robotic system?

1.3 Aim and objectives

The aim of this thesis is to outline an energy-based approach to analyse and develop soft robotic systems in a System Engineering framework. The approach consists of theoretical and experimental analysis.

1. The objectives of the theoretical analysis are:
    - to use energy to describe the current soft actuation technologies on a component level;
    - to classify the current soft actuation technologies in terms of energy and energy transfer characteristics;
    - to understand how requirements expressed in energy will affect the design at a system level.
2. The objectives of the experimental analysis are:
    - to define an approach to apply port-Hamiltonian theory in an experimental approach;
    - to develop an approach to inform design and development from a system-level independent of the component level;

The design criteria in meeting these objectives are:

1. the abstraction approach should be readily applicable to every type of soft actuation technologies;
2. the approach should conform to a System Engineering framework to enable a top-level requirement to be flown down into a component level;
3. the energy-based approach should be based on energy transferred or rate of energy transferred (power).

Soft robots are an emerging area of research. I hope to encourage further advances by approaching the development from a system level where the research community can reduce the gap between the current technologies and the system requirements to foster future task-orientated soft robotic systems.

1.4 Publications

The original work presented in the thesis has led to one journal publication and one conference contribution.

- **H.-T. D. Chun**, Taylor, N.K. and Stokes, A.A., “Energy-Based Abstraction for Soft Robotic System Development”. Advanced Intelligent Systems, 2021, p.2000264.

Peer-reviewed conference publication

- **H.-T. D. Chun**, J. O. Roberts, M. E. Sayed, S. Aracri, and A. A. Stokes,“Towards more Energy Efficient Pneumatic Soft Actuators using a Port-Hamiltonian Approach” in 2019 2nd IEEE International Conference on Soft Robotics (RoboSoft), Seoul, Korea (South), 2019, pp. 277–282.

The following publications resulted during the duration of the studies.

- Erden, M.S. ; **H.-T. D. Chun,** “Muscle Activity Patterns Change with Skill Acquisition for Minimally Invasive Surgery: A Pilot Study” - 2018 7th IEEE International Conference on Biomedical, IEEE, 960-965.
- Mahon, S.T.; Roberts, J.O.; Sayed, M.E.; **Chun, D.H.-T**.; Aracri, S.; McKenzie, R.M.; Nemitz, M.P. and Stokes, A.A. “Capability by Stacking: The Current Design Heuristic for Soft Robots”. Biomimetics 2018, 3, 16.

During the course of my doctoral studies, I was awarded a travel scholarship.

Travel scholarship

- John Moyes Travel Scholarship (£3750) on *Port-Hamiltonian reformulation of pneumatic muscle-like soft actuation* at Adaptive Robotics Laboratory, Osaka University, Japan, by the Royal Society of Edinburgh.

1.5 Outline of the thesis

This thesis is arranged into two sections. The first section outlines an energy-based approach formed by applying bond-graph theory into a range of soft actuation technologies and reformulating in a port-Hamiltonian approach. The second section describes the application of the energy-based approach on a soft pneumatic actuator and adding the energy input and interaction with the environment to the actuator and analysis the system. The thesis consists of five chapters in addition to the present introductory chapter; a chapter on literature review; a chapter on the energy-based approach abstraction; an experiment design and material chapter; a chapter on the results and discussions; and a concluding chapter.

- **Chapter** 2 is a literature review on the underlying concepts used in the thesis, including soft actuation technologies, System Engineering principles, bond-graph theory and the port-Hamiltonian approach.
- **Chapter** 3 presents the energy-based bond-graph representations of different soft actuation technologies to identify the essential energy transfer characteristics in a generic soft robotic system.
- **Chapter** 4 describes the experimental design, methods and materials to apply port-Hamiltonian theory to a closed thermodynamic soft pneumatic actuator system.
- **Chapter** 5 shows the results from the experiment and discuss the formation of the energy-based approach in a System Engineering framework.
- **Chapter** 6 is the concluding chapter which summarises the thesis and discuss the potential impact and limitations of the work on soft robotics research and beyond.

Chapter 2

Literature review

2.1 Introduction

In this chapter, I introduce the background information and literature review of soft robotics systems and the key theories applied in the thesis. In Sec. 2.2, I introduce rigid and soft robotic systems. I give examples of the wide range of soft actuation technologies in Sec. 2.3. In Sec. 2.4, I describe the key principles from System Engineering and reviewed the Vee-Model on the system and component levels. I introduce the bond-graph theory and port-Hamiltonian theory in Sec. 2.5.1 and Sec. 2.6 respectively, which forms the energy-based abstraction approach. In Sec. 2.7, I review how the energy transfer is controlled through examples of soft robotic systems.

The chapter concludes with a summary section, which describes the key aspects that forms the basis of the energy-based approach. The first step is to apply bond-graph theory to represent each soft actuation technologies in terms of energy and rate of energy transfer on a component level, to identify the key energy transfer characteristics. A next step is an experimental approach based on port-Hamiltonian theory to identify design factors that impact the energy transfer characteristics at a system level. The third step is to evaluate whether the energy-based development approach fulfils the key features of the System Engineering framework.

2.2 Rigid and soft robotic systems

2.2.1 Rigid robots as machines in industrial environments

The first significant application of modern robotics stemmed from an industrial setting where the manufacturing tasks are divided into smaller and simpler repetitive tasks. Robots can perform more efficiently or safely compared to workers. These robots were essentially machines that converted energy from one form into useful work done in the mechanical domain and completed the tasks. Davol invented the Unimate robot in 1961, which was regarded as the first industrial robot [16]. The traditional characteristics of rigid robotics were evident on the Unimate robot. Rigid robots were typically made from hard materials, like steel compared to the human body, controlled using inverse kinematics [17], and optimised for a single repetitive task. Rigid robots were widely used in highly repetitive applications within a structured environment. The rigid body assumption for deterministic positioning by the kinematics is capable of performing accurate assembly tasks in factories. The location and orientation of the objects were fixed for the rigid manipulator to interact with them efficiently.

The rigidity in the robots becomes a disadvantage in many applications. Safety becomes an issue when the robots are interacting with an unknown environment. The hard material, typically steel, makes the robot dangerous in physical robot-human interaction. Rigid robots with significant power output are isolated in rooms or cages or behind safety barriers. The hard material on the end of the manipulator cannot grasp soft objects, like tomatoes, without damage. Rigid robots are optimised for repetitive tasks and lack the adaptability required in unstructured environments. The characteristics of rigid robotic systems present challenges in developing robots that can physically enhance our everyday lives, where the environment is often unknown and safety becomes an important design consideration.

2.2.2 What are soft robotic systems?

Soft robotic systems are a different class of robots compared to rigid robotic systems. A soft robot is constructed in part or wholly of soft material and the actuation results in a large deformation of the soft material. The softness of the material is based on comparison with biological materials, such as muscle tissues. The rigid body assumptions and kinematics are no longer valid. The soft robot can deform according to the shape of the object or environment and adapt to the unknown surface. As a result, soft robotic systems can be more adaptive and safer than rigid systems.

The definition of soft robotic systems by the soft robot research community, RoboSoft, is 'Robots/devices that can actively interact with the environment and can undergo large deformations relying on inherent or structural compliance' [13]. Rus and Tolley used Young's Modulus to indicate the softness, which is typically less than 1GPa and is significantly less than the Young's Modulus of steel (from 190 to 215GPa) [1]. The low Young's Modulus dictates a large strain as a result of a given load compared to a high modulus. The energy stored and the energy transferred to do work or interact with the environment will relate to the softness of the robot.

2.2.3 Soft robotic applications

Soft robotics are commonly used in locomotion and manipulation [18, 19]. Exo-suits and assistive devices are a promising area for physical human-robot applications. The amount of assistance from is soft exo-suit is low compared to a rigid exoskeleton system. The technology readiness level is still far away from applications which may lead to direct physical interaction.

A number of high profile applications are described in this paragraph. The Multigait soft robot demonstrated different locomotion gaits and moved through smaller openings with large deformation of the body [2], as shown in the montage in Fig. 1.1. Soft robot systems can also be bio-inspired and bio-mimetic. Soft muscle-like actuators can replicate bio-inspired antagonistic muscle systems [20] for research in the human muscular-skeleton system, and robot fish for ocean observation applications [3]. Ijspeert et al. created a salamander robot that can swim in water and walk on land based on a flexible soft spine [21]. The softness of the material can be matched with the object for safe physical human-robot interaction, for example in assistive devices for comfort [22]. Wehner et al. [23] created a soft exo-suit for gait assistance. Soft Robotics Inc. applied a pneumatic manipulator at the end of a rigid robot arm in a commercial setting, which revolutionised the grasping industry. The soft manipulator can grasp soft items at high speeds and is widely applied in the food industry [15].

There is another class of soft robotics that has a compliant or soft component in between the actuator and the end effector, classed as series elastic actuators [25]. These systems are similar to rigid robotics systems as they rely on rotary motors to provide the angular torque and rotation to actuate the joints. The elastic component can be made from soft materials, but the rest of the system is similar to a rigid robotic system. These robots commonly use electromagnetic actuators which will be discussed in Section 2.3.5.

Collaboration robots (Cobots) are robots that designed to work closely with human operators [26]. Cobots are readily re-programmable by the operators with many safety

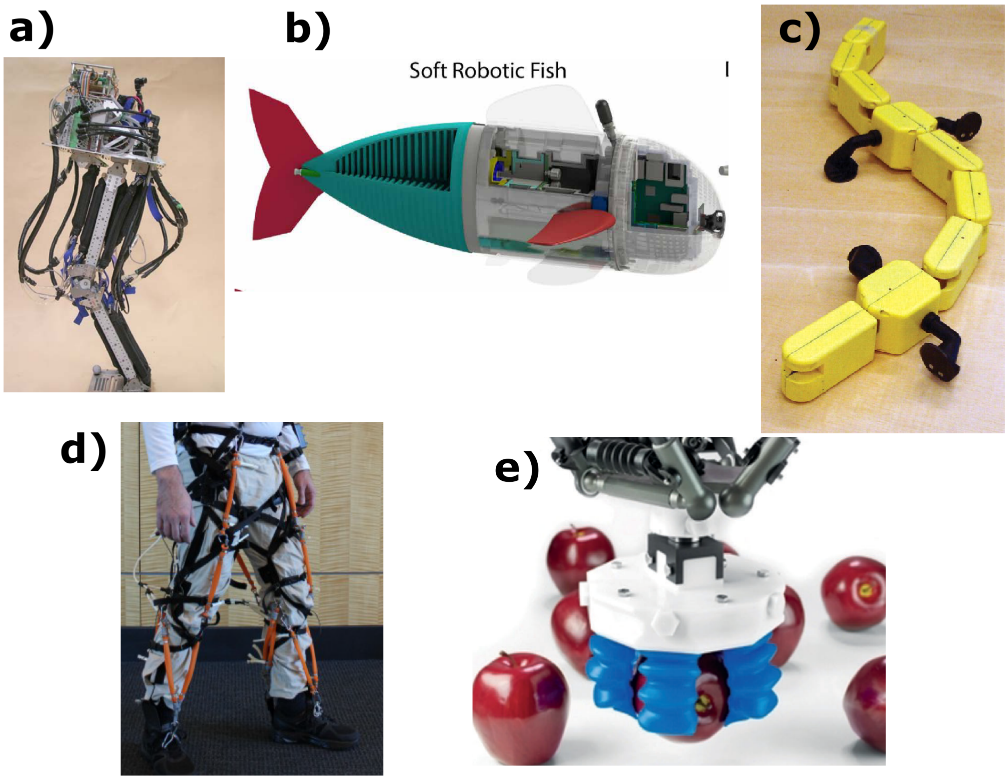

FIGURE 2.1: Examples of soft robots: a) A jumping robot with an anthropomorphic muscular skeleton structure [20], b) fish robot[3], c) salamander robot [24], d) An exosuit [23] and e) a soft gripper [15].

features integrated. The power transferred tends to be low compared to rigid robotics. Series elastic actuators are typically used in Cobots and the safety features are additional sensors, switches, and a reduced power output. Soft robots are inherently safe due to the softness of the body limiting the power transferred from robot to human. Soft robots can potentially have less sensors and switches than Cobots, which simplifies the system.

2.3 Current soft robot technologies

Soft robotics research is an emerging field and different actuation technologies are explored [1]. The wide range of actuation domains opens up the design space to different types of energy storage and transformation characteristics into the mechanical domain for active interaction with the environment. I discuss the principles of how each actuation technology works and present examples from the literature and how the energy transfer characteristics may differ. The method of energy entering the system in actuation and leaving the system for the next cycle provides insight in the energy transfer characteristics of the system.

2.3.1 Pneumatic and fluidic actuation

Pneumatic actuation relies on a pressure difference to the ambient conditions to induce a force on the walls of the chamber [27]. The walls are made of soft materials, which deform elastically, or hyper-elastically. The direction of the force is controlled by the geometry of the chamber and strain limiting layers in certain parts of the chamber. Positive or negative pressure differences are used in actuation. Fluidic actuation replaces the gas or air in the chamber with a liquid. The density, expansion and flow-rate characteristics are different between liquids and gases. The liquid fluidic actuation is typically in a closed system [28].

As previously mentioned, the Multigait robot is capable of locomotion and the deformation of the pneumatic chamber acts as a hinge, without mechanical joints or bearing, which simplified the mechanical design. Mosadegh et al. created a rapid actuation finger [29], through modifying the geometry as shown in Fig. 2.2. Agarwal et al. used a vacuum to actuate a pneumatic spine [30]. Killpack et al. used chambers made of in-expandable film to induce pressure build-up in a multiple chamber arrangement [31]. The deformation, geometry, pressure difference, and material properties are the key design aspects of pneumatic soft actuators.

The Soft Fish by the Massachusetts Institute of Technology uses hydraulic actuation in a closed system to actuate a soft elastomeric tail [3] as shown in Fig. 2.1 (b). A gear pump is required to displace the fluid from one side to another. McKibben actuators are biological muscle-like pneumatic actuators made of rubber tubing and nylon mesh shells and the actuator contracts as the pressure increase [32]. A high pressure compressor provides the source of energy and a separate valve vents the energy to the atmosphere similar to the example shown in Fig.2.1 (a).

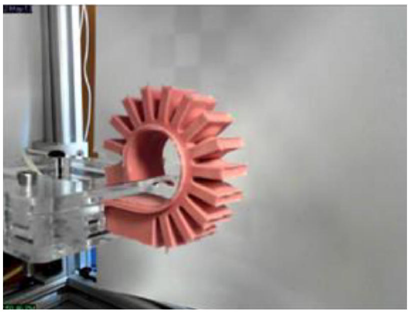

FIGURE 2.2: A pneumatic network that actuates rapidly [29] is an inspiration for this thesis. There are key design features such as wall thicknesses, and materials selection to experiment on to investigate the impact on energy transfer.

The pressure difference between the high pressure source and the atmosphere moves the air or fluid in and out of the system. The energy is dissipated into the atmosphere after each actuation cycle, which will impact the overall efficiency. Therefore a key design feature can be how the air or fluid can be displaced without relying on the high pressure source and the ambient pressure. The high pressure source determines the rate and the magnitude of the energy entering and pressurising the system. The energy leaves the system via the vent to the atmosphere and returns the system pressure to ambient pressure. The high pressure source are controllable for dynamic applications. However, the ambient conditions are difficult to control. A pressure chamber can be used to control the ambient pressure but the utility of the robot will be in the chamber [33].

2.3.2 Chemical actuation

Chemical reactions can be used to induce swelling, temperature change, production of gases, or electrolysis reactions to actuate. Dicker et al. showed a plant-inspired actuator controlled by light [34]. Shepherd et al. and Loefe et al. used combustion to induce a rapid increase of pressure and made jumping robots [35, 36]. Wehner et al. used hydrogen peroxide decomposition in the Octobot [37] as shown in Fig. 2.3 (a). Suzumori used electrolysis of water to make untethered pneumatic actuators [38]. Maeda et al. applied a reversible chemical reactions in a hydro-gel locomotion on a rachet floor [39] as shown in Fig. 2.3 (b). The reversible reaction oscillates between multiple states. Electrical batteries are not discussed because batteries have already demonstrated as an efficient energy source for rigid and soft robotic systems.

Chemical reactions provide novel actuation methods but there are drawbacks. Light-activated reactions are typically slow and unsuitable for dynamic applications. Combustion is difficult to control and the products of the reaction must leave the chamber for the reagents of the next cycle. Hydrogen peroxide decomposition is highly exothermic and difficult to modulate. Electrolysis of water enables the reversible reaction of electricity

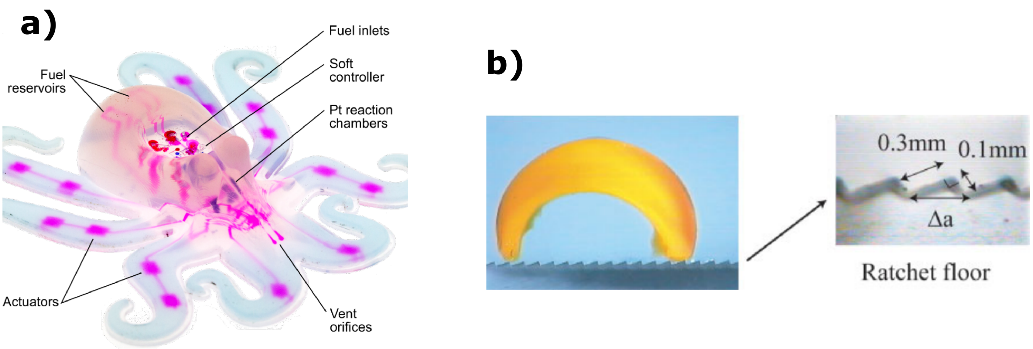

FIGURE 2.3: a) The Octobot [37]. b) The hydro-gel reversible reaction for locomotion application [39]. Two examples of fully soft and untethered robots. However, the energy transferred to the environment is limited in terms of the potential to do work. The motion is controlled by a fluidic oscillator for Octobot, and a reversible reaction for the hydrogel.

between oxygen and hydrogen. The practical aspect of performing useful work done from reversible chemical reactions is not obvious when the chemical potential is similar between the two states. The energy source and energy sink are not clear compared to the hydrogen peroxide decomposition as an example, where energy is clearly released from the hydrogen peroxide reagent.

Energy is stored in the chemical potential of the reactants. Activation energy is required to start the reaction. The reaction rate will influence the dynamics of the system. The gaseous state of the products adds a pneumatic domain to the system. The rate of reaction, such as the rate of combustion or rate of hydrogen peroxide decomposition, is often difficult to control for a stable design as shown by the iterative development of hundreds of Octobot prototypes [37]. The Octobot example shows that the chemical domain is often combined with the fluidic domain for transport the chemicals.

2.3.3 Thermal actuation

Thermal actuation relies on thermal heating and cooling to actuate. Electrical Joule heating is a common approach to provide thermal energy into the actuator. The heat must dissipate after each cycle. The rate of actuation is determined by the heating and dissipation rates, which are influenced by the thermal properties of the materials, the temperature of the heat source and the ambient conditions. The rate of heating may differ from the rate of cooling which will make the dynamics more difficult to control.

Seok et al. used nickel-titanium shape memory alloy to construct the wireframe of the Meshworm [40]. The heating and cooling of different sections along the body enable the worm to undergo peristaltic locomotion. Miriyev et al. created a composite material that combines the elasticity of the material and the large volume expansion from the phase change of liquid to a gaseous state [5]. The composite material is shaped into a range of different geometries, however, the actuation response time is measured in minutes, which is unsuitable for everyday applications.

The limitation of thermal actuation is due to the lack of inductive energy carrier compared to other domains such as pneumatic, fluidic and electrical domains, which is further explained in Sec. 3.3.2. Therefore dynamic applications will be difficult to control as the heat transfer co-efficient of the material and the ambient conditions will determine the rate of energy entering and dissipating the system.

2.3.4 Di-electric actuation

Di-electric actuators are a type of soft actuators that uses electrostatic forces to deform a dielectric elastomer. Electrostatic DEA is used in locomotion [41], grasping [42], and the Peano-HASEL actuator is an example of manipulation [8] as shown in Fig. 1.1 and Fig. 2.4 a. The actuator converts the electrical energy into mechanical work and behaves like a capacitor. The capacitance is a function of the dielectric characteristics of the elastomer and the variables are the permittivity, dielectric strength, the electrode area, and distance between the electrodes [43]. The distance between the electrodes means the characteristics between compression and extension are likely to be different. Harvest energy from the external environment can improve the efficiency of the overall system [44].

Cacucciolo et al. used a dielectric fluid to create a stretchable pump by charge-injection electrohydrodynamics (EHD) [45] as shown in Fig. 2.4 b. A fluidic actuator can be connected to the pump for actuation. The 4.5 kV step input results in a current of 20 μA at 3 kPa. The flow rate at 3 kPa is near 0 $\mu L\, s^{-1}$. Therefore the conversion from electrical power is not high when compared to a TCS MG1000S micro gear liquid pump of about 25% conversion from electrical power to pneumatic power. The electrical energy stays in the capacitance of the dielectric fluid, which limits the energy transduction through the system.

The DEA acts like a capacitor and the conversion from electrical energy to mechanical energy is not high when compared to an electromagnetic actuator. The electrical energy is stored as capacitive energy [46] and [7]. The capacitive charge and discharge characteristics will provide different dynamics when turning on or off. These features will provide challenges in designing dynamic systems with DEA.

Polymer actuators [47, 48] and piezoelectric actuators [49] are other examples that require a high input voltage to induce a deformation. These examples used bond-graph theory to model the actuators respectively. The piezoelectric actuator example showed how the abstracted model of the actuator interacts with the overall system. The experimental data validated the bond-graph model and demonstrated the effectiveness of bond-graph abstraction at both the system level and component level [49]. The piezoelectric actuator showed the potential of using an energy-based approach to describe the actuation, which leads to the question if there is an application or task that a soft robot designer will select piezoelectric actuator compared to other soft actuation technologies based on the energy transfer characteristics as shown by the bond-graph representation.

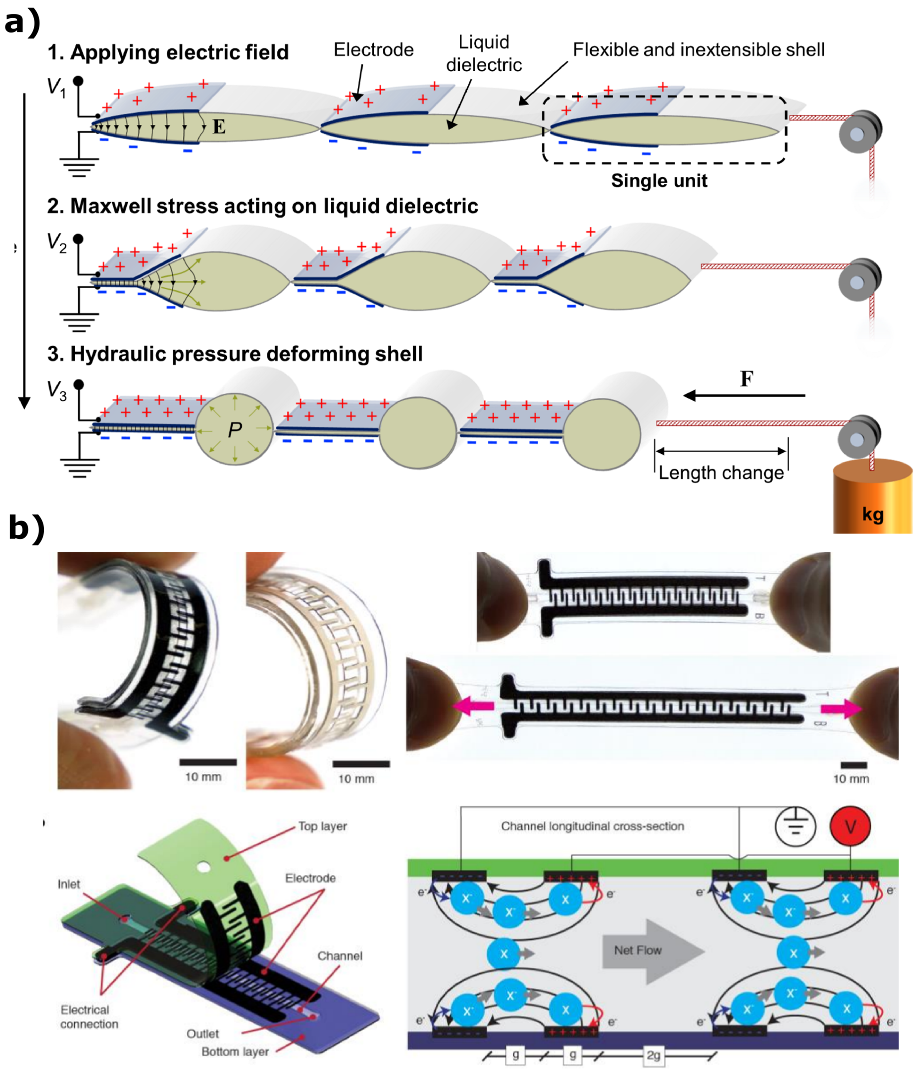

FIGURE 2.4: a) The Peano-HASEL actuator [8] shows an electrical domain and the addition of the fluidic domain to improve the performance of the dielectric actuation. b) The Stretchable pump is an interesting actuator because a high voltage is able to induce a flow rate of a fluid. The nature of the energy transformation very different where a voltage is transformed into a fluid flow whereas typically dielectric actuators transform a voltage into a force.

2.3.5 Electromagnetic actuation

There are examples of soft actuation with the electromagnetic domain. An electrical current in a coil induces an electromagnetic force. The Wormbot and Linbot use an array of modular linear electromagnetic actuators for locomotion through a range of peristaltic wave motions [9, 10] as shown in Fig. 1.1 and the Linbot in additional shown in 2.5 (a). The main components of an electromagnetic actuator are the electrical coils, a permanent magnet and an elastomer. The electrical current in the coils and the magnet induce the actuation force. The elastomer provides the restoration force and the soft characteristics. Yamada et al. [50] connected a servo motor to an elastic strip to make a closed elastic actuator. The motor winds up the elastic strip into an unstable state and triggers an impulse motion, as shown in Fig. 2.5 (b). The elastic strip stores the power from the motor as elastic mechanical energy.

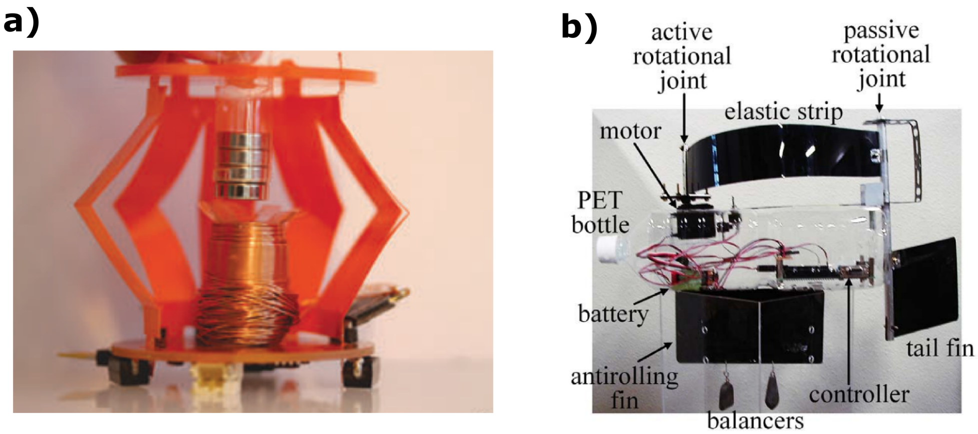

FIGURE 2.5: a) The Linbot with the elastic kirigami structure and b) The closed elastic actuator with an elastic strip at an energised state from energy input from the motor.

Rotary electromagnetic actuators (motors), normally associated with rigid robotic systems, are used in a soft robotic system context [51], as briefly mentioned in 2.2.3 and commonly used in collaboration robots (cobots). Soft characteristics can be achieved with rigid components by various designs, for example, series elastic actuators with temporary capacitive energy storage in series [52], variable stiffness actuators with a separate energy path to control the stiffness [53], or an antagonistic approach with two parallel energy paths from source to sink [54]. The important aspect of the energy transfer is that another energy path exists that can divert the energy away from the user and improves the safety of the cobot.

2.3.6 Hybrid domains actuation

The addition of a fluidic domain with a DEA creates additional design considerations. Kellaris et al. [8] inserted a pocket of di-electric fluid between the electrodes and created the Peano-HASEL actuator as introduced in Sec. 2.3.4. The volume of the closed pocket is reduced when actuated. The resultant pressure build-up exerts a force. The use of dielectric fluid reduces viscous losses and increases the response speed. The mechanical properties of the elastomer are replaced by the pocket of fluid.

Li et al. used di-electric elastomer to induce giant deformations [55]. The compression of the dielectric elastomer changes the system properties. A fixed amount of air is pressurised in the chamber. A voltage is applied to the membrane of the balloon and causes hyper-elastic expansion of the balloon. The total energy of the system is stored within the chamber. The potential work done on the external environment is from the stored pneumatic energy.

Recent soft actuation technologies begin to combine different domains into novel actuators. Aubin et al. combined chemical, electrical, and fluidic domains with a pump and chemical electrolyte. The electrolyte acted as a working fluid and chemical potential energy store [56]. Yoshimura et al. used the Belousov–Zhabotinsky (BZ) reversible reaction to combine the chemical domain with the fluid domain to make a reciprocating machine [57]. Cacucciolo et al. combined electrical and fluidic domain through conduction electrohydrodynamics [45, 58]. The additional combination of a fluidic domain enable recent innovative approach to soft actuation. The energy can be stored in a pressure build-up or in kinetic energy through the dynamic flow of the fluid.

2.4 System Engineering framework

System Engineering (SE) is a disciplined approach to create a system [59]. The combination of technical and commercial multi-disciplinary approach covers the entire life-cycle of a system. This thesis focuses on the technical aspects of the system design part of the approach. The commercial aspects and life-cycle management are out of scope. The technical aspects of design describe how the customer's needs are translated into technical requirements and how the design can be synthesised and validated. The NASA Systems Engineering Handbook provide a version of SE as it should be applied [60]. The terminologies used in the thesis are adapted from the NASA System Engineering handbook.

An abstracted search and rescue scenario is illustrated in Fig. 2.6. The robot in the scenario must be able to gain potential gravitational energy and kinetic energy. The robot should be un-tethered and must be able to carry all the energy required to perform the tasks. The robot must stop at rest and dissipate all the kinetic energy or transformed it into a different form of energy storage. The next section will introduce the NASA Systems Engineering Handbook, which will highlight the key features that an energy-based approach should cover.

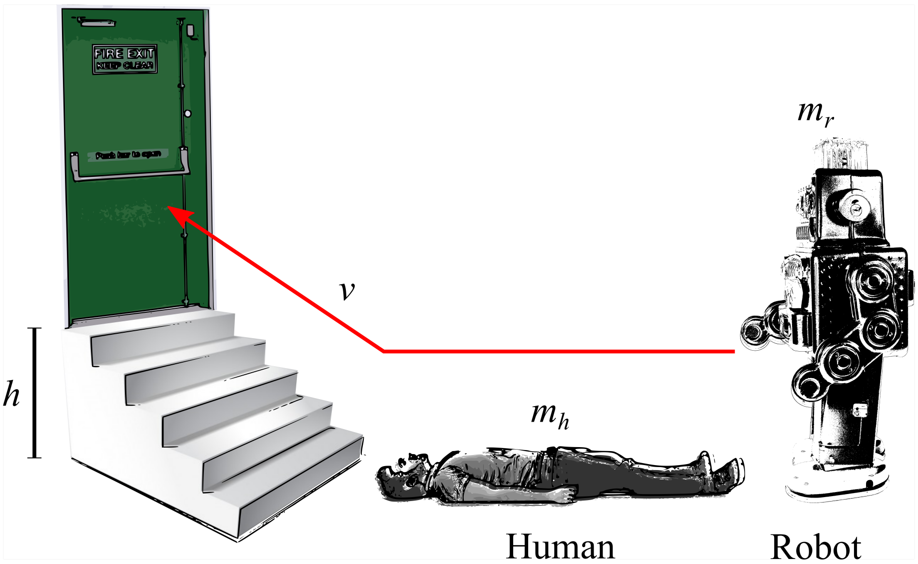

FIGURE 2.6: The scenario shows a robot looking to evacuate a person in a timely manner. The robot must move and stop (gain and lose in kinetic energy from and to another form). The robot must also pick up a person, which is again in gravitational potential energy. The precise nature of navigating the stairs in a stable manner is not investigated here.

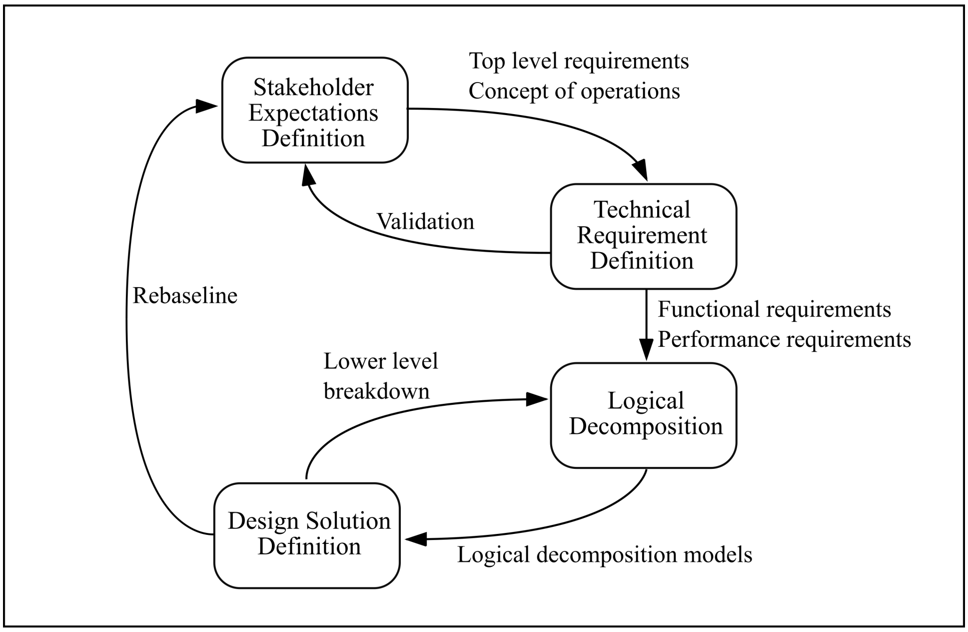

FIGURE 2.7: A simplified systems design process with terminology from NASA Systems Engineering Handbook

2.4.1 NASA Systems Engineering handbook

NASA has an excellent track record in the delivery of high profile projects, such as winning the Space Race to the Moon. The systems design process is made out of multiple iterative loops. Fig. 2.7 shows a simplified system design process based on the NASA SE handbook and highlights the frequent information feedback in system engineering as noted by Blanchard [59].

The initial starting point is the stakeholder expectations definition, where a set of top-level requirements and concepts of operations are agreed upon with the stakeholders. The technical requirement definition provides validation to the top-level requirements and concepts of operations. The output of the technical requirement definition is functional and performance requirements. Functional requirements meet the system's goals and objectives with the question,"what the system/subsystem shall do" Specifications and performance margins are defined with the question, "how well does each function perform?". The validation will assess if each requirement is realistic or tolerances are overly tight. There are other requirements, such as interfaces, maintainability, reliability, verify-ability, and test-ability. Physical human-robot interaction defines a mechanical interface with the environment. There are further requirements relating to the latter part of the life-cycle and are out of scope in this thesis, such as maintainability, and end-of-life activities.

The logical decomposition process defines a range of logical decomposition models to address the technical requirements. The system architecture breakdown into subsystems and into major components is a common logical decomposition approach to a system [61]. The behavioural breakdown is another approach that can lead to more complex systems as outlined by Mahon et al. [62]. The design alternatives are generated in the design solution definition process. The best design alternatives can be selected based on the suitability of the logical decomposition models. The design solution can be unrealistic and will require the stakeholders to re-baseline the initial expectations. A lower level of breakdown of the logical decomposition model is required to assess the design alternatives. The approval to proceed to implementation is based on the existence of the technology or whether new technology development is required.

2.4.2 Top-down development for soft robotic systems

The 'Vee-model' development process [63], as shown in Fig. 2.8 b, provides another view of the iterative cycle between the logical decomposition process and the design solution definition. The requirement is partitioned through a logical decomposition process into a component level and the design solution is integrated from a component level. An abstraction or logical decomposition model is required to enable the designer to select the most suitable actuation technology to integrate into the system. At each abstraction level, feedback between the requirements partition and system integration ensures the final system fulfil the requirements. Boehm described the importance of validation at the upper part and verification at the lower part of the V-model to identify issues early in the development cycle [64].

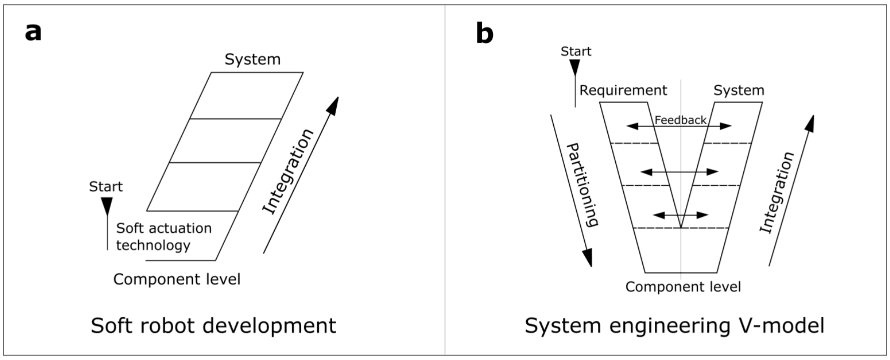

Figure 2.8: a) shows a soft robot which starts from a type of actuation at the component level. b) shows a Vee-Model where the top-level requirement is partitioned down to the component-level and integrated back to a system-level, with feedback ensuring the final system matches the initial requirement.

2.4.3 Top-level requirements of soft robots

The top-level requirements are task-dependent and may have infinite variations. The current soft robotic systems show a range of top-level requirements, which can be described by energy transfer or power. The Resilient Robot demonstrates an untethered application [65], which requires a large onboard energy store. The Octobot is made of fully soft materials [23] however the mechanical energy transferred is low and the Octobot is capable to move each leg. The salamander inspired robot is able to transition between land and water locomotion [21], the energy interaction with the environment and the robot response varies on land and in water. SoFi, the soft fish robot, that can swim in water [3] and has an efficient thermodynamically closed system. Assistive device physically interacts with humans [23] and provide assistance to the user. These examples shows that the top-level requirements can be generalised into kinetic energy in motion, or in a gain of potential energy in lifting a leg. The top-level requirement can be potentially described by energy transfers.

The definition of the soft robotic system and the example of Octobot defined five energy-based abstractions: (1) an energy store which contains the energy input in the system; (2) how the energy enters the system; (3) the transformation from one form into the mechanical domain; (4) the large mechanical deformation, which is a key feature of soft robotics system and stores mechanical energy; and (5) an active energy transfer with the environment. The interaction with the environment is more evident with the bio-inspired locomotion robots such as the MIT Cheetah [40] shows the interaction with the environment, where the minimum cost of transport approaches those of animals [66]. Tucker observed that aquatic locomotion is more efficient and coincident with soft aquatic robots applications [3, 56], which operates in water efficiently. Calisti et al. described a wide range of locomotion modes powered by soft actuation technologies [18]. Soft robotic systems are widely use in locomotion and this paragraph shown that the top-level requirement can be partitioned into five energy interactions.

2.5 Energy-based abstraction approach

Bond-graph theory [12] can be used to build a graphical representation of how the energy flows through a system. Bond-graph theory is a multi-domain approach, which is applicable to different types of soft actuation technologies. The thesis will apply bond-graph theory to current soft actuation technologies to gain an insight into how bond-graph elements can represent each actuation technology. Port-Hamiltonian theory can provide the reformulation of the system into key energy interaction subsystems to verify against the design requirements. The energy-based decomposition can be represented by a port-Hamiltonian structure with key internal and external interactions. The temporary energy storage and dissipation are the internal interactions. The input control actions (energy-in) and interactions with the environment (work done on the environment) are the external interactions.

The next two sections will introduce the bond-graph theory and the port-Hamiltonian approach respectively to combined in an energy-based approach to soft robot development.

2.5.1 Bond-graph theory introduction

Bond-graph theory was devised by Professor H. Paynter in the 1960s at MIT [12]. Bond-graph theory defines that a dynamic system is composed of subsystems, components, or basic elements that interact by exchanging energy through interconnecting power bonds. The bond-graph representation is made of bond-graph elements. The bond-graph elements model the transfer of energy between system components. The graphical nature of bond-graphs provides the visualisation of essential characteristics of a system. A system boundary defines the system of interests and models the energy interactions within. The designing and analyzing the structure of the system can be done with a pencil and paper [67]. Ross et al. applied the word bond-graph to describe two different soft robotic systems [68]. The word bond-graphs uses English words to describe how the energy transferred through the overall system and highlights the major subsystem, which is limits the insight. The bond-graph elements provide additional insight When compared to word bond-graphs to show the essential energy transfer characteristics of the system. The essential energy transfer characteristics form the high-level abstraction that is independent of the actuation technology.

This thesis extends the work of Ross et al. with bond-graph elements and port-Hamiltonian reformulation. The bond-graph elements highlights the essential energy transfer characteristics of different soft actuation technologies. The soft robot designer can make an informed design choice to select the most suitable actuation technology for a given application or identify the technological performance gap between the soft actuation technology and the desired requirements.

Bond-graph theory is based on bonds similar to the chemical bonds between two elements. Each bond represents a power connection between two elements as shown in Fig. 2.9. The half arrow denotes the direction of positive power and the power is carried through the product of two variables, effort and flow, examples are described in Table 2.1. The effort and flow variables are denoted by e and f respectively. The effort and flow variable are classified as power variables and the product of the two variables is power [69].

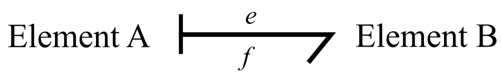

FIGURE 2.9: A bond denoting positive power from element A to element B

Two additional physical quantities are introduced. Generalised momentum, p, and generalised displacement, q, are obtained by the integration of the power variables with respect to time. The generalised momentum is the time integral of the effort variable and the generalised displacement is the time integral of the flow variable. For example, the generalised displacement is the time integral of the velocity flow variable in the mechanical domain and charge is the time integral of the current in the electrical domain. The generalised momentum and displacement are classified as energy variables since they quantify the energy transferred over a time period and accumulated in ideal stores.

2.5.2 Bond-graph elements

The tetrahedron of states [12] shows the time integral relationship between the power and energy variables and the three modelling elements. C-elements and I-elements are ideal energy stores. R-elements are dissipators that convert energy irreversibly into heat. The relationships between the power variables and the modelling elements can be summarised in the tetrahedron of states as shown in Fig. 2.10

The symbols C and I denote the two types of energy stores which are the C-elements and I-elements respectively. The C-element relates the effort variable of the power port to the generalised displacement q. The I-element relates the flow variable, f, of the power port to generalised momentum, p. C-element is the capacitive energy storage where I-element is the inductive energy storage. The symbol R denotes the R-elements, which account for the irreversible conversion into heat. A list of effort, flow, generalised momentum and

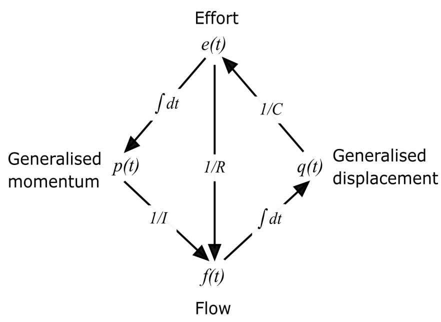

FIGURE 2.10: The tetrahedron of states shows the relationship between the effort and flow variables and the modelling elements.

Energy domain	Effort e	Flow f	Generalised momentum p	Generalised displacement q	R-element R	I-element I	C-element C
Translational mechanics	Force F [N]	Velocity v [m/s]	Momentum p [Ns]	Displacement x [m]	Damping constant b [N·s/m]	Mass m [kg]	Inverse of the spring constant $1/k$ [m/N]
Rotational mechanics	Torque T [Nm]	Angular Velocity ω [rad/s]	Anglular Momentum b [Nms]	Angular Displacement x [rad]	Damping constant b [N s/rad]	Inertia I [Kgm^2]	Inverse of the spring constant $1/k$ [rad/N]
Electro-	Voltage u [V]	Current i [A]	Linkage flux λ [Vs]	Charge q [C]	Resistance R [Ω]	Inductance L [H]	Capacitance C [F]
magnetic	Magnetomotive force V [A]	Magnetic flux rate $\dot{\Phi}$ [Wb/s]	-	Magnetic flux Φ [Wb]	-	-	-
Pneumatic / fluidic	Pressure P [Pa]	Volume flow Q [m^3/s]	Fluidic momentum P_p [Pa·s]	Volume V [m^3]	Fluid resistance R_f [Pa·s/m^3]	Fluid inductance I_f [Pa·s^2/m^3]	Storage C_f [m^3/Pa]
Thermal domain	Temperature T [K]	Entropy flow $\dot{S}$ [J/K/s]	-	Entropy S [J/K]	Thermal resistance R_{th} [K^{2}s/J]	-	Thermal mass C_{th} [J/K^2]

TABLE 2.1: The common variables seen in soft robotic system. Some variables are readily measure-able such as pressure, some variables measure may affect the system, such as flow rate, and some variables are not readily measurable, such as entropy flow.

displacement, and modelling elements used in soft actuation technologies are in Table 2.1.

The sources, junctions, and transformation elements are introduced in the following paragraphs. The bond-graph symbols are denoted in brackets. The following information is based on the textbook by Borutzky [69], to prepare the reader for the bond-graph theory applied in this thesis. A generic schematic of how bond-graph bonds and elements are connected together is shown in Fig. 2.11

The bond-graph elements describe the energy transfer through the system. The energy sources deliver energy into a system. The energy sinks are negative energy sources and

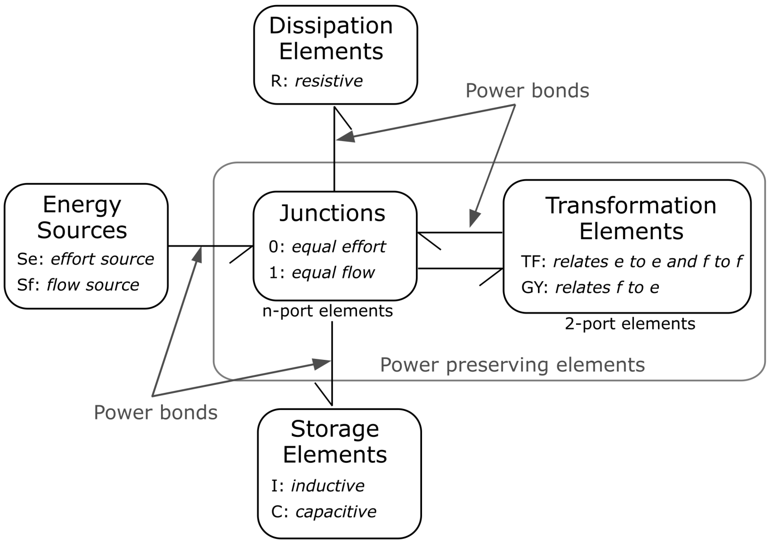

FIGURE 2.11: A schematic that shows how bond-graph elements and bonds are connected to each other. These are the single bond elements (sources and modelling elements), 2-port elements (transformation elements) and n-port junctions. The junctions and transformation elements are power continuous and do not store energy. Additional bond-graph element information added to schematic in textbook by Borutzky [69].

account for the energy flowing out of the system. The sources and sinks represent the boundary conditions of a system embedded in the surroundings. The sources can be an effort source (Se) or a flow source (Sf). The direction of the arrow is away from the Source which denotes a positive power moving away from the source to other bond-graph elements. If the power is negative, then the source is a sink. The energy from the sources entering the system boundary must equal the sum of the energy accounted within the system boundary and energy leaving the system boundary at the sinks, which follows the law of conservation of energy.

Junctions have more than three bonds connected. The junctions distribute power instantaneously and do not store or convert energy into heat. If P_{in} denotes the power into a junction and P_{out} denotes the power out of a junction, then,

$$P_{in} - P_{out} = 0. \tag{2.1}$$

A junction has three or more bonds connected and power enter through node 1 and leave at all the other bonds simultaneously. The total power is zero, as shown by,

$$e_1 f_1 - e_2 f_2 - e_3 f_3 - ... - e_n f_n = 0. \tag{2.2}$$

The simple ways to solve the power balance is to assume either the effort variables or the flow variables are equal. The 0-junction, (0), is the case of the effort variables are equal as Paynter described,

$$e_1 = e_2 = e_3 = ... = e_n \tag{2.3}$$

$$f_1 = f_2 + f_3 + ... + f_n. \tag{2.4}$$

The bond 1 of the junction must point towards the junction and the other bonds must point away from the junction.

The 1-junction, (1), is the case when the flow variables are equal. The sum of all efforts must be zero. The power balance becomes,

$$f_1 = f_2 = f_3 = ... = f_n \tag{2.5}$$

$$e_1 - e_2 - e_3 - ... - e_n = 0. \tag{2.6}$$

The connection of non-mechanical systems of 1-junction is different to mechanical systems. If one bond of the 1-junction is pointed towards an energy store or resistor, then one of the other bonds must point towards the junction while another bond must point away from the junction. The voltage drop across an electrical element with two terminals induces the current through the element and not the sum of the electrical potential differences with respect to ground. The pressure difference across a hydraulic line and not the sum of the pressures that induce the fluid flow. The half arrows pointing to and away from the 1-junction also indicate the flow, e.g. electrical current, volume flow, or mass flow through the element from the higher to the lower potential.

Ideal power-couplers and power transducers transfer power instantaneously and do not store or convert energy into heat, similar to a junction but with only two bonds connecting the input and output. Power conservation denotes,

$$e_1 f_1 = e_2 f_2. \tag{2.7}$$

A two-port transformer (TF) is defined when a constraint on the effort variables is applied.

$$e_1(t) = m \times e_2(t). \tag{2.8}$$

$$f_2(t) = m \times f_1(t). \tag{2.9}$$

where m is a non-negative real parameter. If m is not constant, which is the case for nonlinear soft robotic systems, then the symbol TF becomes MTF to denote a modulated transformer. The one bond points into the transformer and one bond points away from the transformer to denote the input and output respectively.

A two-port gyrator (GY) is defined when a constraint is applied on the input effort variable and the output flow variable. The gyrator ratio, r, is used to define the relationship between the input effort and output flow variables. The power conservation denotes, Power in equals to power out.

$$e_1(t) = r \times f_2(t). \tag{2.10}$$

$$e_2(t) = r \times f_1(t). \tag{2.11}$$

The symbol MGY denotes a gyrator ratio modulated by a function.

This section introduced the fundamentals of bond-graph modelling. The reader can interpret bond-graph representations and extract the basic relationships between the power variables (efforts and flows) and energy variables (generalised momenta and generalised displacement). The causality indicates which side of the bond instantaneously determines the effort or the flow variable, for example, an effort source will define the effort variable and the other side of the bond will define the flow variable. The causality is used to solve the bond-graph model computationally and algebraic loops can be identified, where integration has a preference over differentiation. The focus of the paper is on the graphical representation of the energy transfer from a system to a component level. The following bond-graph theory topics are out of scope; causality, multi-bonds, and pseudobonds. This information can be found in textbooks on bond-graphs [70, 71, 72].

Bond-graph representations will highlight the essential energy transfer characteristics [67]. The power continuous connection between the source, sink and the energy storage is one of the characteristics. The energy transformation of the soft actuation technology can be classified to either a transformer or a gyrator which will influence the dynamics of the system. The steady-state scenario, where all the generalised kinetic energy will equal to zero in the inductive energy storage and all the potential energy are stored in the capacitive energy storage. The application of bond-graph theory in soft robotic systems will provide an additional insight in how designers can create systems that perform useful work.

2.6 Port-Hamiltonian approach

2.6.1 Hamiltonian from Lagrangian from Newtonian

In this section, I used a mass and spring system as an example to demonstrate the key features of the port-Hamiltonian approach. The mass and spring system described in Newtonian, Lagrangian and Hamiltonian highlights the major characteristic of each approach to mechanics as shown in Fig. 2.12. The mass and spring system is relatively simple. The expression in Newton mechanics is limited by the Cartesian coordinate system and limited to the mechanical domain only. The Lagrangian approach introduces generalised coordinates are introduced and the system is represented in terms of energy, which in this case is the interchange between stored elastic energy of the spring and the kinetic energy of the mass. In the Hamiltonian mechanics, the total energy of the system is observed and generalised positions and momenta are introduced. The spring and mass system can be divided into a spring subsystem and mass subsystem. The generalised positions and momentas describe each subsystem provides the interconnection between the subsystems. Equal but opposite forces and the same displacement connect the subsystems. The product of the effort and flow variable is power, rate of energy transfer enabled the analysis of complex multi-domain systems, where the total energy is conserved, and power continuous at junctions and transformation (Power in equal to power out)

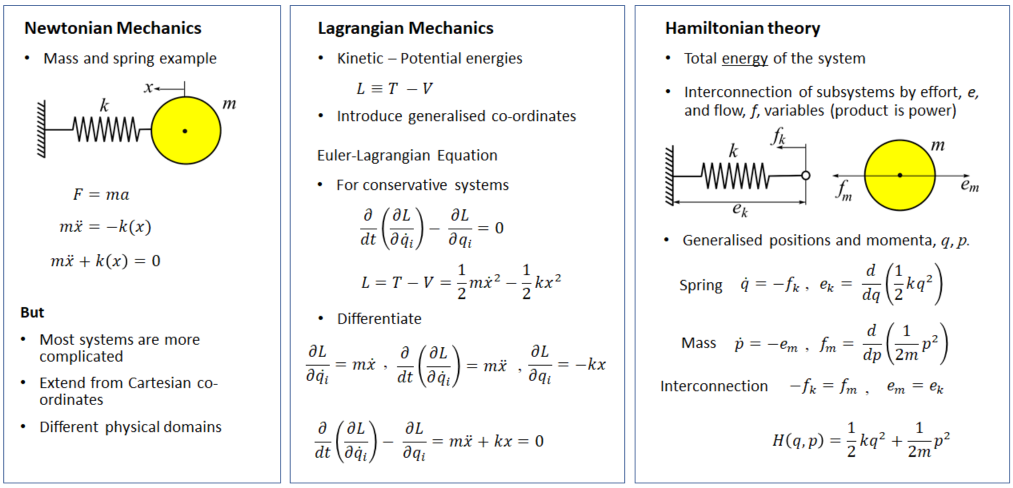

FIGURE 2.12: A mass and spring system represented in Newtonian mechanics, to Lagrangian mechanics to Hamiltonian mechanics.

2.6.2 Port-Hamiltonian theory

The previous paragraph introduced the Hamiltonian as the total energy of a system and how it is possible to divide the system into subsystems. The notion of a Dirac structure [73] is a mathematical description to enforce power conservation and the total power of the linked ports are zero. The structure defines two internal and external ports. The storage (S) and dissipation (R) ports are the internal ports. The control (C) and interaction (I) ports are the external ports describing the controller actions and the interaction of the system with the environment respectively. The port-Hamiltonian structure is shown in Fig. 2.13. Therefore a reformulation is a suitable description of the port-Hamiltonian theory since the energy is reformulated into the internal and external interactions.

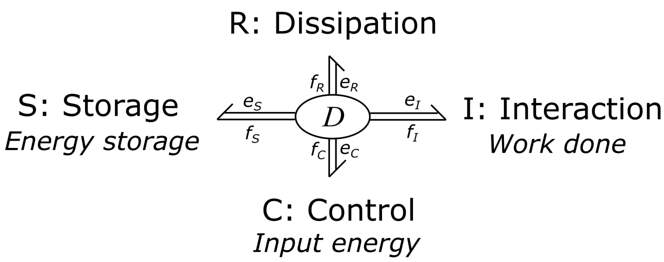

FIGURE 2.13: The port-Hamiltonian structure showing the four energy interactions and the Dirac structure which is power continuous.

The port-Hamiltonian structure can provide the logical decomposition process in System Engineering, where the total energy is broken down into energy entering the system (C), energy accounted within the system boundary (S and R), and energy interaction on the environment (I). The logical decomposition is typically expressed in a tree structure. Fig.2.14 shows the port-Hamiltonian structure represented in a tree and centralised layout. The port-Hamiltonian logical decomposition process breaks down the system into subsystems in terms of energy.

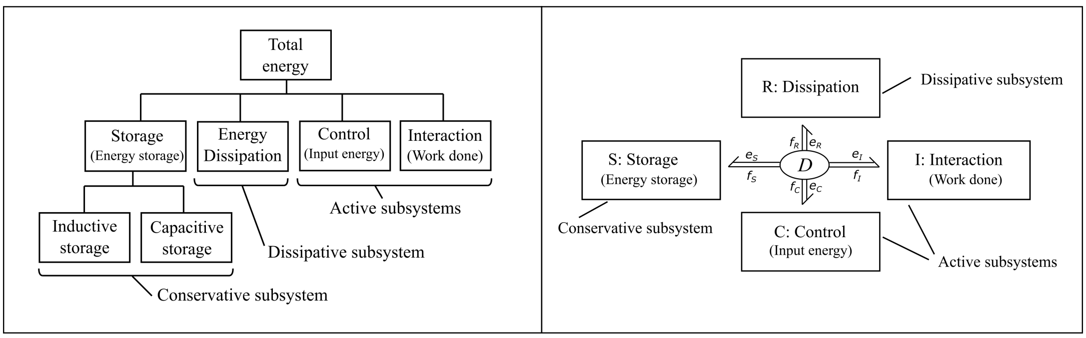

FIGURE 2.14: The logical decomposition structure is typically shown as a tree structure. A centralised structure is equivalent to a tree structure as shown by the port-Hamiltonian structure.

2.6.3 Port-Hamiltonian reformulation at a system level for efficiency

A port-Hamiltonian system is a port-based modelling approach aimed at providing a "lingua franca" for the modelling of multi-domain physical systems [11]. The rate of energy transfer is based on the concept of power conjugate variables, called efforts and flows. The dual product $\langle e|f\rangle$ of an effort, e, and a flow, f, yields power [74]. Port-Hamiltonian theory can be applied to the range of domains common in soft robotic systems, such as fluidic, chemical, thermal, electrical, and mechanical domains [1]. Ross et al. [68] provided the background information about the potential of using port-Hamiltonian theory to control and simulate soft robotic systems. Fig 2.13 shows a general representation of a port-Hamiltonian system. The system is split into internal and external energy interactions. The energy storage port, S, and dissipation port, R, are the internal interactions, while the control port, C, and the interaction port, I, are the external interactions. The Dirac structure distributes the power among the ports via the linkages as denoted by each conjugate pair of effort and flow variables, $\langle e|f\rangle$, with the corresponding subscript.

The power to the storage port is denoted by the conjugate pair $\langle e_S|f_S\rangle$ and is associated with the internal energy storage of the system, which is represented by a Hamiltonian energy function, H. The internal energy contains capacitive and inductive energy storage elements, which are generalised potential energy and generalized kinetic energy. We investigate the static case and the generalized kinetic energy is zero. At this port, the power conjugate variables satisfy the energy balance [74],

$$\frac{dH}{dt} = \langle e_S|f_S\rangle. \tag{2.12}$$

The Dirac structure is power continuous and satisfies the conservation of energy,

$$\langle e_S|f_S\rangle + \langle e_R|f_R\rangle + \langle e_I|f_I\rangle + \langle e_C|f_C\rangle = 0. \tag{2.13}$$

In a case we assume friction to be negligible and that there is no leakage of gas or pressure in a close system.

$$\langle e_R|f_R\rangle = 0. \tag{2.14}$$

The control port and interaction port will have the following relationship based on (2.12), (2.13), and (2.14),

$$\frac{dH}{dt} + \langle e_I | f_I \rangle + \langle e_C | f_C \rangle = 0. \tag{2.15}$$

The power into the control port is denoted by $\langle e_C | f_C \rangle$, which is in the pneumatic domain. The effort variable is pressure, P, and the flow variable is volumetric flow rate, dV/dt. The power into the Interaction port is denoted by $\langle e_I | f_I \rangle$, which is the work done in the mechanical domain. The effort variable is force, F, and the flow variable is velocity, dx/dt. We substitute these variables into (2.15) and integrate with respect to time,

$$H + \int P \left(\frac{dV}{dt} \right) \mathrm{d}t + \int F \left(\frac{dx}{dt} \right) \mathrm{d}t = 0. \tag{2.16}$$

The different energy interactions show that the input energy is routed to the energy storage and the work done.

$$PV = -H - Fx. \tag{2.17}$$

The energy-in is either stored by H or performs the work. We focus on the external interaction for the efficiency, ξ, which is given by:

$$\xi = \frac{Fx}{PV}. \tag{2.18}$$

I use port-Hamiltonian reformulation in Sec. 4.2, where I focus on the external energy interactions to investigate efficient systems. More information and the mathematical background on the port-Hamiltonian approach can be found in the textbook by Duindam et al. [73].

2.7 Energetic characteristics of soft robotic systems.

In this section, I investigate how the energy transfer is controlled with examples of soft robots. Typically the control is done through electronics to control an on/off switch. There are recent developments in digital electronics free control in soft pneumatic actuation [75]. The key energy interactions from the examples highlight how the system can be controlled from an energy perspective.

The energy-based control can be split into three parts. The first part is how the energy enters the system. The initial energy can be also stored in the system. The second part is how the energy is transferred through the system. The final third part is how the energy is transferred to surroundings.

2.7.1 Control of energy in and out of the system

Soft robotic systems are like any machines which convert energy-in into energy-out with the potential to perform work. Therefore, it is important to investigate how the energy is transferred through the system. A closer look at a range of soft robots will reveal the essential energy transfer characteristics.

The Multigait is connected to a high-pressure source and each individual chamber is controlled by 2 valves [2]. One valve controls the input from the high-pressure source and the other valve controls the output to the atmosphere. The valves control how the pneumatic energy enter and leave the system. Similarly, in pneumatic McKibben muscles, the timing of the valves opening and closing can control the change in pressure and the proportional controlled valves can control the rate of pneumatic energy entering through the size of the opening. The rate of energy entering the system will differ to the rate of energy leaving the system.

Octobot has a microfluidic oscillator that modulates the amount of reactant passing through the two channels alternatively. The hydrogen peroxide reactant is passed through and the gaseous oxygen inflates the pneumatic chambers. The reactant carries chemical potential energy and is transformed into pneumatic and heat, which are dissipated into the environment [37]. Heat dissipation is a way for the energy to leave the system.

DEA requires a high voltage source to actuate. The behaviour is similar to the capacitor, where electrical charge is stored. The actuator can lift the object and transfer gravitational potential energy to the object. In electromagnetic actuation, pulse with modulation is a common technique in controlling the magnitude of the current [10]. All these are examples are when energy is entering the system.

The energy can be already stored in the actuator. For example, in the example of DEA giant induced deformations where the control action occurred at the membrane where the DEA compresses and the membrane undergoes hyper-elastic extension from the pressure inside, meaning the pneumatic energy was already stored but the pressure was below the snap-through instability [55].

The large deformation describes mechanical energy storage, which is controlled by the physical parameters and properties; the Young's Modulus, the nonlinear extension properties, mass, and the physical dimensions.

The work done is the energy transferred to the sink. Mechanical work is the product of the force and displacement, which is the time integral of the force and velocity. The physical design determines the direction of the movement [29].

Examples of control by the environment are demonstrated in the fish robot [3] and the salamander robot [24]. The highest acceleration is a result of the highest thrust (force, effort variable) acting on the body and shows the highest power transferred from bond to environment. The approach enables the designer to optimise the interaction of the robot fish in water without a detailed analysis of the hydrodynamics. A different tail will require a different frequency and amplitude for the optimal interaction in the water. The salamander robot motion is controlled by being on land or in water, which controls the central pattern generator.

2.7.2 Energy transfer through soft digital control

Electronic-free control is an interesting emerging area of soft robotic control. The soft robots for extreme environments [75] and bi-stable valve [76] are examples of such control. They all rely on a pressure source and through a serial energy transfer through the logic circuit to do work. The pressure build-up and airflow through different chambers and valves results in complex behaviour. The use of bond-graph theory to graphically represent the energy transfer will be insightful to build a more complex electronic free control system. The energy stored in the pressure build-up and kinetic airflow are the capacitive and inductive energy stores respectively, therefore the bond-graph representation of electronic-free control is an interesting aspect to explore within an energy-based development approach.

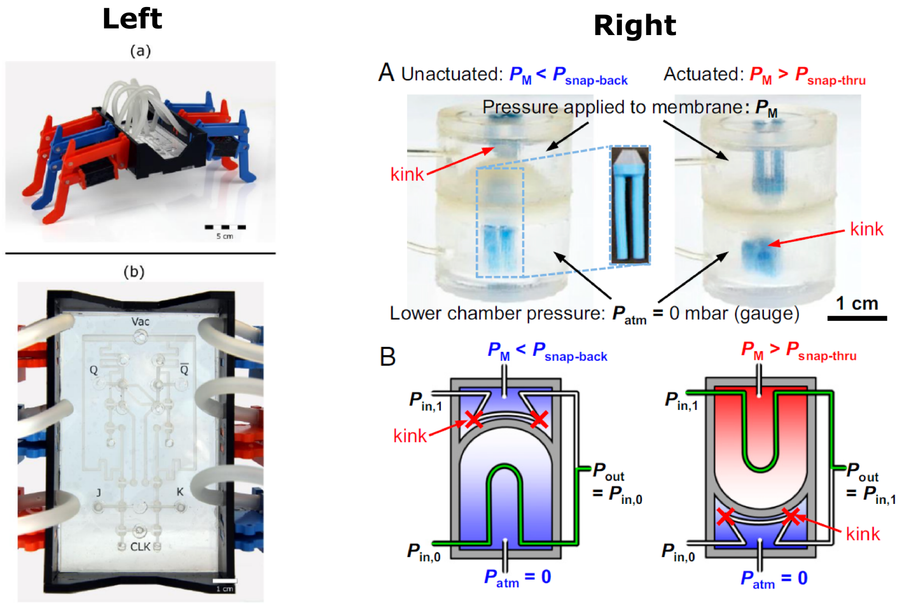

FIGURE 2.15: The picture on the left shows the soft robot for extreme environments [75] with fluidic logical control and the picture on the right shows the bi-stable valve [76]. This fluidic / electronics free control is an exciting area of development. The serial energy transfer from source to sink goes through various capacitive and inductive storage, which may limit the maximum power transfer from source to sink compared to conventional electronic control systems.

2.8 Summary

Soft robot systems are relatively novel compared to rigid robot systems, which meant the ability to create useful everyday soft robotic system is limited. The soft robot designers tend to start from an actuation technology and integrate into a system. The initial choice of technology will impact the performance of the final system. Soft actuation technologies covers many physical domains, therefore soft actuation technologies are difficult to compare and select the most suitable one. As a result, System Engineering approach to develop soft robotic systems is currently not feasible in contrast to rigid robotic systems.

The System Engineering 'Vee model' focuses on two levels, a system level and a component level. An abstraction approach is required to navigate between the two levels. Energy, or the rate of energy transfer (power), can effectively form the abstraction between the two levels. Bond-graph theory has the elements to represent in the component level and port-Hamiltonian reformulation provides a clear system overview. Therefore, the combination of bond-graph theory and port-Hamiltonian reformation has the potential to provide the abstraction which unlocks a System Engineering approach to design soft robotic systems.

The literature review highlights the energy characteristics of common soft actuation technologies, such as pneumatic, chemical, thermal, electrical, and electromagnetic actuation. Pneumatic actuation tend to require heavy compressors, and energy efficiency is low due to venting to atmosphere. Chemical actuation requires a supplemental fluidic domain to provide the inductive energy storage, and thermal energy transfer relies on conduction and radiation. The lack of inductive energy storage is an essential energy transfer characteristic that will impact the dynamics of the system.

Bond-graph theory focuses on the energy transfer through a system. The energy interactions can be split into how the energy enter the system, stored intermediately in the system, the transformation into the mechanical energy, the interaction with the environment or work done, and the energy dissipated between the input and output. The energy stored temporarily in the mechanical domain of the system is the large deformation, which is the one of the two key characteristics of soft robots. The energy interaction with the environment or work done is the active interaction on the environment, which is the other key characteristic of soft robots. Each energy interaction will provide valuable insight relate to the nature of the soft actuation technologies and will enable the designer to select the most appropriate actuation technology to integrate the system.

Chapter 3

Bond-graph abstraction of soft actuation technologies

3.1 Introduction

In this chapter, the energy transfer characteristics are highlighted by the bond-graph representation of the energy transfer in different types of soft actuation technologies. The energy transformation from each physical domain into mechanical work done is represented by bond-graph elements and forms a generalised soft actuator representation which makes up part of the energy-based abstraction in a System Engineering framework.

Soft actuation technologies cover a wide range of physical domains as discussed in Section 2.3. The soft robot designer should use an unspecified-domain approach in order to select the most suitable soft actuation technology and the associated components to meet the top-level system requirement. The literature review in the previous chapter showed that bond-graph theory can form part of an energy-based abstraction in a Systems Engineering approach, which connects the system-level and component-level. Bond-graph elements are the components in this approach.

The road-map highlights how an approach, based on bond-graph theory, can represent and analyse a system from a component level. The bond-graph elements are introduced in Section 2.5.1. The roadmap shows the topics in this chapter:

1. In Sec. 3.2.1, a word bond-graph, introduced in 2.5.1, describes the energy transfer through a generic soft actuator within a generic soft robotic system;
2. In Sec. 3.2.2, the word bond-graph is translated into bond-graph elemental representation and the energy analysed within the system is defined within system boundary;
3. In Sec. 3.3, the insights from the bond-graph element representations of a range of soft actuation technology are shown;
4. In Sec. 3.3.5, examples of adding a fluidic domain to another actuation domain are presented in recent soft actuation technologies;
5. In Sec. 3.4, An assessment of to what extent bond-graph theory can provide the well-defined components to integrate from a component level to a system-level to develop a soft robotic system.

3.2 Bond-graph element representation of a system for an energy-based abstraction

3.2.1 Word bond-graph representation

The first step in applying bond-graph theory is to construct the *word* bond-graph representation, which is the use of words to describe the energy transformations and transfers within the soft robotic system. The energy source, actuator and interaction with the environment is a suitable place to start the analysis. Ross et al. presented two word bond-graph examples [68]; a combustion robot, and a hybrid (soft and hard) robot. The word bond-graphs labelled the key subsystems, which interacted with each other through the power bonds in various physical domains. The interaction at the output is in the mechanical domain, which is common to all soft robotic system. The words used in the examples by Ross et al. are the descriptions of the subsystems on a component level and 3 types of elements; energy storing elements, energy routing elements, and energy dissipating elements, which described what was happening to the energy. The energy storing elements consist of both capacitive and inductive energy storage, modelled by C-element and R-element respectively as introduced in Sec. 2.5.1. Only capacitive energy storage is available in thermal and chemical domains. The energy routing elements are the 1-junctions or 0-junctions or the transformation elements into a different domain. The dissipative elements are R-elements. The energy inputs and task orientated energy outputs are the sources and sinks. A sink is a negative source in bond-graph theory. The signal arrows show how the systems are electronically controlled.

The word bond-graph examples by Ross et al. did not contain a system boundary. The sources and sinks are assumed to be outside of the system boundary because the source elements are assumed to be an infinite source or sink of energy. The total energy accounted in the analysis is the total energy within the system boundary and the amount of energy entering and leaving the system boundary via the sources and sinks. The rate of energy transferred or power in and out of the system boundary are integrated with respect to time to maintain the principle of conservation of energy.

The word bond graph abstraction of a soft actuator within a soft robotic system is shown in Fig. 3.1 [77]. The energy source (1) provides the power into the system in a domain related to the soft actuation technology. The storage (C, I) and dissipation (R) elements model the internal energy interactions in domain 1 (2). There is a junction element that dictates how the energy is routed through domain 1. The transformation element (3) converts energy from one form into the mechanical domain. The mechanical domain also has energy storage (C, I) and dissipation (R) elements. The mechanical

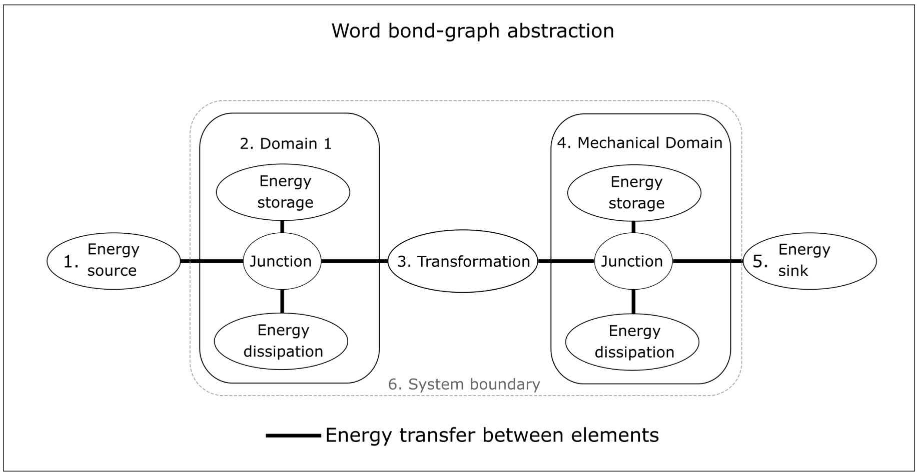

FIGURE 3.1: A word bond-graph of a soft actuator shows non-directional energy transfer between the elements [77]. Directions will be defined in Fig. 3.2.

domain part of the system also performs work and interacts with the environment via the energy sink (5). The word bond-graph representation shows energy transfers with non-directional bonds. Therefore the word bond-graphs can be replaced by bond-graph elements for additional insight in how the energy is transferred through the system.

3.2.2 Bond-graph element representation of a soft actuator

The application of the bond-graph element connection rules in Fig. 2.11 transforms the word bond-graph in Fig. 3.1 into a bond-graph element representation of a soft actuator in Fig. 3.2. Each part of the word bond-graph is represented by bond-graph elements in 3.2. The energy source is either an effort or a flow variable source and the power bond defines the direction of energy entering the system. The actuation technology defines the initial domain. For example, pneumatic actuation includes pneumatic energy in the pneumatic domain.

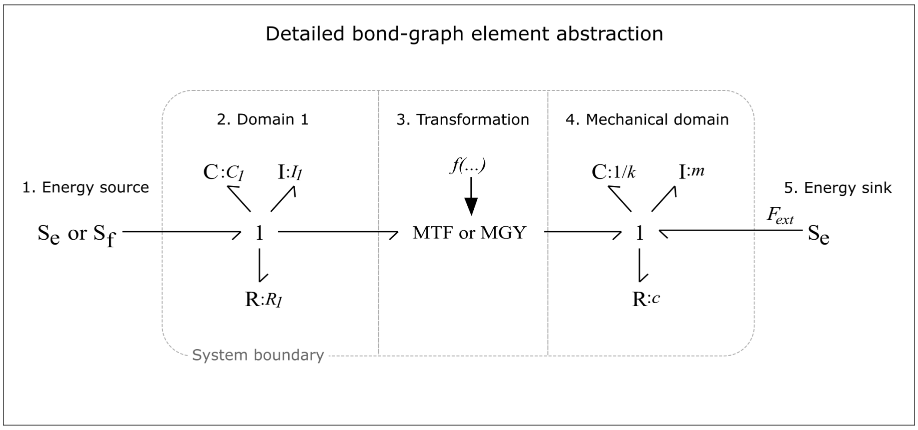

FIGURE 3.2: A bond-graph element representation of a soft actuator which shows how the word bond-graph of Fig. 3.1 is refined into bond-graph element representation [77]

The word bond-graph in Fig. 3.1 can be replaced by bond-graph elements as shown in Fig. 3.2. The energy source fixes either the effort or flow variable into the system, which is encased by the system boundary. The energy stored within the system boundary is accounted for. The product of the effort and flow variables is the power into the system. The bond points away from the source denotes the direction of positive power. The junction is a 1-junction, where the flow variables are equal. The junction routes energy into the capacitive (C) and inductive (I) energy stores. The inductive energy stores are zero in steady-state. The dissipator (R) converts energy into heat, which remains accounted within the system boundary. The energy that is not stored or dissipated is routed into a transformation element, which can either be a transformer (TF) or a gyrator (GY). The transformation element converts the energy from one form into the mechanical domain. Soft robotic systems are complex multi-domain system thus additional domains and transformation elements can be present. The energy is routed through the three modelling elements (C, I, and R). The external interaction from the environment is likely to be a force, which is an effort source. The direction of the arrow into the junction of the mechanical domain denotes a sink.

The parallel or serial energy transfer paths of word bond-graph require further adjustments with 0-junctions or 1-junctions.

The energy source provides the power into the system in domain 1, which has energy storage (C, I) and dissipation (R) elements to model domain 1. The transformation element converts energy from one form into the mechanical domain. The mechanical domain also has energy storage (C, I) and dissipation (R) elements. The mechanical domain part of the system also performs work and interacts with the environment.

The bond-graph abstraction enables a system-level partitioning into a component level, where different soft actuation technologies can be assessed and integrated into a system. In the next section, different soft actuation technologies are abstracted into standardised blocks and the respective energetic characteristics are revealed.

3.3 Bond-graph representations of soft actuation technologies

Different soft actuation technologies were reviewed in Sec. 2.3. Soft actuation technologies commonly convert pneumatic, or fluidic, or thermal, or electrical energy into mechanical energy [78]. The following paragraphs present the schematics and bond-graph element representations of the different soft actuation technologies. The analysis formed part of the journal paper ‘Energy-based abstraction for soft robotic system development’, which used bond-graph theory to review different soft actuation technologies to identify the key energetic characteristics of soft actuation.

3.3.1 Pneumatic actuation

The pneumatic soft actuation technology is introduced in Sec. 2.3.1. The schematic and bond graph representations of a generic pneumatic actuator are shown in Fig. 3.3. The soft pneumatic system is abstracted into the bond-graph element representation of Fig. 3.2. The source of the energy is caused by the change in pressure relative to the ambient pressure, which can be caused by a reaction or connection to a high-pressure source [79]. The energy entering the system is routed into pneumatic and subsequently the mechanical domains, which are stored and dissipated into the respective C, I, and R elements. The pneumatic pressure exerts a force on the chamber of the actuator, which is an effort to effort variable transformation. The physical properties and design of the actuator will determine how the energy is routed. At steady-state, if the wall is made of a hyper-elastic material, then the majority of the energy is stored in the deformation, which is the capacitive mechanical energy storage, or if the wall is made from an inelastic film, then the pressure build-up will be high and the energy is stored in the capacitive pneumatic energy storage.

The bond-graph element graphical representation shows that once the energy entering the system, there are only two routes for the energy to leave the system for the next actuation cycle; (1) a valve to the atmosphere or (2) a restrictor to the atmosphere. The importance of inductive energy storage in the pneumatic domain is evident when compared to thermal actuation, where energy can only be dissipated since there is no inductive energy storage in the thermal domain.

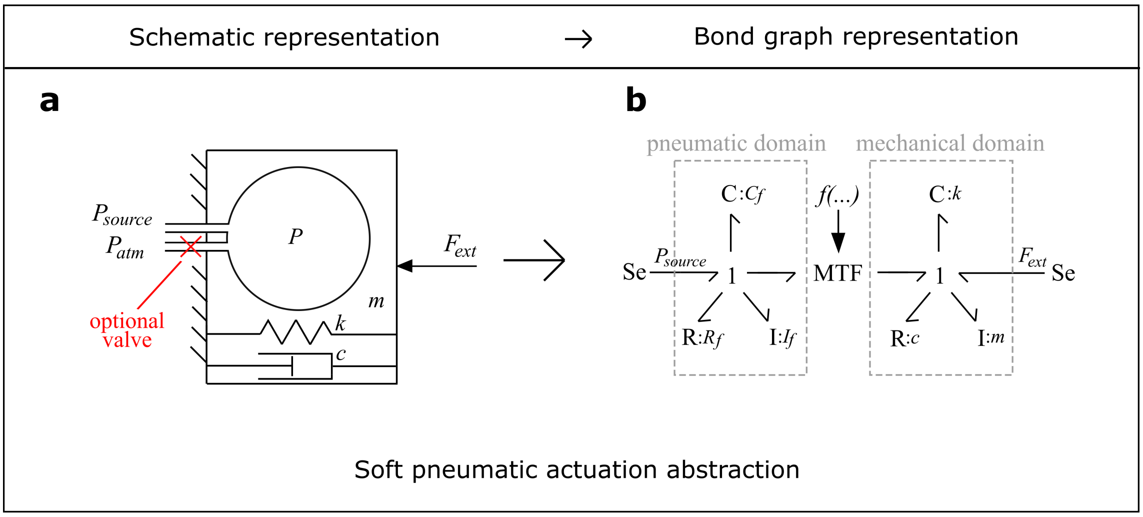

FIGURE 3.3: Schematic (a) and bond-graph element representation (b) of the soft pneumatic actuator, which shows an effort to effort transformation from pneumatic to mechanical domain.

3.3.2 Thermal actuation

The thermal soft actuator is introduced in Sec. 2.3.3. The schematic and bond graph representations of a generic thermal actuator are shown in Fig. 3.4(b). Electrical Joule heating is a common approach for the heat source. The RS element is a combination of a resistive element of the electrical domain and an energy source of the thermal domain [80]. The source is a flow source because the temperature is dependent on the thermal energy emitted from the source and how much is stored in the thermal body. The change in temperature or phase change causes a deformation in the mechanical domain and exerts a force. T1 and T2 denote a difference in temperature between two bodies where the net thermal energy will transfer from hot to cold. The gyrator transformation (MTF) element converts entropy flow to a deformation force in the mechanical domain, which is a flow variable to an effort variable. The transformation is a function of the thermal properties of the material, specific heat capacity, latent heat of the material, and geometry. The stored thermal energy must dissipate through the thermal resistor (R-element) for the next cycle. Currently, cooling circuits are not commonly implemented in soft thermal actuators and the heat is dissipated to the surroundings [5]. Therefore the response of this type of technology is typically slow. Heat transfer via convection is not accounted for in this type of bond-graph analysis. Pseudo bonds describe convection but are incompatible with the bond graphs of the other domains [72].

The essential characteristics of the thermal actuator show that there is no inductive energy storage in the thermal domain [81], which makes transporting energy in and out of the system boundary more difficult. The MGY element is not reversible. The energy stored in actuation must dissipate through heat transfer into the surroundings for the

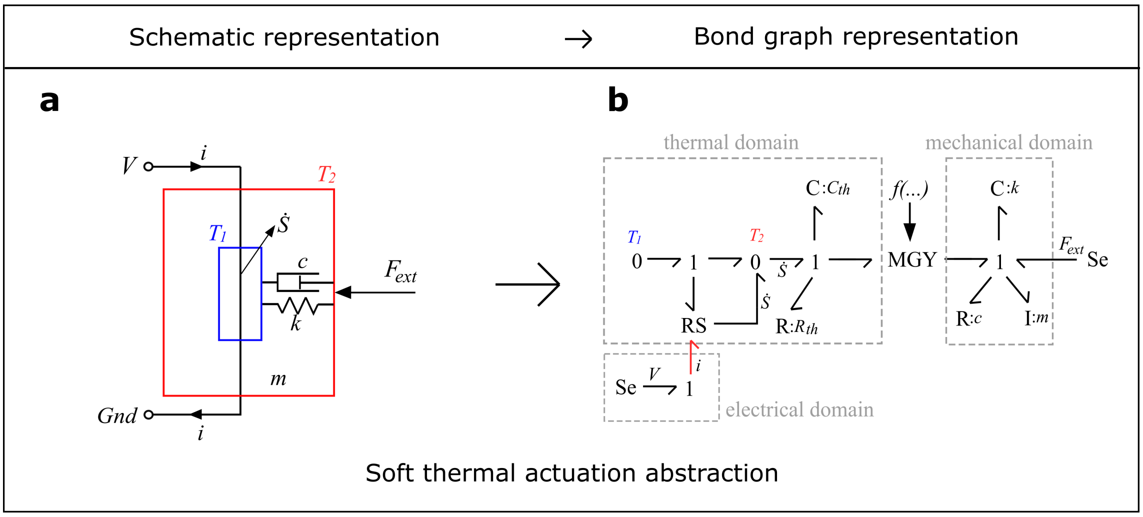

FIGURE 3.4: Schematic (a) and bond-graph element representation (b) of the thermal actuator. The electrical domain provides the energy into the thermal domain which has a gyrator transformation, which as heat enters the system, the temperature increases and the actuator expands. T1 and T2 denote a difference in temperature between two bodies. In the case of phase change the temperature remains constant at the phase change point and the actuator expands.

next cycle. The heat transfer characteristics and the ambient temperature will determine how fast the energy can enter and leave the system and subsequently determines the dynamic response of the system. These energy transfer characteristics are not ideal for fast and efficient systems.

3.3.3 Dielectric actuation

The di-electric (DEA) actuator was introduced in Sec. 2.3.4. The DEA actuation technology is a direct transformation from electrical energy to mechanical energy through electrostatic forces.

The schematic and bond graph representations of a generic electrostatic actuator are shown in Fig. 3.5. The electrodes compress the elastomer with electrostatic forces when a high voltage is applied [82]. The elastomer undergoes mechanical deformation. The energy is temporary stored as a charge and in the deformation of the elastomer. The energy stored in the compressed elastomer restores the actuator back to the off position. The electrical voltage is transformed into a mechanical force, which is an effort to effort variable transformer (MTF) element. The energy transformation element modulated by a function of the capacitance. The essential characteristics of the dielectric actuator are the reversibility of the energy transformation compared to the thermal actuator.

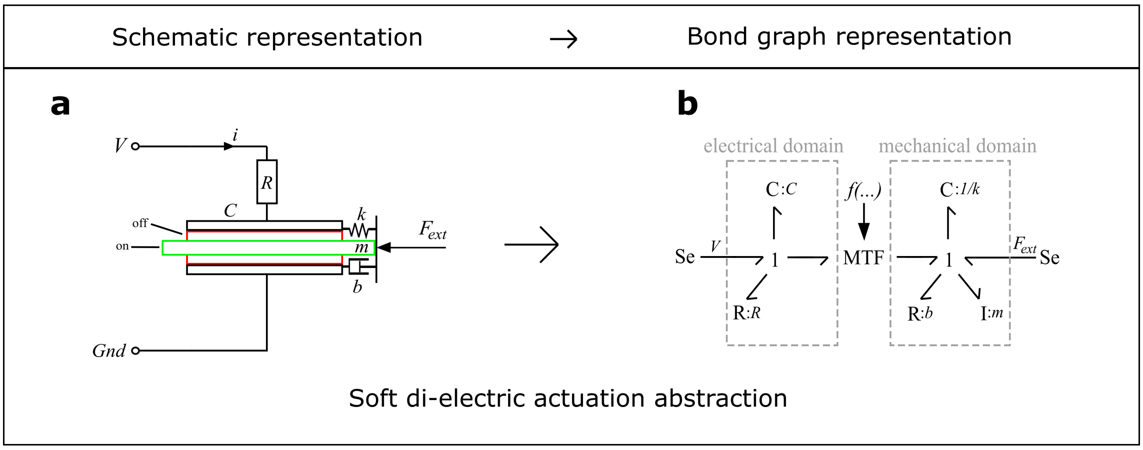

FIGURE 3.5: A Schematic and bond-graph element representations of a di-electric actuator or other electro-static based actuators.

3.3.4 Electromagnetic actuation

The electromagnetic actuator was introduced in Sec. 2.3.5. The actuation technology is the transformation of electrical energy to mechanical energy via the electromagnetic domain. The schematic and the bond graph representation of the electromagnetic actuator is shown in Fig. 3.6. The current induces a force on the permanent magnet. The restoration force is provided by the stiffness of the elastomer which has a hysteresis damping. The actuator has a mass. The elastomer provides the capacitive energy storage in the mechanical domain and the soft characteristics. The energy transformation element is an electrical current to mechanical force, which is a flow to effort gyrator (GY) transformation element. Capacitive energy storage is not present in the electrical domain. The direction of the force is controlled by the direction of the current. The gyrator defines that a flow variable at the input determines the effort variable at the output, which contrasts with the pneumatic and dielectric actuators where the effort variable at the input determines the effort variable at the output. The thermal domain does not have inductive energy storage. The electrical domain, however, can make use of inductive energy to move energy in and out of the actuator quickly. This insight shows that soft electromagnetic actuators are suitable for dynamic applications.

Rotary electromagnetic actuators (motors), normally associated with rigid robotic systems, are used in a soft robotic system context [51]. Soft characteristics can be achieved with rigid components by various designs; series elastic actuators with temporary capacitive energy storage in series [52], which is similar to the bond-graph representation in Fig. 3.6. Variable stiffness actuators with a separate energy path to control the stiffness [53], or an antagonistic approach with two parallel energy paths from source to sink [54], which will involve a 0-junction. The distinction between series elastic electromagnetic actuators and soft actuators fades from an energy-based abstraction point of view.

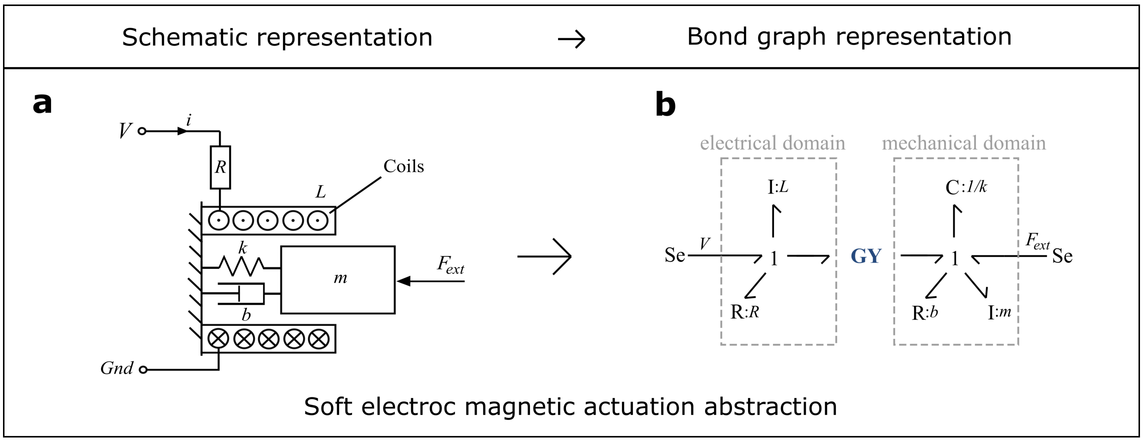

FIGURE 3.6: A Schematic and bond-graph element representations of a soft electrical actuator.

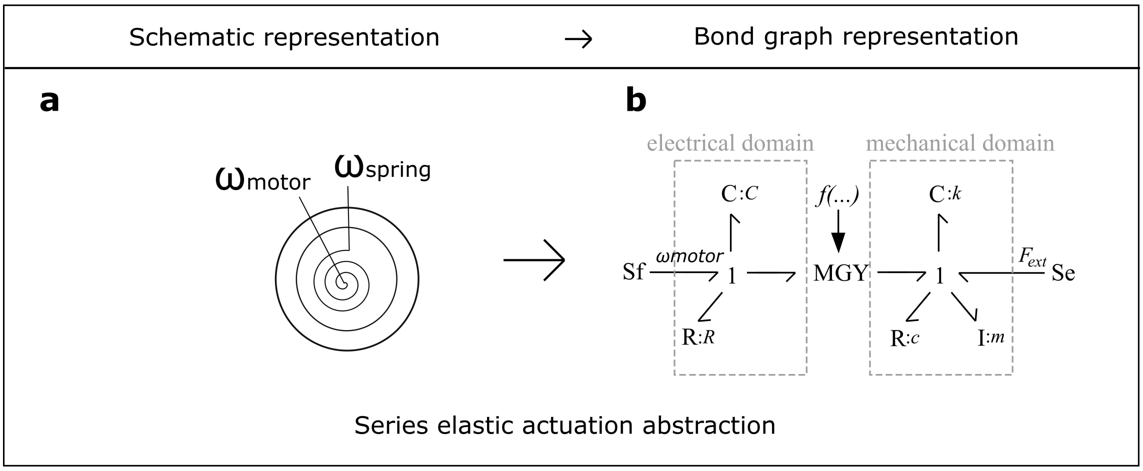

FIGURE 3.7: A Schematic and bond-graph element representations of a series elastic actuator, where there is a spring between the motor and the and end effector.

The schematic and bond-graph representations of series elastic actuator is shown in Fig. 3.7. The displacement of motor and displacement of the spring shows a temporary energy storage in the mechanical domain. This feature prevents a direct path for the energy to transfer from the motor to the human where a high amount of energy transferred in a short time can result in injuries. The mechanical spring can temporarily store the energy and the energy can either move back to the motor or increase the time for the energy to transfer to the human, which enhances the safety of the actuator.

3.3.5 Hybrid domain actuation

In this hybrid domain section, I created abstractions of current soft actuation systems which encompasses multiple domains. For example, the Peano-HASEL actuator combined electrical and fluidic domains [8]. The authors replaced the dielectric elastomer with an in-extensible pocket of dielectric fluid. The force is transmitted through the incompressible fluid. The hysteresis is reduced compared to an actuator with the dielectric elastomer. Peano-HASEL actuators addressed the limitations of electrostatic and fluidic actuators, by achieving large displacement and fast response. The schematic and the bond graph representations of the Peano-HASEL actuator are shown in Fig. 3.8(b). The dielectric elastomer of Fig. 3.5 is replaced by a closed pocket of dielectric fluid. The addition of the fluidic domain and the change from an elastomer to an in-extensible film pocket of fluid results in different energy storage and dissipation characteristics in the mechanical domain.

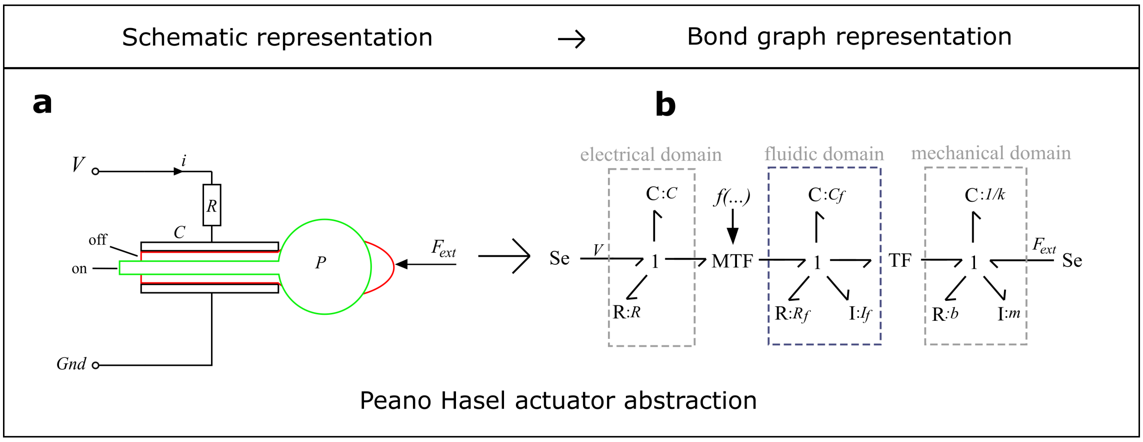

FIGURE 3.8: A Schematic and bond-graph element representations of the Peano-HASEL actuator.

Li et al. used a hyper-elastic dielectric elastomer to induce giant deformations [55]. The pressurised container has a surface with the elastomer. The compression of the dielectric elastomer reduces the pressure for snap-through hyper-extension. A voltage is applied to the membrane of the balloon and causes hyper-elastic expansion of the balloon. A fixed amount of air is pressurised in the chamber. The total energy of the system is stored within the chamber. The potential work done on the external environment is from the stored pneumatic energy instead of the electrical energy in the dielectric elastomer.

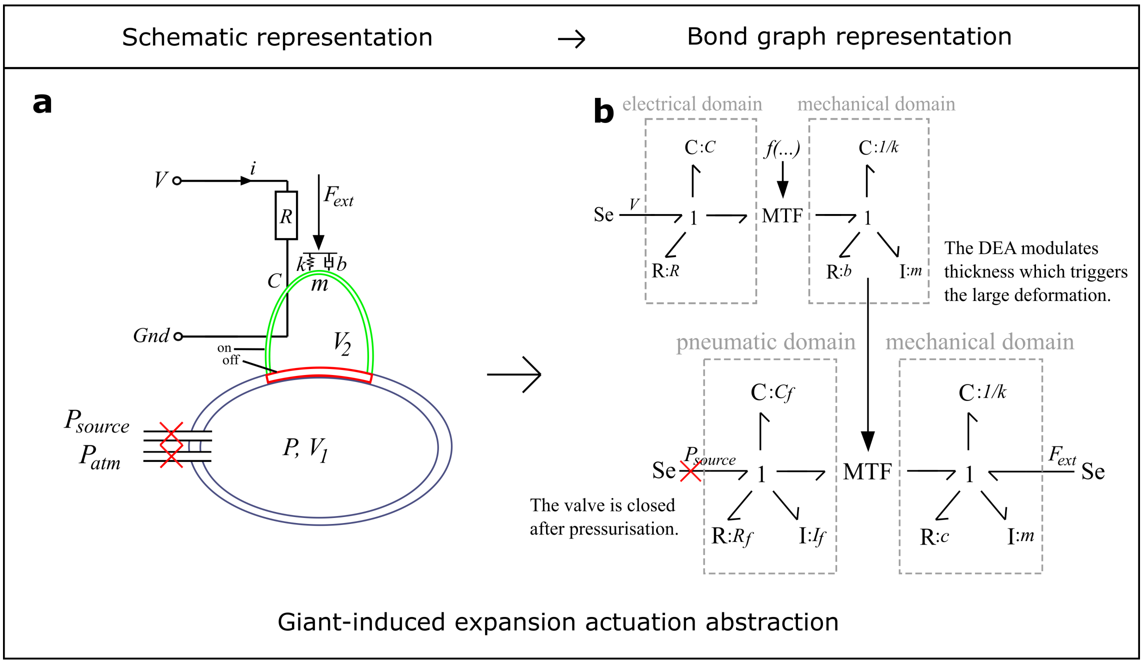

FIGURE 3.9: A Schematic and bond-graph element representations of a giant induced deformation actuator.

Yoshimura et al. used the Belousov–Zhabotinsky (BZ) reversible reaction to combine the chemical domain with the fluid domain to make a reciprocating machine [57]. There is no clear identifiable energy sink. The chemical potential of the BZ gel defines the rate of swelling which displaces a volume of fluid as shown in Fig. 3.10. The bond-graph representation shows when the energy is transferred when the volume of fluid is displaced, however, it is a reversible reaction, the energy must come back from the fluidic domain instead of interaction on the environment. Hence there is not a clear sink to show the energy interaction with the environment. The initial source of chemical potential energy can be assumed to be stored in the Capacitive element, hence no clear source of energy. The energy in system appears to be self contained and oscillates between chemical and fluidic domains.

Cacucciolo et al. combined electrical and fluidic domain through conduction electro-hydrodynamics [45, 58]. The direct transformation from electrical into mechanical energy is through the interaction between the electric and flow fields. The interaction acts as an effective gyrator (GY) where the high electrical voltage, transformed into a fluid flow at the output when connected as a closed-loop system, i.e. joining the fluid output to the input.

This shows the difference between the Peano-HASEL actuator where the voltage induces a build-up of pressure, compared to a flow rate in an electro-hydrodynamic actuator as shown in Fig. 3.11.

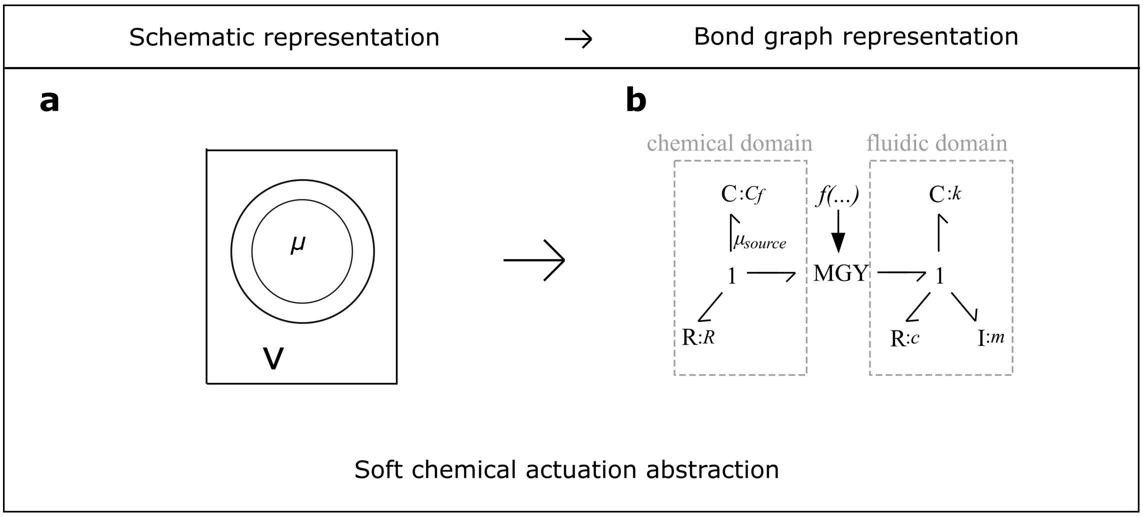

FIGURE 3.10: A Schematic and bond-graph element representations of a chemical swelling actuator where the swelling displaces a volume of fluid.

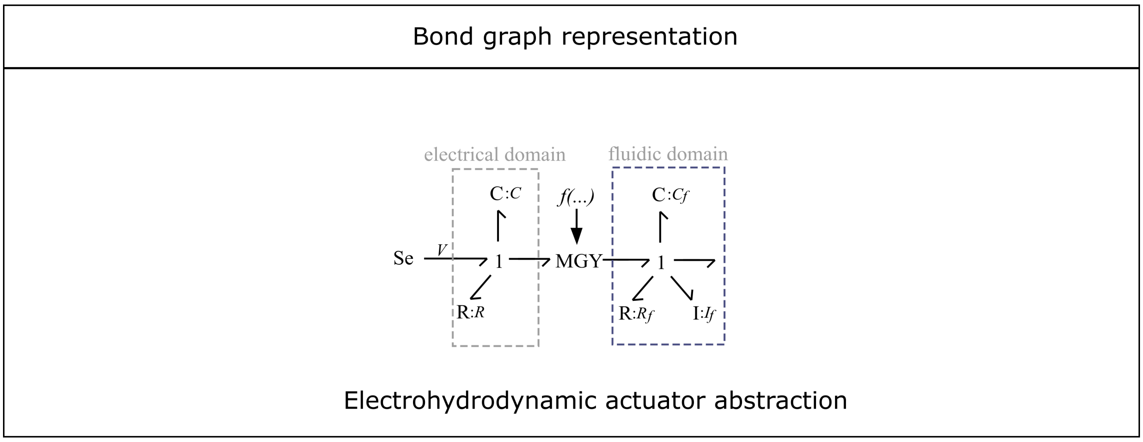

FIGURE 3.11: A bond-graph element representation of electro-hydrodynamic actuator. The transformation element is changed from a TF to a GY where the voltage induces a flow rate compared to the bond-graph element representation of a dielectric actuator.

3.4 Bond-graph elements to create well-defined components

In this section, I discuss how the work presented in this chapter fits into a System Engineering approach with the scenario outlined in Fig. 2.6. The top-level requirement in terms of energy can be compared with and the energy transfer characteristics of different soft actuation to identify the most feasible actuation technology from a component level. The bond-graph elements are compared with the physical equivalent components to understand how the energy-based abstraction can inform the system design from a component level.

3.4.1 Energy transfer characteristics from top-level system requirement

The search and rescue scenario in Fig. 2.6 of Sec. 2.4.1 includes tasks such as locomotion, manipulation and grasping. The purpose of this scenario is to show the top-level energy requirements. Other precise features of each task such as, opening doors, lifting a human in a stable way, and negotiating the stairs, are out of scope. Locomotion relates to the gain in kinetic energy. The lifting of a person suggests a gain in gravitational potential energy. Moving up- and down-stairs involve changes in both kinetic and gravitational potential energies. The acceleration and deceleration require the gain and dissipation of kinetic energy. When a human is involved, safety constraints can be applied to the maximum rate of energy transfer. The scenario in Fig. 2.6 is a search and rescue scenario that suggests a time constraint; thus a minimum rate of energy transfer can also be applied and subsequently, a performance envelope can be defined. The energy transfer characteristics from the top-level system requirement can be defined in gravitational potential energy and kinetic energy with a maximum and minimum rate of transfer constraints. The total energy requirement is further investigated with a port-Hamiltonian approach in the latter chapters 4 and 5. The next step is to look at the read-across from bond-graph elements to the components of the relevant physical domain.

The pneumatic, thermal actuators, and di-electric actuators rely on an effort variable (pressure, temperature, and voltage) to induce a force in the mechanical domain. The energy is transferred from the initial domain to the mechanical domain with the energy primary stored in the capacitive storage, which is generalised potential energy. Therefore actuators with an effort-variable input may be suitable in these lifting applications. However, the ambient conditions will impact the thermal actuators and high voltage DEA actuators may raise public safety concerns. In applications involving kinetic energy, the capacitive energy stored needs to be moved in and out of the system, which requires inductive energy storage. Thermal or chemical actuation is not ideal for dynamic applications because energy leaving the system is limited by the dissipators because there is no inductive energy storage.

The soft electro-magnetic and the electro-hydrodynamic actuators involve gyrators (GY) as the transformation elements. The effort variable at the input defines the flow variable at the output.

3.4.2 Towards System Engineering with well-defined blocks

The bond-graph representation of each actuation technology shows that the abstraction of component level results in standard blocks, with an I-element, a C-element, and an

R-element connected to a 1-junction in each domain, with the exception to thermal and chemical domains where I -elements do not exist. The energy transformation is modulated by a function, which is dependent on the specific actuation technology. The effort or flow source suggest how the system is powered. A flow source needs the power to be continuously on to actuate, whereas in an effort source, the energy from the initial power input is stored and how the energy can be transferred away from the system for the next cycle.

The standard blocks in Fig. 3.2 of the six modelling elements in a two-domain actuation technology, the transformation modulation and whether a transformation element is a gyrator or transformer provide the key design decisions. Therefore a soft robot designer can integrate these standard blocks to construct on a system level. The next step is to understand how these standard blocks can become well-defined blocks. One aspect is how bond-graph elements match with the physical component in different domains. The materials properties and geometries of pneumatic chambers, thermal expansion blocks, and the capacitance of the DEA elastomers or fluidic pockets all modulate how the energy is stored within the soft actuator domain and the mechanical domain. Electromagnetic components, such as motors, coils.

3.4.3 Limitation of bond-graph representations of soft actuation system

This chapter shows that bond-graph element representations provide additional insight into identifying the energy transfer characteristics. However there are limitations to this approach:-

1. The C, I, R elements describe a linear relationship, which is unsuitable for many nonlinear characteristics of soft actuation, for example, the hyper elastic deformation in pneumatic actuation, or the heat and displacement relationship with shape memory alloys.
2. Each representation models a specific situation. For example, multiple bond-graph representations are required to model high pressure inlet valve open and another to model venting to atmosphere.
3. Some parameters are discrete, such as valve opening are either fully open or fully closed. Partially open may require another representation to model.
4. Physical components in electrical and mechanical domains match directly with bond-graph modelling elements. For example, capacitor and springs for C-elements,

or inductor and mass for I-elements, or resistor and damper for R-elements in electrical and mechanical domains respectively. Components in other domains such as pneumatic and thermal actuation technologies, require a combination of modelling elements in multiple domains, for example, a change of a parameter of the material of the pneumatic chamber will change the bond-graph modelling elements (C, I, R-elements) simultaneously in both the pneumatic and mechanical domains. Outside of electrical and mechanical domains, components are complex to represent with bond-graph elements.

3.5 Summary

This chapter presents the bond-graph representations of the energy transfer of different soft actuation technologies. The soft robot designer can compare the energy transfer characteristics of different bond-graph representations and select the most suitable actuation technology in a System Engineering approach.

The essential energy transfer characteristics are essentially divided into 5 energy interactions; 1.) the energy source; 2.) the intermediate energy storage; 3.) the energy dissipation; 4.) the energy transformation; and 5.) the interaction with the environment. The verification of a soft pneumatic actuator is in Chapters 4 and 5.

The nonlinear nature of soft actuation technologies limits the model accuracy of the bond-graph elements representation. This approach can supplement actuation-technology-specific system-level analysis like the pneumatic supply system work from Joshi and Paik [83]. Other approaches can be applying port-Hamiltonian reformulation to characterize system efficiency [84], or developing an energy-based controller [85]. This energy-based abstraction offers a step towards applying a System Engineering approach, and this type of thinking and analysis should help to develop task-orientated soft robotic systems into products that will impact our everyday lives.

Chapter 4

Port Hamiltonian description of soft robotic system

4.1 Introduction

This chapter presents the experimental design, methods and materials to extend a soft pneumatic actuator into a system, and to apply port-Hamiltonian theory on a system level. Port-Hamiltonian approach can be used to provide an energy-based logical decomposition model at the system level. This work resulted in the RoboSoft 2019 conference entry 'Towards more Energy Efficient Pneumatic Soft Actuators using a Port-Hamiltonian Approach' [84].

In the experiment "Port-Hamiltonian reformulation of the pneumatic finger system", Port-Hamiltonian reformulation is applied to a soft pneumatic system to identify the key energy interactions. The soft pneumatic finger actuator, inspired by Mosadegh et al. [29], is integrated into a system with a syringe and a mass and pulley. The syringe is used to provide the energy input and the mass and pulley system controls the force applied on the finger tip with the weight, which is the product of mass and acceleration due to gravity, and is the interaction with the environment. The port-Hamiltonian external interactions are the energy-in and energy-out of the system, which defines the efficiency of the system. The efficiency is a fundamental performance measure of any machines. The soft pneumatic finger actuator has two major design parameters that can impact the performance of the actuator. The material properties of the pneumatic finger and the internal critical wall thickness influence the deformation and energy transfer of the pneumatic finger.

Sec. 4.2 presents the experimental design and hardware used to demonstrate the port-Hamiltonian approach. Sec. 4.3 outlined the type of data expected and the process approach used. Sec. 4.4 describes the methods and materials used in the experiments. In Sec. 4.5, I summarised the key features of the experiment and how the approach supplements the energy-based System Engineering framework.

4.2 Experimental design

The key aspect of the experiment is to measure the various energy interactions within a system. The port-Hamiltonian approach was introduced in Sec. 2.6 which reformulates the energy interactions into internal and external interactions. The internal interactions are represented by the bond-graph modelling (C,I,R) elements and the external interactions are the sources and sinks.

The first step is to integrate the pneumatic finger actuator into a system which will require components to provide the source and the sink to complete a system. The next step is to apply the port-Hamiltonian reformulation to identify the energy interactions as shown in Fig. 2.13. The product of effort and flow variables is power. The power can be further integrated by time to estimate the energy transferred. Table 2.1 is a list of common variables. The tetrahedron of states in Fig. 2.10 described the relationship between the variables. The energy stored in each subsystem is the time integral of the power transmitted.

The last step is to ensure all the energy are accounted and apply assumptions on heat transfer to ensure energy conservation. For example, the temperature of the system stays constant. I.e. energy entering the system are not converted into heat. These assumptions ensure energy conservation and should be considered on a case by case basis. The energy interactions are measured through the effort or flow variables or other variables like displacement which is the time integral of velocity. Design of Experiment is used to generate a list of experiments to perform and derive a statistical function between the ratio of energy-in and energy-out (efficiency) with respect to the two design parameters.

4.2.1 Port-Hamiltonian reformulation of the pneumatic finger system

A soft pneumatic system is an example of a soft robotic system. The pneumatic finger actuator in this experiment is inspired by Mosadegh et al. in their work, "Pneumatic Networks for Soft Robotics that Actuate Rapidly" [29], as shown in Fig. 2.2. Fig. 4.1

shows a sketch of the pneumatic finger. The pneumatic finger is fixed at one end. A small channel connects the pneumatic networks together, denoted by the grey ellipses. The material properties of Material 1 and Material 2 determine the deformation direction, when Material 1 has hyperelasticity and Material 2 is in-extensible, the finger will bend downwards. The pneumatic chambers within Material 1 expand when the pressure increases and the increased pressure exerts a force on the chamber walls.

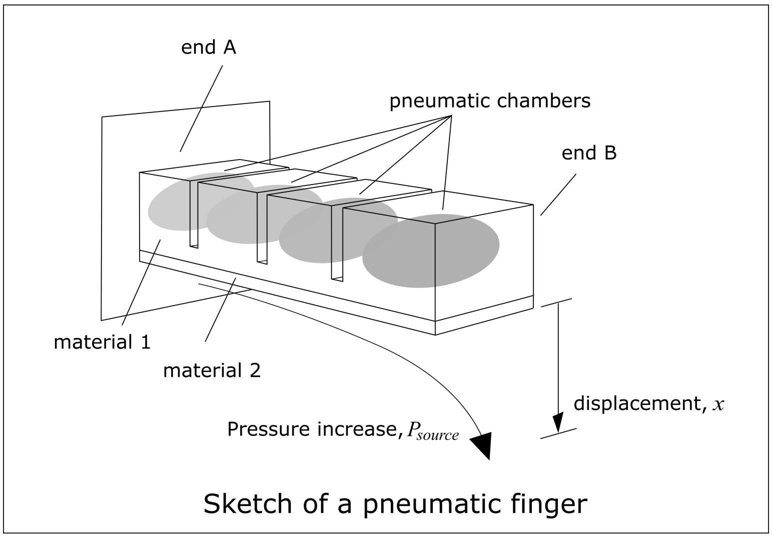

FIGURE 4.1: A sketch shows a pneumatic finger, which shows the pneumatic actuator fixed at one end, the direction of displacement, and is made up of an elastic material 1 and an inelastic material 2.

The pneumatic finger actuator transforms pneumatic energy into mechanical energy, i.e. a volume of air under a pressure into a mechanical force to deform the walls and subsequently movement. Fig. 4.2 shows the bond-graph representation of a pneumatic actuator, which was introduced in Sec. 3.3.1. The pneumatic and mechanical domains are shown in the bond-graph representation. The geometry of the pneumatic chamber and the properties of Material 1 controls how the modulated transformation element (MTF) transforms pneumatic energy into mechanical energy and vice-versa because the transformation is reversible. MTF, Modulated transformer is defined by a function, which is related to the material properties and the geometry design of the pneumatic finger. The system boundary is enclosed over all the bond-graph elements aside from the sources (Se). The pressure, P, and the volume flow rates are the measurable effort and flow variables respectively in the pneumatic domain. The force and velocity are the measurable effort and flow variables respectively in the mechanical domain. The bond-graph representation can be used to identify which variables can be measured. Other variables shown in Table 2.1 are not measurable, such as the flow variable in the thermal domain, entropy flow. The energy transferred through the system can be calculated with measurable or estimated effort and flow variables.

The steady-state condition when the actuator is at rest, provides a convenient measurement point because the inductive energy storage is zero, which greatly simplifies the temporary energy store (S) within the port-Hamiltonian structure. The inductive energy storage becomes zero in Fig.2.14. In addition, the volume flow rate is typically difficult to measure but the syringe reading provides the final volume displaced, which is the time integral of the rate of volume change. Therefore steady-state conditions can simplify the measurement of dynamic variables such as velocity and volume flow-rate in static conditions.

The port-Hamiltonian reformulation in Fig. 4.3 shows how each bond-graph element in Fig. 4.2 fits the different energy interactions. Storage (S) denotes C-elements and I-elements in both pneumatic and mechanical domains. Energy is stored temporarily in the two domains. Dissipation (R) are the R-elements in the pneumatic and mechanical domains, which are the fluidic friction and hysteresis of the materials. The Dirac structure denotes the power continuous connections within the bond-graph representation. The junction and transformation elements do not store energy.

The source and sink are the external interactions. The source describes the controllable actions (C), which is the pneumatic energy going into the system. The sink is the interaction (I), which is the work done on the mass. Bond graph element defines that sources and sinks are outside of the system boundary and assumed to be infinite. Therefore,

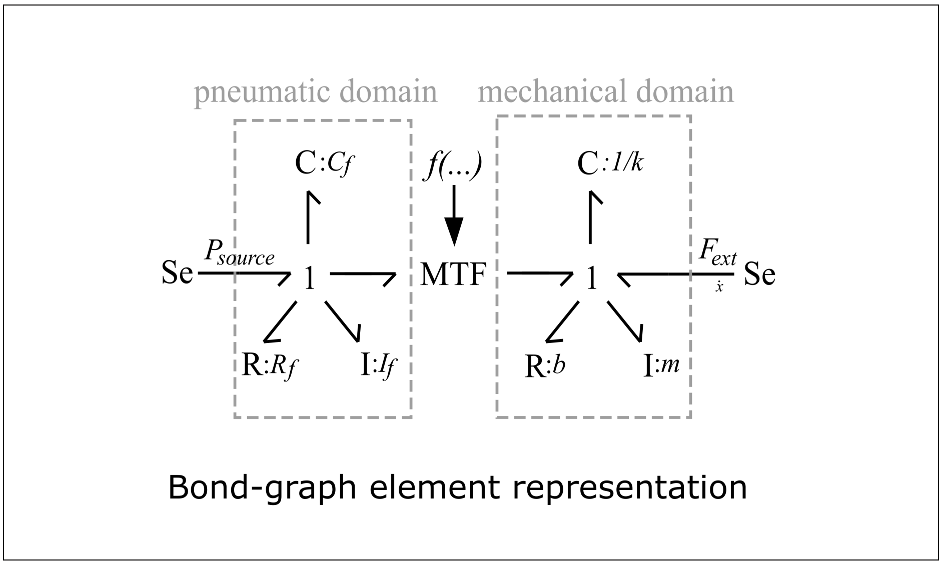

FIGURE 4.2: The bond-graph representation of a pneumatic actuator, as shown in Sec. 3.3.1, shows the pneumatic and mechanical domains, the modelling elements, the transformation element, the source and the sink

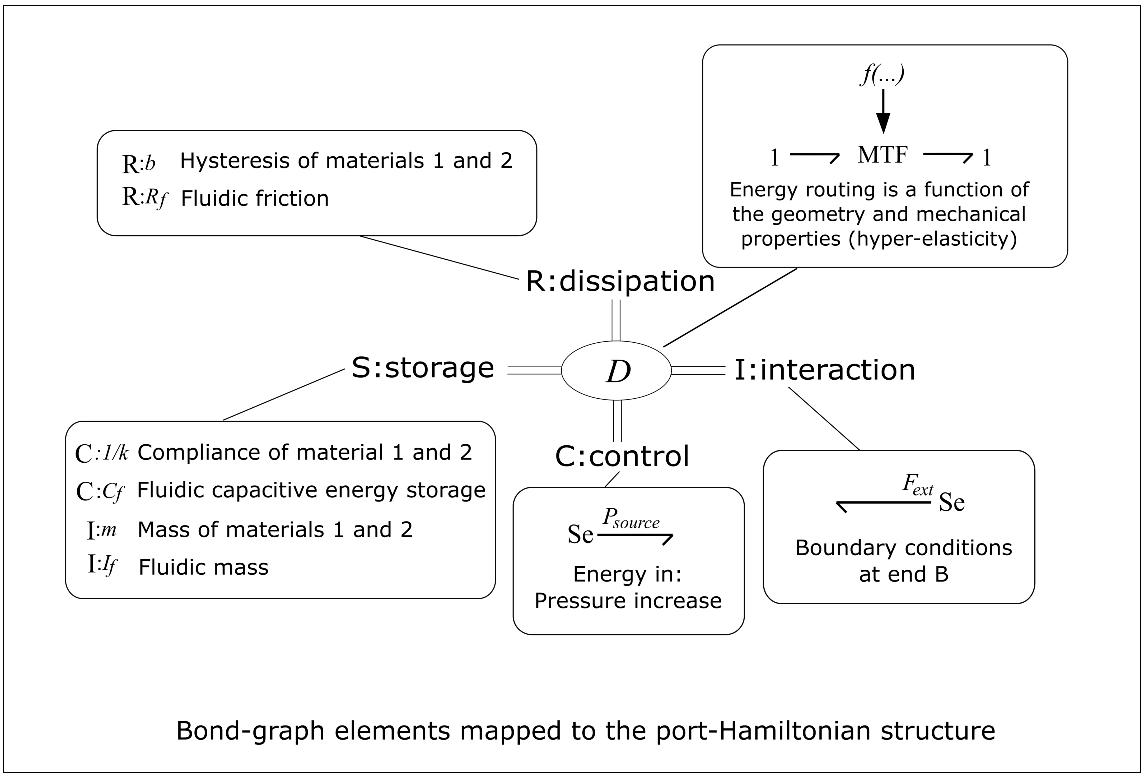

FIGURE 4.3: The port-Hamiltonian structure, where the four energy interactions are mapped with the bond-graph elements.

the sinks and sources also describe the boundary conditions. The Dirac structure ensures the conservation of energy. Energy entering the system boundary must either stay within the system boundary or leaves the system boundary through the sink.

The energy characteristics of the storage elements (I-elements and C-elements) and the dissipation elements model the actuator. The addition of the sources and sinks completes the system and bond-graph elements are integrated from a component level to a system level in a System Engineering framework.

4.2.2 The schematic of the experiment

The previous section introduced the pneumatic soft actuator, and the bond-graph representation. The actuator require an energy source and sink to complete a system. A gas syringe provides the mechanism to input energy. The action of pressing the syringe inputs the energy. The change in volume, is a flow source. The final displaced volume is measured to compute the change in energy. The output is a mass and pulley system. The pulley redirects the force from the weight of the mass. A marker ensures the pneumatic finger pulls the mass to a consistent height. The magnitude of the work done can be controlled by varying the mass. This work done represents the active energy interaction with the environment.

The energy-interactions of the port-Hamiltonian structure are colour-coded and letters (S,I and C) in Fig. 4.4 and match correspondingly to the schematic of the experiment in Fig. 4.5. The R element in this case is assumed to be low. Energy dissipated in the Resistive element is typically in the form of heat. Fig. 4.5 (a) shows the front view in which 5mm wall thickness around the Pneu-Net chambers. A small pneumatic channel is used to connect each Pneu-Net. Fig. 4.5 (b) shows the side view of the schematic of the experiment. The energy input into the system by compressing the syringe is denoted as C: Control. The pressure sensor is connected to a T-piece and measures the pressure in the syringe, and the Pneu-Nets. The energy storage includes the pneumatic energy stored in the volume of air (including the T-piece) and the mechanical deformation of the highlighted area. The external energy interaction, also denoted as work done is shown by the pulley, cable and mass. The pulley provides the change in direction of the force. I can calculate the work done by the product of displacement and weight.

The system in the experiment is a closed system where the amount of air is fixed and assumes the pneumatic to mechanical energy transformation is almost fully reversible as noted by Paynter [12]. Since the syringe is compressed slowly, the energy loss through friction and heat is negligible. The thermodynamic assumptions are that the work done is isothermal. The four port-Hamiltonian interactions become three interactions. Therefore, if two interactions are measured, then the third interaction can be calculated. The control action of the input energy (C) and the work done (external interaction) is measured and the energy temporary stored energy (S) can be estimated.

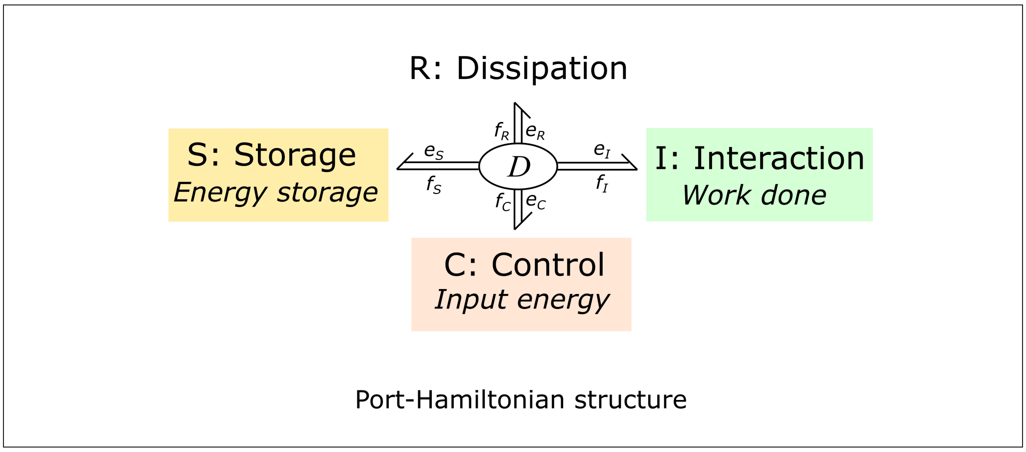

FIGURE 4.4: The port-Hamiltonian structure with each interaction highlighted to match colour with the schematic of the Experiment A. Dissipation is not highlighted and assumed to be zero in actuation where the energy transformation is near fully reversible.

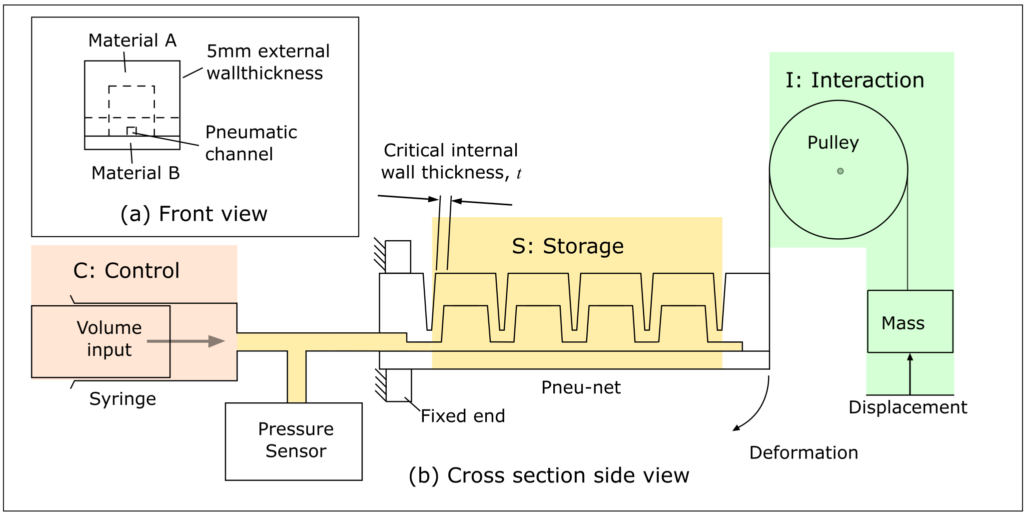

FIGURE 4.5: Insert Figure (a) shows the front view of the pneumatic finger shows material A and B make up the pneumatic finger. Figure (b) shows the schematic of Experiment 1. A syringe acts as the energy input, C, into the system, where there is a pressure sensor and the pneumatic finger is fixed one end. The stored energy, S, is stored through the pneumatic pressure in Pneu-nets and mechanical deformation of the pneumatic finger. The critical internal wall thickness is shown and controls the deformation. The pulley directs the force. The external energy interaction (I) is the product of the weight and the displacement of the mass.

4.3 Data collection and processing methods

The objective is to collect data of the variables in Table 2.1 to investigate how the energy is transferred through the system. The pressure is readily measurable in pneumatic systems. Volume flow rate is more challenging, however the finally change of volume can be observed. The volume compressed to lift the mass to a consistent height is measured. The absolute pressure are collected as a time series array, where the peak pressure is extracted, and the ambient pressure is accounted for the gauge pressure within the system. The volume compressed on the syringe are measured. The mass in the carrier are recorded. The mass and the constant displacement controls the work done on the environment.

The function between the energy entering the system and work done on the environment provides useful measures such as the efficiency of the system. The function between energy- in and energy-out also provides insights in how the port-Hamiltonian Dirac structure routes the power between the external energy interactions and the internal energy interactions. I used a Design of Experiment (DoE) to derive a function in terms of efficiency. The Design of Experiment approach will be expanded in the next paragraph.

4.3.1 Design of experiment (DoE) approach

Design of Experiment is an approach to derive mathematical functions to explore the relationships between variables based on the statistical theories by Ronald Fisher in 1922 [86]. The approach increases in robustness through randomisation of trials. The Design of Experiment (DoE) [87] approach to derive the list of experimental trials to compute the statistical models of the efficiency against the two design variables, internal wall thickness and material types. JMP is a widely available commercial software that can be used to apply the DoE function to randomize the list of experiment trials and to generate a robust predictive model of the efficiency and the design parameters. I measured the volume input and pressure change for a given wall thickness and mass for that experiment trial. A statistical function of how the efficiency varied with respect to different design factors can be observed. The design factors are the critical internal wall thickness and the two different Ecoflex materials. The control variable was the work done by the system.

4.4 Methods and materials

4.4.1 Experiment method - pneumatic finger actuator

I used the gas syringe to measure the amount of air pushed into the system, which is the time integral of the volume flow rate. I controlled the force by varying the mass, which for this type of . The internal wall thickness ranged from 1mm to 4mm and the mass ranged from 10g to 40g. The external walls are 5mm thick therefore the internal thickness must be less than 5mm to maintain the deformation direction. The work done was over a 70mm displacement. I repeated each pressure and volume readings five times and used the average. I applied this method for both Ecoflex 00-30 and Ecoflex 00-50 to provide a comparison between the two materials. Ecoflex 00-10 is prone to rupture due to the softness of the material. The statistical relationship provided insights into the external interactions and the Dirac structure of the port-Hamiltonian. The readings were repeated three times for robustness.

I measured the energy-in and calculated the work done to derive the efficiency. The work done is the product of the weight and the displacement. The 70mm displacement was an appropriate value for the dimensions of the actuator and the suitable mass ranged from 10g to 40g. I used a marker to set the displacement. I used standard masses of 10g and 20g for the range of 10g to 40g. The energy-in is the product of the pressure change and the volume inserted into the system as per equation (2.18).

The experiment instructions are listed below.

1. Set-up experiment as Fig. 4.6.
2. Fit the pneumatic finger with the right wall thickness and material and the mass on the carrier as per design of experiment (DoE) list.
3. Start the pressure data-logger to begin the experiment.
4. Manually compress the syringe until the mass reach the top of the red marker
5. Record the compressed volume (100ml minus the reading).
6. Repeat the previous step 4 times to gain 5 peak pressure readings.
7. Stop the datalogger and label the data with the wall thickness, material and mass on the carrier.
8. Move to the next entry design of experiment.
9. Repeat point 3 to 7 until the design of experiment is complete.

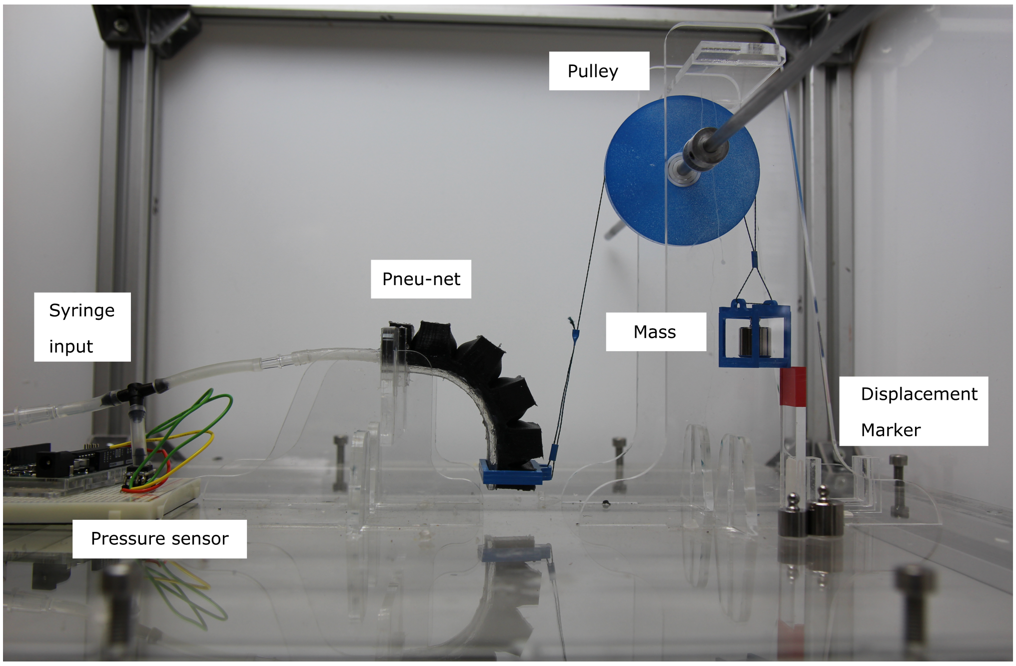

FIGURE 4.6: The photo of the experimental set-up is shown. A syringe, T-piece, pneumatic finger, pulley, mass and displacement marker forms the key parts of the experiment.

The measurement errors are summarised in Table 4.1. The internal wall thickness and the volume input are the major error contributions. The volume readings can be repeated and the error can be reduced. The error in the internal wall thickness relates to the accuracy of the 3D printed moulds and the alignment between the upper and lower moulds. Additional alignment holes in the moulds improved the accuracy of the castings between the top and bottom halves of the mould.

TABLE 4.1: The variable, error, the minimum measured value, and the percentage are listed. The volume input is the biggest potential source of measurement error. The potential error in the wall thickness is due to the 3D print quality of the external and internal moulds.

Variable	Error	Minimum value	Percentage (%)
Pressure	12Pa	12000Pa	0.1
Volume	0.5ml	20ml	2.5
Mass	0.005g	10g	0.05
Displacement	0.5mm	70mm	0.7
Wall thickness	0.2mm	1mm	20

4.4.2 Materials for pneumatic finger

A 3D model of the mould is created using Solidworks©. The model is made of a bottom plate, middle section and a top plate. The bottom plate is a laser cut 4mm acrylic sheet, which helps the separation of the mould and Eco-flex materials. The three parts were combined to create the mould and Ecoflex 00-30 and 00-50 are poured to a mould to create the top half of the pneumatic finger actuators.

The pneu-net actuators are made of Material A and Material B as shown in Fig. 4.5 (a). Ecoflex 00-30 and Ecoflex 00-50 are used for Material A. Ecoflex 00-10 is too fragile to use as the 1mm wall would rupture easily under pressure. Polydimethylsiloxane (PDMS) is used as an in-extendable bottom layer for Material B. 2mm thick flat acrylic sheets with a rectangular cutouts are used to create the mould for pouring PDMS.

The design of the moulds are based on the example by Mosadegh et al. [29]. I modified the mould with a 5° draft angle on the critical internal walls to aid the removal of the pneu-net from the mould. I used a 3D printer (Copymaster 3D 500) to manufacture the moulds.

A range of moulds with pneu-nets of different internal wall thicknesses ranging from 1mm to 4mm. I mixed the Ecoflex as per the manufacturer's instructions, degassed under vacuum, and poured it into the moulds. The mould for the PDMS was made from laminated 2mm acrylic sheets for a consistent thickness. I left both materials to cure for 12 hours. I bonded the two materials together with Sil-Poxy and used Sil-Poxy to bond a 5cm silicone tubing (6mm outer diameter / 4mm inner diameter) to the pneumatic channel for the volume input. I fabricated eight pneu-nets as listed in Table 4.2. I used Sil-Poxy to bond the fixed end of the pneu-net to a detachable acrylic mounting for each pneu-net. Ecoflex 00-10 was prone to rupture during removal from mould due to being too soft. More material would have been useful in establishing a function of material properties on energy transfer through the system. Eco-flex 00-30 and Eco-flex 00-50 present only 2 data-points for material since Ecoflex 00-10 was too fragile. More materials will result in additional material properties to be tested.

I used a pressure sensor (BMP280) with a serial output to a laptop to record the pressure change. I measured the volume input from the syringe which had 1ml intervals. The external interaction, which is the work done on the lifting the mass against gravity, is controlled by varying the mass. The action of changing the mass also changes the inertia of the system, (the I-element in the mechanical domain). The result is that acceleration would be lower for the higher mass values. This presents a difficulty in the investigation of the dynamics of the system, when the dynamics of the air entering the system, is impacted by the mass changing. This shows that the steady-state at rest condition

Table 4.2: The range of materials and different thicknesses of the pneu-net actuators used to derive the statistical models in the experiment.

Variation	Material A	Material B	Wall thickness (mm)
1	Ecoflex 00-30	PDMS	1
2	Ecoflex 00-30	PDMS	2
3	Ecoflex 00-30	PDMS	3
4	Ecoflex 00-30	PDMS	4
5	Ecoflex 00-50	PDMS	1
6	Ecoflex 00-50	PDMS	2
7	Ecoflex 00-50	PDMS	3
8	Ecoflex 00-50	PDMS	4

provides another advantage in simplifying the inductive elements (I-elements). A more complex pulley spring system like the one used in [88], where the spring can provide the force and a pulley can adjust the length of the cable.

4.4.3 Role of simulation

Simulation is more complex for soft robotic systems due to multiple variables are changing in a partial differential equation (PDE), which tends to require finite element or other computational intensive approach to solve. Bond-graph theory are readily applied in solving ordinary differential equations (ODEs), which only one variable is changing each time. The understanding of how energy is routed through the soft actuator will enable to create a "look-up table" or a black-box type approach to simulate soft robotics as described by Ross et al. [68]. Duriez derived a model of a soft actuator and applied positional control in real-time [89], however when the actuator interacts with the environment, a large energy transfer may potentially increase the error. This highlights a potential advantage of using actual measurement data to create the model. This is a starting point to lead to an energy-based control approach to soft robotic systems, however the number of energy interaction data-points are low. In summary, it is possible to create a theoretical model of the pneumatic actuator to investigate the relationships between material, wall thickness and the energy transferred. The approach to empirically derive a different model may improve robustness and avoids model verification as actual response are recorded and used.

4.5 Summary

This chapter introduced the experimental setup used to measure the energy interactions of a pneumatic system. The pneumatic finger actuator is complimented with a syringe and a pulley-mass subsystem to become a complete system. The bond-graph representation and port-Hamiltonian structure shows how the representation relates to physical experiment. The energy-in are measured for a specific work done on the environment. The efficiency is a performance measure that the energy-in and the work-done (energy output) can be easily computed and optimised.

The focus on steady-state at rest case reduces the inductive energy storage terms in the bond-graph representation to zero. The generalised kinetic energy is zero at steadystate, when everything is at rest. The parameters are defined by the dimensions and the material properties of the soft pneumatic actuator. The materials are Ecoflex 00-30 and Ecoflex 00-50 which stretches hyper-elastically. The thickness of the internal walls must be less than 5mm to maintain a consistent deformation direction. The size of the pneumatic finger defined that 70mm is a suitable displacement for the mass. The mass ranged from 0g to 40g, which is relates to the ability of the pneumatic finger to lift such mass and is a influenced by the size and materials of the pneumatic finger.

The port-Hamiltonian structure how the internal energy interactions describe the actuator and the system is completed by adding the energy input and work done, which the sources and sinks respectively. I described an approach to investigate design features that impact the efficiency which is a ratio of work done over energy-in.

Chapter 5

Results and discussion

5.1 Introduction

Chapter 5 presents the results from the experiment and discussion. The experiment showed an example of extending a soft pneumatic actuator into system and applying bond-graph representation and port-Hamiltonian reformulation to identify the key energy interactions. The experiment also shows how selected design parameters, such as the internal wall thickness and material properties of the pneumatic finger can impact the efficiency, which is the ratio of energy entering the system and performing work done on the environment.

5.2 Results of port-Hamiltonian reformulation of the pneumatic finger system

5.2.1 Efficiency as a function of wall thickness and work done

The results are efficiency response-surface plots as a function of the wall thickness and the mass. Fig. 5.1 and Fig 5.2 show the efficiency response-surface plots for Ecoflex 00-30 and Ecoflex 00-50 respectively. The overall efficiency of the pneu-net finger actuator is less than 3%. The majority (97%) of the energy is routed to the storage interaction in the mechanical and pneumatic domains. The energy stored in the mechanical domain restores the elastic deformation and dissipates through the hysteresis of the viscoelastic material. The material properties and geometry will play a role in minimizing the energy stored and dissipated in the mechanical domain. The energy stored in the pneumatic domain is vented to the atmosphere. The efficiency can potentially increase if the pressure is not vented to the atmosphere. This suggests a different way to displace the volume of air inside instead of utilising the ambient pressure of the atmosphere.

An example of how efficiency is computed. The energy-in is the volume compressed multiplied by the pressure increase. For Ecoflex 00-30, 54ml (0.000054m^3) of air was compressed resulted in a gauge pressure of 16868Pa to lift a 0.030kg mass by 0.07m. The work done is 0.0206J. The efficiency is the work done divided by the energy-in. The efficiency is 2.26 percent.

I observed two general trends from the surface plots. (1.) The wall thickness axis showed that a thinner wall thickness results in a more efficient actuator and (2.) The mass axis showed that there is an optimal work done value for a given wall thickness. This means that for any soft pneumatic fingers, there is a an optimal work done value for a given displacement. The thinner the wall is the more efficient the system can be, therefore a stronger material like Ecoflex 00-50 will enable the designer to implement a thinner wall compared to an actuator made of Ecoflex 00-30 to perform the same load.

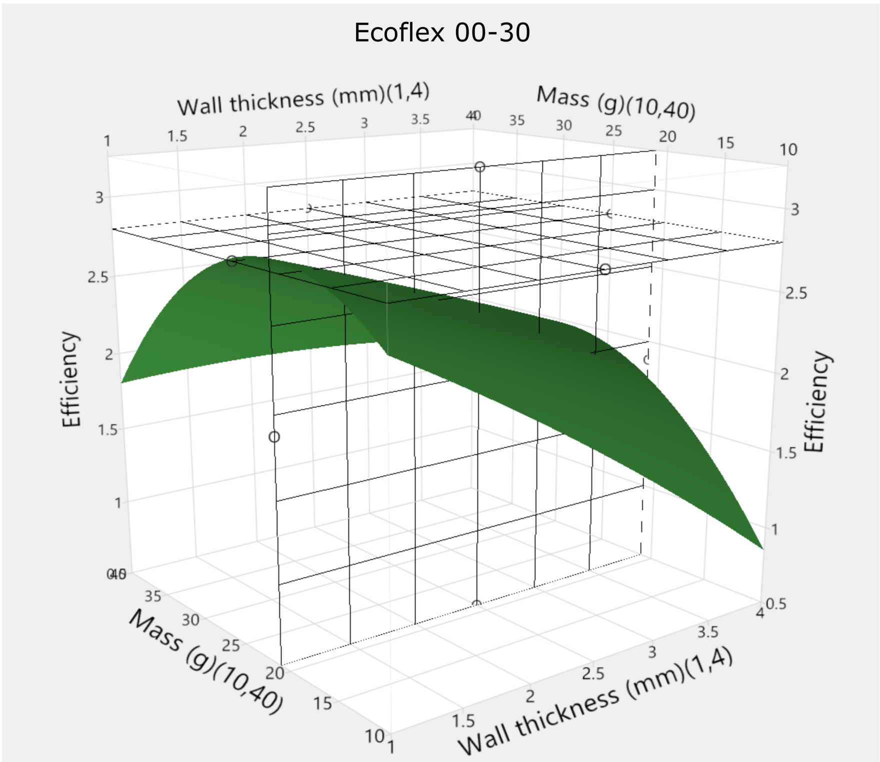

FIGURE 5.1: The efficiency surface profile of the pneu-nets made of Ecoflex 00-30 shows the highest efficiency at 1mm thickness and an optimal work-done on a 21g mass.

The surface plots of Ecoflex 00-30 in Fig. 5.1 and Ecoflex 00-50 in Fig. 5.2 have different profiles when viewing from the wall thickness point of view. Ecoflex 00-30 is relatively linear whereas Ecoflex 0050 has a gradual decrease in gradient which resulted in looking like a saddle point. The confidence levels of the statistical model are further assessed in Fig. 5.3, Fig. 5.4 and Fig. 5.5.

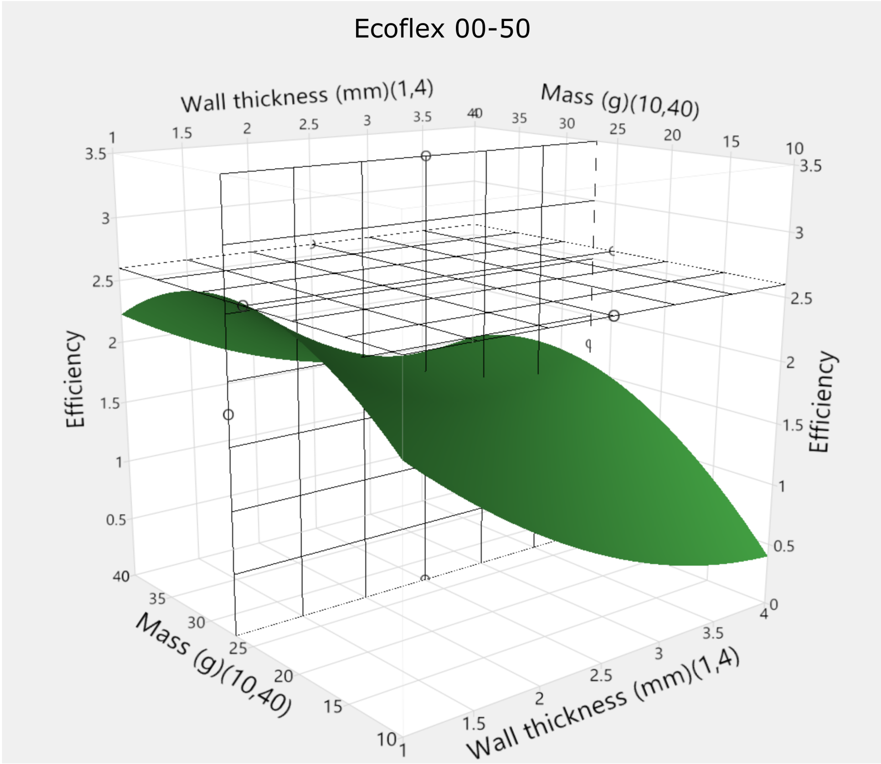

Figure 5.2: The efficiency surface profile of the pneu-nets made of Ecoflex 00-50 shows the highest efficiency at 1mm thickness and an optimal work-done on a 27g mass.

I compared the efficiency for Ecoflex 00-30 and Ecoflex 00-50 pneu-nets in table 5.1. I observed that Ecoflex 00-30 is more efficient than Ecoflex 00-50 for three quadrants of the surface plots; (1mm, 10g), (4mm, 10g) and (4mm, 40g). Ecoflex 00-50 is more efficient than Ecoflex 00-30 in the low wall thickness and high work done (1mm, 40g). Ecoflex 00-50 has a higher tensile strength than Ecoflex 00-30, while other material properties are similar. The pneu-net actuator is more efficient with a stiffer material at higher work done values. The high work done, low wall thickness is the ideal quadrant to move towards more energy-efficient actuators with a higher work done.

The highest efficiency is achieved with the thinnest wall thickness and there is an associated optimum work done for a given material. Ecoflex 00-30 is 0.021kg at 0.070m, and Ecoflex 00-50 is 0.027kg at 0.070m. Therefore, the results suggest the higher Ecoflex rating, the stiffer the material can result in higher work-done and higher efficiency because the wall thickness can be minimised for a given load. The experimental approach provided an insight into the energy routing of the system, where higher magnitude of energy can be routed with a stiffer material and the efficiency can be optimised with a thinner wall thickness.

Table 5.1: A comparison of the Ecoflex 00-30 and Ecoflex 00-50 pneu-nets efficiency. The efficiency shows that a softer material is more efficient apart from when the wall thickness is low and the work done is high. *The max efficiency is highest at 1mm wall thickness with work done on different masses.

Wall thickness (mm)	Mass (g)	Ecoflex 00-30 ξ (%)	Ecoflex 00-50 ξ (%)
1	10	2.5	1.9
1	40	1.7	2.2
4	10	0.9	0.4
4	40	1.6	1.5
1	-	2.8 (*21g)	2.6 (*27g)

Fig. 5.3 and Fig 5.4 show an alternative view of the surface plot. The shaded regions show a 95% confidence level in the function. The Ecoflex 00-50 plots in Fig. 5.4 shows a thicker error bar for the wall thickness than the Ecoflex 00-30 plots in Fig. 5.3. Therefore the Ecoflex 00-50 surface plot of Fig. 5.2 should be more similar to the surface plot of Ecoflex 00-30.

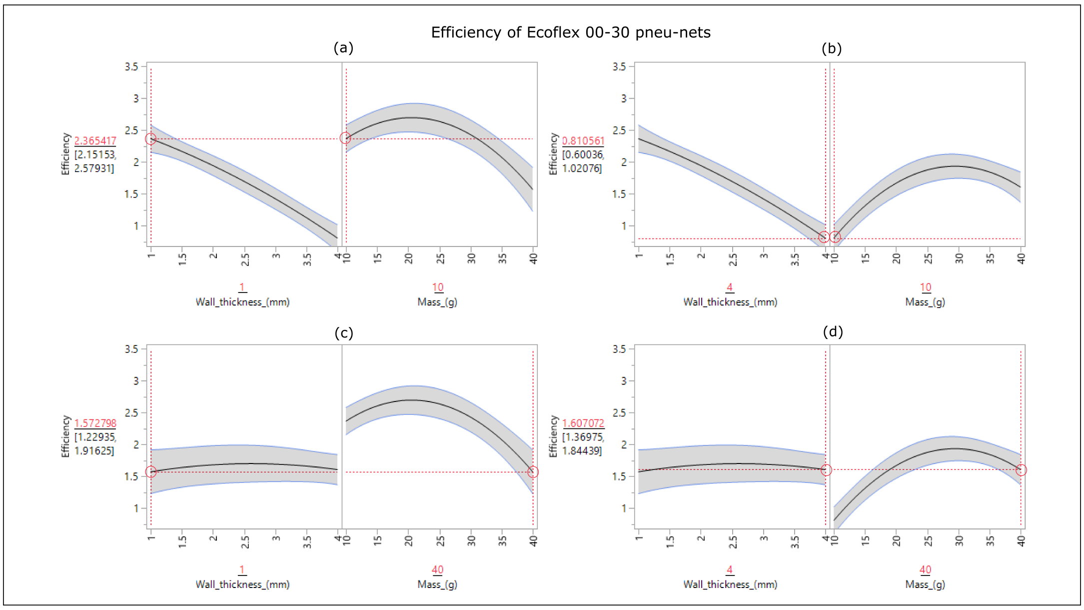

FIGURE 5.3: The efficiency plot of Ecoflex 00-30 in additional details a) shows efficiency at a low wall thickness and a low work done. b) shows efficiency at a high wall thickness and a low work done, c) shows efficiency at a low wall thickness and a high work done, and d) shows efficiency at a high wall thickness and a high work done.

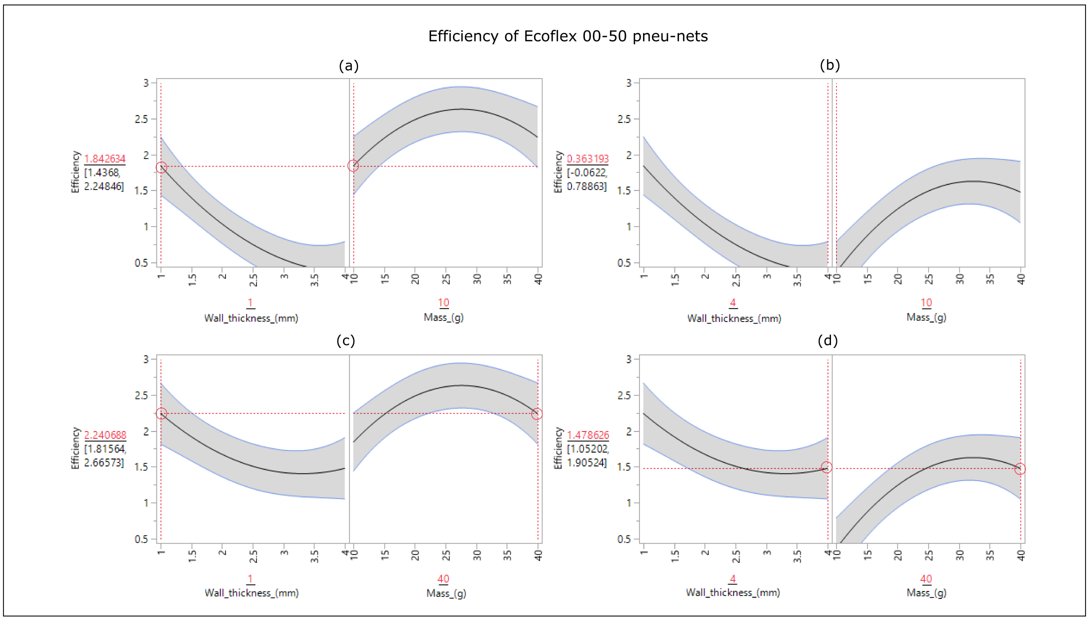

FIGURE 5.4: The efficiency plot of Ecoflex 00-50 in additional details a) shows efficiency at a low wall thickness and a low work done. b) shows efficiency at a high wall thickness and a low work done, c) shows efficiency at a low wall thickness and a high work done, and d) shows efficiency at a high wall thickness and a high work done.

The change in material from Ecoflex 00-30 to Ecoflex 00-50 is a stiffer material according to the manufacturer Smooth-On © Inc.. In Fig. 5.5, pressure increases with a stiffer material at both low and high mass values. The mass values controlled the amount of work done. However at high work done values, the volume of air input decreases as material becomes stiffer, as shown by Fig. 5.5 (b). This is an important finding, as it shows the potential scalability of this type of actuator. For example, the most stiff hyper elastic material can be used as a test point to see if it can exert the required force and higher work-done on the mass for this type of pneumatic actuator design, before additional features such as fiber-reinforcement [90] is required to increase the energy transferred through the actuator.

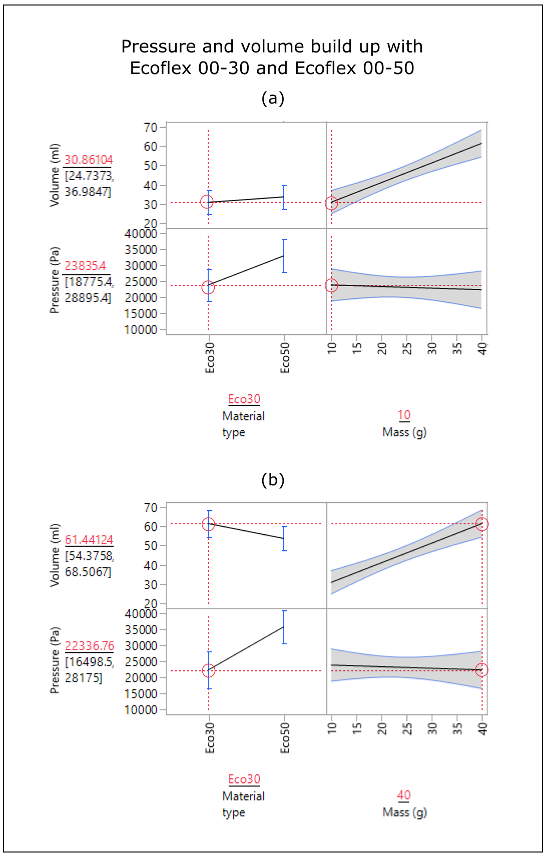

FIGURE 5.5: The material impact on the pressure and volume, when the material changed from Ecoflex 00-30 to the stiffer Ecoflex 00-50.

5.3 Discussions

5.3.1 System Engineering framework

The port-Hamiltonian reformulation is an abstracted approach for the system level. The System Engineering Vee-Model, Fig. 2.8, is applied with bond-graph elements on a component-level and a port-Hamiltonian structure on a system-level. However, it is worth noting in a System Engineering approach, there are a number of other logical decomposition processes. The energy-based abstraction is only one of the approaches and will require other approaches to fully define and develop a system.

The experiment showed that the system can be optimised by matching the right properties of the material and the work done. This approach can potentially help to investigate the scalability of a type of component to meet a certain performance requirement. Additional experiments can derive empirical standard blocks to describe how different magnitudes of energy transfer can be transferred through a component.

5.3.2 Measuring the effort and flow variables to characterise a system

The effort and flow variables in different domains in Table 2.1 are measurable or, at least, either effort or flow variable are measurable. In the experiments, the flow rate proved to be difficult to measure. There are constant flow-rate apparatus available that could have defined a flow source to the experiments. Mass is used to control the forces from the environment, which also impact the inertia of the system. However, I used the steady-state, at rest as the measurement point when kinetic energy was zero.

5.3.3 Port-Hamiltonian reformulation to investigate a system

Port-Hamiltonian reformulation enables the separation of the system into internal energy interactions of the actuator and the external energy interactions, which include the energy entering the actuator and, interaction on the environment. The external energy interactions are often overlooked as the attention is typically on the novel actuation. However, external interactions are an indispensable part of a complete system.

The energy input can be an effort or a flow source as shown in bond-graph theory. I used a flow source for Experiment 1 and an effort source for Experiment 2 for the same pneumatic actuation technology. The designer can be quite flexible in selecting the source of energy.

The external interaction on the environment in both experiments is based on point load. This is mainly due to being easier than distributed load. This approach opens up investigations into the boundary conditions between the actuator and the environment. This is particular interesting as the sink describes the boundary conditions between the system boundary and the actuator, which would be interesting in underwater applications[91].

5.3.4 Limitations of the experiment approach

The experiment opened an energy-based approach approach to characterise a soft robotic system. The external energy interactions, energy-in and energy-out are observed to derive the efficiency. There are 2 other energy interactions which are approximated (storage) or assumed to be zero dissipation. There are limitations with the experiment approach, which are:

1. The port-Hamiltonian structure has 4 energy interactions and additional instrumentation is required if all 4 interactions are measured.
2. The experiment approach is focused on the energy transfer routing at steady-state (at rest) conditions and as a result, this approach lacks insights into the dynamics of the system.
3. The different mass values in the carrier vary the work done over the same displacement and the total system inertia values vary at the same time, which further increases the difficulty of investigating the dynamics of the system.
4. The data-points are only valid for the given work done and volume input, which are low in sample size because there are only 4 weight values and 4 wall thickness. If this approach is extended to cover more data-points for large data-process approach will be required.
5. Constant flow-rate syringes can be used to apply a constraint to the volume flow rate input. This would provide additional insight into how the system responds to step flow rate input. More data in both domains would be required to capture the response, such as the velocity of the mass, and the rate of deformation of the pneumatic actuator, which can be capture by a camera.
6. The deformation of the pneumatic finger can be captured to approximate the relationship between energy stored and deformation.
7. Friction and hysteresis were ignored which is a valid assumption for low speed as the syringe was compressed slowly.

8. The pneumatic finger actuator is represented by bond-graph elements in both the pneumatic and mechanical domains. Therefore modifying the actuator will result in a different energy transfer characteristics. The 1 mm and 4 mm wall thicknesses can provide the interpolation in between to an extent. The physical component is represented by two different domains makes it difficult to develop in a systematic way, compared to an electrical resist.

9. The pulley experimental layout applied a constraint in the direction of force, which greatly simplifies the interaction with the environment. The angle of the force acting on the finger tip is changing constantly. How this point load is translated to real life application is also unknown.

5.4 Summary

In this chapter, I presented the results of the experiment and discussed the context of System Engineering. The port-Hamiltonian structure provides the abstraction at a system-level and a bond-graph elements representation at the component-level. One of the technical requirement definitions can be a performance requirement of target efficiency and that effectively defines both the requirement of the energy input and energy output. The port-Hamiltonian approach provides one of the logical decomposition models in a Vee-Model framework with bond-graph representations. The design solution definition will require standard blocks of the soft actuation technology. In this thesis, I provided an overall block to describe a type of pneumatic finger. Therefore, it will take the whole Soft Robotics research community to embrace an energy-based approach to define standard blocks for different soft actuation technologies. These standard blocks provide the lower level breakdown to investigate the scale-ability of the energy transfer characteristics. The soft robot developer can verify whether the performance requirement in terms of energy transfer characteristics can be achieved. The move towards System Engineering development of soft robotic systems can begin.

Chapter 6

Conclusion and future work

6.1 Conclusions

In summary, the aim of my PhD research was to investigate the development process of soft robotic systems. The framework follows a Systems Engineering Vee-Model approach, where an abstraction between component-level and system-level with the port-Hamiltonian structure. My work involved the application of bond-graph theory on a range of soft actuation technologies to identify a method of abstraction to characterise all the different technologies. I extended a soft pneumatic actuation into a system and applied the port-Hamiltonian reformulation to investigate the external energy interactions and efficiency of the system as a function of two different design parameters, 1. inner wall thickness, and 2. material properties.

This investigation followed a System Engineering framework, which highlighted the need for an abstraction approach on a system-level and a component-level. The approach has to be applicable to a wide range of soft actuation technologies, and an energy-based approach can be describe the energy transfer in different domains in a soft robotic system. Bond-graph elements can represent the component-level and the port-Hamiltonian structure can represent the system-level.

The main findings of my work include:

- Bond-graph elements representation can cover a wide range of soft actuation technologies.
- A combination of bond-graph elements representations relates to the physical components of the respective soft actuation technologies, which can be defined as a standard block.

- The port-Hamiltonian structure provides 4 energy interactions of a system to analyse and develop on a system level.
- The system in steady-state and at rest will reduce the inductive terms for analysis.
- The energy-in and energy-out (work done) is impacted by a range of design decisions that this approach can identify a way to optimise.

6.2 Impact of work

This work has demonstrated that an energy-based approach is suitable for many different types of soft actuation technologies. The developer can pick the most suitable actuation technology for each application and investigate the scale-ability of each technology in terms of energy transferred to identify suitable applications for future soft robotic systems.

The port-Hamiltonian approach highlights the interaction with the environment which is often forgotten. Soft robot developers can use an energy-based approach to characterise their chosen actuation technology and based on the energy transfer characteristics to refine further the research interest. This work has an impact in the following areas:-

- The development of an energy-based approach in a System Engineering framework to analyse and develop soft robotic systems.
- The categorisation of current soft actuation technologies based on energy transfer characteristics to gain additional insights in the research area.
- The development of an experimental approach for empirically deriving the energy transfer model of the soft actuation system on the system level.
- The energy-based approach will enable the development of more energy-efficient soft robotic systems. Higher efficiency systems will unlock further untethered applications which will move soft robotic applications away from the laboratory into real world practical applications.

6.3 Future directions

6.3.1 Standard energy transfer characterisation blocks on a component level.

Standard energy transfer characteristic blocks for different components have the potential to create more task-orientated soft robotic systems through a System Engineering approach. The effort and flow variables of input and output bonds can characterise the components and the designer can identify parameters that impact the scale-ability of the component in terms of the energy interaction at a system level. The standard blocks on a component level will integrate to the system level to satisfy the top-level requirement.

The potential impact of the standard energy transfer characterisation is the creation of modelling blocks which describe the energy transfer of the component or subsystem. For example, a modelling block that based on an input of an effort variable will output a flow variable back. The simulation approach as described by the perspective paper by Ross et al. [68] where port-Hamiltonian blocks are interconnected.

6.3.2 Energy interaction with the environment.

The Soft Robotics community can focus on the leveraging the external energy interaction with the environment to create task orientated systems. The energy interaction with the surroundings such as in water or airflow. This area is complimentary to the Morphological Computation approaches, where the energy interchange across the system boundary between the actuator and the environment offers an interesting area for research. The Puppy robot by Iida et al. [92] is widely cited as an example of Morphological Computation in action, where the routing of energy input, kinetic energy storage and energy interaction with the environment are the capacitive and inductive energy storage of the robot and the energy interchange between the environment and the actuator forms an interesting starting point to investigate the energy transfer at the system boundary.

The potential impact is that the energy from the environment and energy source of the soft robot becomes less distinctive. The soft robot can utilise the energy from the surrounding to create efficient systems. If the environment can become a source of energy for the system, the distinction between energy source and sink can be removed and interesting untethered soft robotic systems are feasible.

6.3.3 Soft actuation technologies with gyrator energy transformation.

The case of the effort variable in domain 1 transforming into a flow variable in domain 2 provides an interesting actuator design. The high voltage inducing a flow rate of dielectric fluid results in an interesting research direction because this type of actuation has directional advantages and provides more control over the dynamics of the system. The majority of the current soft actuation technologies are based on an effort to effort variable transformation.

The potential impact of a soft gyrator transformation will enable faster dynamic responses. The effort variable at the input applies a constraint to the flow variable at the output. This type of soft actuator can be the soft robotics equivalent of the electromagnetic motor in rigid robotics, which greatly increased the numbers of applications of rigid robotics. A soft gyrator has the potential to expand the applications of soft robotics.

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