Energy-Based Abstraction for Soft Robotic System Development

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Soft robots are designed to convert stored energy into useful work done. Typically, the soft robot designer starts from a type of soft actuation technology at a component level, rather than from a systems engineering level. The characteristics of soft actuation technology may apply constraints on the final system. Bond-graph theory can be used to graphically represent a model of the energy transfer through a system. Top-level abstraction can be in the form of a word bond-graph and bond-graph elements can form a lower component level abstraction. Herein, bond-graph abstraction is applied to different soft actuators and their essential characteristics are identified from an energy-based perspective. Several distinct soft actuation technologies are represented using bond-graph components for each of the key elements: the energy source, the intermediate energy storage, energy dissipation, energy transformation, and the interaction with the environment. By applying this analysis, the soft robot designer is enabled to select the most suitable actuation technology to fulfill their top-level system requirements independently of the actuation domain. A systems engineering approach to develop soft robotic systems leads to more everyday products that impact our everyday lives.

1. Introduction

Soft robotic systems are complex multidomains machines that transform energy from a source into useful work done. The soft actuators convert stored energy from one form, such as chemical, mechanical, pneumatic, hydraulic, and electrical energy, into *mechanical* useful work done.[1] The current starting point to design a soft robotic system is based on selecting a type of actuation technology and only then do designers explore potential applications. This is a bottom-up design approach from the component level. The actuation technology defines the energy transfer characteristics and it may restrict the potential applications of the soft robotic system. A systems engineering inspired top-down development approach starts with a set of requirements which then enable the *design process* to start from a system level.[2] An abstraction approach enables development from a system level to create task-orientated soft robotic systems.

In this review piece, we use an energy-based abstraction based on bond-graphs[3] to identify the key energy transfer characteristics of different soft actuation technologies. The essential energy transfer characteristics enable the soft robot designers to select the most suitable technology for the task or application. This energy-based approach paves way for systems engineering approach to design soft robotic systems.

1.1. Top-Down Development for Soft Robotic Systems

The current soft robotic system development approach starts from a type of actuation technology. The initial choice of the soft actuation technology at the component level defines the rest of the system. The current soft robot development process is shown in **Figure 1**a. In systems engineering, the "V-model" development process starts from a top-level requirement and an abstraction process partitions the requirement into the component level.[4] The designer can use the abstraction to select the most suitable actuation technology to integrate into the system from the component level. The V-model is shown in Figure 1b. At each abstraction level, a feedback between the requirements partition and system integration ensures the final system satisfies 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 at the development cycle.[5]

Soft robotics systems are machines and the key requirement is to transfer stored energy from a source and convert it into useful work done on the environment. Energy and power are the "lingua franca" between different multidomain physical systems.[6] An energy-based abstraction can be used to partition

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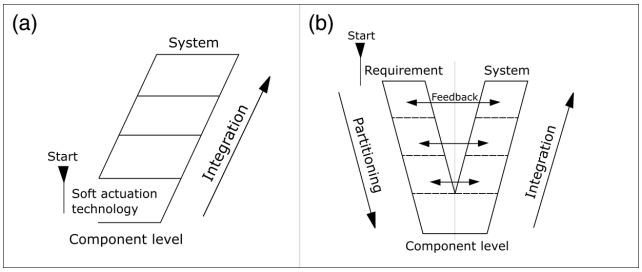

Figure 1. Overview sketch of the development process for soft robotic system and in the context of system engineering showing: a) development from a soft actuation technology defines the component level and subsequently the integration of the resultant system. b) A V-model[4] in system engineering shows that development can start from the top-level requirement and partition down to component level through an abstraction to supplement the integration of the system.

the system down to a component level. Bond-graph models can provide quick validation through measuring the physical variables and verification through further refinement of the bond-graph models.

1.2. Energy-Based Abstraction to Highlight Essential System Characteristics

The RoboSoft research community defined soft robots as "robots/devices that can actively interact with the environment and can undergo 'large' deformations relying on inherent or structural compliance".[7] The top-level abstraction must include a mechanical deformation and active interaction with the environment. Wehner et al. created the Octobot,[8] which is an untethered and fully soft robot. The robot has an energy store, a microfluidic controller, and pneumatic actuators. The hydrogen peroxide tanks stored the chemical energy. The microfluidic and catalysts controlled the flow and reaction rate. The pneumatic actuators transformed pneumatic energy into mechanical energy. The definition of soft robotic system and the example of Octobot defined five energy abstractions: 1) an energy store; 2) how energy is transported into the system; 3) a transformation from one form into the mechanical domain; 4) large mechanical deformation; and 5) an active interaction with the environment. The interaction with environment is more evident with the bio-inspired locomotion robots such as the MIT Cheetah,[9] which shows the interaction with the environment, where the minimum cost of transport approaches those of animals.[10] Tucker observed that aquatic locomotion is more efficient and coincident with soft aquatic robots applications,[11,12] which interacts with the water efficiently. Calisti et al. described a wide range of locomotion modes powered by soft actuation technologies.[13]

Ross at al. demonstrated the importance of a system level analysis to gain predictive capabilities for designers to understand. The authors suggested a perspective step-by-step framework to analyze the thermodynamics underlying soft robotic systems.[14] The framework is based on bond-graph theory[3] and port-Hamiltonian theory.[15] Two bond-graphs examples showed how the energy transfer through the whole system provides a system level view and how performance measures such as efficiency can be optimized and thereby increasing the utility. In this article, we apply bond-graph elements to review different soft actuation technologies to highlight the essential characteristics and functional blocks within a soft robotic system.

1.3. Introduction to Bond-Graph Theory

Henry Paynter developed bond-graph theory as a method of modeling multidomain dynamic systems.[3] The bond-graphs are graphical representations of the energy transfer through a system across multiple physical domains. Bond-graph theory defines that a dynamic system consists of elements that interact by exchanging and transferring energy through interconnecting power bonds.[16] The rate of energy transfer, power, is the product of effort, "e," and flow, "f," variables. The direction of positive power is denoted by a half-arrow connecting one element to another, as shown in **Figure 2**a. The time integral of effort and flow variables are the generalized momentum, "p," and the generalized position, "q," respectively. Bond-graph elements can be classed into single bond and multibond elements. There are three types of single bond-graph elements: sources, energy stores, and dissipators.[17] Sources are denoted by "S," and the subscript "e" or "f" is dependent on whether the source imposes a constraint on the effort or flow variable into the system, respectively. A source is a sink when the power is negative, i.e., energy moves from within the system boundary to the surroundings. The sources describe the boundary conditions of the system. Capacitive and inductive energy stores are the two types of energy stores, denoted by "C" and "I," respectively. C elements store generalized potential energy like an electrical capacitor or a mechanical spring. I elements store generalized kinetic energy like an electrical inductor or a mechanical mass. C elements form a constitutive relationship with generalized displacement and I elements form a constitutive relationship with generalized momentum. R elements dissipate energy like an electrical resistor or a mechanical damper.

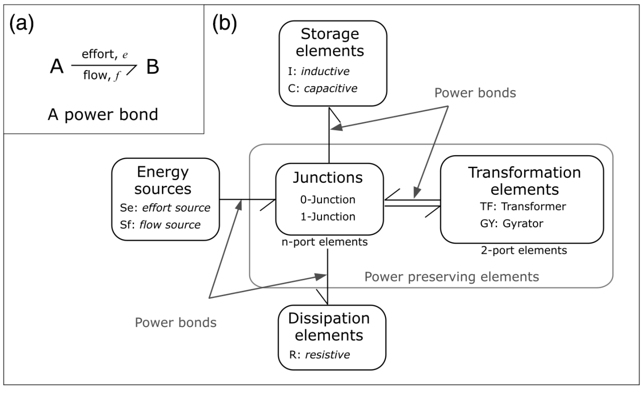

Figure 2. Introduction to bond-graph theory: a) a bond denoting a positive power transferred from element A to element B. The power is the product of the effort and flow variables. b) A schematic diagram that shows how bond-graph elements are connected to each other. Single port elements: sources; storage; dissipation, and 2-port elements are connected to junctions (*n*-port elements). The junctions and transformation elements are power preserving elements which satisfy the conservation of energy.

Junction and transformation elements have more than one bond connected and are power continuous, where the power-in is equal to the power-out, to satisfy the conservation of energy. 0-junctions and 1-junctions have three bonds or more. 0-junctions model a parallel connection, where the effort variables are equal at each bond. 1-junctions model a series connection, where the flow variables are equal at each bond. The transformation elements have two bonds, and are transformer, "TF," and gyrator, "GY." Transformers apply a constraint on the effort variable of the input bond and the effort variable of the output bond, for example, a mechanical lever. Gyrators apply a constraint between the effort variable of the input bond and the flow variable of the output bond. If the transformation is modulated by a function, then a prefix M- is added to the transformation element.

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,[18] where integration has a preference over differentiation. The focus of the article is on the graphical representation of the energy transfer from a system to a component level.

A bond-graph energy-based abstraction of a soft robotic system can be shown in a layout similar to Figure 2b. The sources transmit power into the junctions, and the direction of the arrow denotes positive power. Negative power means the source is a sink. The junction elements route the power into single bond elements (C, I, R elements) and/or two bonds transformation (TF, GY) elements. The transformation elements have two bonds, denoting an input power of one domain transforming into an output power of another domain. The input and output of the transformation elements are connected to junctions which connect to other elements of the representation. The conservation of energy dictates that junctions and transformation elements are power preserving elements.[19] Multiport transformation elements provide an alternative representation.[20]

1.4. Bond-Graph Element Representation of a System for an Energy-Based Abstraction

The first step is to apply a word bond-graph to the soft actuation within a soft robotic system.[14] **Figure 3**a shows the word bond-graph abstraction of a soft robotic actuator. 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 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 word bond-graph in Figure 3a can be replaced by bond-graph elements, as shown in Figure 3b. 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. The product of the effort and flow variables is the power into the system. The bond point away from the source denotes the direction of positive power. The junction is a

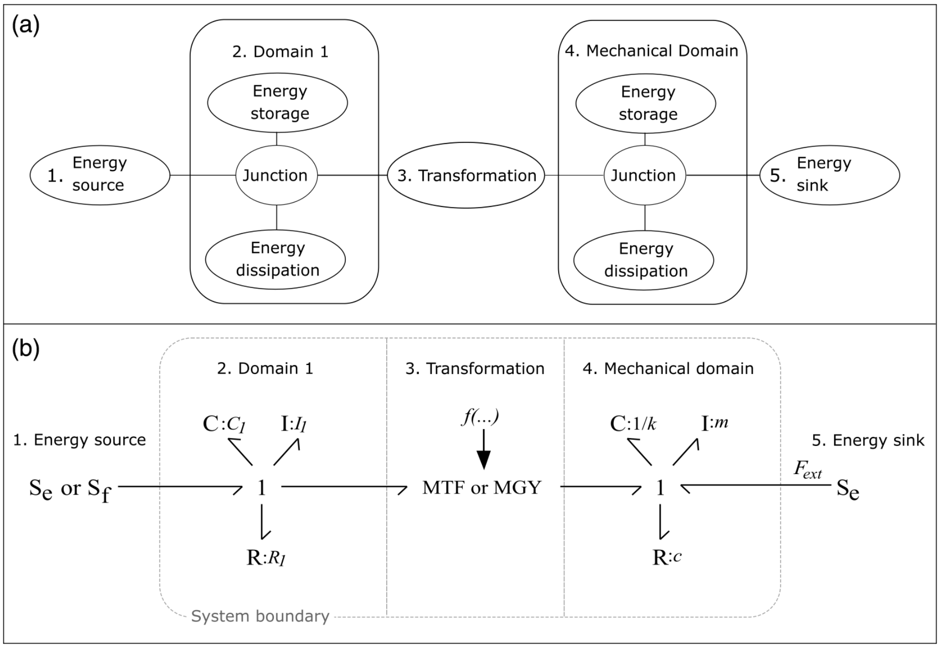

Figure 3. Energy-based abstraction of a soft system: a) word bond-graph showing the five key energy characteristics: the energy source; energy in domain 1; transformation into the mechanical domain; energy in the mechanical domain; and the energy sink. b) The energy-based abstraction represented by bond-graph elements. The source can either apply a constraint on the effort or flow variable. Energy enters the system boundary and dependent on the domain, the energy is stored in the C element and I element, and dissipates through the R element. The actuation technology determines how the energy is transformed into the mechanical domain. The function denotes a nonlinear relationship based on other variables. The large deformation is displacement from the mechanical energy stored in the C element. The energy sink is denoted by the force (effort variable) on the system.

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 in the system boundary. The energy that is not stored or dissipated is routed into a transformation element, which can either be a TF or a GY. The transformation element converts the energy from one form into the mechanical domain. Soft robotic systems are complex multidomain system, thus additional domains and transformation elements can be present. The energy is routed through the three modeling 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 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 standardized blocks and the respective energetic characteristics are revealed.

2. Energy-Based Abstraction of Soft Robots

Soft actuation technologies commonly convert pneumatic, thermal, or electrical energy into mechanical energy.[21] The following subsections present the schematics and bond-graph representations of four soft actuation technologies.

2.1. Pneumatic Actuation

Soft pneumatic actuators are common in soft robotic systems, from locomotion to manipulation tasks.[22] The Multigait robot and the Resilient robot use a quadrupedal arrangement with individual pneumatic networks (pneu-net) to crawl.[23,24] The Arthrobot uses elastomeric "balloons" and tendons to replicate spider-like locomotion.[25] Examples of manipulation are lifting or moving an arm or as a continuum grasper.[26] Multiple chambers can be used to vary the pressure of the system for different arm displacements.[27] The thin inelastic film imposes physical constraint for the volume expansion to vary the arm stiffness with different pressures.[28] A vacuum is used to actuate an exoskeleton spine.[29] Chemicals can be used to transport energy and reactions create a high rate of pressure increase. Combustion is used in jumping robots.[30,31] An electrical spark is required which increases the complexity of the system. Hydrogen peroxide decomposition is used by the Octobot[8] to actuate each pneu-net. The hydrogen peroxide decomposes into hydrogen and oxygen from a liquid reagent to gaseous products and actuates the pneu-nets. Restrictors are used to vent the pressure buildup to the atmosphere for the next cycle.

The schematic and bond-graph representations of a generic pneumatic actuator are shown in **Figure 4**a. The soft pneumatic system is abstracted into the bond-graph element representation of Figure 3b. 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.[32] The energy into the system is routed into pneumatic and 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 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 hyperelastic material, then the majority of the energy is stored in the deformation, which is the capacitive energy storage in the mechanical domain, or if the wall is made from an inelastic film, then the pressure buildup is high and the energy is stored in the capacitive energy storage of the pneumatic

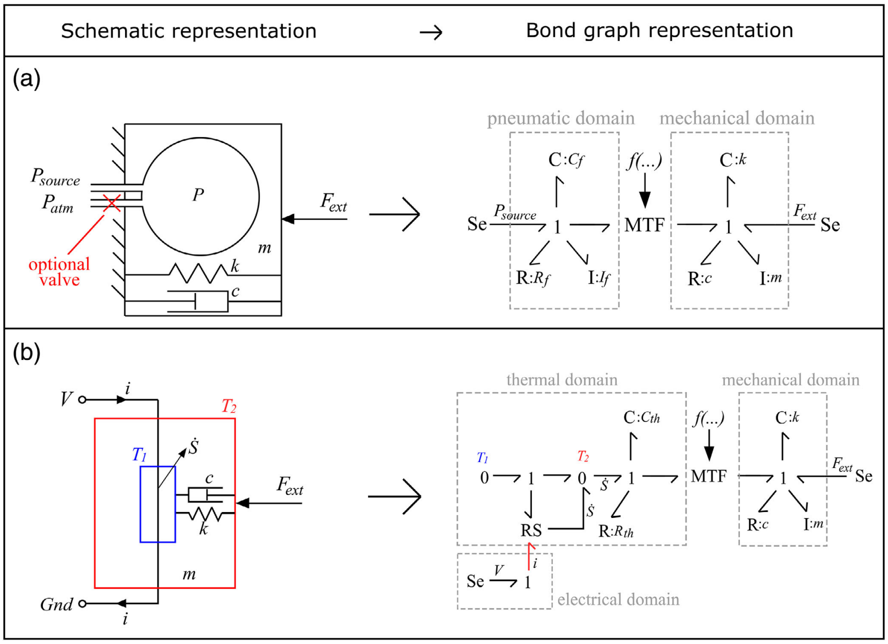

Figure 4. Bond-graph representations of a) pneumatic and b) thermal soft actuation technologies.

domain. The graphical representation also shows once energy entered the system, there are only two routes for the energy to leave the system for the next actuation cycle: 1) a valve to atmosphere which or 2) a restrictor to atmosphere. The importance of inductive energy storage in the pneumatic domain is evident when compared with thermal actuation.

2.2. Thermal Actuation

Thermal actuators rely on thermal expansion and contraction through heating and cooling. Shape memory alloys (SMAs)[33,34] and thermal expansion blocks[35,36] are thermal soft actuators. These actuators have potential to exert large forces.[37] Phase changes, from solid to liquid[35] and liquid to gas,[38] increase the deformation and expansion. Joule heating is a common approach to control the heat source, which adds an electrical domain to the system. The heat energy stored in the actuator and must be dissipated for the next cycle.

The schematic and bond-graph representations of a generic thermal actuator are shown in Figure 4b. Joule heating requires an energy source in the electrical domain. The resistor and source (RS) element is a combination of a resistive element of the electrical domain and a source of the thermal domain.[39] The change in temperature or phase causes a deformation in the mechanical domain and exerts a force. The modulated gyrator and modulated transformer (MGY) 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 heat transfer, specific heat capacity, latent heat of the material, and the geometry. The stored thermal capacitive energy must dissipate through the thermal resistance for the next cycle. Currently, cooling circuits are not implemented in soft thermal actuators. Heat is dissipated to the surroundings.[38] Heat transfer via convection is not accounted in this type of bond-graph analysis. Pseudobonds describe convection but are incompatible with the bond-graphs of the other domains.[40]

The essential characteristics of the thermal actuator show that there is no inductive energy storage in the thermal domain,[41] which makes transporting energy in and out of the system boundary more difficult. The energy stored in actuation must dissipate through heat transfer into the surroundings for the next cycle. The heat transfer characteristics and the ambient temperature will determine the dynamics. These energy transfer characteristics are not ideal for dynamic and efficient systems.

2.3. Electromechanical Actuation

Dielectric actuators are a type of soft actuators that use electrostatic forces to deform a dielectric elastomer. Electrostatic actuators are used in locomotion,[42] grasping,[43] and manipulation.[44] The actuator converts the electrical energy directly 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.[45] The distance between the electrodes will mean the characteristics between compression and extension are likely to be different. Harvest energy from the external environment can improve efficiency of the overall system.[46]

The schematic and bond-graph representations of a generic electrostatic actuator are shown in **Figure 5**a. The electrodes compress the elastomer with electrostatic forces when a voltage is applied.[47] The elastomer undergoes mechanical deformation. The intermediate energy is stored as 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 is modulated by a function of the capacitance. The essential characteristics of the dielectric actuator are the reversibility of the energy transformation compared with the thermal actuator.

Kellaris et al. developed the Peano-HASEL actuator.[44] The authors replaced the dielectric elastomer with an inextensible pocket of dielectric fluid. The force is transmitted through the incompressible fluid. The hysteresis is reduced compared with 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 Figure 5b. The dielectric elastomer of Figure 5a is replaced by a pocket of dielectric fluid. The addition of the fluidic domain and the change from an elastomer to a thin film pocket in the mechanical domain resulted in different energy storage and dissipation characteristics in each domain.

Polymer actuators[20,48] and piezoelectric actuator[49] are other examples of actuation that requires an 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]

2.4. Electromagnetic Actuation

The Wormbot and Linbot use an array of modular linear electromagnetic actuators for locomotion through a range of peristaltic wave motions.[50,51] 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 restoring forces and the soft characteristics. Yamada et al.[52] 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. The power that is supplied through the motors builds up the mechanical energy stored in the elastic strip, and this technique highlights the potential of separating the external interaction with environment with the electrical domain.

A schematic, and the bond-graph representation, of the electromagnetic actuator is shown in Figure 5c. The current induces a force on the permanent magnet. The restoration force

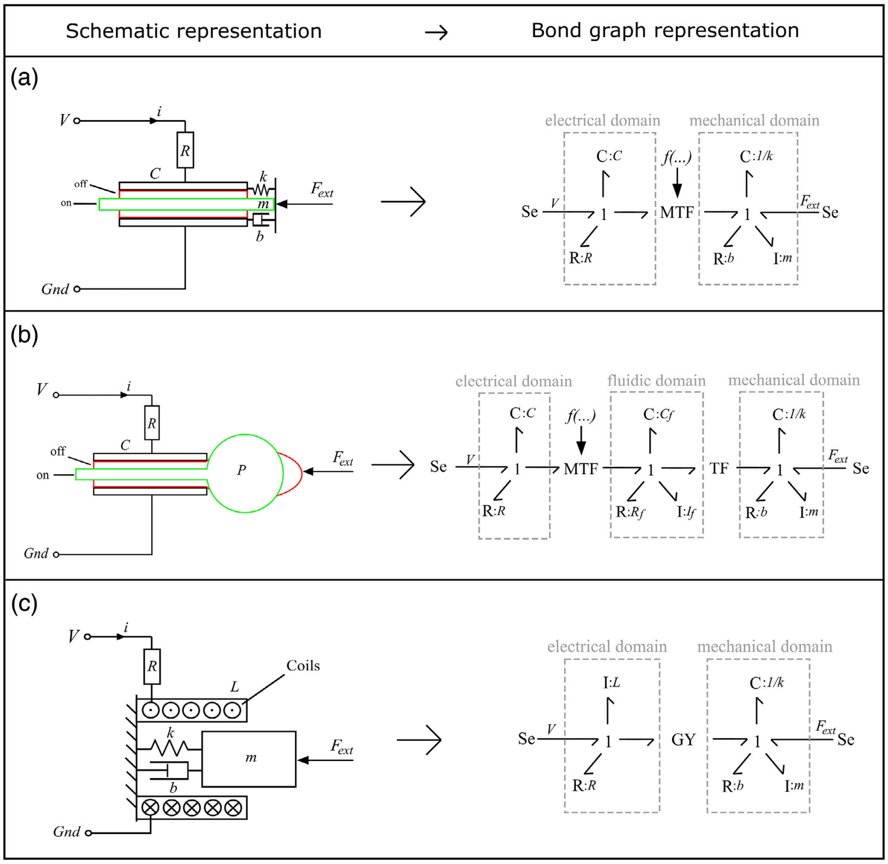

Figure 5. Bond-graph representations of a) dielectrical elastomer actuation and b) Peano-HASEL actuator and c) soft electromagnetic actuation.

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 flow to effort 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 GY 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 an 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 in dynamic applications.

Rotary electromagnetic actuators (motors), normally associated with rigid robotic systems, are used in a soft robotic system context.[53] Soft characteristics can be achieved with rigid components by various designs: series elastic actuators with a temporary capacitive energy storage in series,[54] which is similar to the bond-graph representation in Figure 5c; variable stiffness actuators with a separate energy path to control the stiffness[55]; or an antagonistic approach with two parallel energy paths from source to sink.[56] The distinction between hard electromagnetic actuators and soft actuators fades from an energy-based abstraction point of view.

2.5. Hybrid Domain Actuation

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.[12] 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] The interaction with the environment will be important to characterize to observe the useful work done. Cacucciolo et al. combined electrical and fluidic domain through conduction electrohydrodynamics.[58,59] The direct transformation from electrical into mechanical energy is through the interaction between the electric and flow fields. The interaction acts as an effective GY where the high electrical voltage transformed into a fluid flow at the output.

The hybrid domain actuators provide additional energy transfer characteristics through the addition of a fluid domain as a chemical energy carrier, a chemical reaction that directly induces a force, and fluid flow induced directly from an electrical field.

These hybrid systems can also be abstracted into bond-graph representations and may prove more suitable for certain applications.

3. Conclusion

In this review piece, we showed how bond-graph theory can generalize different soft actuation technologies into energy-based bond-graph representations. This energy-based abstraction enables a systems engineering development approach where the designer can connect the top-level requirement of the soft robotic system to the energy transfer characteristics represented by bond-graph elements. The bond-graph abstraction enables validation at the system level and verification at the component level which captures the essence of the V-model in systems engineering.

The key energetic characteristics are identified into 1) the energy source, 2) intermediate energy storage, 3) energy dissipation, 4) transformation, and 5) the interaction with the environment. The designer can use this standardized model of bond-graph elements to compare different actuation technologies and to select the most suitable one to integrate into the system. This approach can supplement actuation technology-specific system level analysis like the pneumatic supply system work from Joshi and Paik[60] to investigate other technologies. Other approaches can be applying port-Hamiltonian reformulation to characterize system efficiency,[61] or developing an energy-based controller.[62] This energy-based abstraction offers a step toward applying a systems engineering approach, and this type of thinking and analysis should help to mature soft robotic systems into products that will impact our everyday lives.

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Conflict of Interest

The authors declare no conflict of interest.

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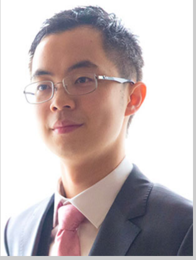

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