# Towards more Energy Efficient Pneumatic Soft Actuators using a Port-Hamiltonian Approach*

Ho-Tak D. Chun, Jamie O. Roberts†, Mohammed E. Sayed†, Simona Araci†, and Adam A. Stokes

***Abstract*— Soft pneumatic actuators are very popular in the soft robotic community due to their ease of manufacturing and simplicity of control. Currently, the efficiency of such soft actuators and their ability to do useful work are rarely investigated in a formal approach. The lack of task-orientated development approaches presents a barrier to utilize soft robotic systems in our everyday lives. In this paper, we describe an experimental approach based on port-Hamiltonian theory applied on a type of pneumatic network (pneu-net) actuator to investigate the efficiency of task-orientated work. We can obtain efficiency from the external interactions of the port-Hamiltonian system. If we can minimize the internal energy interactions, then the power continuous nature of the port-Hamiltonian structure ensures more input energy will result in more useful work done at the output. We found out that higher efficiency actuators can be achieved with a softer material and a thinner wall thickness in the desired direction of the deformation. The internal mechanical energy storage is reduced as a result. However, if the task requires a higher work-done then a stiffer material is required. We can start to define a design approach based on the task. The task can be generalized in terms of energy. We can select the material properties suitable for the magnitude of work done. We can design the geometry to minimize the internal energy stored. The empirical model of the port-Hamiltonian structure provides insights into how the mechanical efficiency varies in terms of design parameters and the port-Hamiltonian approach is a step towards more practical, task-orientated soft robotic systems.**

## I. INTRODUCTION

Soft actuators have advantages when compared to traditional rigid robotic systems due to their inherent compliance [1]. Pneumatic soft actuators, and in particular, the ‘pneu-net’ actuator [2], became popular among researchers in various applications, despite their low mechanical efficiency [3]. A thermodynamic analysis of how the energy is transformed into useful work done will provide valuable insights into actuator development for practical applications where the energy efficiency is a key performance criterion.

### *A. Background*

The pneu-net is an intrinsically soft device that uses a pressure differential to induce deformation. Pneu-nets are used in a range of applications. Shepherd et al. [4] and Tolley et al. [5] used pneu-nets in locomotion and Ilievski et al. [2] made a gripper from pneu-nets. Different performance criteria and applications have been developed recently. Mosadegh et al. [6] developed a design that achieved high actuation rates to play the piano. Wehner et al. [7] integrated control functionality within the fully soft Octobot. Polygerinos et al. [8] applied pneu-nets into an soft pneumatic glove for rehabilitation. The pneu-net, like other intrinsically soft devices, is ideally suited for physical human-robot interaction and it is important for these devices to perform useful work efficiently.

Individual aspects of a pneumatic soft robotic system have been characterized. Sun et al. [9] characterized the common soft elastomeric materials. Wehner et al. [10] investigated the characteristics of different pneumatic energy sources and highlighted the importance of matching the pressure and flow rate. Nemiroski et al. [11] performed a thermodynamic analysis on a single Arthrobot joint to evaluate the energy efficiency, but the paper did not provide any insight into how the energy is transferred through the system.

A port-Hamiltonian system is a port-based modelling approach aimed at providing a “lingua franca” for the modelling of multi-domain physical systems [12] based on energy. 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 [13]. 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].

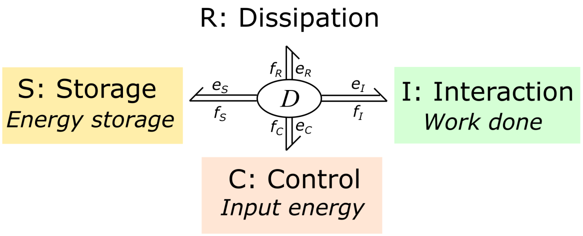

Fig. 1. A port-Hamiltonian system. The Dirac structure, $D$, defines a power-continuous connection between the energy interaction ports. Internal energy interactions are represented by the storage port, S and the dissipation port, R. The external energy interactions are represented by the control port, C and the interaction port, I.

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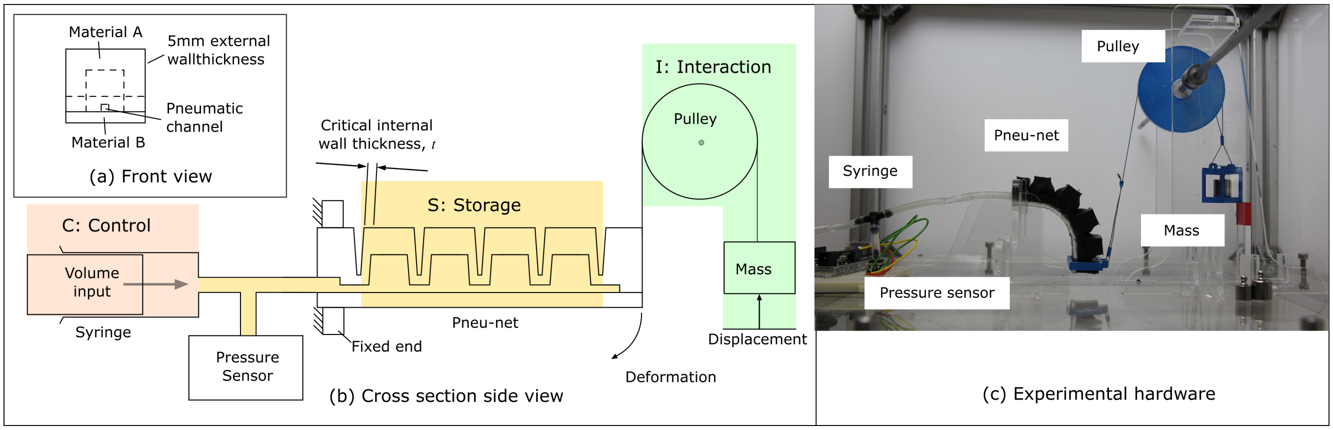

(a) Front view

(b) Cross section side view

(c) Experimental hardware

Fig. 2. (a) shows the front view of the pneu-net actuator. The pneu-net is made of material A and B bonded together. (b) shows the cross sectional side view of the pneu-net actuator and the schematic of the experiment. The critical internal wall thickness controls the deformation. The fixed end of the actuator is connected to a syringe and pressure sensor. The free end of the actuator is connected to a pulley and mass system to measure the useful work done. The different coloured areas and labels refer to the port-Hamiltonian structure in Fig.1, where Control, C, denotes the energy input through a volume input. Storage, S, is the energy storage element and Interaction, I, is the work done. (c) shows the experimental hardware.

Ross et al. [14] provided the background information about the potential of using port-Hamiltonian theory to control and simulate soft robotic systems. Fig 1 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 in Fig. 1.

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 the generalized 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 [13],

$$\frac{dH}{dt} = \langle e_S|f_S\rangle. \tag{1}$$

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

$$\langle e_S|f_S\rangle + \langle e_R|f_R\rangle + \langle e_I|f_I\rangle + \langle e_C|f_C\rangle = 0. \tag{2}$$

We assume friction to be negligible and that there is no leakage of gas or pressure.

$$\langle e_R|f_R\rangle = 0. \tag{3}$$

The control port and interaction port will have the following relationship based on (1), (2), and (3),

$$\frac{dH}{dt} + \langle e_I|f_I\rangle + \langle e_C|f_C\rangle = 0. \tag{4}$$

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 (4) and integrate with respect to time,

$$H + \int P\left(\frac{dV}{dt}\right)\mathrm{d}t + \int F\left(\frac{dx}{dt}\right)\mathrm{d}t = 0. \tag{5}$$

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

$$PV = -H - Fx. \tag{6}$$

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

$$\xi = \frac{Fx}{PV}. \tag{7}$$

In this paper, we focus on the external energy interactions. More information and the mathematical background on the port-Hamiltonian approach can be found in the textbook by Duindam et al. [15].

## II. EXPERIMENTAL DESIGN

We designed an experiment to analyze the external energy interactions of the pneu-net actuator and investigate the efficiency. We used a Design of Experiment (DoE) [16] approach to derive the list of experimental trials to compute the statistical models of the efficiency. Fig. 2 (b) shows the schematic of the experiment. The entire soft pneumatic system is defined as the syringe, pneu-net actuator, pulley, and mass. The control interaction is the energy-in, which is given by the volume input from the syringe and the resultant change of pressure. Therefore, the friction and inertia of the plunger of the syringe is not accounted. The external interaction is the work done which is measured by the magnitude and the displacement of the mass. The rest of the energy is routed to the energy storage, $H$, which is a function of the internal wall thickness and material of the pneu-nets. The thermodynamic assumptions are that the work done is isothermal and the system is closed. We considered the dissipation to be zero because there is no leakage and friction is negligible. The interactions of the port-Hamiltonian structure in Fig. 1 are labelled in Fig. 2 (b).

### A. Preparation of materials

The schematic of the experiment and the actual hardware set-up are shown in Fig. 2 (b) and (c) respectively. We used laser-cut 5mm acrylic to construct the test fixtures. The test fixtures included a stand to mount the pneu-net and a separate stand 85mm apart to mount the pulley. The distance between the two stands was the length of the pneu-net actuator, which enabled the full deformation and actuation of the pneu-net. We used a 60ml syringe to provide the volume input. We used a T-piece to connect the pressure sensor and the actuator with the syringe. We created a closed volume for the experiment. One end of the actuator is fixed to the test fixture and a ring is used to connect the free end to the mass via a light weight and inextensible line to the pulley.

The pneu-net actuators are made of Material A and Material B as shown in Fig. 2 (a). We used Ecoflex 00-30 and Ecoflex 00-50 for Material A and polydimethylsiloxane (PDMS) for Material B. We used Solidworks to design the moulds based on a design by Mosadegh et al. [6]. We modified the mould with a 5° draft angle on the critical internal walls to aid the removal of the pneu-net from the mould. We used a 3D printer (Copymaster 3D 500) to manufacture the moulds to cast pneu-nets of different internal wall thicknesses ranging from 1mm to 4mm. We mixed the Ecoflex as per the manufacturer's instructions, degassed, and poured into the moulds. The mould for the PDMS was made from laminated 2mm acrylic sheets for a consistent thickness. We left both materials to cure for 12 hours. We bonded the two materials together with Sil-Poxy and we also used Sil-Poxy to bond a 5cm silicon tubing (6mm outer diameter / 4mm inner diameter) to the pneumatic channel for the volume input. We fabricated eight pneu-nets as listed in Table I. We used Sil-Poxy to bond the fixed end of the pneu-net to a detachable acrylic mounting for each pneu-net.

### B. Methods of Measurement and Characterization

We measured the work done and the energy-in 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. We used a marker to set the displacement. We 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 to the system. We used a pressure sensor (BMP280) with a serial output to a laptop to record the pressure change. We measured the volume input from the syringe which had 1ml interval.

TABLE I

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 |

The measurement errors are summarized in Table II. The internal wall thickness and the volume input are the major error contributions. The volume readings can be repeated. 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. We placed additional alignment holes in the moulds to improve the accuracy of the castings.

TABLE II

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 |

We used JMP [17] to characterize the efficiency of the pneu-net actuator with respect to the internal wall thickness, work done and material type (Ecoflex 00-30 and Ecoflex 00-50). The output profiles are predictive models of the efficiency as a function of the internal wall thickness and the work done for different materials. The statistical model required a definition of the responses and factors. The responses were the efficiency, volume input and the pressure increase. The factors were the following: (1) wall thickness, (2) material type, and (3) mass.

We used the JMP DoE function to randomize the list of experiment trials and to generate the predictive model. We measured the volume input and pressure change for a given wall thickness and mass for that experiment trial. The wall thickness ranged from 1mm to 4mm and the mass ranged from 10g to 40g. The work-done was over a 70mm displacement. We repeated each pressure and volume readings five times and used the average. We applied this method for both Ecoflex 00-30 and Ecoflex 00-50 to provide

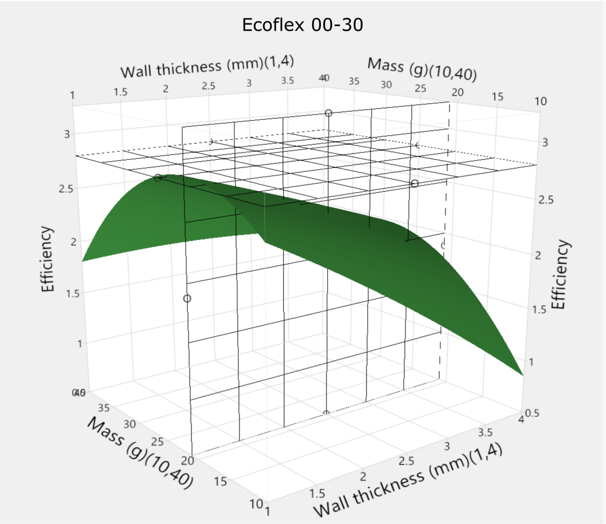

Fig. 3. The efficiency surface profile of the pneu-nets made of Ecoflex 00-30 shows the highest efficiency at 1mm thickness and an optimal work-done on a 25g mass.

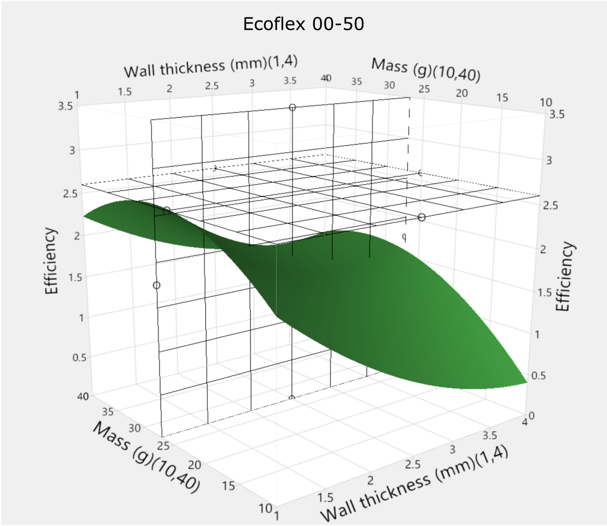

Fig. 4. The efficiency surface profile of the pneu-nets made of Ecoflex 00-50 shows the highest efficiency at 1mm thickness and an optimal work-done on a 27g mass.

a comparison between the two materials. The statistical relationship provides insights into the external interactions and the Dirac structure of the port-Hamiltonian.

## III. RESULTS AND DISCUSSION

### A. Results

*1) Efficiency as a function of wall thickness and work done:* The results are efficiency response-surface plots as a functions of the wall thickness and the mass. Fig. 3 and Fig 4. show the efficiency response-surface plots for Ecoflex 00-30 and Ecoflex 00-50 respectively. The overall efficiency of the pneu-net 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 atmosphere. The efficiency can potentially increase if the pneumatic energy stored is vented to an intermediate pressure and routed back into the input.

We 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.

We compared the efficiency for Ecoflex 00-30 and Ecoflex 00-50 pneu-nets in table (III). We 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 [18], while other material properties are similar. The pneu-net actuator is more efficient with a stiffer material at higher work done. The high work done, low wall thickness is the ideal quadrant to move towards more energy efficient actuators with a higher work done.

TABLE III
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 $\xi$ (%) | Ecoflex 00-50 $\xi$ (%) |
|---|---|---|---|
| 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) |

### B. Discussions

*1) Efficiency characterization by a port-Hamiltonian approach:* The Interaction, I, and Control, C, of a port-Hamiltonian structure provides the mechanical efficiency. The mechanical efficiency of the pneu-net design in this study was low as summarized by Table III. The Arthrobot, from the study performed by Nemiroski et al. [11], had a comparable efficiency of 1%. The Arthrobot elastomeric expansion was not constrained which lead to a lower efficiency. Fibre reinforced pneu-nets [19], [20], [21] can limit the expansion in the direction, which does not contribute to the work done to increase the efficiency. The pneu-net used in our experiment had external wall thickness of 5mm, as shown in Fig. 2 (a), and when the internal wall thickness was 4mm, the direction of deformation changed. The direction of deformation is difficult to control with only one material. The fabrication process increases in complexity with the fibre reinforcement compared to the simple two-layer pneu-nets used in this experiment.

The energy-based view focused on the energy-in and work done by allowing us to overlook the dynamics of the system and the changes in the geometry and the direction of the force. The compressibility of air and the hyper-elastic expansion of the pneu-net are accounted in the energy storage of the port-Hamiltonian structure. Port-Hamiltonian structure is useful in reformulating the system into which energy interactions to investigate.

*2) The pneumatic energy storage:* The internal energy storage, $H$, has a pneumatic energy storage component in addition to the mechanical energy storage. The initial chamber volume varied with different wall thickness because the external dimensions of the actuator is constant. The difference is low compared to the total volume of the system including the 60ml syringe. There are pneumatic actuators which have zero initial chamber volume by Park et al. [22]. The initial volume can be another factor that affects the energy routing of the system.

*3) Task-orientated development approach with external interactions:* This study also showed the importance of the external interaction on efficiency in task-orientated work. The task in the study was to lift a mass 70mm vertically via a pulley. The total work done for 40g is 0.027J, given by $mgh$. The energy-in ranges from 0.5J to 1J. The scalability of the work done to perform practical everyday tasks for soft pneumatic actuators remains an open question. We can begin to answer the question by characterizing the task into work done over a given geometry. A specific stiffness can match the magnitude of the work done. The geometry can be optimized through minimizing the critical wall thickness and initial volume to maximize the efficiency. An energy density measure of the energy stored over a volume can characterise the usefulness of a type of actuation and the ability to match the work done requirements. We need further work in characterizing the task in terms of energy and matching the suitable stiffness to create a task-orientated development approach for soft robotic systems.

*4) Future work:* The dynamic case will provide further insights into the internal energy interactions; energy storage, $H$ and the dissipation, R. The energy storage has both inductive and capacitive energy components. The inductive and capacitive energy storage can provide a dynamic, empirical model of the actuator [14]. The energy stored can provide the state of the actuator. We can move away from the kinematic and positional control of soft robotics systems and move towards dynamic and force feedback control for interaction with unstructured environment. In future work, we will analyze how the energy stored is affected by dynamic changes from the external energy interactions.

## IV. CONCLUSIONS

The port-Hamiltonian approach provides a convenient structure to derive the mechanical efficiency based on the external energy interactions. The work done on the environment and the energy-in are key factors if the soft robot is to be useful and practical. This approach includes a focus on external energy interaction as a step towards the development of energy efficient and task-orientated soft robotic systems.

The pneu-net actuator is characterized into energy interactions in terms of design parameters. The designer can focus on the interaction requirement and select suitable design parameters. The energy-based generalization provides a high level abstraction and opens up the comparison between different soft robotic technologies to match the energy interaction characteristics with the task.

This empirical model-free statistical description of the actuator can be applied in the control and simulation of soft robotic systems [14] in a predictive feed-forward control based on the external energy interactions. The internal energy interactions provide an additional avenue to control the soft robot by the interconnection of different energy storage and dissipation elements [23]. The internal energy storage describes the dynamics of the system and the dynamics can be exploited for control with morphological computation [24].

Application of the port-Hamiltonian approach is useful in the development, characterization and control of soft robotic systems, by using this approach the next generation of soft robotic systems will be more practical and useful.

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