Practical control methods for vacuum driven soft actuator modules

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***Abstract*—Vacuum-powered Soft Pneumatic Actuator (V-SPA) Modules have been described to afford advantages for rapid development of reconfigurable, multi-DoF soft pneumatic robots powered by vacuum by reducing their logistical complexity, however they also present new challenges in the control of resulting systems. This framework features modules joined together over a simple embedded pneumatic and serial communication network and requires a unique approach to both low-level control implementation and high-level control strategy. We describe the structure and activation characteristics of a V-SPA Module and present practical methods for its control. These methods utilize software generated PWM activation through a unique serial protocol designed for LED networks and a heuristic mapping strategy for simplifying the spherical control of 3-DoF actuator modules.**

***Index Terms*— Soft pneumatic actuators, heuristic control, modular robots, vacuum power, vacuum actuators**

I. Introduction

As the field of soft robotics continues to grow, new challenges presented to the community continue to expand and diversify as well. While the initial task of soft robotics research was to develop new methods of performing work and force output using both smart materials and pneumatic pressure, subsequent effort has begun to focus on the control of systems powered by these new soft technologies. Both efforts are still very present and ongoing, with a large variety of Soft Pneumatic Actuators (SPAs) to be found representing the diversity and scope of interest in the domain [1]–[6]. While the cornerstone of research in soft robotics will always focus to some extent on developing new core technologies, as new fabrication process are developed [7], [8], new materials are engineered [8], [9], and different applications become the target of compliant robotics [10]–[12], a wider, system-level view of design is becoming increasingly necessary in order to facilitate the control and integration more complex multi-DoF soft robots. Examples of such systems have been pursued and successfully implemented, including soft manipulator arms [13]–[15], and mobile robots [16], [17], however, they are still developed through independent effort without approaching the task of soft pneumatic system design in a truly systematic way.

Our approach to enabling more efficient design of SPA based systems is through the integration of common subsystem components into modular, interchangeable *electro-pneumatic* base units. Previous work presented the development of V-SPA (Vacuum-powered Soft Pneumatic Actuator) Modules which leverage this approach to realize multi-DoF soft robots with extended peripheral capabilities powered by vacuum as a single power source [18]. The use of vacuum powered actuation is not an important or necessary aspect of this method for modular soft robot design, as it is possible to develop similar modules powered by more conventional SPAs, however their function and control can be generalized for application in either case.

V-SPA modules allow for the rapid development of large-scale soft robotic systems without the need for deep consideration of low-level design. Other work has investigated the use of modularity to leverage soft-system “bottom-up assembly” [19], however this work neglects the remaining challenge of logistical integration and control. The key concept of leveraging *decentralized control* to accomplish plug-and-play functionality has been explored to a certain extent through robots with control valves locally integrated near the actuators [20], [21], and others which use the supply line itself to address individual actuators in series [22]. These ideas touch on the importance of decentralized control as a means to accomplish particular design objectives, but do not formalize the concept in a way that can be extended as a design rule to enable other complex, or multi-DoF soft systems to be rapidly, and easily implemented. Furthermore these do not offer solutions or methods for simplifying the *control strategy* for the large-scale soft systems which are produced.

It is our aim to develop and validate a topological and control framework for reducing the complexity and design effort required to realize new and more capable, multi-

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functional, multi-DoF soft robotic systems, through the investigation of V-SPA Modules. Here we will demonstrate:

- A *plug-and-play* reconfigurable, 3-DoF soft robot actuator module, the V-SPA Module
- PWM control characterization of a V-SPA Module
- A heuristic strategy for simplified control of decentralized soft actuator modules

II. V-SPA Module Description

V-SPA Modules enable rapid and robust design and reconfiguration of soft robots, by consolidating hardware in a more efficient and plug-and-play package. A module is comprised of two main sections: actuator units, and embedded control network hardware. The first of these is comprised of multiple V-SPAs. The second section contains integrated electrical and pneumatic control hardware key to enabling modular and reconfigurable functionality. See Fig. 1 for the main components of a V-SPA module.

A. Vacuum-powered Soft Pneumatic Actuators (V-SPAs)

V-SPAs posess unique attributes useful in many soft robotic systems, especially with many-DoF. Being comprised primarily of foam and only a thin layer of silicone rubber,

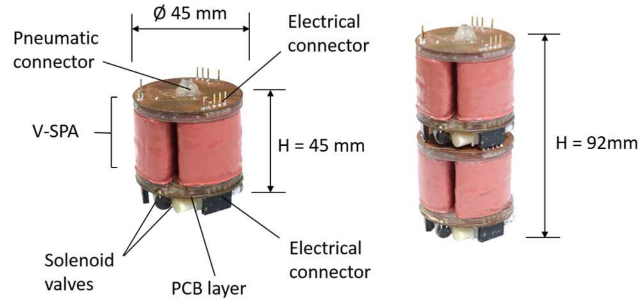

Fig. 1. The upper half of a V-SPA Module contains three vacuum powered soft actuators, and an interface plate for serial stacking of other modules. The lower half contains a PCB and control valves, used to address each actuator independently.

these actuators are exceptionally lightweight, for given torque output. Utilizing vacuum for actuation, they also offer failsafe operation which prevents over pressurization or explosive failure, and sets a natural saturation limit on force generation beyond the threshold dictated by ambient pressure. These actuators are arranged at 120° intervals to form a cylindrical V-SPA Module with 3-DoF, corresponding to each of the three actuators utilized (see the inset of Fig. 2.). The top and

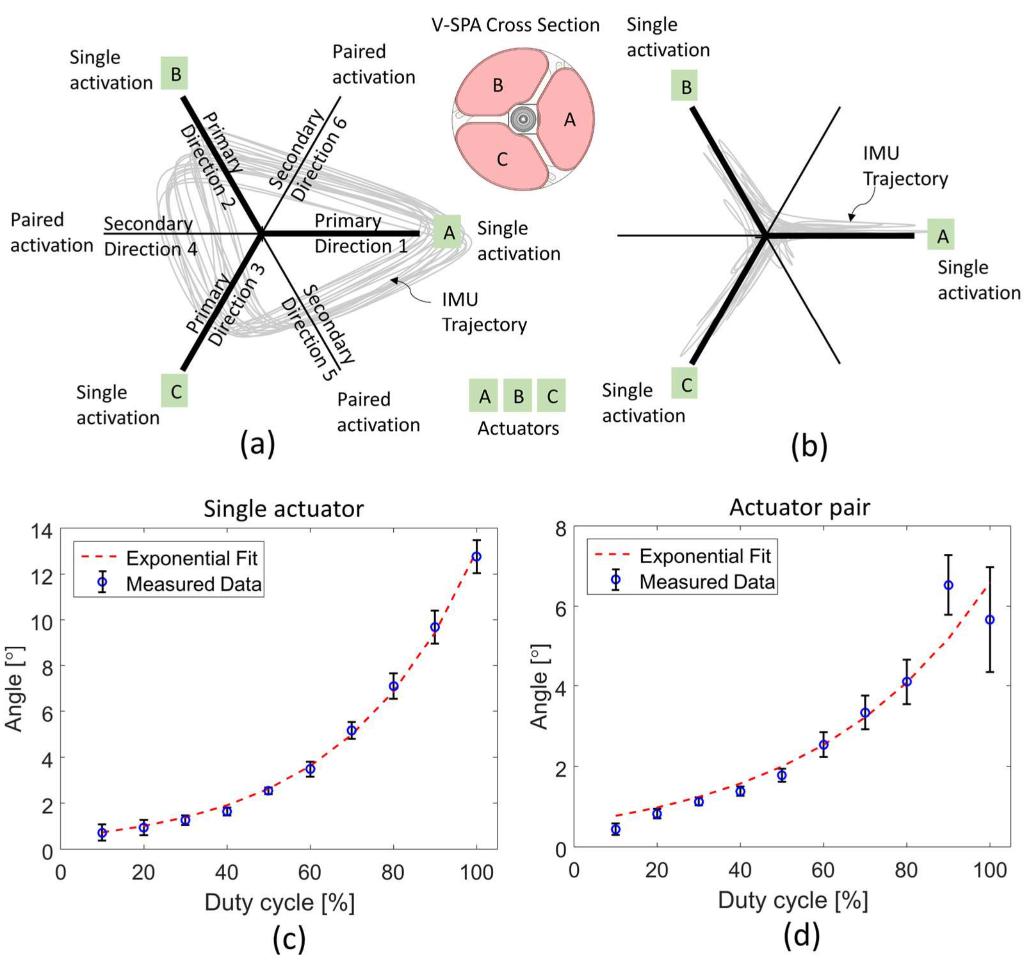

Fig. 2. (a) A cyclic test was performed using only binary actuation to command a V-SPA Module to each of its three primary deflection directions sequentially, and an Inertial Measurement Unit (IMU) recorded the angular trajectory shown in grey. (b) A 10-cycle test was performed on an V-SPA Module with a PWM controlled sweep of each actuator from 0-100% duty cycle. The trajectory of an IMU mounted to the module is shown in grey. While the path is not as repeatable as the binary control method, it does not deviate significantly from the primary plane of actuation. Part (c) depicts the relationship of control commands to angular output for a single actuator and shows minimal error. Part (d) shows a similar measurement taken with two adjacent actuators activated together to produce motion along the secondary directions of the V-SPA Module, yielding lower angular output and higher variability. In both (c) and (d) a model was obtained by fitting an exponential to measurements taken at multiple positions from 0-100% duty cycle.

bottom surfaces of the actuators are attached with an adhesive to rigid plates, which are only otherwise supported by a flexible central silicone tubing conduit to which the vacuum supply is attached. This flexible central conduit acts secondarily as a constraint only to limit vertical motions of the top and bottom plates of the module, but otherwise allows angular displacement of the plates, forming the basis of a soft joint. With three actuators, this joint is capable of angular displacement in any radial direction depending on the combination and degree of activation of the individual actuator units [18].

B. Decentralized Control Hardware

The critical components required to facilitate features of modularity in V-SPA Modules include solenoid valves (Lee, LHDA0531115H), RGB LED driver ICs (WS2811), and mating interface connectors. The integration of valves directly in place with the actuator units eliminates the need for independent supply lines to peripheral control manifolds. Additionally, a single pressure supply line is utilized and distributed to each actuator through an internal onboard manifold from an off-board pressure source, while pneumatic connectors at the top and bottom of the V-SPA Module allow each to be serially connected to additional modules by simply joining the shared supply. To compliment the reduction in the number of pneumatic supply lines to many actuators across many modules, a similar reduction in electrical control lines was achieved by adopting the use of LED driver ICs to enable communication to all modules over a single electrical signal line. Typically used for independent control of 3-channel LEDs used in large matrix displays, the outputs of each IC are connected to amplifier circuits capable of then driving the

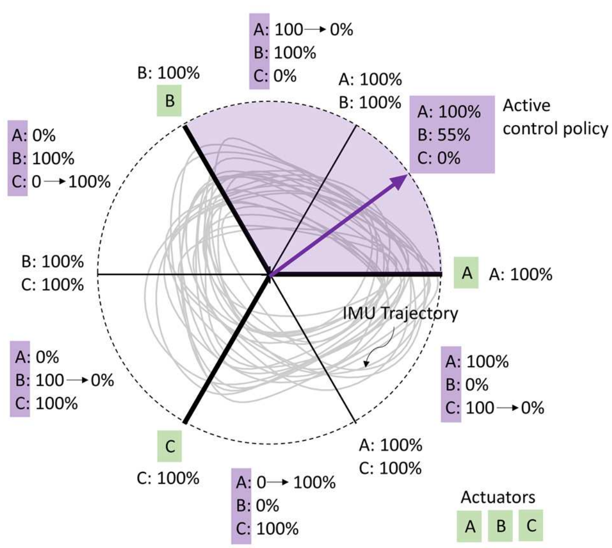

Fig. 3. This heuristic control map translates a two-dimensional virtual control vector (large purple arrow) into actuator commands for a V-SPA Module. Each of the three major regions bounded by the actuator lines of action are subdivided further in half to yield 6 distinct regions wherein the control policy to each actuator unit is unique as a function of the control vector. The allocation of control effort in terms of duty cycle is proportionally determined as a function of angular proximity to adjacent actuators. This model was used to translate two-axis joystick commands to approximate spherical motion control, as well as for following a repeating cyclical trajectory, measured by an IMU and traced out in light grey.

solenoid valves onboard the V-SPA Modules, using the same digital protocol developed for controlling light displays. Electrical connectors serve a similar purpose to the pneumatic connectors, allowing a single signal connection in addition to electrical power from an off-board central microcontroller and power supply, respectively, to be passed between adjacent modules and shared.

A large benefit to this design is the current extensive ubiquity of the hardware and software, which makes the parts available at very low cost and at very small scales (many LEDs contain the same circuitry *built into* the diode housing). While some drawbacks may be found in comparison to other alternatives using dedicated, embedded microcontrollers in every module, the simplicity of the settled solution offers even more benefit in their place. Among already mentioned advantages, the RGB driver solution is demonstrably robust, allowing real-time connection and disconnection of modular devices without interruption to communication with other modules, allowing for truly *plug-and-play* actuator modules.

III. Control Methods

V-SPA Modules enable a unique capability to directly and independently control each of many active DoFs in complex soft robotic structures over a single, shared communication line in either of two possible modes, depending on the intended application. For rough positioning tasks, a fast and highly repeatable method of *binary* actuation may be employed. To achieve more high resolution positioning, V-SPA Modules can also be controlled via Pulse Width Modulation (PWM) of the onboard solenoid valves. Either of these methods can be adopted by other soft robots of similar or various morphologies, and are not unique to the modules developed here.

A. Binary Actuation

The most straightforward and simple method to control V-SPA Modules is through the discrete, binary activation of each embedded actuator control valve. In this mode, each valve is either completely ON or OFF, and the resulting motion of the module is limited to fixed positions, as shown by the three corners of the grey motion trajectory of a module traced in Fig. 2a. The trajectory shown depicts the angular deflection of the V-SPA Module along the two axes defining the motion, and not the absolute position of a marker through space. In this way, although the motion of the module is spherical in nature, the angular trajectory shown encompasses this information in a 2D format. The difference in maximum deflection in each primary direction reveals stark variability between different actuators, which results primarily from the non-homogeneous manual fabrication methods employed in their construction. Despite this however, the motion of the actuators is seen to be repeatable as the shape of the trajectory remains similar for many cycles.

Many other systems have been studied both for the design of novel binary actuators, and to derive efficient methods and algorithms for computing inverse kinematics, and path planning [23]–[26]. A particular benefit to this technique is the avoidance of transient nonlinear behavior which is often the crux of soft systems control. Only the endpoint of the actuator needs to be considered, and furthermore, the selection of configurations of a binary robot, even with many DoF is finite, greatly simplifying the effort needed to control this type of robot. With three actuators contained in each V-SPA Module, this yields three angular set-points along *primary* lines of action, corresponding to the activation of only a single actuator at a time. Additionally, the actuators in a V-SPA Module can be activated in adjacent pairs, yielding three set-points along *secondary* directions, directly opposite the primary ones.

Fig. 2a and Fig. 2b illustrates these six directions of motion resulting from only binary activation which can be utilized most effectively by incorporating multiple V-SPA Modules in a given system, particularly in serial configuration. In this arrangement, the combinatory multiplication of fixed positions yields even greater possibilities for workspace coverage. In applications where great accuracy is not required this may be sufficient alone, however the same modules can be used for intermediate, or continuous positioning if desired using an alternate mode of activation, through PWM.

B. *Continuous Actuation Using PWM*

Continuous, non-discrete, operation of V-SPA Modules may be found useful in applications requiring accuracy greater than that made possible by discrete actuation alone. Soft actuators can achieve intermediate positions, between entirely at rest and fully inflated, by varying their supply pressure. One way to regulate the pressure supplied to an actuator is indirectly through the modulation of flow, using PWM control of high-bandwidth solenoid valves. By changing the duty cycle of electrical activation for a valve connected to an SPA the actuator can be commanded to variable positions determined by an often nonlinear relationship. This mapping varies with the specific actuator, valve, and pneumatic components used to connect the system together, but can be characterized and fit with a model to provide a useful reference for open and closed loop control. Fig. 2b shows the trajectory of a V-SPA Module through multiple cycles of single actuator under PWM control, sweeping through a full range of duty cycle input values. An exponential trend was revealed across varying duty cycle values relating to the output angle of deflection, for single and paired V-SPA activation, shown in Fig. 2c and Fig. 2d, respectively.

While the method of PWM control of flow and pressure is not novel in the field of soft robotics [27], the implementation of this method in the framework of the V-SPA Module architecture requires an indirect and unique approach to achieve the same goal. As the valves are built into the modules and networked through a dedicated communication IC over a shared signal line, they cannot be directly powered from a PWM signal generator, as is typically done. Instead, every channel of the onboard communication IC is addressed using a timed, 24-byte protocol regulated by a centralized microcontroller and software functions. For this reason, a custom "soft PWM" signal generator was necessarily created to send encoded command updates at high frequency from a 32-bit, 48MHz Teensy-LC microcontroller to the valves inside the V-SPA Modules. This method thus allows for PWM control of the solenoid valves embedded in a network of modules to be independently controlled with varying duty factors, in much the same way as they would from independent, non-shared power lines. The drawback to this method, however, is a greatly increased load on the controller itself. To generate the required signal, an interrupt based timer was implemented which reduced the amount of time available to execute control commands, resulting in interrupted communication to the actuators, and a moderately unstable output. Fig. 2d shows the resulting trend of duty cycle versus angle with higher variability for a pair of actuators activated simultaneously to produce angular deflection along a secondary line of action. Only one actuator unit in a V-SPA Module was found to perform reliably at a time under PWM control, with minimal noise. Consequently, this was found to be a leading cause of difficulty in implementing fully three-dimensional control. Nevertheless, utilizing more efficient programming methods and a simplified control scheme, it was possible to demonstrate more complex motion profiles.

C. *Open loop spherical control*

A simple open loop control algorithm was developed to approximate spherical motion with a V-SPA Module, leveraging the 3D workspace afforded by its multiple actuators without the need for a complex kinematic model. This method maps a two-dimensional unit control vector to the three actuators in a module based on its virtual superposition over six regions bounded by the module’s primary and secondary directions of deflection. (Fig. 3.) The magnitude of the control vector is taken to be the maximum “control effort” available for allocation as a duty cycle command prescribed to the two actuators bounding the active region represented by the vector, while the direction of the vector determines the proportional distribution of that effort between the actuators. While the actuator in closest proximity or direct alignment with the control vector is activated to full effort, the proportion of activation for the second actuator is determined by the angular distance of the virtual vector to its location. The activation is scaled linearly with this angular distance in such a way to achieve 100% of available “control effort” when the vector is directly between two actuators, thus yielding a deflection along one of the secondary lines of action, and decreasing to 0% as the vector approaches the other actuator set to full activation, yielding net motion along the primary line of action of that actuator.

This heuristic technique provides only a coarse emulation of spherical motion, but nevertheless demonstrates that V-SPA Modules can be utilized for wider workspace and range of applications than allowed by nominal binary control alone, and provides a useful representation as the basis for more refined control in a closed loop system. Moreover, this improvement in utility can be achieved without complex kinematic modeling of a generally nonlinear system.

IV. Discussion

The trajectories plotted for different conventional pneumatic actuator control methods in Figs. 2 reveal a tradeoff between repeatability and workspace for the V-SPA Modules presented here. The simplest method utilizing only binary control does appear to track a wide path covering area apparently equal or greater to that covered by the most elaborate control schemes shown here, for approximated spherical control. The figure does not show however that much of the trajectory plotted is in transience between the vertices of each rounded triangular curve, corresponding to the fixed points reached at the end of every actuator units' stroke. Thus in reality, this is the sparsest workspace illustrated. On the other hand, the tracked path of the IMU does in fact to be repeatable in size, shape, and position. These trends are the opposite with the plot of the module angular trajectory under full 3-DoF control. This mode combined the use of PWM control of actuator pressure to achieve intermediate actuator positions, with a heuristic control map to quickly set the output angle of the V-SPA Module without explicit kinematic derivations or nonlinear modelling. While expectedly less accurate than a rigorous control scheme, the method demonstrates a simple means of control that may sufficiently serve needs underrepresented in the field of controls – that generally being the practice of mechanically informed control policy estimation.

It was also shown that the mapping of a PWM duty cycle control input to the resulting individual actuator angular deflection can be characterized relatively well using a single exponential fit, however a different fit was obtained for the same measurement of adjacent actuators in pairs. The implication of this fits the expectation that when used in different combinations, of different actuators and duty cycles, the relationship between the control input and angular motion output is very nonlinear. Moreover, the trend obtained for the actuator pair characterization showed an increase in variability which presents a challenge to designing any kind of closed loop controller.

While the V-SPA Modules studied here are powered by vacuum, a nearly identical design could be implemented with any type of pneumatic supply or actuator. Similarly the practical control methods and simplified approach to expanding the utility of a multi-DoF soft actuator without the need for more complex control techniques to satisfy certain performance metrics can easily be adapted to any soft pneumatic system.

V. Conclusion

Following a methodical approach to system-level soft robot design, V-SPA Modules employ a network based architecture pertinent not only to modular robots, or vacuum based actuation, but to the entire field of soft robotics as it moves towards more complex, robust hardware and corresponding control. With this new approach to soft robot design enabling plug-and-play reconfigurability and facilitation of higher-DoF systems, a corresponding adaptation of control strategies may be applied to accommodate both increased DoF and new hardware topology. For V-SPA Modules, it has been shown here that variable actuation modes and heuristic strategies can be used to mitigate some of the complexity derived from scalable, modular soft robotic systems. These methods can be generalized for use by modules based on similar hardware architecture toward improving the cycle time and efficiency of soft robot design and development.

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