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A Control and Drive System for Pneumatic Soft Robots: PneuSoRD

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***Abstract*— This article describes an open-source hardware platform for controlling pneumatic soft robotic systems and presents the comparison of control schemes with on-off and proportional valves. The Pneumatic Soft Robotics Driver (PneuSoRD) can be used with up to one pump and pressure accumulator, 26 on-off valves, and 5 proportional valves, any of which can be operated in open or closed-loop control using up to 12 sensor inputs, which allows for the simultaneous control of a large number of soft actuators. The electronic driver connects to a National Instruments myRIO controller or an Arduino Due with the use of an adapter shield. A library of pressure control algorithms in both LabVIEW and Simulink is provided that includes bang-bang control, hysteresis control and PID control using on-off or proportional valves. LabVIEW and Simulink provide user-friendly interfaces for rapid prototyping of control algorithms and real-time evaluation of pressure dynamics. The characteristics and performance of these control methods and pneumatic setups are evaluated to simplify the choice of valves and control algorithm for a given application.**

I. Introduction

Many soft robots are composed of soft fluidic actuators with hydraulic or pneumatic actuation [1]–[3]. Due to their high compliance and bio-compatibility, fluid-driven soft robots show great potential for biomedical applications including minimally invasive surgery [4], rehabilitation [5], [6] and elderly assistance [7]. While these actuators have been extensively used in the literature, the fluid power systems used within the soft robotics community have received less attention [8], [9].

Pneumatic actuation can be achieved with syringe pumps or compressed air systems. Syringe pumps are typically slow and limited to the small volumes of the syringe chambers [10], [11]. Consequently, the majority of pneumatic systems in soft robotics employ air compressors. The main components of compressed air systems are the pump or source, an optional accumulator, and the valves for controlling flow direction [9].

The most popular pneumatic control architecture for soft robots is the fluidic control board, an open source hardware platform available from the Soft Robotics Toolkit [5], [12]. The board consists mainly of a diaphragm pump and a set of 3/2 (3-way, 2-position) on-off solenoid valves. MOSFET Transistors allow the use of Pulse-Width Modulation (PWM) to control flow rate or actuator pressure. Pressure can also be controlled in open-loop using pressure regulators, however this allows only one system-wide pressure. Control algorithms are implemented on an Arduino microcontroller [13], [14]. The addition of an air receiver (storage reservoir or gas tank) to the pneumatic system smooths pulsating flow and prevents excessively temporary pressure drop during sudden short-term demand [15], [16]. Moreover, the air receiver allows for reduced energy consumption and fast pressurisation of soft actuators [8].

Various setups with solenoid valves have been described in the soft robotics literature [17]–[19]. For the 3/2 valve system as shown in Fig. 1a, the inlet port is connected to the compressor or the receiver, the outlet port is connected to the soft actuator and the exhaust port is open to atmosphere [20]. In order to reduce energy consumption and improve lifetime of the valves, more complex 3/3 (3-way, 3-position) or 5/3 (5-way, 3-position) valves can be used [21], as shown in Fig. 1b. Alternatively, a system with two 2/2 (2-way, 2-position) valves can be considered [18], [19], see Fig. 1c. Proportional valves outperform on-off solenoid valves in regards to tracking precision and steady-state accuracy but are 3-4 times more expensive [22].

The increasing complexity of soft robotic systems requires the capability for controlling a large number of actuators ($>$10), possibly in closed-loop, with multiple valves per actuator [21], [23]. The scope of applications include rehabilitation devices, wearable technologies, minimally invasive devices and bio-inspired soft robots. For example:

- Soft robotic hands with up to 8 or 10 fiber-reinforced or pneumatic network actuators [5], [24].
- Surgical manipulators with 12 fluidic chambers and 2 stiffening chambers [23].
- Worm-like and snake-like soft robots with any number from 3 [11], [25] up to 12 chambers [13], [26]–[28].
- Soft robotic manipulators with a tentacle-inspired structure and up to 16 chambers [29].

The fluidic control board [12] uses an Arduino Mega which has 15 digital outputs that can implement a software defined PWM up to $\sim$50 kHz. Likewise, a variation uses an Arduino Uno which has 6 digital outputs that can implement a software defined PWM at 1 kHz. The minimum practical frequency for power electronics such as buck-converters or class-D power amplifiers is 50 kHz. Therefore, an Arduino-based system must be able to produce higher frequency PWM outputs.

The Arduino Due is the preferred controller as this includes 6 electrical PWM generators, an 84 MHz processor, large flash memory, and 12bit ADC resolution. The Arduino Mega is also compatible with PneuSoRD but is limited to

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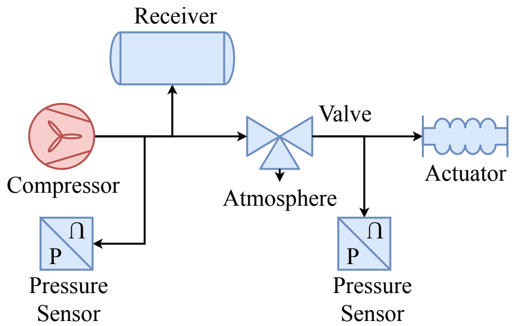
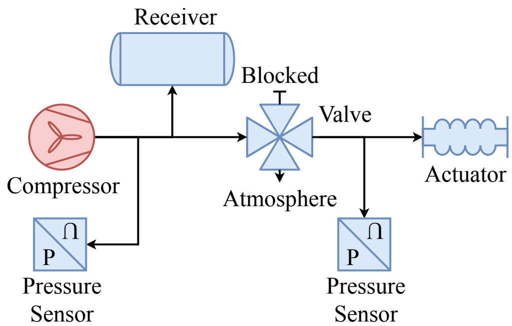
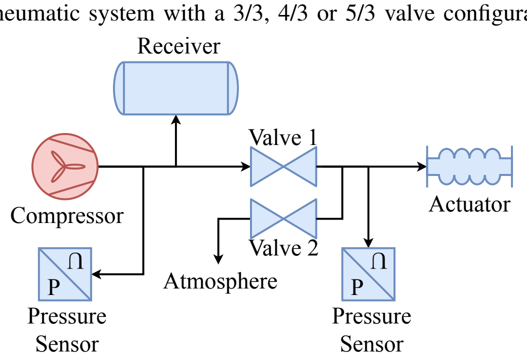


(a) Pneumatic system with a 3/2 valve configuration.



(b) Pneumatic system with a 3/3, 4/3 or 5/3 valve configuration.



(c) Pneumatic system with 2x 2/2 valve configuration.

Fig. 1: Example setups of solenoid valve configurations described in the soft robotics literature.

one motor driver, 26 on-off channels, and zero proportional channels.

A. *Contributions of this work*

The primary contributions of this article are: 1) an open-source power electronics driver for pneumatic systems in soft robotics with various valve configurations, 2) a library of ready-to-use controller algorithms in both LabVIEW and Simulink, and 3) a comparison of valve configurations and control algorithms performance to simplify the selection process for a given application. The PCB files for the driver and control algorithms are shared on a GitHub repository. https://github.com/PrecisionMechatronicsLab/PneuSoRD

The open-source power electronics is described in Section III. This system is readily extensible and can drive one pump and pressure accumulator, 26 on-off valves, and 5 proportional valves. These can be operated in open or closed-loop control modes using up to 12 sensor inputs. Each output is fully protected against short-circuit and overload conditions. The pump and proportional valve outputs are designed to operate with a 40 kHz PWM signal for high efficiency production of arbitrary voltages with output currents up to 700 mA.

The power electronics connect directly to a National Instruments myRIO controller or an Arduino Due with the provided adapter shield. A library of pressure control algorithms is presented in Section IV for control modes including, bang-bang control, hysteresis control, and PID control using on-off or proportional valves. The characteristics and performance of these methods are evaluated in Section V using PneuSoRD with soft pneumatic actuators. Furthermore, in Section V, a soft robotic hand is used to demonstrate the simultaneous control of multiple actuators. The results are summarised to provide soft roboticists with a method for selecting appropriate valve configurations and control algorithm for a given application.

II. System Overview

The Pneumatic Soft Robotics Driver (PneuSoRD) shown in Fig. 2 is an open-source power electronics device for controlling pneumatic soft robots with a large number of actuators. This system is designed around the two major categories of valve types: 1) on-off valves with single or multiple solenoids, which require a binary input, and 2) proportional valves, which require a variable DC voltage. The PneuSoRD design includes circuit channels for both of these options. Each circuit channel is designed to suit the widest possible range of valve options. Each circuit channel can be driven by either: a myRIO 1950 embedded controller with LabVIEW, or an Arduino Due with Simulink. Both LabVIEW and Simulink allow real-time tuning of control parameters signal visualisation. Control algorithms can also be implemented in Arduino code, as described in the Soft Robotics Toolkit.

Typically, pneumatic soft robots consist of a large number of simultaneously actuated chambers [5], [11], [21], [23]–[28]. Pneumatic systems with 3/2 on-off valves require a single valve for each chamber, while systems with 2/2 on-off valves require two valves per chamber. Pneumatic systems with proportional valves can incorporate two or three valves depending on the application. The driver presented here allows for the control of up to 31 valves for use in a multitude of applications. The number of sensor inputs is limited by the number of analog inputs provided by the controller. The myRIO contains 8 ADC pins and the Arduino Due extends this to 12 with the added adapter shield. Consequently, 8 sensors input headers are included on the PneuSoRD and can be used to perform independent feedback control on 8 chambers, with the additional 4 on the adapter. Note that more chambers can be actuated if they are allowed to share the same pressure.

The drive requirements for proportional and on-off valves are summarised in Table I. An electrical PWM is used to drive the proportional valves through a buck converter,

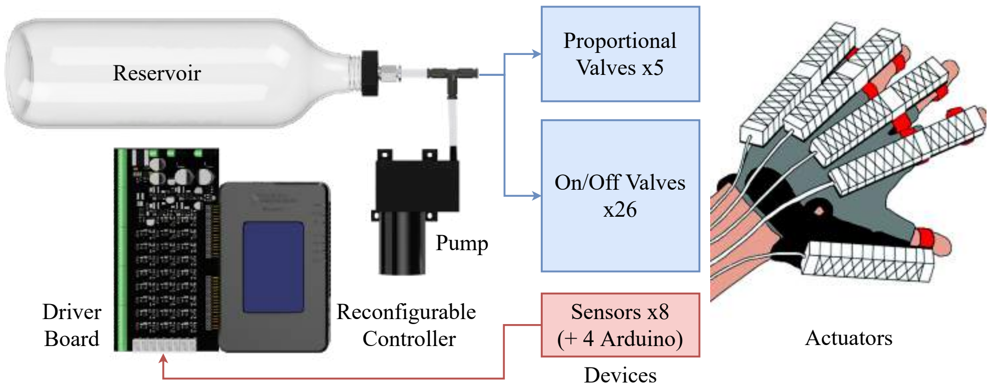


Fig. 2: Overview of the Pneumatic Soft Robotics Driver (PneuSoRD), including the electronics driver board and National Instruments myRIO controller, which is connected to a single pump and air receiver, up to 5 proportional valves, and 26 on-off valves. The soft robotic glove was reproduced with permission from [30]. Copyright 2019, Mary Ann Liebert, Inc.

TABLE I: Drive Methods.

Valve Configuration	Electrical PWM	Pneumatic PWM
3/2 on-off valve		x
2/2 on-off valves		x
2/2 prop. valves	x	

which produces the required DC voltage. This circuit forms a linear power amplifier controlled by a variable pulse width, constant frequency square wave. On the other hand, a pneumatic PWM directly switches on-off valves to produce the required pressure.

The PneuSoRD has two power inputs that allow two voltages between 7V and 25V (e.g. 12V and 24V) to supply any combination of channels, which are selected by jumpers on the PCB. The primary power supply voltage is also used to generate +5 V for digital logic and protection functions. The second power supply is only required if there are a combination of valves which require different supply voltages, e.g. 12V and 24V.

III. Electrical Design

Each channel has been designed to maximise the variety of valves that can be driven. Fig. 3 shows the implementation of three drive designs and the feedback sensor electronics.

A. Motor/Proportional Drive

The PneuSoRD has 6 Proportional Drive modules. The motor driver in Fig. 3a is sized for a peak current up to 1.4 A. This driver is designed for DC motor pumps that typically require a current of 500 mA to 1 A. This output could also be used to drive a logic signal for a larger pump. The 5 proportional drivers also in Fig. 3a are sized for a peak current capacity up to 700 mA. This driver is designed for driving proportional valves that typically require 200 mA to 500 mA.

The motor and proportional valve drivers are based off a synchronous rectifier buck converter Fig. 3b. The switch is driven by a 40-200 kHz PWM signal with a variable duty cycle, which can be generated by the myRIO or Arduino Due controllers. The switch (DRV88703.6A) is a half-bridge motor driver and was selected for the comprehensive overload protection, which is described in Section III-D.

Each circuit channel can be supplied by either of two power supply inputs via a jumper on each circuit channel. The maximum output current is set by the *Rsen* resistor, which provides over-current and short-circuit protection. In the default configuration, the motor driver channel can supply 1.4 A continuously and 2.5 A peak, which is adjustable up to 3.6 A. The remaining 5 proportional driver channels can supply 500 mA continuously and 700 mA peak, which is adjustable to any lower value.

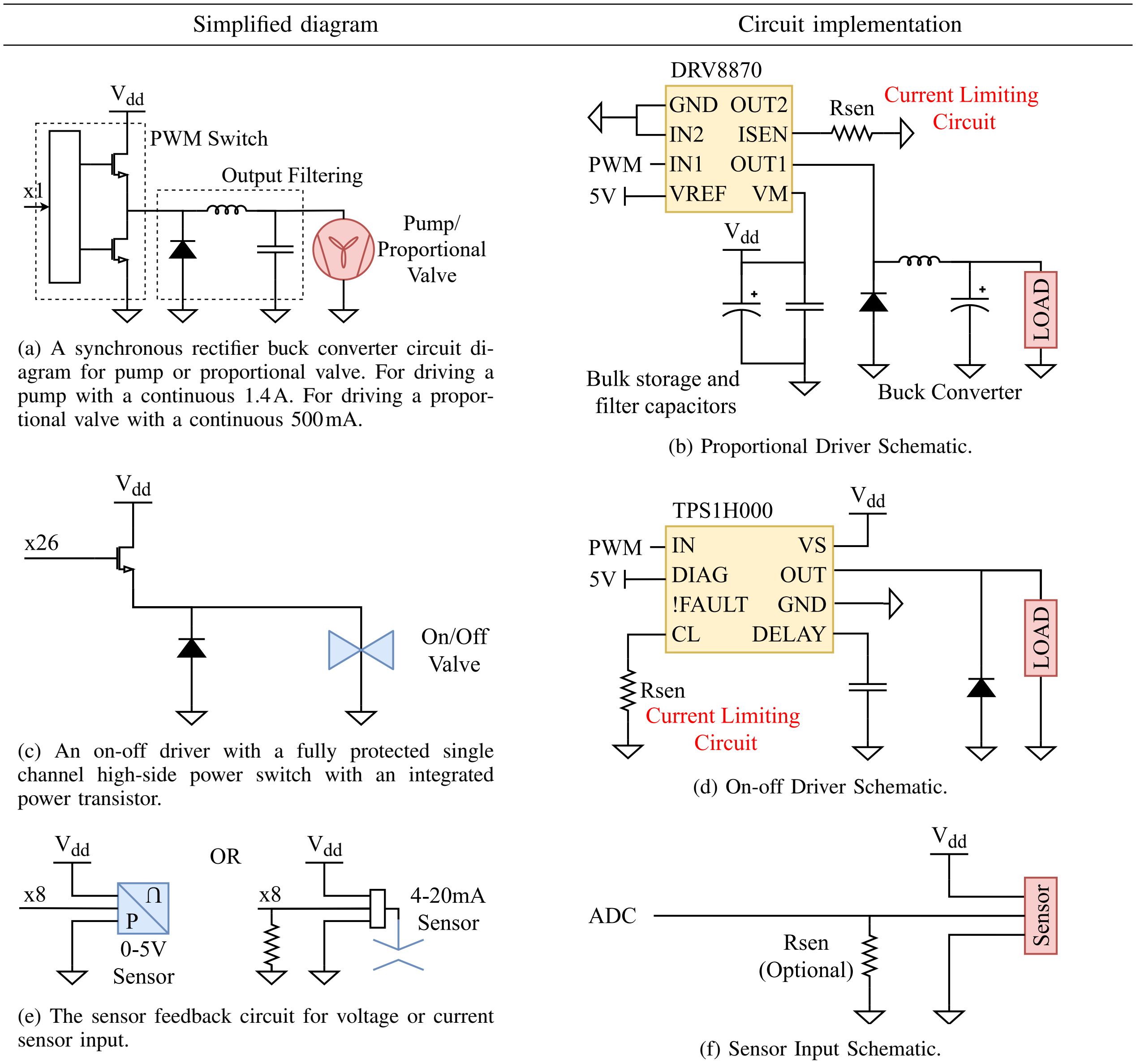
B. On-Off Drive

Since on-off valves can be driven by a digital signal, the PneuSoRD uses 26 digital pins on the myRIO and Arduino Due. The TPS1H000 is a fully protected single channel high-side power switch with an integrated power transistor as shown in Figs. 3c and 3d. Each drive contains an adjustable current limit that can be adjusted via the *Rsen* resistor. This protection feature limits the inrush or overload current. The trip delay capacitor has been selected to minimise the trip time if a fault event occurs. A light emitting diode is connected to the fault pin, which provides user feedback during a fault condition.

Each drive channel can be supplied by either of the power supply inputs via a jumper on each channel. The on-off channels can supply 500 mA continuously, with a peak of 500 mA, which is adjustable up to 1 A.

C. Sensor Input

A total of 8 sensor input headers are included on the PneuSoRD as shown in Figs. 3e and 3f, with an additional 4 included on the Arduino Due shield. A linear regulator



(a) A synchronous rectifier buck converter circuit diagram for pump or proportional valve. For driving a pump with a continuous 1.4 A. For driving a proportional valve with a continuous 500 mA.

(b) Proportional Driver Schematic.

(c) An on-off driver with a fully protected single channel high-side power switch with an integrated power transistor.

(d) On-off Driver Schematic.

(e) The sensor feedback circuit for voltage or current sensor input.

(f) Sensor Input Schematic.

Fig. 3: Electrical module diagrams.

provides each sensor with 5 V, this reduces sensor noises caused by noise on the power rail due to the switching of the other components. Primarily, this input is designed for 0-5 V sensors that can be read via the ADC input of the microcontroller. An optional resistor can be added to suit 4 mA to 20 mA style sensors.

D. Overload Protection

The overload protection for the following channel types is listed below:

Proportional Drive (DRV88703.6A):

- undervoltage lockout
- overcurrent protection with adjustable current limit
- thermal shutdown
- automatic fault recovery

On-Off Drive (TPS1H000):

- short-to-gnd
- overcurrent protection with adjustable current limit
- thermal shutdown
- open-load detection

These protection capabilities ensure the longevity of the valves and sensors and protect the attached microcontroller.

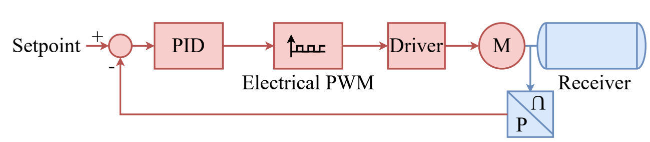
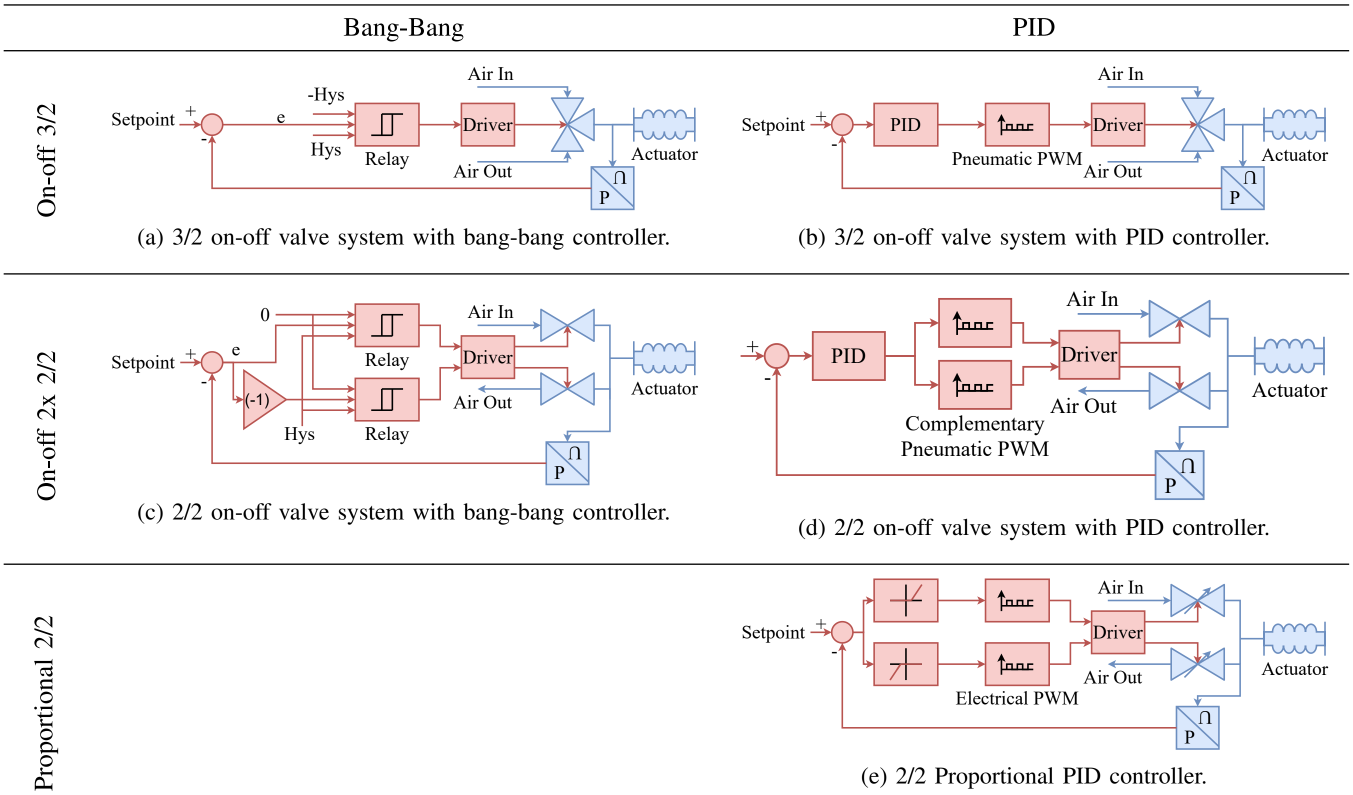


Fig. 4: Motor driver control scheme.

Fig. 5: Control schemes for each valve type.



(a) 3/2 on-off valve system with bang-bang controller.

(b) 3/2 on-off valve system with PID controller.

(c) 2/2 on-off valve system with bang-bang controller.

(d) 2/2 on-off valve system with PID controller.

(e) 2/2 Proportional PID controller.

IV. Implementation of Pneumatic Controllers

The accumulator pressure requires closed-loop control to provide a constant source pressure. This is achieved by controlling the motor voltage by regulating the duty cycle using a PID controller, as shown in Fig. 4.

Pressure feedback control can also be implemented for each actuator. The following subsections describe the implementation of control algorithms for a range of valve configurations. A library of implementations for LabVIEW and Simulink are freely available from the authors at https://github.com/PrecisionMechatronicsLab/PneuSoRD

A. Pneumatic Systems with 3/2 On-Off Valves

For the system with a 3/2 on-off valve, the PID controller is implemented by regulating the duty cycle of the PWM wave into the valve between zero and 100%, which is used to switch the valve continuously between two states at a fixed frequency, e.g. 40 Hz Fig. 5b. Alternatively, the bang-bang controller is implemented with two states, which are:

$$\text{ON:}\quad P < P_{ref} - h \tag{1}$$

$$\text{OFF:}\quad P > P_{ref} + h \tag{2}$$

where P is the measured pressure, P_{ref} is the reference pressure and h is half the size of the hysteresis band. Lower values of hysteresis result in less steady-state error but also higher switching frequency. These conditions are implemented by using a relay block in Simulink or a relay function in a subsystem in LabVIEW with “switch on point” equal to h and “switch off point” equal to $-h$ Fig. 5a. Note that hysteresis is introduced for the bang-bang controllers to prevent excessive switching, which is particularly beneficial for the systems with 2/2 valves.

B. Pneumatic Systems with 2/2 On-Off Valves

For the system with two 2/2 on-off valves, the first valve (control u_1) is used for charging by allowing air flow from the receiver into the actuator. The second valve (control u_2) is used for discharging by allowing flow from the actuator into atmosphere.

The PID controller is implemented by regulating the duty cycle of complementary PWM signals at a fixed frequency Fig. 5d. For the bang-bang controller, three states can be used. In the first state, valve 1 is used for charging the actuator while valve 2 is blocked, i.e. $u_1 = 1$ and $u_2 = 0$. In the second state, both valves are blocked and no flow is allowed from the receiver or into the atmosphere, i.e. $u_1 = 0$ and $u_2 = 0$. Finally, in the third state, valve 2 is used to discharge the actuator into the atmosphere while valve 1 is blocked, i.e. $u_1 = 0$ and $u_2 = 1$. These conditions can be implemented using a case structure (state machine) with three states or by considering the logic below with two relays Fig. 5c:

$$\text{Valve 1}\begin{cases}\text{Switch on:} & P_{ref} - P > h\\ \text{Switch off:} & P_{ref} - P = 0\end{cases} \tag{3}$$

$$\text{Valve 2}\begin{cases}\text{Switch on:} & P_{ref}-P<-h\\ \text{Switch off:} & P_{ref}-P=0\end{cases} \quad (4)$$

C. Pneumatic Systems with 2/2 Proportional Valves

As for 2/2 proportional valves, the mapping from input voltage to output flow is approximately linear over the operating range. As shown in Fig. 5e, a small deadband can be implemented for each valve around the zero error point. Outside of this region a linear mapping between error and duty cycle can be produced to regulate the pressure in the system. Alternatively, the use of a bang-bang controller would not be recommended, as this would effectively be treating the proportional valve as a two state on/off valve.

V. Experimental Results

In this section, the pneumatic controllers and valve setups are compared using pneumatic network actuators (slow PneuNet) [31]. Next, a soft robotic hand is used as an application to demonstrate the capabilities of the PneuSoRD for controlling multiple soft actuators.

A. Fabrication of Soft Robotic Hand

The fabrication process follows the conventional molding procedure for soft fluidic elastomer robots [32], [33]. Molds are designed in Autodesk Inventor and 3D-printed using an Original Prusa I3 MK3S (Prusa Research). Silicone rubber (DragonSkin 10) is mixed at a 1:1 ratio and degassed. The mixture is poured into the bottom mold, which is then clamped to the top mold. After 5 hours, the actuator is removed and a strain limiting layer (fiberglass fabric) is glued to the open side with a layer of DragonSkin. For the soft robotic hand, five of these actuators are used as fingers and glued to a 3D-printed hollow hand model depicted in Fig. 6.

B. Comparison of Control Schemes and Valve Configurations

The PneuSoRD can be used to drive a wide range of air pumps, sensors and valves. For a discussion on the selection of pneumatic parameters such as pump flow, valve conductance and receiver volume and pressure, the reader is referred to [9], [34], [35].

An example application is presented in this work employing the PneuSoRD with a diaphragm pump (KYK50BPM), a 2 L air receiver, 3/2 on-off solenoid valves (V114), 2/2 proportional valves (Burkert 238928), pressure sensors (SEN0257, DFRobot) and 6 mm tubing between each of these elements. To preserve rise and fall times and thus ensure a fair comparison between methods, 2/2 on-off valves are obtained from the V114 3/2 valves by blocking the exhaust port.

The PID controller can be experimentally tuned in real time using the front panel in LabVIEW or external mode in Simulink. To minimise switching events due to the noise from the pressure sensor, the bang-bang controller is implemented with $h = 4$ kPa. The receiver pressure is regulated at 100 kPa, while the soft actuator pressure reference includes the step and sinusoidal components shown

(a) Hand gesture with two actuators (Front view).

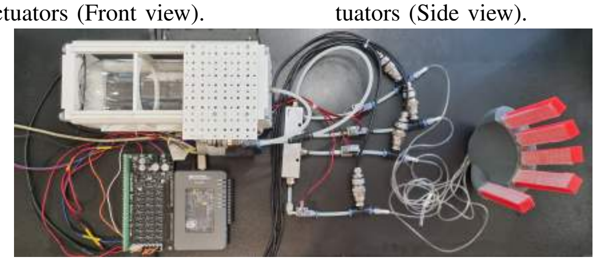
(b) Hand gesture with two actuators (Side view).

(c) Hand gesture with three actuators (Front view).

(d) Hand gesture with three actuators (Side view).

(e) Hand gesture with four actuators (Front view).

(f) Hand gesture with four actuators (Side view).

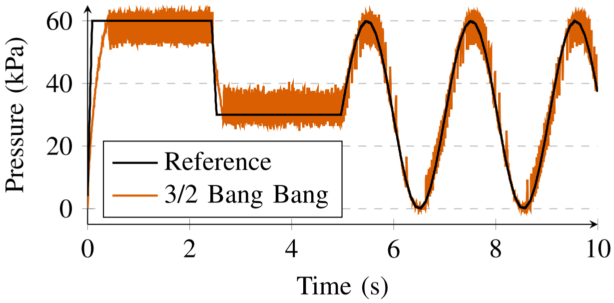


(g) Hand Experimental Setup

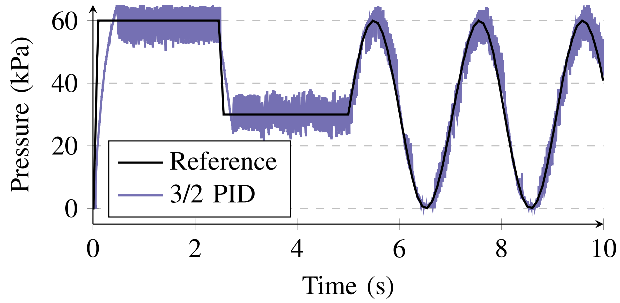
Fig. 6: Soft robotic hand gestures using pneumatic network bending actuators.

in Fig. 7 for each valve configuration and controller. The 3/2 on-off valve system constantly inflates and deflates the soft actuator during pressure regulation, regardless of the control algorithm, which causes the pressure in the actuator to continuously oscillate around its target. In contrast, systems with 2/2 on-off valves show significantly less pressure ripple as a result of the third state in which both valves are closed during pressure regulation. This can also be seen in the proportional valve system.

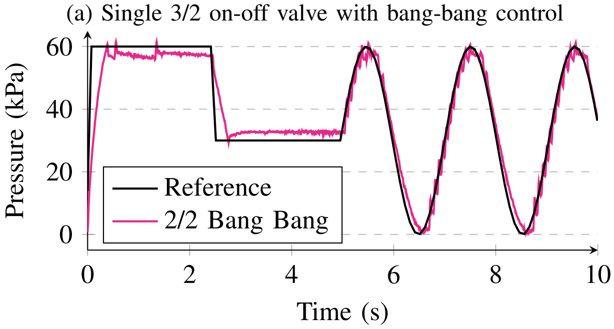
Table II provides a comparison of pneumatic systems for soft robotic applications. Accuracy refers to tracking error and control refers to the level of complexity in the control algorithm and hardware requirements. Systems with 3/2 valves are widely used due to their low price and straightforward implementation, especially considering their use in the fluidic control board. However, systems



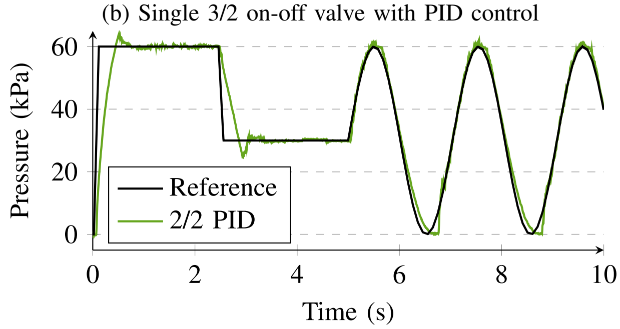
(a) Single 3/2 on-off valve with bang-bang control



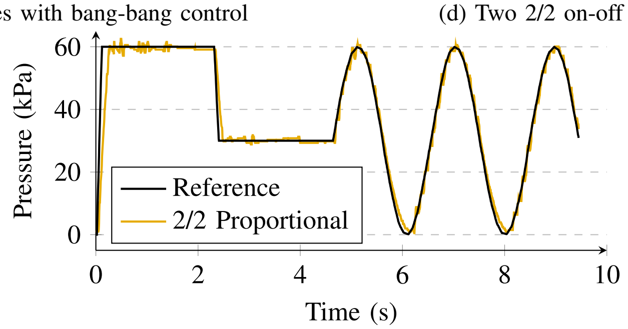
(b) Single 3/2 on-off valve with PID control



(c) Two 2/2 on-off valves with bang-bang control



(d) Two 2/2 on-off valves with PID control



(e) Two 2/2 Proportional valves with PID control

Fig. 7: Comparison of closed-loop performance for a slow PneuNet actuator with three pneumatic configurations and two control algorithms. The pneumatic configurations include a single 3/2 on-off valve (a,b), two 2/2 on-off valves (c,d), and two two-way proportional valves (e). The control algorithms include bang-bang control (a,c), PID control with pneumatic PWM (b,d), and PID with proportional valves (e).

TABLE II: Comparison of pneumatic system setups.

Setup	Cost (AUD)	Lifetime	Accuracy	Control
3/2 on-off valve	~\$40-70	Low	Medium	Simple
2/2 on-off valves	~\$80-150	Medium	High	Complex
2/2 prop. valves	~\$300-500	High	High	Complex

with 2/2 valves offer the advantages of reduced energy consumption, reduced pressure ripple and improved lifetime due to a reduced number of switching events, particularly for constant pressure set-points. Systems with proportional valves add more complexity to the drive and control design, and did not significantly reduce the tracking error in this comparison. Therefore, a pneumatic system consisting of two 2/2 on-off valves is recommended for the majority of applications.

The capability of the PneuSoRD to simultaneously control multiple actuators is illustrated using a soft robotic hand in Fig. 6. In this case, a range of hand gestures are obtained by regulating the pressure of the pneumatic network actuators using four 3/2 on-off valves and PID controllers.

VI. Conclusions

This article describes an open-source control and drive system for pneumatic soft robots. The PCB board is capable of acquiring data from up to 12 pressure sensors and can control up to 31 pneumatic chambers simultaneously. Compared to alternatives, the PneuSoRD system is compatible with both proportional and on-off valves and includes multiple protection mechanisms for the pump motor and valves.

Three options are supported for implementation of the control algorithms:

- LabVIEW programming language with myRIO controller;
- Simulink programming language with Arduino Due controller;
- Arduino code with Arduino Due controller.

The LabVIEW and Simulink options are recommended due to their user-friendly interfaces and compatibility for real-time tuning of control strategies.

An experimental comparison of three valve configurations and three control methods, revealed that two, two-way on-off valves provide an advantageous trade-off between tracking error, cost and valve lifetime. The general guidelines described here can be used to select the pneumatic system components and control technique for an application. The PCB, LabVIEW and Simulink files are available online at https://github.com/PrecisionMechatronicsLab/PneuSoRD

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