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A Wireless Compact Control Unit (WiCCU) for Untethered Pneumatic Soft Robots

Luigi Manfredi, Alfred Cuschieri

Abstract— **The performance of a soft pneumatic robot (SPR) relies on the synergy between the mechanical design and the control unit that implements a closed-loop control between sensors and actuators. Most controllers are designed by using off-the-shelf components. Although commercial parts present high precision and reliability, they are heavy and bulky, limiting the realisation and design of untethered robots.**
The present study describes a wireless pneumatic control unit of a compact and light design that can control up to 3 pneumatic chambers. The unit includes pressure sensors and high precision miniaturised proportional valves. To simplify both the electrical cabling and the air tubes connections, a compact manifold is used to connect valves and pressure sensors. The control unit uses a Bluetooth RS232 serial module for a wireless communication.
The mechatronic design is reported describing the electronic hardware, the manifold solution, and the firmware implementation. Experiments report i) the control of a linear pneumatic actuator (LPA), and ii) a simultaneous activation of 3 LPAs connected to a base providing 3 degrees of freedom (DOFs).

I. INTRODUCTION

Soft pneumatic robots have been widely studied during the last decades for their high compliant behaviour and safe interaction with the surrounding environment [1], [2]. Research institutes have reported soft pneumatic systems for various applications, e.g. actuators with several degrees of freedom (DOFs) [3]–[7], planar and spatial manipulation [8], [9], rehabilitation [10], [11], and various other applications [12]. The majority of the reported studies use an open-loop control to test the mechanical performance. Closed-loop is mainly implemented by using off-the shelf components because of their high precision, reliability and the fact that they can be integrated with software, e.g. MATLAB® or LabVIEW, to easily implement a more sophisticated control behaviour. However, this approach limits the design of untethered robots, as these require a compact and light control unit.
The present study reports a Wireless Compact Control Unit (WiCCU) for the design of untethered pneumatic soft robots. The design includes the state-of-the-art of miniaturised proportional valves for a precise control of the pressure inside a pneumatic chamber. Miniaturised pressure sensors are soldered on top of the electronic board and pressed to a manifold, to secure a sealed connection by means of a rubber O-ring. Inlet and outlet proportional valves are connected to the top of the 3D printed manifold. A Bluetooth module allows a wireless communication with an external device (e.g. laptop or a real time workstation) by using a serial port RS232. A DSP (digital signal processor) implements the low-level control (LLC). It includes a pressure PID (Proportional, Integrative, Derivative) closed-loop controller for each output chamber, by a communication protocol with an external device. WiCCU is hexagonal in shape to reduce overall size needed to allocate the 6 proportional valves (3 inlet and 3 outlet) in a star configuration: the hexagonal size length being 29 mm, height of 23 mm, width of 51 mm, and a total weight of 95 g.
Experiments on pressure closed-loop control, step and sinusoidal profile with a frequency up to 0.5 Hz, have been reported for a linear pneumatic actuator (LPA). A small platform with 3 DOFs was constructed to report the simultaneous and precise control of 3 independent LPAs.

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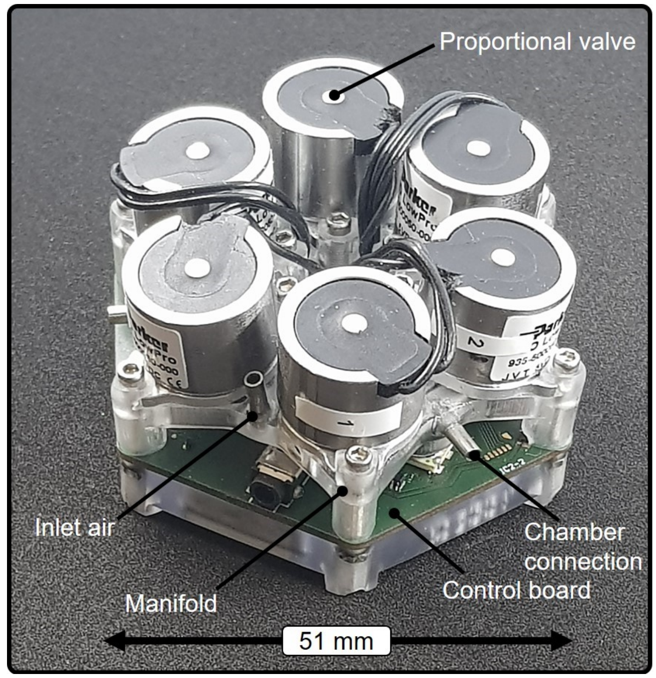

Fig. 1. WiCCU has a size of 51x23 mm, and a weight of 95 g. It can control up to 3 independent pneumatic chambers. It is composed of 6 miniaturised proportional valves, 3 pressure sensors, a Bluetooth module and a control board with a DSP.

II. STATE-OF-THE-ART

The design of a pneumatic soft robot requires a control unit with sensors, valves, and an air/gas supplier. The air/gas is provided by electrical pumps [13], a chemical pressure generator [14], or a small tank with high pressurised $C0_2$ gas [8].

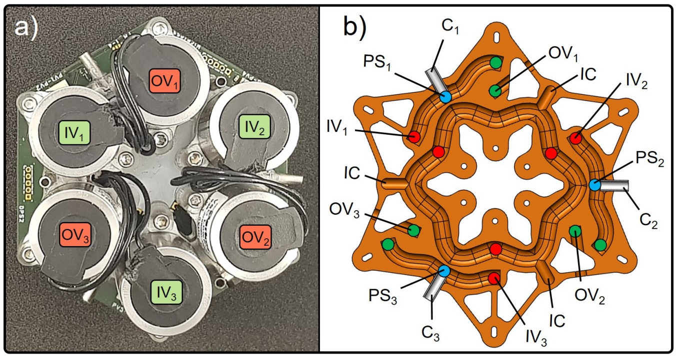

Fig. 2. WiCCU top (a) and manifold cross-sectional view (b). The red and green spots are the connections to the inlets and outlet nozzles of the valves. The blue spots are the pressure sensors, PS_i. Part of the internal material was removed to reduce the weight.

The first soft robot with all the components on-board was reported by Wehner et al. [14]. It has a chemical pressure generator for activation of the pneumatic chambers. Although this work represents a step forward in the design of untethered robots, the slow motion and output power limit its application.

Tolley et al. [13] reported a quadruped robot 65 cm in length, weighting 5 kg, with on-board control unit, and all the required components for a fully untethered robot. The big size of the robot was required to carry the heavy control unit. The air was generated by an on-board electrical pump.

Marchese et al. [8] reported an autonomous soft fish robot with on-board control and a small compressed gas cylinder and regulator, to provide the air for the pneumatic actuator by using proportional and on-off valves.

Booth et al. [15] reported the design of a small pneumatic pressure regulator for the design of a distributed control using on-off valves to regulate the pressure and a big-bang control strategy. On-off valves have the advantage of being lighter and easier to be controlled than proportional valves, although the latter can perform a more precise control of the output air-flow and pressure.

Another example of fluid control unit can be found on the Soft Robotics tool-kit website [16]: the design and construction of a fluid control board for educational purposes is described in detail. It includes off-the-shelf components and an Arduino board firmware to implement a soft pneumatic control by the use of solenoid valves.

WiCCU design compared to the previously reported controllers' unit for untethered robot presents the following advantages:

i) use of on-board miniaturised proportional valves ensuring high precision control for 3 independent outputs airflow to implement a complex pressure profile, such as a sinusoidal wave;
ii) design of a miniaturised manifold with pressure sensors directly connected to the chamber air flow with no need of any additional tubes, reducing the overall size and facilitating its integration in the design of an untethered pneumatic robot;
iii) an integrated Bluetooth wireless module connection to avoid any wire for the communication with an external device controller.

III. Material and Methods

WiCCU is composed of 3 parts connected in 4 layers: i) 6 proportional valves (3 inlet and 3 outlet); ii) a manifold; iii) a Bluetooth wireless module; iv) an electronic PCB (printed circuit board) with on-board pressure sensors and a DSP (Digital Signal Processor). Each component is described in the following sections starting from the top layer, the pneumatic hardware.

A. Pneumatic hardware

Most of the miniaturised control units for pneumatic devices uses on-off valves [15]. Advantages include light weight and a simple control implementation by means of a digital output. A big-bang control is required to implement a closed-loop with pressure sensors. The state-of-the-art of miniaturised on-off valves (Parker X-Valve - Miniature Pneumatic Solenoid Valve) presents an activation time of at least 20 ms, which corresponds to an on-off bandwidth of less than 25 Hz. Its weight is 4.5 g and its size measures 23.27x7.87x12.19 mm. The continuous activation of the valve limits its life and reliability, which Parker reports as 25 million cycles in the worst-case scenario. Considering a continuously activation of the valve at 25 Hz, the worst-case life time can be considered as being 278 hours, about 11 and a half days. This on-off controller also creates spikes on the output pressure. These spikes are partially filtered by the soft behaviour of a pneumatic device, although this low frequency may create resonant problems during use. This on-off solution limits the precision of the output-controlled variable, especially when a sinusoidal wave is required to be implemented. In fact, a previous study [15] has reported a ramp profile closed-loop control with a period of 50 seconds, 0.02 Hz.

There is a limited range of miniaturised proportional valves available in the market. The use of proportional valves requires the DSP to provide an analogue output and this may increase the complexity of the control architecture. A DSP analogue output can be implemented by using a PWM (Pulse Width Modulation) and a low pass filter for each valve. In addition, proportional valves compared to on-off valves are slightly bigger and heavier, and the power consumption may be higher. However, the proportional regulation of the air nozzle provides a precise control of the output flow, even when the input air pressure of the control unit is much higher than the output pressure inside a pneumatic chamber. Because of this advantage, the design of WiCCU uses miniaturised proportional valves (MPVs). The smallest available in the marked, to date, are the Parker VSO® LowPro Miniature Proportional Valves, with a weight of 12g, a size of 20.32x15.87x13.50 mm, a response time of 10ms. A comparison of the on-off and proportional valves available in the market to date is reported in table I.

Control Mode	Brand	Model	Size (mm)	Weight (g)	Max P. (kPa)	Max Flow Rate (LPM)	Response Time (ms)	Max Power (W)	Life Cyc. (Million)
Proportional	Parker	VSO	20.32x15.87x13.50	12.0	690	57	10	2	100
Proportional	SMC	PVQ10	35.00X26.60X16	ND	700	6	ND	2	25
On-Off	Parker	X-Valve	23.40x7.90x8.90	4.5	690	11	20	0.5-1	25
On-Off	SMC	VQ100	28.00X29.20X18.10	12.6	700	134	ON=3.5, OFF=2	1	200

TABLE I

ON-OFF AND PROPORTIONAL VALVES COMPARISON

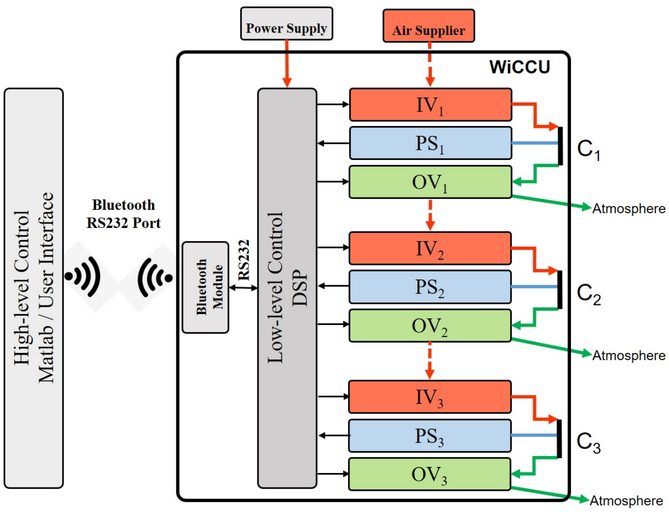

Fig. 3. Control architecture composed of a low-level control implemented in a DSP, 3 input valves (IV_i), 3 output valves (OV_i), 3 pressure sensors (PS_i), and a wireless Bluetooth module.

B. Manifold

The manifold is 3D printed from Polyjet RGD525, as it is shown in figure 2. A cross-section (figure 2-b) shows the flow connections between the air generator and the output chambers OC_i. It has 3 tubes connectors of 2.5 mm diameters having multiple inputs in case higher air flow is required. The air generator is connected to an input channel (IC), which courses around the inner part of the manifold. It has a cross-section area of 6.28 mm^2, a total length of 95 mm, and it is connected to the 3 inlet valves (IV_i) port. An output channel, 3 in total, connects the IV_i output port together to the output chamber (OC_i), the input port of the output valve (OV_i), and the pressure sensors (PS_i). Each output channel has a cross-section area of 4.40 mm^2 and a total length of 22.50 mm. A rubber O-ring (outer and inner diameter, and cross section of 7x3x2 mm) seals the PS_i connection to the manifold. To secure the sealing and avoid any air leakage, the electronic board and the PS_i are pressed to the manifold. The manifold and the frame are connected using 6 screws with nuts to distribute the forces on the PCB. An additional frame supports the bottom side of the PCB to avoid any mechanical stress, which is higher in proximity of the PS_i.

C. Control architecture

The WiCCU control architecture is shown in figure 3. The PCB includes 3 pressure sensors (PS_i, $i = 1, 2, 3$), a Microchip DSP (dsPIC33EP128GM304), and it is connected by means of an RS232 serial port to a wireless Bluetooth module (Guangzhou HC Information Technology Co. Ltd., HC-06). The PSs are from Honeywell NBP series, SMT-PN lead-less, with a maximal pressure of 207 kPa, an error of ± 0.25%, and a size of 7.00x7.00x3.84 mm. They are in a Winston bridge configuration and the signal is amplified and sent to the 12-bit A/D converter of the DSP. The resolution is 80 Pa for a single digital step.

The Bluetooth module works like a bridge between an external device and WiCCU. Any external device can send and receive data by adding the Bluetooth module in the system peripherals, which creates a standard RS232 with a bandwidth up to 1 Mbit/s. Multiple units can be connected together to create a network with a higher number of pneumatic devices.

Each proportional valve (PV_i) is controlled by adjusting the duty cycle of a PWM (pulse width modulation) output (PWM_{di}). It has a 12 bits resolution, and a voltage step of 1.22 mV, when the input power is 5 V. The DMA (Direct Memory Access) acquires the 3 PS_i analogue output and it stores their values in an array 3x1. The use of the DMA reduces the computational burden to the DSP. The firmware implements 2 parallel tasks: i) communication from and to the Bluetooth module and data signal decoding; ii) 3 PID controllers, 1 for each chamber (C_i). The PID controller closes the loop at 1.5 KHz between the commanded pressure P_{ri} and the chamber pressure P_i. The output of the PID controller is the duty cycle of the PWM_i (PWM_{d_i}), with a frequency of 15 KHz. In addition, WiCCU has an open-loop mode to control only the PWM_{di} output, which allows any user to implement a high-level control in an external real-time workstation. The closed-loop control is described by the following equation:

$$PWM_{d_i} = K_p e_P + K_i \int_{t-T_0}^{t} e_P + K_d \frac{de_P}{dt} \qquad (1)$$
$$e_P = P_{ri} - P_r$$

$$\begin{aligned} & if\ (PWM_{d_i} < 0) \\ & \qquad \begin{cases} PWM_{IV_i} = -PWM_{di} + PWM_{do} \\ PWM_{OV_i} = 0 \end{cases} \\ & else\,if\ (PWM_{d_i} > 0) \\ & \qquad \begin{cases} PWM_{IV_i} = 0 \\ PWM_{OV_i} = PWM_{di} + PWM_{do} \end{cases} \end{aligned} \qquad (2)$$

The equation 1 describes a PID controller and the equation 2 describes the PWM_{di} to each proportional valve. PWM_{do} is the minimal voltage threshold needed to activate the valve. In this study, MATLAB® has been used to control and monitor the data, i.e. pressure sensors (P_i) and PWM_{di} outputs.

D. Power Consumption

The control board voltage input ranges from 5 up to 12 V. A battery pack or a USB port with the power specification reported in table II can power WiCCU. To limit the voltage to the proportional valve, a maximal PWM duty cycle can be adjusted in the control setting, according to the input voltage: $PWM_{MAX} = 2^{12} \cdot V_{PV}/V_i$, where 2^{12} is the resolution of the PWM output, V_{PV}= 5 V is the nominal voltage of the proportional valve, and V_i is the input voltage. This limit of the PWM will reduce the range of resolution of the voltage output. The power consumption of WiCCU is 0.3 W when all the valves are deactivated. The worst scenario is when the 3 valves are simultaneously activated with the maximal PWM_{di}, then the total consumption is 6.3 W, with a consumption of 2 W for each PV. The average consumption of the PV reported by Parker (Warwich, United Kingdom), is 1 W, becoming 3.3 W when 3 valves are activated. In the reported experiments, the PWM_{di} never achieved the maximal value. The worst-case scenario is unlikely to happen because this requires that all the input pressure is transferred to the output chamber.
The autonomy of the control unit is related to the additional batteries weight required in an untethered robot. As an example, considering an on-board battery pack of 3 Alkaline AAA, V_{in}= 4.5V, total weight of 34.5 g (3x11.5 g), capacity of 0.6x3=1.8 Wh, the average autonomy of the control unit would be about 32 minutes. With 3 Alkaline AA batteries, the total weight would be of 3x24g=72 g, with a capacity of 4.28 Wh and the average autonomy would be 1 hour and 18 minutes.
Table II reports the features of the control unit.

Number of LPAs	3
Valves	Proportional
Control Mode	Proportional
PWM Resolution	12 bits - 1 digit = 1.22 mV@5V
Pressure sensor range	0 - 207 kPa
Pressure sensor resolution	12 bits - 1 digit = 80 Pa
Communication	Bluetooth RS232 @ 1Mbps
Power Consumption	Min=0.3 W - Av=3.3 W - Max=6.3 W
Weight	95 g
Size	51x23 mm
Average Autonomy	3 AAA battery - 34.5 g - 32 m 3 AA battery - 72.0 g - 1h 18 m

TABLE II
WICCU FEATURES

IV. RESULTS AND DISCUSSION

Two pneumatic hardware have been built to test WiCCU as it is shown in figure 4: a LPA and a platform base with 3 LPA. In both cases, experiments reported step and sinusoidal wave pressure profiles and PWM_{di} for each LPA_i. All the experiments were performed by using a low-cost pump for airbrush AS-18, with a maximal pressure of 700 kPa, and airflow of 20-23 L/min). The maximal pressure of the air-pump was limited to 200 kPa, which is the maximal range of the pressure sensors.

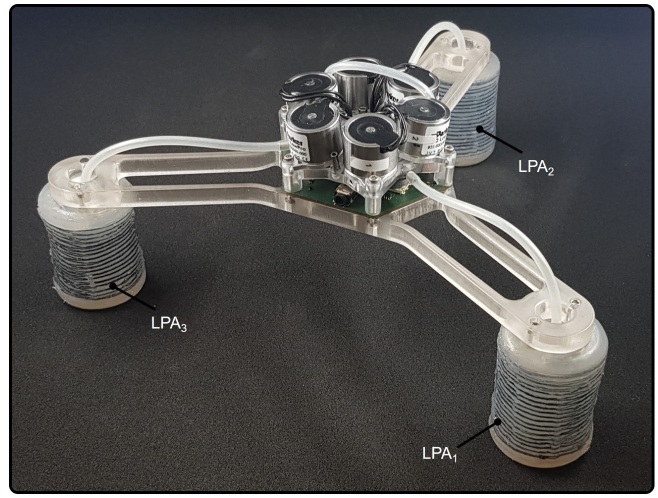

Fig. 4. Base with 3 LPAs controlled by WiCCU, which is fixed on top by using 6 screws.

A. Linear Pneumatic Actuator (LPA)

The LPA has a cylindrical shape, an external and internal diameter, a total length of 30x22x30 mm, as it is shown in figure 4. The air cross-section area is 283.50 mm^2. All the experiments were performed with the LPA in vertical position and with no external load. A step profile has been investigated with different commanded pressures, $P_r = \{20, 30, 40, 50, 70, 90\}$ kPa as shown in figure 5-a. The tuning of the PID controller was done before performing the experiments by trial and error, and the final parameters were: $K_p = 10,\ K_i = 1, K_d = 5\ , PWM_0 = 500,\ T_0 = 150ms$. This was the best combination of the PID parameters to avoid oscillations and overshot of the pressure with the designed LPA. Ten trials for each step were performed and the average value reported in the graphs. There were no evidence of any negative overshot. This was related to the fast response of the system and the K_d parameter of the PID controller. As an example, figure 5-d shows the 40 kPa step profile with the PWM_{di} for the input and output valves. It is evident that the inlet valve reduces the PWM_{di} when the commanded pressure is approaching. This is related to the choice of the K_d parameter. The PWM_d of the OV has a spike to avoid any negative overshot and to achieve the desired pressure P_r. A small spike, when the pressure rises, is related to both the elastic behaviour of the LPA and the K_d parameter. This spike is quickly compensated with the PID and no oscillation is shown in the pressure profile. To further investigate the performance of WiCCU, pressure sinusoidal waves have been implemented: $P_r = P_o + P_A sin(2\pi f_o(t - t_o))$. Figure 5 (b and c) shows the pressure profile (blue line) and the PWM_{di} activation of the inlet (PWM_{IV}, red line) and outlet (PWM_{OV}, green line) valves.

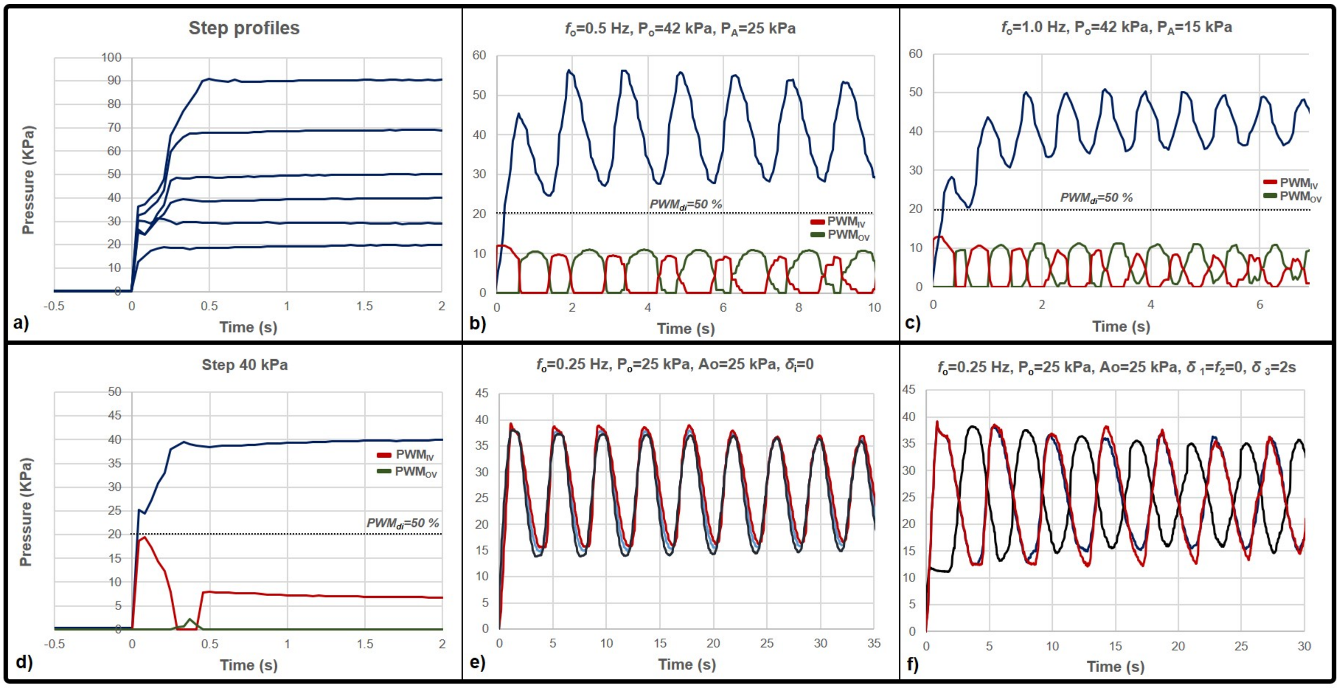

Fig. 5. Experiments performed: a) step profiles, from 20 to 90 kPa; b) LPA sinusoidal wave $P_r = 42 + 25\, sin(2\pi\, 0.5\, t)$ in blue line, together with PWM_{di} for the inlet (red line) and outlet (green line) valves; c) LPA sinusoidal wave $P_r = 42 + 15 sin(2\pi\, t)$; d) step profile at 40 kPa with PWM_{di} for the inlet and outlet valves; e) base control with simultaneous activation of the 3 LPAs with the same sinusoidal wave; f) base control with simultaneous activation of 3 LPAs, same phase for LPA_1 (black line) and LPA_2 (blue line), and opposite phase LPA_3 (red line).

The system can follow a sinusoidal wave at 0.5 Hz with an amplitude of P_A = 25 kPa, and with an amplitude of P_A=15 kPa at 1.0 Hz. The PWM_d, after a transient time, is higher for the IV than for the OV. This is related to the input airflow which is higher than the output airflow to deflate the chamber. A vacuum pump connected to each OV_i would reduce this time and consequently would increase the sinusoidal wave frequency that can be performed by the LPA. A transient phase is shown in the first part of the sinusoidal control. The results of the step profile and the sinusoidal wave are reported in the figure 5 (a, b, c, d).

B. Platform with 3 LPAs

Simultaneous activations of 3 different LPAs was tested in a platform with 3 DOFs with WiCCU fixed by 6 screws on top of it, as shown in figure 4. An external air pump and a power unit were connected to WiCCU with 1 air tube and 2 wires (positive and negative voltage). Experiments were performed with sinusoidal profiles to all the chamber simultaneously and with 1 LPA in opposite phase. Sinusoidal waves $P_{ri} = P_0 + P_A sin[2\pi f - i(t - \delta_i)]$ with $f = 0.25$ Hz with same phase for all the LPAs, and $\delta_3 = 2$ seconds, for the LPA_3. Graphs in figure 5 (e, f) shows the sinusoidal waves profiles.

PID parameters were the same for each LPA. When the sinusoidal waves were all in phase, the commanded pressure were all similar and no spikes were detected (Fig. 5-e). When the sinusoidal wave phase in LP_3 was opposite to LP_1, and LP_2, spikes and overshoot were evident in the profile (5-f). This is related to the disturbance of the simultaneous activation of the input and outlet valves that have produced noise in the air flow. This noise is related to the air pump used for these experiments, not able to produce a constant air flow. In addition, the platform was not fixed to the ground and therefore the friction force between each LPA and ground could have affected the stability of the output pressure profile.

V. Conclusion

The design and experiments of a novel Wireless Compact Control Unit (WiCCU) are reported. This unit can be used to design an untethered pneumatic device because of i) its light weight, ii) high precision to control various pressure profiles, iii) a low power consumption, and iv) wireless communication. Experiments to control a LPA and the simultaneous activation of 3 LPAs with sinusoidal pressure profiles have shown good precision and repeatability. The wireless solution and the manifold included in the compact design, reduces the number of wires and tubes needed to design a pneumatic device. Several units can be controlled together by using RS232 serial ports from a single or multiple device for a distributed high-level control. WiCCU addresses the design of a fully untethered robot by using on-board battery and a small tank of air/gas.

Additional improvements can be made by including other sensors in the control loop, such as IMU (Inertial Measurement Unit) and stretchable sensors in each LPA. This can allow the device to implement a posture stability control and position control of the 3DOFs base.

REFERENCES

[1] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots." *Nature*, vol. 521, no. 7553, pp. 467–475, 2015. [Online]. Available: http://www.nature.com/nature/journal/v521/n7553/abs/nature14543.html

[2] C. Laschi, B. Mazzolai, and M. Cianchetti, "Soft robotics: Technologies and systems pushing the boundaries of robot abilities," *Science Robotics*, vol. 1, no. 1, 2016. [Online]. Available: http://robotics.sciencemag.org/content/1/1/eaah3690

[3] K. Suzumori, S. Iikura, and H. Tanaka, "Flexible microactuator for miniature robots," in *Micro Electro Mechanical Systems, 1991, MEMS '91, Proceedings. An Investigation of Micro Structures, Sensors, Actuators, Machines and Robots. IEEE*, Jan 1991, pp. 204–209.

[4] S. K., I. S., and T. H., "Development of flexible microactuator and its applications to robotic mechanisms," in *Robotics and Automation, 1991. Proceedings., 1991 IEEE International Conference on*, Apr 1991, pp. 1622–1627 vol.2.

[5] L. Manfredi, L. Yue, J. Zhang, and A. Cuschieri, "A 4 DOFs variable stiffness soft module," in *IEEE RoboSoft*, Apr. 2018.

[6] L. Manfredi, L. Yue, and A. Cuschieri, "A 3 DOFs mini variable stiffness soft pneumatic actuator," in *Proc. ACTUATOR 2018; 16th Int. Conf. New Actuators*, June 2018, pp. 1–4.

[7] L. Manfredi, F. Putzu, S. Guler, Y. Huan, and A. Cuschieri, "4 DOFs hollow soft pneumatic actuator - HOSE," *Materials Research Express*, vol. 6, no. 4, p. 045703, jan 2019. [Online]. Available: https://doi.org/10.1088/2053-1591/aaebea

[8] A. D. Marchese, R. K. Katzschmann, and D. Rus, "Whole arm planning for a soft and highly compliant 2d robotic manipulator," in *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Sept 2014, pp. 554–560.

[9] A. D. Marchese and D. Rus, "Design, kinematics, and control of a soft spatial fluidic elastomer manipulator," *The International Journal of Robotics Research*, vol. 35, no. 7, pp. 840–869, 2016. [Online]. Available: https://doi.org/10.1177/0278364915587925

[10] P. Polygerinos, K. C. Galloway, E. Savage, M. Herman, K. O. Donnell, and C. J. Walsh, "Soft robotic glove for hand rehabilitation and task specific training," in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, May 2015, pp. 2913–2919.

[11] C.-Y. Chu and R. M. Patterson, "Soft robotic devices for hand rehabilitation and assistance: a narrative review," *Journal of NeuroEngineering and Rehabilitation*, vol. 15, no. 1, p. 9, Feb 2018. [Online]. Available: https://doi.org/10.1186/s12984-018-0350-6

[12] D. Trivedi, C. D. Rahn, W. M. Kier, and I. D. Walker, "Soft robotics: Biological inspiration, state of the art, and future research," *Appl. Bionics Biomechanics*, vol. 5, no. 3, pp. 99–117, July 2008. [Online]. Available: http://dx.doi.org/10.1080/11762320802557865

[13] T. Michael, T., S. Robert, F., M. Bobak, G. Kevin, C., W. Michael, K. Michael, W. Robert, J., and W. George, M., "A resilient, untethered soft robot," *Soft Robotics*, vol. 1, pp. 213–223, 2014.

[14] M. Wehner, R. L. Truby, D. J. Fitzgerald, B. Mosadegh, G. M. Whitesides, J. A. Lewis, and R. J. Wood, "An integrated design and fabrication strategy for entirely soft, autonomous robots," *Nature*, vol. 536, pp. 451–466, 2016.

[15] J. W. Booth, J. C. Case, E. L. White, D. S. Shah, and R. Kramer-Bottiglio, "An addressable pneumatic regulator for distributed control of soft robots," in *2018 IEEE International Conference on Soft Robotics (RoboSoft)*, April 2018, pp. 25–30.

[16] "Softrobotictoolkit," https://softroboticstoolkit.com/, accessed: 2018-11-11.