Hybrid Pneumatic-Hydraulic Actuator with Adaptable Stiffness

Al-Hababheh O., Bino B., Surbil M., Badrieh M., Khasawneh S.

Abstract: This work presents a method to control the stiffness of a hybrid actuator. The resulting stiffness is required to meet the conditions of real life applications, such as human prosthetics, human-robot interaction, and delicate robot interaction. The hybrid actuator is basically a pneumatic-hydraulic muscle, which can operate simultaneously in both pneumatic and hydraulic modes. The main challenge in this work is to manage the switching between pneumatic and hydraulic modes. In pneumatic mode when a load is applied to the actuator, air in the tank is allowed to compress resulting in muscle extension. While in hydraulic mode, the fluid is pressurized and the resultant system stiffness is higher. In both cases, the McKibben muscle is full with hydraulic fluid. It has been shown that the performance of the actuator is mostly the same in terms of response and bandwidth in both modes of operation. The use of different types of controllers to improve the system performance is investigated. It is found that the parallel configuration combined with PID controller is the best solution for achieving the required muscle performance.

Keywords: Variable stiffness muscle, Pneumatic muscle, Human robot interaction, Hybrid actuator, Pneumatic-hydraulic actuator

I. INTRODUCTION

Interaction between humans and robots requires proper safety measures, including compliant manipulation. This requirement can be problematic for many conventional actuators [1], which typically use high stiffness to achieve high performance, thereby increasing inertia and leading to large impact forces upon collision. In order to fulfill the interaction requirements, two types of actuators can be used; McKibben pneumatic artificial muscle (PAM) and hydraulic artificial muscles (HAM). PAMs are lightweight, compliant and capable of higher specific work than comparably-sized HAMs and electric motors. On the other hand, HAMs are known to be more powerful than PAMs. However, if these two muscles are combined together, some interesting characteristics can be obtained.The function of PAM depends on air compressibility. However, in some applications, HAM should be added to provide more stiffness to the actuator. In addition, other advantages of using HAM include faster response time and better position control. The work done by Focchi [2] showed that the use of HAM provides higher stiffness. However, the drawback of HAM is that it is not flexible and thus not appropriate for human interaction. Therefore, a possible solution would be the use of combined PAM/HAM design, where the PAM interfaces the human and the HAM is used only when high power is needed. Xiang et al. [3] found that seamless switching between the two modes is a challenge. They used PID controller for the pneumatic valve and P controller for the hydraulic valve, so as to achieve smooth switching between the two modes. In order to improve the transition of switching, this work investigates using different types of controllers and different configurations of the hydraulic and pneumatic circuits. Applications of McKibben muscles include prosthetics and robotic actuators, where typical compression ratio can be around 30%. In order to study the combined effect of using these two types of muscles, a model for each type should first be identified. After that the combined model is investigated.

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***** Correspondence Author

Al-Hababheh O.*, Mechatronics Engineering Department, the University of Jordan, Amman, Jordan. Email: o.habahbeh@ju.edu.jo

Bino B.,Mechatronics Engineering Department, the University of Jordan, Amman, Jordan, Email: basheer.bino@gmail.com

Surbil M.,Mechatronics Engineering Department, the University of Jordan, Amman, Jordan, Email: murad19962009@yahoo.com

Badrieh M., Mechatronics Engineering Department, the University of Jordan, Amman, Jordan, Email: moaz-m-b@hotmail.com

Khasawneh S., Mechatronics Engineering Department, the University of Jordan, Amman, Jordan, Email: saeed_khasawneh@yahoo.com

II. PAM MODEL

The PAM system requires a directional control valve, double acting cylinder, sensors, processor, and air compressor. In order to simulate the position control of PAM actuator, a mathematical model is needed. A state-space formulation of the transfer function of the PAM system is [4]:

$$G(s)_{Pneumatic} = \frac{-.51s^2+6.4s+92}{s^3+16s^2+86s+.39} \qquad (1)$$

III. HAM MODEL

The HAM actuator is controlled by a hydraulic valve that allows the liquid to contract into the muscle and shrink it, causing the lift of the load. When the valve is activated by a voltage, it allows the hydraulic fluid to flow from the pump to the muscle. The fluid entering the muscle causes it to retract and lift the load [3]. The components of the HAM model include directional control valve, cylinder, pump, pressure relief valve, and mechanical load, which is a spring-mass-damper system. The mass and the maximum stroke are set as 0.33 kg and 400 mm, respectively [3], while the main control parameter is the position of the muscle. The specifications of the hydraulic fluid used are shown in Table 1.

Table 1: Specifications of the hydraulic fluid

Fluid density	850 kg/m^3
Kinematic viscosity	1.8×10^{-5} m^2/s
Bulk modulus at atm. pressure	8×10^8 Pa
Relative amount of trapped air	0.005

The actuator can be extended or retracted by an input step signal which is used to control the hydraulic valve. As a result, an output of first-order response is obtained as shown in figure 1; where the gain "K" is found as 129 mm. If it is multiplied by the time constant "0.63" it will provide the output for one "τ" as 81 mm. The corresponding value of "t" is 0.56 s. Therefore, the transfer function can be written as:

$$G(s)_{Hydraulic} = \frac{129}{.56s+1} \quad (2)$$

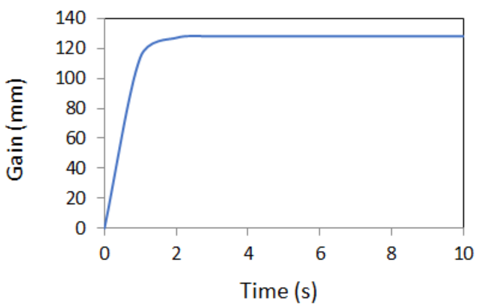

Fig. 1: Hydraulic output signal

IV. COMBINED PAM/HAM MODEL

The block diagram of the combined PAM/HAM system is shown in figure 2. The control of the combined design involves both hydraulic and pneumatic valves. The muscle position will be controlled using different methods. The control scheme used in this work is shown in figure 3, where a switch allows the hydraulic control loop to be disabled. The controller includes a mode switch which enables switching between hydraulic and pneumatic modes. In hydraulic mode, the pneumatic valve can be open or closed contingent upon the need to extend or retract the muscle. Whereas in pneumatic mode, the duty cycle of the fluid driven valve is set to its maximum position. However, while working in pressure driven mode, the PID controller is utilized to drive both the fluid powered valve and the pneumatic valve. The fluid valve is used to control the stream rate of pressure driven liquid, while the pneumatic valve is used to pressurize or depressurize the muscle, by filling or venting the liquid. The Pulse-width modulation (PWM) duty cycle of the signal connected to the two valves is given by a code which depends on the required position.

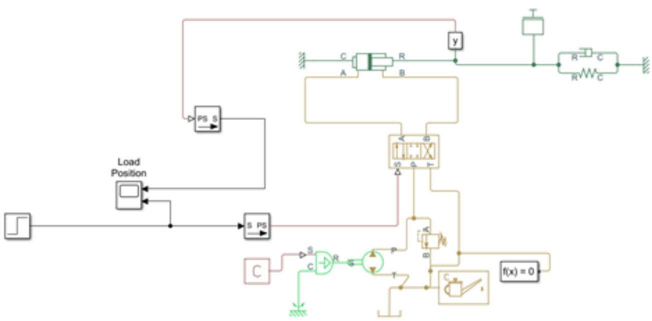

Fig. 2: System block diagram

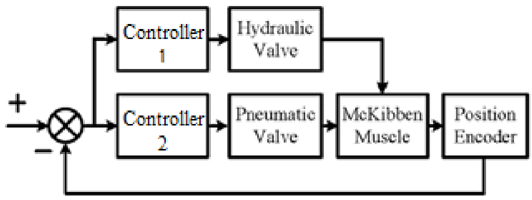

Fig. 3: Simultaneous control of pneumatic and hydraulic valves

In this work, the main goal is to simultaneously control the two valves (hydraulic and pneumatic). In pneumatic mode, the hydraulic valve is always open, while in hydraulic mode, the pneumatic valve is either at maximum fill or maximum vent. The basic operation of the muscle requires the control of position and speed. Since the speed cannot be used as input for the hydraulic valve, a controller is added to the system so as to set the duty cycle proportional to the joint position error [2]. When both pneumatic and hydraulic valves are run in parallel without controllers, the system will have noise. Therefore, a controller is needed to improve the system performance. The control parameters used in the simulations are shown in Table 2.

Table 2: Controller input parameters

Setup	Controller Type	K_p	K_i	K_d
Series	***P***	0.00641	0	0
	I	0	9.853e-08	0
	PI	0.0064	9.127e-05	0
	PD	0.00236	0	0
	PID	0.00562	0.000732	0.0048
Parallel	***P***	0.00772	0	0
	I	0	0.009	0
	PI	0.00556	0.00981	0
	PD	0.00949	0	0
	PID	0.00556	0.00981	0
Pneumatic Block	***PWM***	84.873	12.772	-15.616
Extend response		0	0.0198	0
Retract response		0.0132	0.0285	0.000484

4.1. PWM design

The pneumatic valve is activated by a step input voltage, while the hydraulic valve is fully open. A transfer function is used for the parallel hydraulic-pneumatic valves. The input step signal runs from 0 to 400 mm, as shown in figure 4. This is the switching signal between extension and retraction of the actuator. The actuator is first extended by the hydraulic valve, where the switch runs for 5 seconds when the slope of the signal is positive. For the next 5 seconds, the slope of the signal will be negative, which means the pneumatic valve is extended. In figure 5, the pneumatic valve is fully open in order to extend the actuator, while a controller is used for the hydraulic valve. This means both hydraulic and pneumatic valves will open at the same time. Actuator retraction is shown in figure 6, which is accomplished by discharging air in the muscle and tuning the hydraulic valve to the desired value. This happens during the last five seconds when the slope of the signal is negative. The responses of the PWM are shown in figures 7, 8, and 10; where the pneumatic mode is shown in figure 7, the hydraulic mode extension isshown in figure 8, and the hydraulic mode retraction is shown in figure 9.

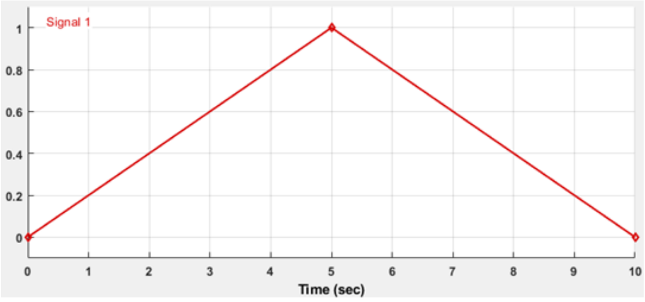

Fig. 4: Retract and extend switching circuit

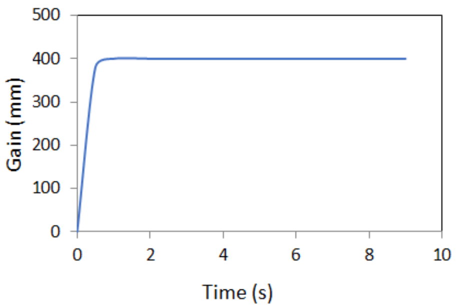

Fig. 5: Actuator extension signal

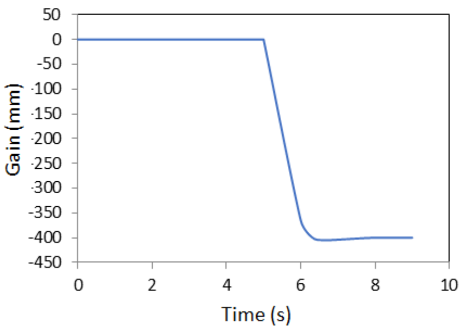

Fig. 6: Retract circuit output

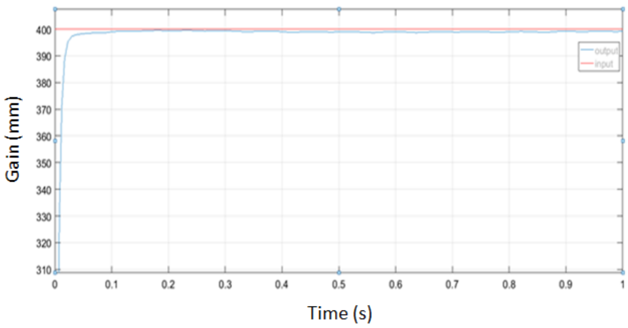

Fig. 7: Subsystem for pneumatic mode PWM

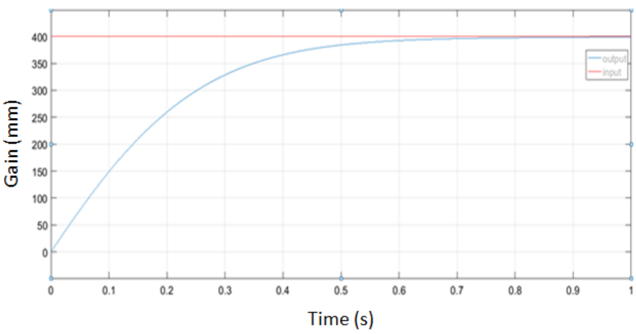

Fig. 8: Hydraulic mode- extend (PWM)

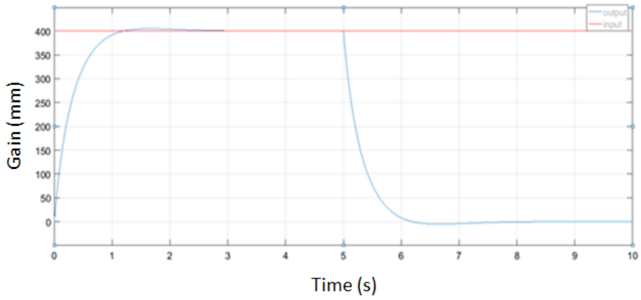

Fig. 9: Hydraulic mode- Retract (PWM)

4.2. Series design

The pneumatic and hydraulic valves are arranged in series, as shown in figure 10. The response of this system is unstable. Therefore, a controller is used in the loop. Sample responses to this arrangement are shown in figure 11 and 12. The resulting control parameters are compared in figures 16-19.

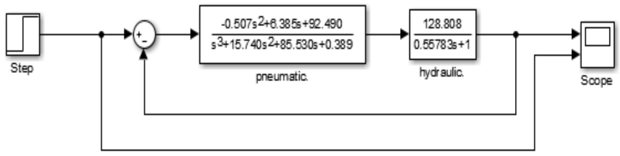

Fig. 10: Series configuration

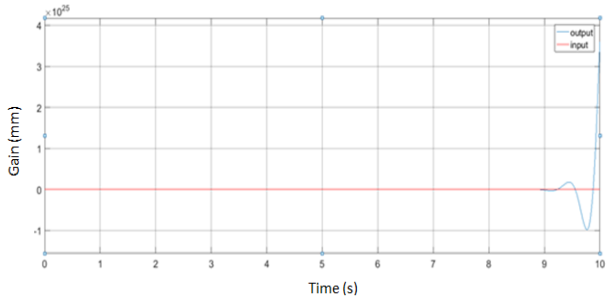

Fig. 11: Output result for series connection

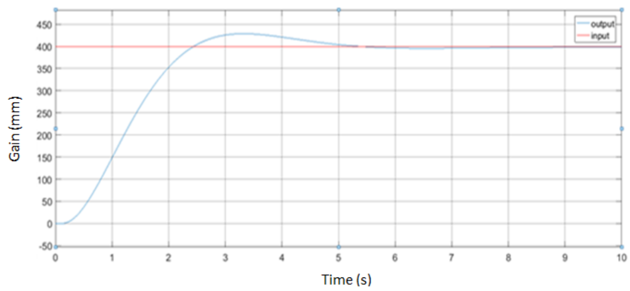

Fig. 12: P controller output result for series

4.3. Parallel design

When the pneumatic and hydraulic valves are set in parallel, as shown in figure 13, the system becomes stable, but with high noise. Therefore, a controller is used to improve the system performance. Sample outputs for parallel configuration are shown in figure 14 and 15. Different types of controllers are used as shown in figures 16-19.

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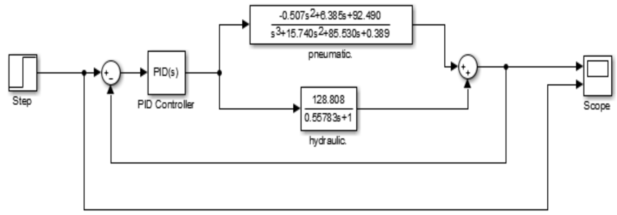

Fig. 13: Parallel configuration with controller

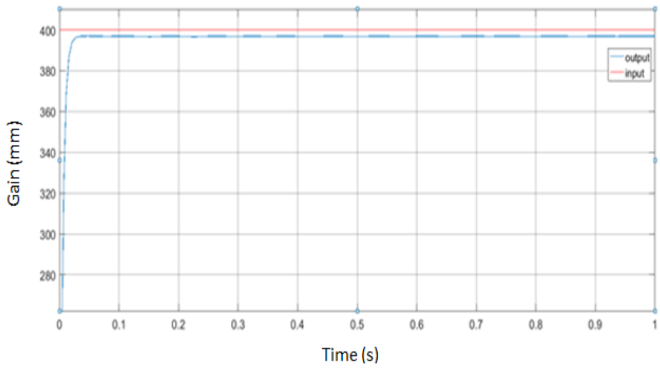

Fig. 14: Output for parallel connection

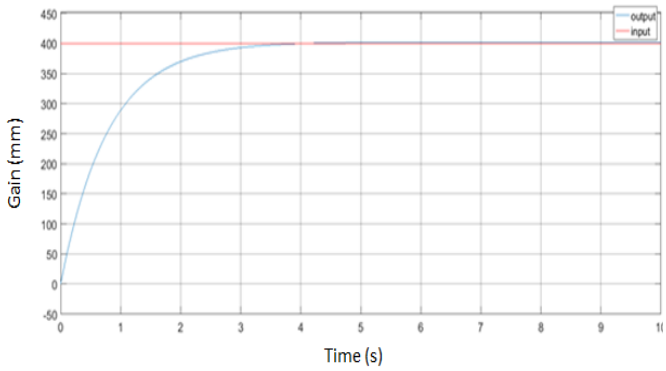

Fig. 15: PI controller output for parallel

V. CONTROL RESPONSE

The system performance under multiple configurations including different designs and controllers is summarized in figures 16-19. The figures include responses such as Rise time, Settling time, Over-shoot, and Steady-state error. The configurations include series, parallel, PWM, extend and retract, while the controllers include P, I, PI, PD, and PID. As shown in figure 16, the rise time for parallel proportional, series integral and parallel PD is the highest. While it is lowest for parallel integral, series proportional, series PI, parallel PI, parallel PID, and series PID.In figure 17, the series integral and series PID have the highest settling times, while parallel PD and P have the lowest settling time. In figure 18, the highest overshoot occurs in series proportional, series integral, parallel integral, series PI, and series PID. However, the lowest overshoot occurs in parallel P and PD. In figure 19, the highest steady-state error occurs in parallel proportional and parallel PD. On the other hand, the lowest steady-state error occurs in series integral and PID. From the above discussion it can be concluded that parallel PID is the best configuration-controller combination, as it has the least errors among all other combinations.

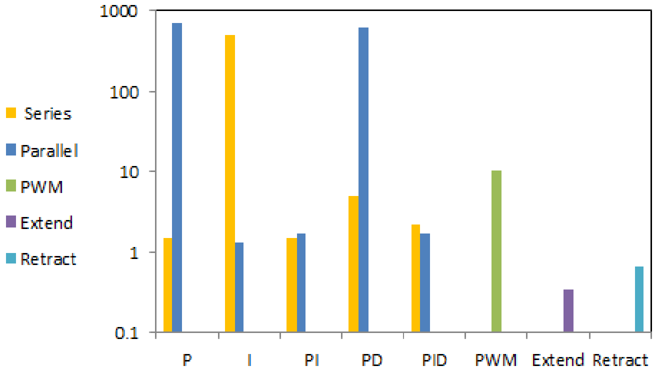

Fig. 16: Rise time (ms)

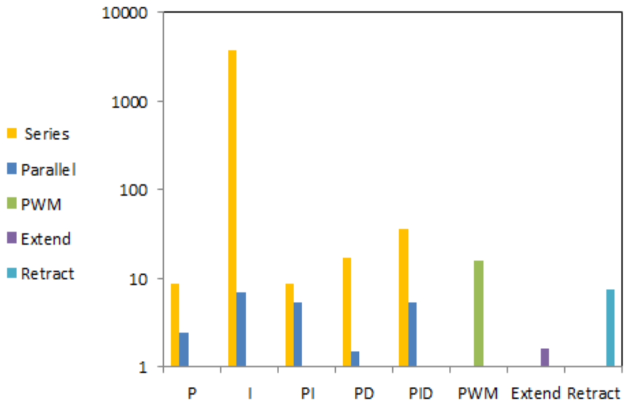

Fig. 17: Settling time (ms)

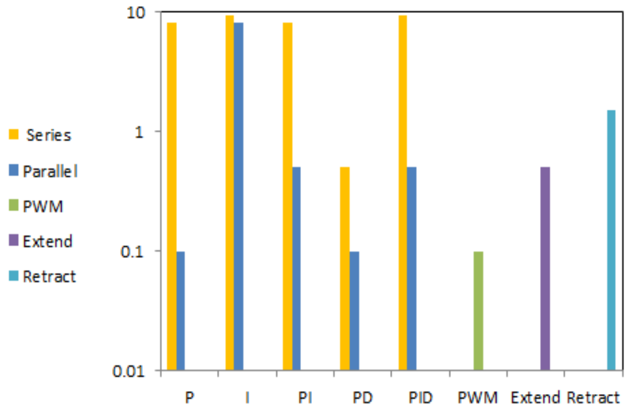

Fig. 18: Overshoot (%)

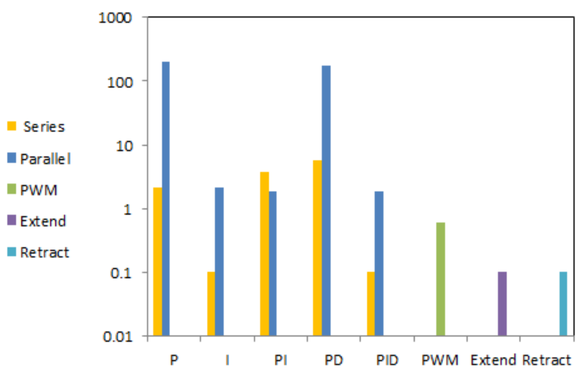

Fig. 19: Steady-state error (%)

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VI. CONCLUSION

The goal of this work was to develop a method to control McKibben muscles while operating in both compliant pneumatic and stiffer hydraulic modes. It is a challenge to manage the switching between pneumatic and hydraulic modes. The suggested method to accomplish that is to keep the hydraulic fluid in the McKibben muscle even when it is operating pneumatically. This is done using a tank which contains both air and hydraulic fluid. In pneumatic mode when a load is applied to the actuator, air in the tank is allowed to compress resulting in muscle extension. On the other hand, in hydraulic mode, air is not allowed to compress and the resultant system stiffness is higher. In both cases, the McKibben muscle is full with hydraulic fluid. It has been shown that the performance of the actuator is mostly the same in terms of response and bandwidth in both modes of operation. The use of different types of controllers to improve the system performance is investigated. Finally, it can be concluded that the combination of the parallel configuration with the PID controller provides the best performance. For future work, it is recommended to explore additional control mechanisms for the parallel configuration which could possibly provide better performance. In addition, building a prototype of this model will help to test the reliability of this design for real life applications.

REFERENCES

1. G. K. Klute, J. M. Czerniecki, B. Hannaford, "Artificial muscles: Actuators for biorobotic systems", *Int'l J. Robotics Research*, vol. 21, No. 4, 2002, pp.295-309.
2. M. Focchi, E. Guglielmino, C. Semini, A. Parmiggiani, N. Tsagarakis, B. Vanderborght, D. G. Caldwell, "Water/air performance analysis of a fluidicmuscle", *2010 IEEE/RSJ International Conf. Intelligent Robots & Systems (IROS S2010)*; Taipei, pp.2194-4199.
3. C. Xiang, M. E. Giannaccini, T. Theodoridis, L. Hao, S. Nefti-Meziani, S. Davis, "Variable stiffness Mckibben muscles with hydraulic and pneumatic operating modes", *J. Advanced Robotics*, vol. 30, No. 13, 2016, pp.889-899.
4. S. Salim, S. Najib, M. F. A. Rahmat, M. Faudzi, Z. H. Ismail, N. Sunar, "Position control of pneumatic actuator using self-regulation nonlinear PID", *J. Mathematical Problems in Engineering*, 2014.

AUTHORS PROFILE

Al-Habahbeh O.earned his B.Sc degree in Mechanical Engineering from the University of Jordan in 1995. He took several positions in industry in Jordan and abroad before obtaining M.Sc degree in Mechanical Engineering. After that he obtained PhD degree in Mechanical Engineering from Clarkson University. After graduation, he joined the University of Jordan as Assistant Professor. He served as Director of Career Guidance and Alumni Office/ King Abdullah II Fund for Development, as well as Vice Dean of Students Affairs. Currently, he holds the position of Associate Professor of Mechatronics Engineering. His research interests include green energy, aviation, and mechatronics. He has published over 30 Journal and conference papers as well as two books.

Bino B.was a Mechatronics Engineering student at the University of Jordan. He worked on a research project on Hybrid pneumatic-hydraulic actuator with adaptable stiffness.

Surbil M.was a Mechatronics Engineering student at the University of Jordan. He worked on a research project on Hybrid pneumatic-hydraulic actuator with adaptable stiffness.

Badrieh M.was a Mechatronics Engineering student at the University of Jordan. He worked on a research project on Hybrid pneumatic-hydraulic actuator with adaptable stiffness.

Khasawneh S.was a Mechatronics Engineering student at the University of Jordan. He worked on a research project on Hybrid pneumatic-hydraulic actuator with adaptable stiffness.