IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 5, 2019, accepted February 28, 2019, date of publication March 5, 2019, date of current version March 25, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2903234

Development of a Power Assist Lifting Device With a Fuzzy PID Speed Regulator

YESSET RAZIYEV, RAMIL GARIFULIN, ALMAS SHINTEMIROV, (Member, IEEE), AND TON DUC DO, (Member, IEEE)
Department of Robotics and Mechatronics, Nazarbayev University, Z05H0P9 Astana, Kazakhstan

Corresponding author: Ton Duc Do (doduc.ton@nu.edu.kz)

This work was supported by Nazarbayev University through the NU-ORAU program, under Grant no. # 06/06.17.24.

ABSTRACT This paper introduces the development of a one-degree-of-freedom (1DOF) power assist device that helps to lift objects and facilitate the operator's job. The existing designs were examined for different control approaches and human-robot cooperation intuitiveness. The project involves the mechanical design of the experimental setup and development of advantageous control system. Since a task for the device is highly dependent on the mass of handling object, an adaptive strategy is a major concern of control system design. The controller design is represented by two loops to control admittance and velocity. To reduce the response time of the device, two velocity controllers are designed and compared with the embedded one. The first is a conventional proportional-integral-derivative controller which has shown better performance than the native controller. The second is derived from the first using fuzzy logic for better handling of different manipulation scenarios. The results illustrate that a faster response of the device can be achieved using a fuzzy logic controller due to the nonlinear nature that allows adapting to changes in velocity error and applied load.

INDEX TERMS Power assist robot, feedback control, industry, object manipulation, fuzzy logic control.

I. INTRODUCTION

Manipulation of objects is a common task in industries such as automotive, construction, mining, transport, manufacturing, etc., which is normally performed manually or by automated manipulation. Lifting heavy loads as well as the frequent carrying of lightweight objects is exhausting and represent significant risk factors for musculoskeletal diseases for industry workers [1]. On the other hand, traditional lifting devices such as cranes with switch controller lack in flexibility and require trained human operator. In this paper, we propose a solution that combines power and mechanical strength of conventional machines and human decision-making ability coupled with the precision of object positioning to perform manipulation tasks in a more intuitive way that require fewer skills [2].

Power assist lifting devices are creating a safer work environment and higher environmental ratings (more tolerant to dust and liquid) in comparison to basic lifters such as compressed air and manually powered hoist, decreasing injury instances, and increasing productivity. Moreover, advantages include rapid return on investment through increased productivity and reduced product damage due to a reasonable amount of time, that can be saved using controlled power assist lifting devices [3].

There exists a number of control strategies for the outer control loop. The method of controlling the ratio of force output to motion input called impedance based control was developed three decades ago [4] still remains quite popular control strategy. It was applied in the mobile mechanism that was created by Lee *et al.* [5], semi-active assist mechanism developed by Kusaka *et al.* [6]. Duchaine and Gosselin [7], Ikeura and Inooka [8] demonstrated the effectiveness of variable impedance control scheme over traditional position control in tasks that require human-robot cooperation.

Another contemporary control approach is admittance control, which is the inverse of impedance. With the help of neural networks, Dimeas *et al.* [9] established a sustainable control model that can adapt to the different object weights. Gosselin *et al.* [10] argue that there is a tradeoff between the applied force and smoother motion for fixed admittance, therefore variable admittance control is preferred. Lecours *et al.* [11] addressed stability issues on the same prototype solved using admittance control technique.

The associate editor coordinating the review of this manuscript and approving it for publication was Yang Tang.

Two distinct implementations were combined by Ott *et al.* [12] in the hybrid control system applied to lightweight industrial arm developed by KUKA and German Aerospace Center (DLR) to take advantage of robust operation of impedance and accuracy of admittance control.

Most of the intelligent assist devices mentioned previously are estimating the applied force using torque/force sensors [4]–[13]. We decided to take advantage of this approach, as it allowed faster creating of a simpler prototype comparing to sensorless technique, but at a higher cost. The applied sensor configuration allowed intuitively manipulating an object.

The other control system design concern is to develop a robust velocity control that could provide small tracking error and fast response to the operator's commands regardless of changes in load. The first approach was to develop a conventional PID velocity controller. According to Farkas *et al.* [14] there some significant drawbacks in using it, particularly non-robust handling of various loads and poor response for non-linear systems.

One of the possible solutions is to introduce an advanced control technique using fuzzy logic to reject the weaknesses of traditional controllers. There are two common implementation approaches: the first is to use fuzzy logic to adjust proportional, integral and derivative gains of the controller similar to one implemented by Kuantama *et al.* [15], Park *et al.* [16], Tao *et al.* [17]. The second is to develop a controller based on fuzzy logic as was proposed and used in papers by Abeywardena *et al.* [18], Xing and Yang [19], Zaky and Metwaly [20], Betin *et al.* [21], Stnean *et al.* [22], Almatheel and Abdelrahman [24], Usman and Rajpurohit [25]. We modified a controller based on fuzzy logic by introducing proportional-derivative-plus-integral (PD+I) controller to reduce computational time.

Our objective was to create a simple 1DOF power assist lifting device and design the advantageous control system, combining better approaches for admittance and velocity control. This paper presents the development stages, including the mechanical design of the setup and control system design. Comparison between the performance of the fuzzy logic velocity controller and conventional controllers was made to illustrate the superiority of the proposed fuzzy logic control approach.

II. DESIGN OF EXPERIMENTAL SETUP

The prototype of a 1DOF lifting device is developed to apply control scheme directly to the physical system. An encoder is attached to the gearhead shaft to measure output angular position and velocity, followed by bearing stage and 3D printed plastic spool to host a nylon cord. The force sensor was also attached to the cord through rope suspension and meant to carry a hook for the load. Fig. 1 refers to actual setup and Table 1 lists characteristics of mechanical and electrical parts used for design.

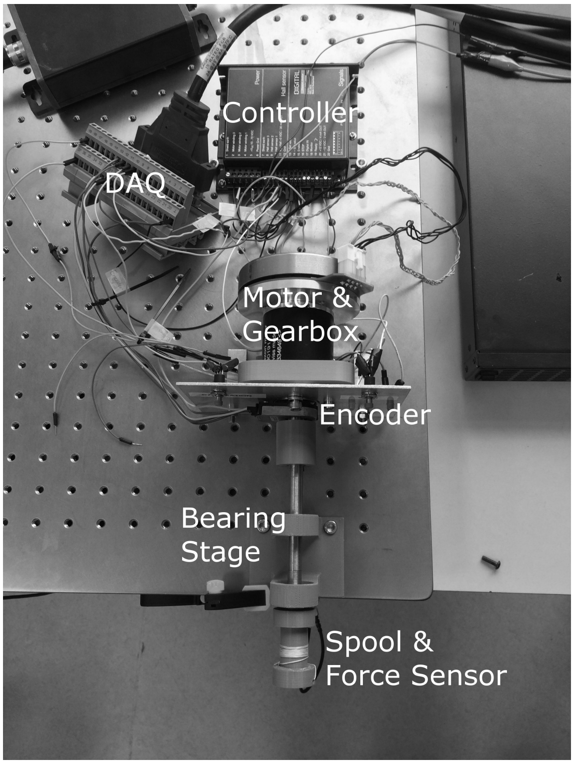


FIGURE 1. Top view of the power assist lifting device with components labeled.

TABLE 1. Specifications of mechanical and electrical parts used in prototype.

Component	Technical Specifications	
	Parameter	Details
Servomotor	Type	DC brushless
	Manufacturer	Maxon Motor, Switzerland
	Part number	244879
	Nominal Voltage	48 V
	Nominal Current	2.27 A
	Nominal Torque	533 mNm
	Nominal Speed	1610 rpm
Gearbox	Type	GP
	Manufacturer	Maxon Motor, Switzerland
	Part number	223085
	Reduction	19:1
	Shaft Type	with key
Controller	Type	4-quadrant digital
	Manufacturer	Maxon Motor, Switzerland
	Part number	306089
	Built-in control modes	Speed, current(torque), voltage
DAQ	Type	37-Pin analog and digital I/O
	Manufacturer	National Instruments, USA
	Part number	PCI-6221
Force sensor	Type	F/T Sensor
	Manufacturer	ATI Industrial Automation, USA
	Part	Nano17 IP65
	Calibration	SI-50-0.5
	Sensing Range	Fz: 70 N
	Resolution	Fz: 1/80 N
	Axis Overload	Fz: 480N
	Shape	Round
	Weight	0.0408 kg
Encoder	Type	Modular Incremental Encoder
	Manufacturer	CUI INC, USA
	Part number	AMT102-V
	Resolution	1024 PPR

For motor holder aluminum was chosen since we needed durable, stiff motor housing to avoid vibrations and at the same time the material easy to process at a machine shop. In addition, to eliminate motor-gearbox axial precession, gearbox supports were designed. For spool and attachments to force sensor we used a 3D printer to create plastic parts.

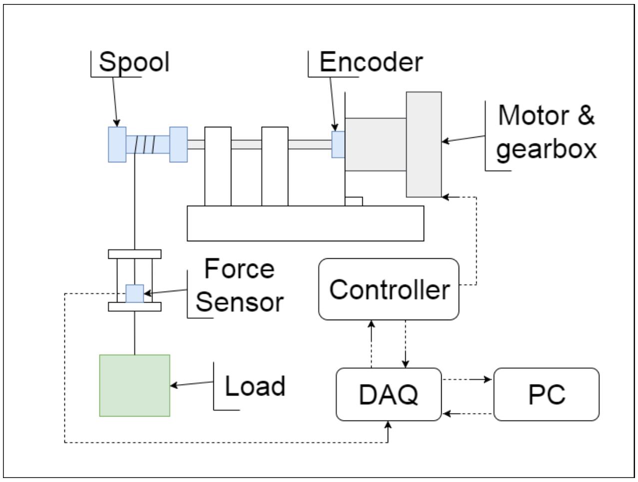


FIGURE 2. Setup schematic.

To ensure there is no stress on the gearbox shaft the bearing stage is added. The bearing stage includes two ball bearings, bearings holder, steel shaft and shaft adapter with key coupling. For more durability of 3D printed parts, the material was changed from ABS to PLA. The rope suspension system was designed to increase loading capacity.

The device has two modes: Calibration and Operation. Switch between modes is performed hitting *Calibration* button. Turned on a green LED indicates that the Operation mode is chosen. Initially, the device is set to the Operation mode with a reference load of 0 kg so it can be pulled down to ground level or the level of the load.

In the Calibration mode lifting at low speed is performed so the load can be attached. Pushing *Calibration* button again latches attached load value as the reference mass. This allows to manipulate loads with different masses and add or remove objects during operation.

In Operation mode, lifting and lowering can be performed by putting force from 1.5 N to 3.75 N in either direction. A force exceeding 3.75 N results in the maximum speed of 1200 rpm on the motor side.

To prevent hitting the spool, a position limit is added in the way that the device stops when reaching initial position. This implies safety in case of object loss or improper operator actions. Pushing the emergency stop button leads to the complete stop of the system.

According to sensor specifications, the operating range allows applying force up to 70 N, which restricts the weight of the manipulated object, considering force applied by operator and safety factor, to 6 kg. To push the limit, a rope suspension system is introduced. The load is distributed and the tensile stress on the sensor is considerably reduced. This increased load capacity to 23 kg considering the safety factor. In this paper, the maximum tested weight is 15 kg.

III. CONTROL STRATEGY

The proposed cascaded control scheme, that can be seen in Fig.4(a), includes admittance, velocity, and current control loops. The design is focused on admittance and velocity controllers, while current control is implemented using Maxon controller. Admittance block receives force difference dF between reference force, which is the weight of a manipulated object, and force applied to force sensor. The output velocity reference is fed to the velocity controller which ensures stable operation of the plant for various loads. The corresponding *Simulink* model is shown in Fig. 4(b).

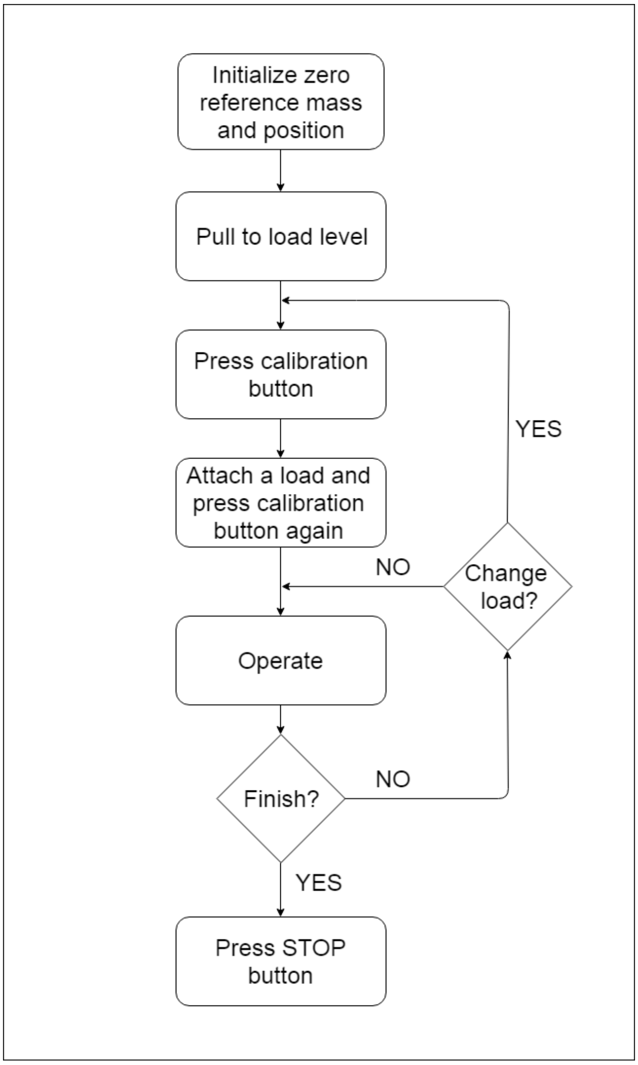


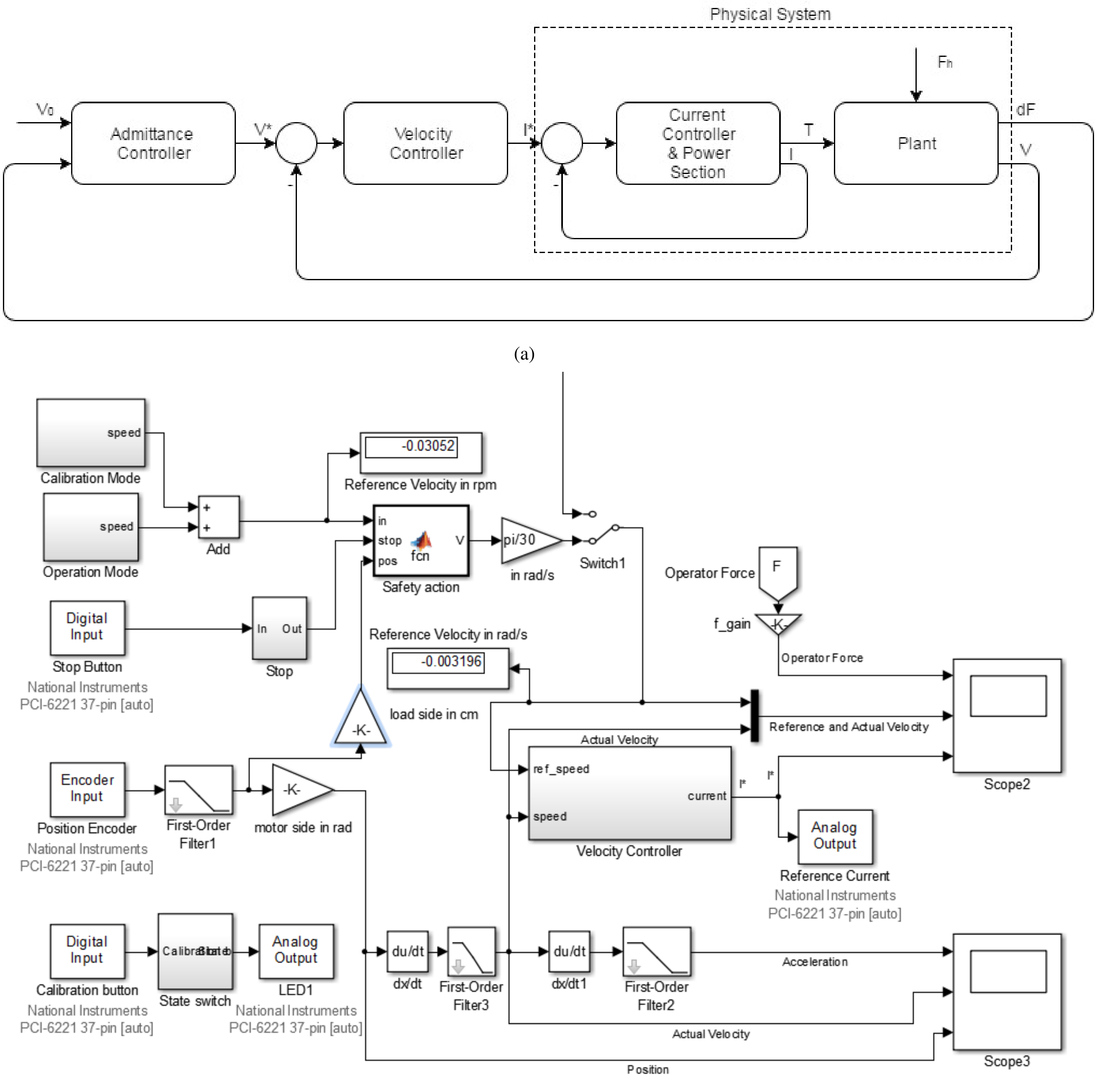
FIGURE 3. Operating procedure flowchart.

A. ADMITTANCE CONTROLLER

The objective was to establish a relation between input force and output velocity reference:

$$V = K_p dF + K_d \frac{dF}{dt} \tag{1}$$

A PD controller is used for this purpose. Tuning was performed using the Ziegler-Nichols method. To reject unintentional force command on the sensor, a dead zone is added in the range from -1.5 N to 1.5 N.



(a)

(b)

FIGURE 4. **Control scheme of the device. (a) Block diagram of the control scheme of the device. (b) Simulink model of the control scheme of the device.**

B. VELOCITY CONTROLLER

1) CONVENTIONAL PID

A velocity controller takes velocity as input and outputs reference current. Feedback velocity is acquired by differentiating position encoder output and is fed to velocity controller. The velocity controller was tuned using the standard Symmetrical Optimum (SO) tuning method for PI gains.

$$G_{SO\omega} = \frac{K_{fbi}J}{4K_mK_{fb\omega}T_\mu} + \frac{K_{fbi}J}{32K_mK_{fb\omega}T_\mu^2 s} = K_{p\omega} + \frac{K_{i\omega}}{s} \quad (2)$$

The derivative action was also added to decrease settling time and output ripples. The obtained model gave a good tracking error and resistance to load disturbance changes i.e. low steady-state error.

The performance of the designed velocity controller is compared with the Maxon controller in velocity mode. The results are presented in Table 3.

2) FUZZY LOGIC CONTROLLER

Another approach that is chosen to design the velocity controller is fuzzy logic. This method utilizes more empirical

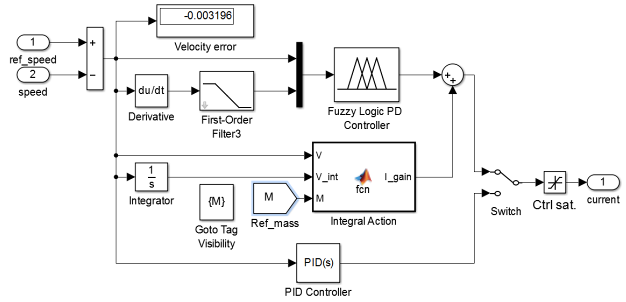


FIGURE 5. Simulink model of velocity controller.

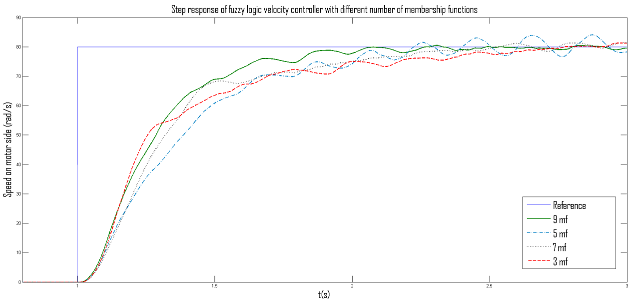


FIGURE 6. Step responses of fuzzy velocity controllers with different number of membership functions.

knowledge gained in the process of manipulation. Fuzzy modeling allows building a copy of conventional controller with additional degrees of freedom produced by the nonlinear nature of the controller. Further tuning made the controller more flexible and adaptive to different control scenarios that were defined by the rule base.

The general procedure [15] of fuzzy controller design is following:

- Tune a PID controller using conventional method.

TABLE 2. Rule generation table for fuzzy PD controller.

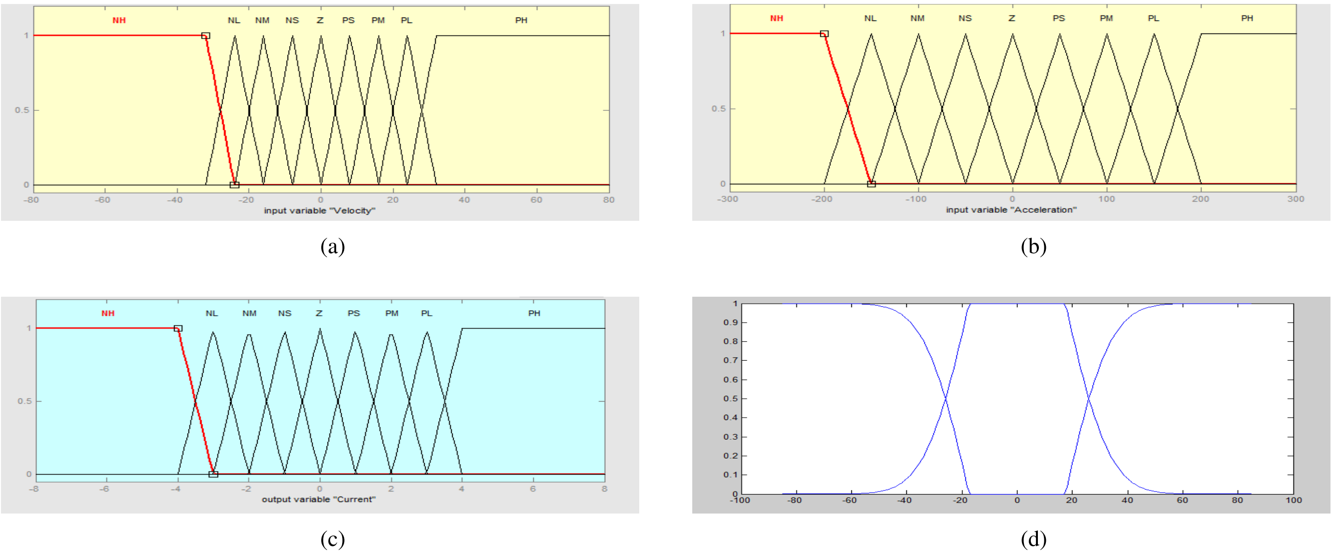
Δ e / e	PH	PL	PM	PS	Z	NS	NM	NL	NH
PH	PH	PH	PH	PL	PL	PM	PM	PS	Z
PL	PH	PH	PL	PL	PM	PM	PS	Z	NS
PM	PH	PL	PL	PM	PM	PS	Z	NS	NM
PS	PL	PL	PM	PM	PS	Z	NS	NM	NM
Z	PL	PM	PM	PS	Z	NS	NM	NM	NL
NS	PM	PM	PS	Z	NS	NM	NM	NL	NL
NM	PM	PS	Z	NS	NM	NM	NL	NL	NH
NL	PS	Z	NS	NM	NM	NL	NL	NH	NH
NH	Z	NS	NM	NM	NL	NL	NH	NH	NH

- Construct a fuzzy controller equivalent to the tuned PID.
- Do further tuning of the fuzzy controller using heuristics.

Next step is to design a fuzzy logic controller (FLC) and compare its performance to the conventional one. On each input, there were chosen nine membership functions: negative huge (NH), negative large (NL), negative medium (NM), negative small (NS), zero (Z) and positive small (PS), positive medium (PM), positive large (PL) and positive huge (PH). Since there are three inputs (proportional, derivative and integral actions) each having nine membership function design it would result in the controller with 729 rules. To minimize computational time, it is convenient to introduce two controllers that are equivalent to PD+I instead of one equivalent to PID. The MATLAB Simulink model is shown in Fig. 5.

The controller equivalent to PD with nine membership functions yields better transient response than controllers with three, five and seven membership functions as can be seen in Fig. 6. The integral action was adjusted in a linear fashion according to the weight of a load. This configuration allows obtaining only 84 rules instead of 729, where 81 of them are derived for PD controller and listed in Table 2, and the other three for an integral part and listed below:

- IF e is N THEN $K_i * \frac{e}{s}$ is P



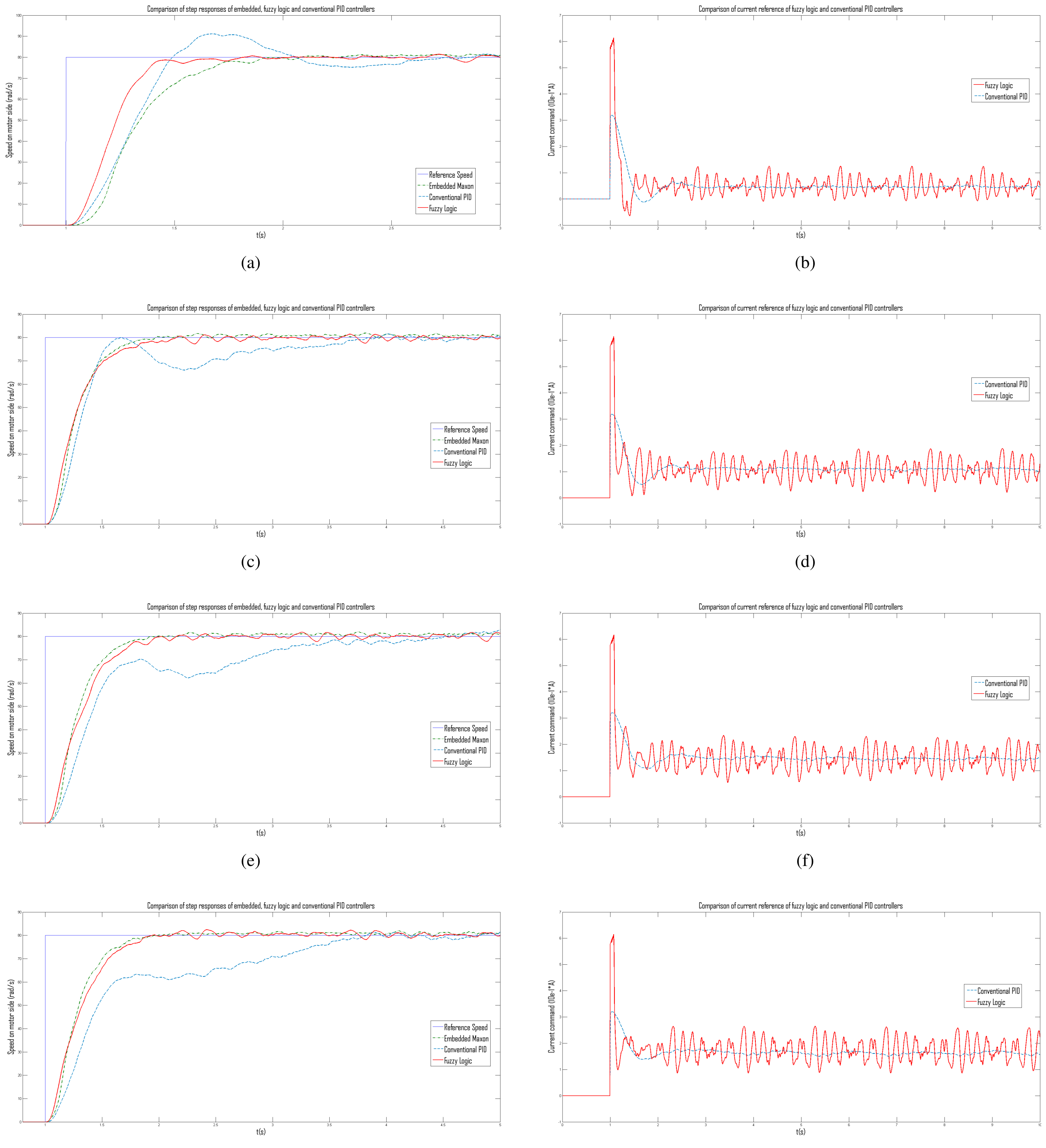
(a)

(b)

(c)

(d)

FIGURE 7. Membership functions. (a) Membership function definition for input variable velocity. (b) Membership function definition for input variable acceleration. (c) Membership function definition for output variable current. (d) Membership function definition for integral action.



(a) (b)

(c) (d)

(e) (f)

(g) (h)

FIGURE 8. **Step responses of embedded, fuzzy logic and conventional PID velocity controllers (a), (c), (e), (g). Current control command of fuzzy logic and conventional PID velocity controllers (b), (d), (f), (h). (a) No load. (b) No load. (c) 5 kg load. (d) 5 kg load. (e) 10 kg load. (f) 10 kg load. (g) 15 kg load. (h) 15 kg load.**

- IF e is Z THEN $K_i * \frac{e}{s}$ is Z
- IF e is P THEN $K_i * \frac{e}{s}$ is N

The membership functions of the fuzzy PD controller were designed to obtain the result that is equivalent to the one from conventional. The new controller was tuned by increasing proportional gain for large error e to reduce rise time. The triangular shape of membership functions was chosen to reduce complexity and computational time using the rule

TABLE 3. Performance of controllers at different load.

Parameter \ Controller Type	Maxon	PID	FLC
No load			
$T_r, (s)$	0.606	0.427	0.361
$T_s, (s)$	0.841	2.848	0.819
$M_p, (\%)$	1.46	13.900	0.087
$e_{ss}, (\%)$	1.25	1.781	1.093
Ripples, (%)	2.962	3.225	4.752
5 kg			
$T_r, (s)$	0.550	0.489	0.585
$T_s, (s)$	0.971	2.914	1.146
$M_p, (\%)$	2.175	-17.500	0.787
$e_{ss}, (\%)$	1.250	0.800	0.600
Ripples, (%)	2.825	5.987	4.850
10 kg			
$T_r, (s)$	0.547	1.877	0.637
$T_s, (s)$	1.23	3.573	1.352
$M_p, (\%)$	2.137	-22.200	1.500
$e_{ss}, (\%)$	1.25	1.063	0.231
Ripples, (%)	2.775	6.675	5.063
15 kg			
$T_r, (s)$	0.533	2.141	0.595
$T_s, (s)$	1.268	2.822	1.123
$M_p, (\%)$	1.360	-23.600	2.560
$e_{ss}, (\%)$	1.250	1.275	0.543
Ripples, (%)	2.737	9.075	5.013

base. The exact parameters of membership functions for input and output variables are shown in Fig. 7 (a)-(c).

Membership functions of integral gain are represented by Gaussian functions on Fig. 7 (d). For the large error, integral action is boosted to decrease settling time. For the small error, there was established a relation between the gain and the weight of a load. The step response of FLC is given in Fig. 8. Further tuning fuzzy controller using heuristics yielded better performance compared to the result of the previous controller.

IV. RESULTS AND DISCUSSION

For admittance control loop it is sufficient to apply the strategy that utilizes a simple PD controller. The main concern of control design is the velocity control loop.

A conventional PID controller faces a challenge when applied to nonlinear systems. In this particular case, it failed to adapt to different loads and demonstrated poorer performance as the load has increased. In comparison to the embedded black-box Maxon controller, its behavior is not sufficient to match industry demands.

The more advanced controller based on fuzzy logic yielded superior result compared to previously designed PID controller and showed fast transient response and small steady-state error for various loads. With the FLC velocity rises by 1.21 times faster and settling time is decreased by 4.26 times. For the unloaded case, the results are presented in Table 3. As can be seen from Fig. 8(b),(d),(f),(h), at the start of velocity step command FLC gives higher current that gives faster transient response compared to PID. These results are practically equivalent to the performance of manufacturer's controller, although its design was based mainly on empirical data of object manipulation.

On the other hand, FLC has a worse current output command, having bigger ripples compared to PID. The possible reason is the adaptive nature of FLC that constantly adjusts the current command according to the rule base.

V. CONCLUSION

In this paper, we showed the development of power-assisted device and its advanced feedback control system using a fuzzy algorithm. As a first step existing solutions were examined and the pathway for our project was selected. Next, the mechanical design was performed to build the prototype. The control scheme based on admittance control and fuzzy logic velocity control was designed to meet the project objectives.

The performance of FLC has shown better results comparing to the conventional PID controller, dramatically improving rise and settling time of the system and similar performance to the Maxon controller.

VI. ACKNOWLEDGMENT

(Almas Shintemirov and Ton Duc Do contributed equally to this work.)

REFERENCES

[1] M. Widia, S. Z. M. Dawal, and N. Yusoff, "Future research on manual lifting tasks in the automotive industry," *Malaysian J. Public Health Med.*, vol. 16, pp. 61–68, Jan. 2016.
[2] A. Niinuma, T. Miyoshi, K. Terashima, and Y. Miyashita, "Evaluation of effectiveness of a power-assisted wire suspension system compared to conventional machine," in *Proc. Int. Conf. Mechatronics Automat.*, Changchun, China, Aug. 2009, pp. 369–374.
[3] *Industry Report: Intelligent Lifting Devices*, Gorbel, New York, NY, USA, 2015.
[4] N. Hogan, "Impedance control: An approach to manipulation," *Trans. ASME*, vol. 107, pp. 8–16, Mar. 1985.
[5] H.-K. Lee, T. Takubo, H. Arai, and K. Tanie, "Control of Mobile Manipulators for Power Assist Systems," in *Proc. IEEE Int. Conf. Syst., Man, Cybern.*, Tokyo, Japan, Oct. 1999, pp. 989–994.
[6] T. Kusaka, T. Tanaka, S. Kaneko, and H. Kajiwara, "Skill assist and power assist for periodic motions by using semi-active assist mechanism with energy control," in *Proc. IEEE Int. Conf. Robot. Biomimetics*, Phuket, Thailand, Dec. 2011, pp. 2187–2192.
[7] V. Duchaine and C. M. Gosselin, "General model of human-robot cooperation using a novel velocity based variable impedance control," in *Proc. 2nd Joint EuroHaptics Conf. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, Tsukuba, Japan, Mar. 2007, pp. 446–451.
[8] R. Ikeura and H. Inooka, "Variable impedance control of a robot for cooperation with a human," in *Proc. IEEE Int. Conf. Robot. Automat.*, Nagoya, Japan, May 1995, pp. 3097–3102.
[9] F. Dimeas, P. Koustoumpardis, and N. Aspragathos, "Admittance neuro-control of a lifting device to reduce human effort," *Adv. Robot.*, vol. 27, no. 13, pp. 1013–1022, Jun. 2013.
[10] C. Gosselin *et al.*, "A friendly beast of burden: A human-assistive robot for handling large payloads," *IEEE Robot. Autom. Mag.*, vol. 20, no. 4, pp. 139–147, Dec. 2013.
[11] A. Lecours, B. Mayer-St-Onge, and C. Gosselin, "Variable admittance control of a four-degree-of-freedom intelligent assist device," in *Proc. IEEE Int. Conf. Robot. Automat.*, Saint Paul, MN, USA, May 2012, pp. 3903–3908.
[12] C. Ott, R. Mukherjee, Y. Nakamura, "Unified impedance and admittance control," in *Proc. IEEE Int. Conf. Robot. Automat.*, Anchorage, AK, USA, May 2010, pp. 554–561.
[13] S. M. M. Rahman and R. Ikeura, "Weight-prediction-based predictive optimal position and force controls of a power assist robotic system for object manipulation," *IEEE Trans. Ind. Electron.*, vol. 63, no. 9, pp. 5964–5975, Sep. 2016.

[14] F. Farkas, A. Zakharov, and S. Z. Varga, "Speed and position controller for DC drives using fuzzy logic," in *Applied Electromagnetics and Mechanics*. Amsterdam, Netherlands: IOS Press, 2000, pp. 213–220.

[15] E. Kuantama, T. Vesselenyi, S. Dzitac, and R. Tarca, "PID and fuzzy-PID control model for quadcopter attitude with disturbance parameter," *Int. J. Comput., Commun. Control*, vol. 12, no. 4, pp. 519–532, Aug. 2017.

[16] S. Park, Y.-J. Ryoo, and D.-Y. Im, "Fuzzy steering control of three-wheels based omnidirectional mobile robot," in *Proc. Int. Conf. Fuzzy Theory Appl. (iFuzzy)*, Taichung, Taiwan, Nov. 2016, pp. 1–6.

[17] Y. Tao *et al.*, "Fuzzy PID control method of deburring industrial robots," in *J. Intell. Fuzzy Syst.*, vol. 29, no. 6, pp. 2447–2455, 2015.

[18] D. M. W. Abeywardena, L. A. K. Amaratunga, S. A. A. Shakoor, and S. R. Munasinghe, "A velocity feedback fuzzy logic controller for stable hovering of a quad rotor UAV," in *Proc. Int. Conf. Ind. Inf. Syst. (ICIIS)*, Sri Lanka, Dec. 2009, pp. 558–562.

[19] L. Xing and S. Yang, "Fuzzy-PID controller with variable integral parameter for temperature control in variable air volume air conditioning systems," in *Proc. Int. Conf. Elect. Control Eng.*, Wuhan, China, Jun. 2010, pp. 1050–1053.

[20] M. S. Zaky, M. K. Metwaly, "A performance investigation of a four-switch three-phase inverter-fed IM drives at low speeds using fuzzy logic and PI controllers," *IEEE Trans. Power Electron.*, vol. 32, no. 5, pp. 3741–3753, May 2017.

[21] F. Betin, D. Pinchon, and G.-A. Capolino, "Fuzzy logic applied to speed control of a stepping motor drive," *IEEE Trans. Ind. Electron.*, vol. 47, no. 3, pp. 610–622, Jun. 2000.

[22] A. Stînean, C.-A. Bojan-Dragos, R.-E. Precup, S. Preitl, and E. M. Petriu, "Takagi-Sugeno PD+I fuzzy control of processes with variable moment of inertia," in *Proc. Int. Symp. Innov. Intell. Syst. Appl. (INISTA)*, Madrid, Spain, Sep. 2015, pp. 1–8.

[23] J. J. Espinosa, J. P. L. Vanderwalle, and V. Wertz, "Fuzzy Control," in *Fuzzy Logic, Identification and Predictive Control*, New York, NY, USA: Springer-Verlag, 2005, ch. 5, sec. 1, pp. 124–129.

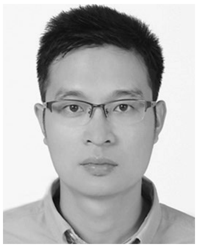
[24] Y. A. Almatheel and A. Abdelrahman, "Speed control of DC motor using fuzzy logic controller," in *Proc. Int. Conf. Commun., Control, Comput. Electron. Eng. (ICCCCEE)*, Khartoum, Sudan, Jan. 2017, pp. 1–8.

[25] A. Usman and B. S. Rajpurohit, "Speed control of a BLDC motor using fuzzy logic controller," in *Proc. IEEE 1st Int. Conf. Power Electron., Intell. Control Energy Syst. (ICPEICES)*, Delhi, India, Jul. 2016, pp. 1–6.

YESSET RAZIYEV received the B.Sc. degree in robotics and mechatronics from Nazarbayev University, Kazakhstan. He was a Research Assistant with the Robotics and Mechatronics Department, in 2017, and also with the Electronic and Electrical Engineering Department, Nazarbayev University, in 2018. His research interests include fuzzy logic control system design, the IoT applications of asset smart monitoring, and control methods in swarm robotics.

RAMIL GARIFULIN, photograph and biography not available at the time of publication.

ALMAS SHINTEMIROV (S'07–M'12) received the engineering degree in electrical engineering and the Ph.D. degree in technical sciences from Pavlodar State University, Pavlodar, Kazakhstan, in 2001 and 2004, respectively, and the Ph.D. degree in electrical engineering and electronics from the University of Liverpool, Liverpool, U.K., in 2009. In 2009, he joined the newly established Nazarbayev University, Astana, Kazakhstan, to work in various administrative and research positions setting up the university academic schools and research centers. In 2011, he joined as a Founding Faculty Member with the Department of Robotics and Mechatronics, Nazarbayev University, where he is currently an Associate Professor of robotics and mechatronics and directs the Astana Laboratory for Robotic and Intelligent Systems (www.alaris.kz). His research interests include the optimal control of industrial, assistive and mobile robots, human-machine interfaces for robot control, and mechatronic systems design. He is a member of the IEEE Robotics and Automation Society.



TON DUC DO (S'12–M'14) received the B.S. and M.S. degrees in electrical engineering from the Hanoi University of Science and Technology, Hanoi, Vietnam, in 2007 and 2009, respectively, and the Ph.D. degree in electrical engineering from Dongguk University, Seoul, South Korea, in 2014.

From 2008 to 2009, he was with the Division of Electrical Engineering, Thuy Loi University, Vietnam, as a Lecturer. He was with the Division of Electronics and Electrical Engineering, Dongguk University, as a Postdoctoral Researcher, in 2014. He was also a Senior Researcher with the Pioneer Research Center for Controlling Dementia by Converging Technology, Gyeongsang National University, South Korea, from 2014 to 2015. Since 2015, he has been an Assistant Professor with the Department of Robotics and Mechatronics, Nazarbayev University, Kazakhstan. His research interests include the field of advanced control system design, electric machine drives, renewable energy conversion systems, uninterruptible power supplies, electromagnetic actuator systems, targeted drug delivery systems, and nanorobots.

Dr. Do received the Best Research Award from Dongguk University, in 2014. He is currently an Associate Editor of the IEEE ACCESS.

• • •