Control of an Assistive Robot for Paraplegics using PID Controller with Sliding Perturbation Observer

Hamza Khan
School of Mechanical Engineering, Pusan National University, Busan, South Korea
Email: hamzakhan.0496@gmail.com

Saad Jamshed Abbasi and Min Cheol Lee*
School of Mechanical Engineering, Pusan National University, Busan, South Korea
Email: saadjamshed93@gmail.com, mclee@pusan.ac.kr

***Abstract*—Paraplegia means immobilization of the lower body as a result of damage to the spinal cord. Rehabilitation of paraplegics become and important research topic to help the patients in restoring and improving their quality of life. This paper focuses on the position control design of an assistive robot's sit-stand mechanism developed for people with paraplegia to help them in transforming their position from sitting to stand and vice versa. Two control techniques were proposed and compared, including conventional PID and PID integrated with non-linear observer known as sliding perturbation observer (PIDSPO). The control algorithms were designed and then implemented in MATLAB/Simulink environment. The simulation results exemplified that PID is a linear control, therefore, when controlling the system with uncertainties and disturbances, the system response experience oscillations and overshoot. On the other hand, PIDSPO is a robust control with a linear control algorithm integrated with a non-linear compensator shows better performance than PID even in the presence of external disturbances.**

***Index Terms*— paraplegia, assistive robot, PID, SPO, PIDSPO**

I. Introduction

Paraplegia refers to the loss of movement or sense in lower limbs, usually caused by damage or injury to the spinal cord. Spinal cord injury can bound a person to a wheelchair and a lifetime of medical assistance. The paralysis caused by this spinal cord injury has different stages, ranging from reduced leg control to complete inability to actuate the lower limb. Various studies were done on assistive rehabilitation robots. These robots were focused on assisting the patient in restoring their mobility. These studies helped in making such a mechanism that will allow the patient to reinstate the mobility of the affected limb. Such kind of mechanism assists the patients during their training sessions [1,2].

A variety of different actuation methods have been used for the assistive mechanism. [3] proposes a 3-DOF assistive robot for people with paraplegia using an electro-hydraulic servo system using position control. [4] presented an exoskeleton framework known as Robot Suit Hall to assist the patients during position transformation from sitting to stand and vice versa. [5] introduced a rehabilitation device for people with paraplegia. The device targets to restore movement of the patient through making use of a sufficient amount of electrical stimulus based totally upon the perspective of the knee joint. [6] Presents a compact active knee rehabilitation orthotic device (AKROD) that accommodates unsure damping at the knee joint.

The main concern of rehabilitation devices is the presence of an onboard control system. Previously developed device designs have focused on the mechanical issues of construction and operation, but very few numbers of projects have been identified that investigate the robust control of the active knee joint. An assistive robot with standing-up capabilities has been made to provide the functionality of standing-up from a chair/bed and moving around using a joystick for elderly people and patients suffering from paraplegia [7]. The device under study was designed to help the patients restore the movement with feedback control of the active knee joint.

Various control techniques have been proposed and implemented on rehabilitation devices, with each algorithm having its advantages and disadvantages. In [8], a PID controller is discussed, which enhances rehabilitation device performance. In [9], sliding mode control (SMC) on a similar device was implemented. Still, because of the non-linear dynamics, there were chattering in the control signal, which caused oscillation in the output position.

This paper focuses on the robust control design for the assistive device to remove such chattering with a perturbation compensation technique known as a sliding perturbation observer (SPO) [10, 11]. SPO utilizes only partial state feedback to estimate the system states and perturbation with reasonable accuracy, which helps the controller to reduce chattering by compensating the perturbation. The main advantage of SPO is that it does not require accurate system dynamics information. For position control, SPO was integrated with the PID controller to form a robust control PIDSPO and validated through simulations. The system was first linearized to observe the performance of PIDSPO undoubtedly.

doi: 10.18178/ijmerr.10.4.196-201

Initially, PID was implemented with manually and auto-tuned gains. But PID shows oscillations and overshoot in the system response [12]. The oscillations and overshoot were then removed with the help of SPO, resulting in the robust performance of the system. Also, the mass of the patient was considered and introduced as an external disturbance to the system. The results show that meanwhile, the system is controlling, SPO precisely estimates the external disturbance resulting in oscillations and overshoot free response.

The manuscript is organized as: section 2 presents the sit-stand mechanism model, section 3 describes the design of the controller, section 4 is about simulation and results, where section 5 entails the conclusion.

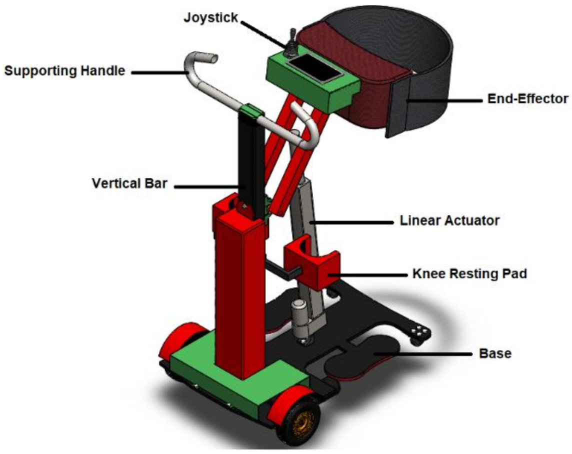

Figure 1. Assistive robot CAD model

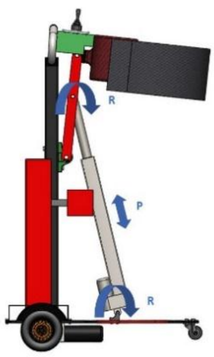

Figure 2. RPR configuration of the sit-stand mechanism

II. Modeling of Sit-Stand Mechanism

The virtual prototype of the existing hardware is presented in Fig. 1. The computer-aided design (CAD) of the assistive device involves two parts; one is the sit-stand mechanism, which transforms position from sitting to stand and vice versa. The second is the mobile platform, which is controlled using a joystick to move around. Maryam and Zareena considered the sit-stand mechanism as RPR (Revolute-Prismatic-Revolute) configuration [13]. RPR configuration is presented in Fig. 2. In this system, three links were integrated into three joints in the RPR configuration. Furthermore, the dynamic modeling for simulations and system analysis were carried out based on the Lagrange approach. The general representation of the Lagrange equation is given as [14]

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + N(\theta,\dot{\theta}) = \tau \tag{1}$$

where τ represents the actuator torque, $M(\theta)$ represents the mass matrix, $C(\theta,\dot{\theta})$ is the Coriolis matrix, and $N(\theta,\dot{\theta})$ is the gravity term. The equations of motion derived for the existing assistive robot [9] are given as

$$\begin{aligned}\tau_1 = (m_1 l_1^2 + Izz_1 + m_2 d_2^2 + Iyy_2 + m_3 l_{c3}^2 + Ixx_3 S_3^2 \\ + Iyy_3 C_3^2)\ddot{\theta}_1 + 2m_2 d_2 \dot{d}_2 \dot{\theta}_1 - m_2 d_2 \dot{\theta}_1^2 + \\ (m_1 l_1 + m_2 d_2) g C_1 + m_3 g l_{c3}(S_1 S_3 - C_1 C_3)\end{aligned} \tag{2}$$

$$\tau_2 = (m_2 + m_3)\ddot{d}_2 - m_2 d_2 \dot{\theta}_1^2 + m_2 g S_1 \tag{3}$$

$$\begin{aligned}\tau_3 = (m_3 l_{c3}^2 + Izz_3)\ddot{\theta}_3 - (Ixx_3 S_3 C_3 - Iyy_3 S_3 C_3)\dot{\theta}_1^2 \\ + m_3 g l_{c3}(C_1 C_3 - S_1 S_3)\end{aligned} \tag{4}$$

where d_2 is the prismatic joint displacement, τ_i are the torque at i-th joint, I is the moment of inertia, l is the link length, and m is the mass of each link. Where

$$C_i = Cos\theta_i \text{ and } S_i = Sin\theta_i \tag{5}$$

III. Controller Formulation

This section presents the formulation of the PID controller, non-linear estimator sliding perturbation observer (SPO), and integration of PID and SPO (PIDSPO).

A. PID

PID is one of the oldest and most popular control techniques. Currently, PID is still being used by many researchers and industries for their work. PID consists of three terms which are Proportional (P), Integral (I), and Derivative (D) term. The general form of PID controller in [15] can be written as

$$u = k_p\, e + k_i \int e\,(\tau)\, d\tau + k_d \frac{de}{d\tau} \tag{6}$$

where u, e, k_p, k_i and k_d represents the control signal and error, the proportional gain, integral gain, and derivative gain of PID controller, respectively.

1) PID Tuning

To implement the PID controller, the tuning of the PID controller is a critical part that influences the system response. Ziegler Nichols's closed-loop method for PID controller tuning was used. Ziegler Nichols's closed-loop tuning allows using the critical gain values K_{cr} and the critical period of oscillations P_{cr} to calculate k_p.

TABLE I. Tuning Parameters for Closed-Loop Method

Controller	Parameters		
	k_p	T_i	T_d
P	$5K_{cr}$	∞	0
PI	$0.45K_{cr}$	$0.833P_{cr}$	0
PID	$0.6K_{cr}$	$0.5P_{cr}$	$0.125P_{cr}$

Now the general form of PID for Ziegler Nicholas tunning can be written as

$$u = k_p \left(e + \frac{1}{T_i}\int_0^t e(\tau)\, d\tau + T_d \frac{de}{d\tau}\right) \qquad (7)$$

where T_i and T_d represents the constant of integral time and derivative time, respectively. The tuning parameters of the PID controller are selected based on Table I. For PID controller tuning using the Ziegler Nichols closed loop method, the following steps were performed

- Initially, considering the closed-loop system with the P controller only.
- Set a small value k_p and run the system.
- Increase the k_p gain until the system response becomes unstable.
- Increase the gain until steady-state oscillations occur.
- Note the values of gain as K_{cr} and P_{cr} from the oscillations.
- Use these values in (7) to determine necessary settings of the controller [16]

B. PIDSPO

PIDSPO is a linear control with a non-linear compensation technique. PIDSPO is an integration of the PID controller and sliding perturbation observer (SPO). The block diagram of PIDSPO is shown in Fig. 3.

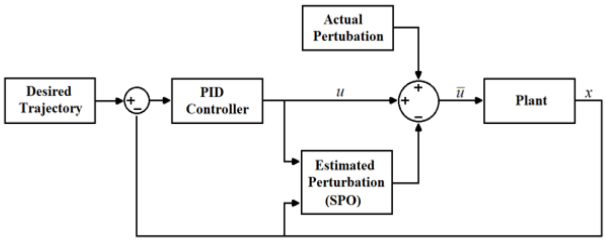

Figure 3. PIDSPO block diagram

1) Sliding Perturbation Observer (SPO)

SPO is a non-linear observer that utilizes partial feedback (position) to estimate velocity and system perturbation [11]. Perturbation (ψ) includes all the non-linear dynamics, uncertainties, and external disturbances. The structure of SPO to estimate the perturbation is given as

$$\dot{\hat{x}}_1 = \hat{x}_2 - k_1.sat(\tilde{x}_1) - \alpha_1.\tilde{x}_1 \qquad (8)$$

$$\dot{\hat{x}}_2 = -k_2.sat(\tilde{x}_1) + \alpha_3.\overline{u} - \alpha_2.\tilde{x}_1 + \hat{\psi} \qquad (9)$$

$$\dot{\hat{x}}_3 = \alpha_3^2.(\alpha_3.\hat{x}_2 + \overline{u} - \hat{x}_3) \qquad (10)$$

$$\hat{\psi} = \alpha_3(\alpha_3 \cdot \hat{x}_2 - \hat{x}_3) \qquad (11)$$

where $k_1, k_2, \alpha_3, \alpha_1, \alpha_2$ are constants with positive values. The components with "^" sign are the estimated values where "~" represents the error between actual and the estimated value. $\hat{x}_1$ and $\hat{x}_2$ are the structure of the sliding observer representing the estimated position and velocity, where $\hat{x}_3$ is a new state variable to estimate the perturbation. The saturation function reduces the sliding surface chattering and is given as

$$sat(\tilde{x}_1) = \begin{cases} \tilde{x}_1/|\tilde{x}_1|, & if\ |\tilde{x}_1| \geq \varepsilon_o \\ \tilde{x}_1/\varepsilon_o, & if\ |\tilde{x}_1| \leq \varepsilon_o \end{cases} \qquad (12)$$

where ε_o is the boundary layer of SPO. Term $\tilde{x}_1$ can be calculated as

$$\dot{\tilde{x}}_1 = \tilde{x}_2 - k_1.sat(\tilde{x}_1) - \alpha_1.\tilde{x}_1 \qquad (13)$$

$$\dot{\tilde{x}}_2 = -k_2.sat(\tilde{x}_1) - \alpha_2.\tilde{x}_1 + \tilde{\psi} \qquad (14)$$

$$\dot{\tilde{x}}_3 = \alpha_3^2(\alpha_3\tilde{x}_2 - \tilde{x}_3) + \psi/\alpha_3 \qquad (15)$$

$$\tilde{\psi} = \dot{\tilde{x}}_2 + (k_2/k_1)\tilde{x}_2 \qquad (16)$$

2) PID integration with SPO (PIDSPO)

To integrate the PID with SPO, defining a new control variable $\bar{u}$ with an arbitrary positive number α_{3j} to decouple the control variable

$$f_j(x) + \sum_{i=1}^{n} b_{ji}(x)u_i = \alpha_{3j}\bar{u} \qquad (7)$$

For the new control variable, the estimated error between the desired and estimated position is given as

$$\hat{e} = \hat{x} - x_d \qquad (18)$$

It can also be written as

$$\hat{e} = \hat{x}_1 - x_d \qquad (19)$$

Defining $\bar{u}$ as

$$\overline{u} = k_p\, \hat{e} + k_i \int \hat{e}(\tau)\, d\tau + k_d \frac{d\hat{e}}{d\tau} - m\hat{\psi} \qquad (22)$$

where m is perturbation constant. To integrate PID with SPO, substituting (20) in (17) to get the desired control input for the system. Where the SPO coefficient relation is given as

$$\frac{k_1}{\varepsilon_o} = 3\lambda_d, \frac{k_2}{\varepsilon_o} = \lambda_d, \alpha_{3=}\sqrt{\frac{\lambda_d}{3}} \qquad (23)$$

IV. Simulations and Results

For the simulations, MATLAB® Simulink software has been used. Fig. 4. shows the Simulink blocks model of the sit-stand mechanism. The position control loop of PID takes feedback of displacement (d_2) and calculates the error based on the desired elongation. The control input is then generated. Where in the case of PIDSPO, the structure of the controller is shown in Fig. 4.

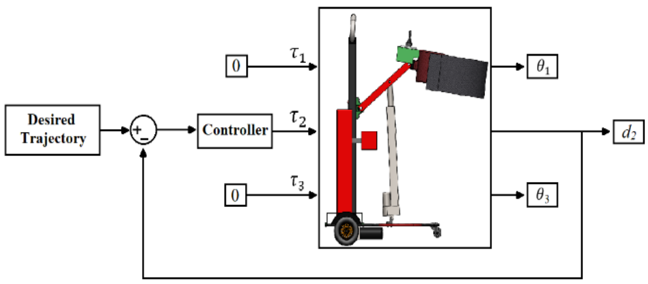

Figure 4. Position control of the assistive device

The maximum desired position is taken as 0.4m, which is the maximum extendable length of the linear actuator used. The mass of the patient is considered as the external disturbance because the dynamic equations were evaluated without patients, as the patient mass varies patient to patient. The maximum allowable weight is 80Kg where the torque required for a linear actuator to hold the patient [17] is given as

$$T_{hold} = \frac{FD_p}{2} = \frac{80\times9.8\times0.026}{2} = 10.192\ \text{Nm} \quad (22)$$

where F is the force due to gravity and D_p is the pitch diameter of the threaded bar of the linear-actuator. The simulations are performed for maximum allowable parameters to check system response. Furthermore, the system was linearized to observe the working of PIDSPO more clearly. The linearized transfer function of the prismatic joint obtained from (2), (3) and (4) is given as

$$d_2 = \frac{6.38s^4+9.389s^2}{40s^6+2.392s^4} \quad (23)$$

A. PID Controller

Initially, the PID controller was manually tuned using the Ziegler Nichols closed-loop tuning method. The obtained PID gains are given in Table II. Where the response of the linear system presented in (23) with manually tuned PID controller is shown in Fig. 5.

TABLE II. MANUALLY TUNED PID GAINS

Joint	Gains		
	k_p	k_i	k_d
d_2	65	25	6.25

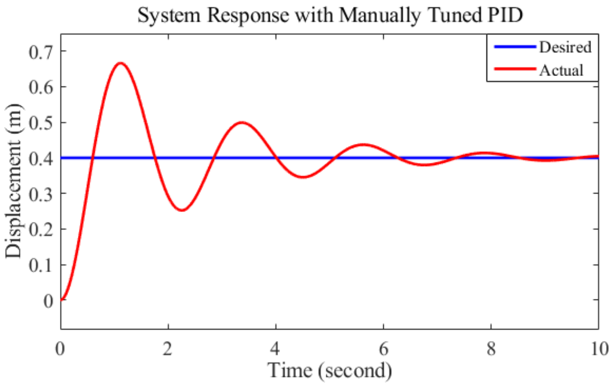

Figure 5. System response with manually tuned PID control

The controlled system with Ziegler Nichols tuned PID has oscillations as the required torque to precisely control the system was insufficient because of the small PID gains. Therefore, the PID controller was auto-tuned using Simulink auto-tuner, and the resulted gains of PID are shown in Table III. The system response for the auto-tuned PID is shown in Fig. 6.

TABLE III. AUTO-TUNED PID GAINS

Joint	Gains		
	k_p	k_i	k_d
d_2	1232	1158	112.07

After auto-tuning the PID controller, the system response shows better performance. But now, because of high gains, the system confronts a sudden overshoot because of high torque generated initially. This overshoot is not feasible for the device holding the patient. Therefore, the overshoot should be removed from the system response. To do so, PID controller was integrated with the non-linear compensation technique resulting in PIDSPO a robust controller.

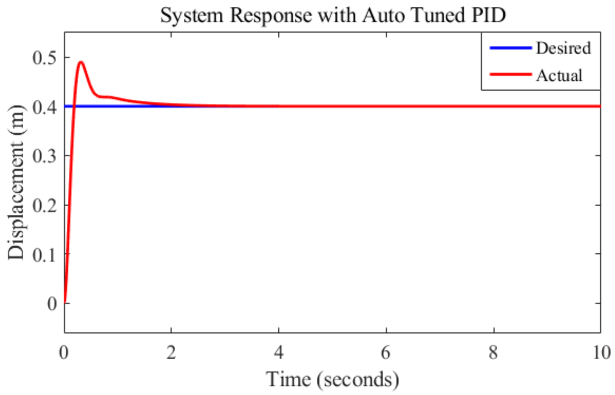

Figure 6. System response with manually tuned PID control

B. PIDSPO Controller

PIDSPO is a robust linear controller with a non-linear perturbation compensation technique. Perturbation includes all the non-linearities, system uncertainties and disturbances. The integration procedure is illustrated in Section III-B-2. As mentioned before that the patient mass was considered as external disturbance to the system, so introducing the resulting torque calculated in (22) as disturbance to the system. Based on the block diagram in Fig. 3, SPO will estimate this disturbance and will compensates its effect from the system response to make the system response oscillations and overshoot free. PIDSPO parameters to control the system are given in Table IV, and the resultant system response is presented in Fig. 7.

TABLE IV. PIDSPO GAINS

Joint	Gains							
	λ	ε_o	k_1	k_2	α_3	k_p	k_i	k_d
d_2	15	1	45	675	2.23	20	12	8

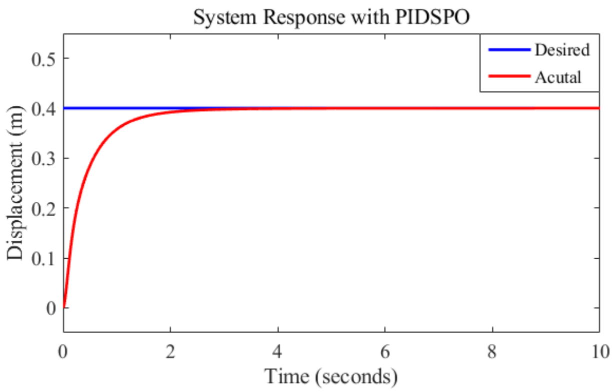

Figure 7. System response with PIDSPO

Now the system response with PIDSPO shows no oscillations and overshoot and resulting in very smooth output as compared to the response in Fig. 5 and Fig. 6, even in the presence of external disturbance. This is because of the disturbance compensation by SPO.

On the other hand, the actual and the estimated perturbation is presented in Fig. 8. which shows that the system tracks the actual perturbation very precisely. Therefore, the system response is refined and robust. Furthermore, another advantage of using PIDSPO is that now the system is controllable with small PID gains as compared to auto-tuned PID controller.

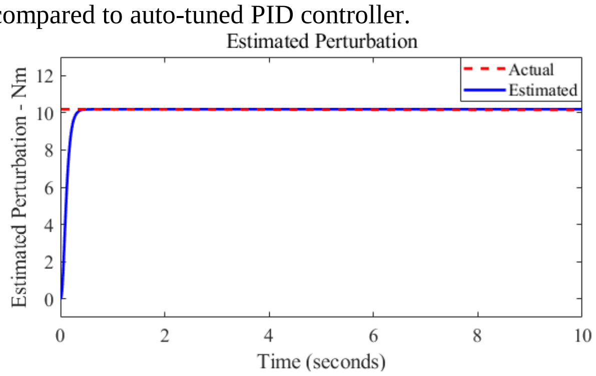

Figure 8. Actual and estimated perturbation

V. Conclusion

In this research, a new control scheme known as PIDSPO has been proposed for an assistive device for a paraplegic patient. The device was developed to help the patients, but without an onboard control scheme, it is unsafe for patients. Conventional PID and a new paradigm of PID called PIDSPO were compared through simulations, and it has been observed that PIDSPO performs better than PID without oscillations in system response and with small PID gains. The mass of the patient was taken as an external disturbance as the mass differs from patient to patient. Initially, the system was linearized, and then an external torque (holding torque) as the effect of patient mass was introduced as an external disturbance. SPO estimated the holding torque according to the presented mass very accurately and compensated that from the system response and giving better results with robust system performance. In the future, it is intended to implement sliding mode control with sliding perturbation observer (SMCSPO) to further improve the system response with the actual system dynamics.

Conflict of Interest

The authors declare no conflict of interest

Author Contributions

HK conducted the research, proposed the algorithm, and wrote the paper. SJA helped in the analysis of the algorithm. MCL supervised the research. All the authors had approved the final version.

Acknowledgment

This research was supported by the nuclear research and development program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (MSIT, Korea). [NRF-2019M2C9A1057807] and by the Technology Innovation Program (10073147, Development of Robot Manipulation Technology by Using Artificial Intelligence) funded By the Ministry of Trade, Industry & Energy (MOTIE, Korea).

References

[1] I. Díaz, J. J. Gil, and E. Sánchez, "Lower-limb robotic rehabilitation: Literature review and challenges," *Journal of Robotics*, vol. 2011, pp. no 759764, 1-11, 2011.

[2] O. Salah, A. A. Ramadan, S. Sessa, and A. A. Abo-Ismail, "A systematic approach for design a low-cost mobility assistive device for elderly people," *International Journal of Medical Health, Biomedical, Bioengineering and Pharmaceutical Engineering*, vol. 5, pp. 36-41, 2011.

[3] R. Kamnik and T. Bajd, "Standing-up robot: an assistive rehabilitative device for training and assessment," *Journal of Medical Engineering & Technology*, vol. 28, no. 2, pp. 74-80, 2004.

[4] A. Tsukahara, R. Kawanishi, Y. Hasegawa, and Y. Sankai, "Sit-to-stand and stand-to-sit transfer support for complete paraplegic patients with robot suit HAL," *Advanced Robotics*, vol. 24, no. 11, pp. 1615-1638, 2010.

[5] F. Previdi, M. Ferrarin, I. Carpinella, and S. Savaresi, "Modelling and control of a device for rehabilitation of paraplegic patients," in *American Control Conference*, pp. 2030-2035, 2007.

[6] J. Nikitczuk, B. Weinberg, P. K. Canavan, and C. Mavroidis, "Active knee rehabilitation orthotic device with variable damping characteristics implemented via an electrorheological fluid," *IEEE/ASME Transactions on Mechatronics*, vol. 15, no. 6, pp. 952-960, 2009.

[7] S. Khan, M. F. Zeb, N. Ghafoor, S. Jamshed, M. R. Afzal, and A. Eizad, "Design of an assistance robot for patients suffering from Paraplegia," in *2015 15th International Conference on Control, Automation and Systems (ICCAS)*, pp. 830-834, 2015.

[8] L. Khan, M. Irfan, and H. Ali, "Implementation of GA in designing control system for paraplegic walking movement using walker," *World Applied Sciences Journal*, vol. 7, no. 9, pp. 1164-1175, 2009.

[9] A. Abdullah and Z. Kausar, "Control of sit to stand mechanism of assistive Device for paraplegics," *Journal of Physics: Conference Series*, vol. 1016, no. 1, pp. 1-5, 2018.

[10] H. Khan, S. J. Abbasi, K. D. Kallu, and M. C. Lee, "Robust control design of 6-DOF robot for nuclear power plant dismantling," in *Proc. 2019 IEEE International Conference on RoboticsAutomation in Industry (ICRAI)*, 2019, pp. 1-7.

[11] K. D. Kallu, S. J. Abbasi, H. Khan, J. Wang, and M. C. Lee, "Implementation of a TSMCSPO controller on a 3-DOF hydraulic manipulator for position tracking and sensor-less force estimation," *IEEE Access*, vol. 7, pp. 177035-177047, 2019

[12] H. Khan, S. J. Abbasi, K. D. Kallu, and M.-C. Lee, "Feedback control of sit-stand mechanism of an assistive device for paraplegics," *ICROS*, pp. 3-4, 2019.

[13] M. Khan and Z. Kausar, "Kinematics modeling and mechanism configuration selection of a mechatronic assistive device for paraplegic patients," in *Proc.the 5th International Conference on Mechatronics and Control Engineering*, pp. 27-32, 2016.

[14] J. J. Craig, "Manipulator dynamics," *Introduction to Robotics*: Pearson/Prentice Hall, pp. 185-186, 2005.

[15] F. Memon and C. Shao, "An optimal approach to online tuning method for PID type iterative learning control," *International Journal of Control, Automation and Systems*, vol. 18, no. 8, pp. 1926-1935, 2020.

[16] M. Edu. "Tunning for PID controller." [Online]. Available: http://faculty.mercer.edu/jenkins_he/documents/TuningforPIDControllers.pdf (accessed).

[17] R. S. Khurmi and J. K. Gupta, "Power screws," *Machine Design*, pp. 624-676, 2005.

Hamza Khan is doing M.S degree in Mechanical Engineering from Pusan National University, Busan, Korea since 2019. He received the B.S degree in Mechatronics Engineering from Air University, Islamabad, Pakistan in 2018. His research interests include non-linear control, robot manipulator and system identification.

Saad Jamshed Abbasi is doing Ph.D. degree in Mechanical Engineering from Pusan National University, Busan, Korea since 2018. He Received the M.S degree in Mechanical Engineering from Pusan National University, Busan, Korea in 2018. He received the B.S degree in Mechatronics Engineering from Air University, Islamabad, Pakistan in 2015. His research interests include non-linear control, robot manipulator and system identification.

Min Cheol Lee received the B.S. degree in Mechanical Engineering from Pusan National University, Busan, Korea in 1983, M.S. degree in Engineering Sciences and Ph.D. degree in Applied Physics from University of Tsukuba, Tsukuba, Japan in 1991, respectively. He was a Visiting Professor at North Carolina State University from Aug. 2000 to Aug. 2001 and at Perdue University from Aug.2009 toAug.2010, respectively. From 1991 to currently, he is a Professor in the School of Mechanical Engineering of Pusan National University, South Korea. His research interests include intelligent robot control, autonomous mobile robot, medical robot, signal processing to identify a system, robust control of a system, sensor application, and mechatronics.