Discrete Incremental Trajectory Control Strategy for Knee Powered Exoskeleton

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doi: https://doi.org/10.37285/bsp.SACAD2025.68

***Abstract* — In this paper, the design and development of a novel electrically powered augmentative type lower limb active exoskeleton is proposed. A cascade control strategy involving model-independent discrete incremental proportional integral - derivative (PI-D) controller for position control, and proportional integral (PI) controller for current and velocity control is formulated to track the human gait accurately in a timely manner. To validate the mechanical design and control scheme of the proposed exoskeleton, an extensive analysis and testing of the proposed exoskeleton is conducted on software, test bench, hanging dummy and human subject. The effectiveness of the proposed controller design scheme is demonstrated via comparison of the gait tracking performance with the proportional – derivative (PD) controller. The time lag between the movement of user and the response of the exoskeleton is also evaluated. The results obtained via a comprehensive four-phase testing are a testimony to the efficacy of the proposed incremental PI-D controlled exoskeleton structure.**

I. Introduction

Exoskeleton technology has garnered increasing interests and witnessed tremendous growth in the recent years. Exoskeletons are wearable robotic mechatronic devices developed for enhancing user strength to lift heavy loads, providing assistance during walking and helping disabled people to regain mobility. [1], [2]. The upper extremity exoskeletons provide support and power augmentation to the upper part of the human body including shoulders, arms, and torso, whereas the lower extremity exoskeletons aid in enhancing the strength and endurance of the lower part of body such as hips, knee and ankle. In military applications, the exoskeletons enable a soldier to carry heavy weights by increasing strength to muscles, while simultaneously reducing fatigue and the risk of injury. The exoskeleton also acts as an assistive device for the rehabilitation of paralyzed people and enables them to regain the ability to stand upright and walk smoothly [3]–[5].

The earliest reference of research work in exoskeleton is found in the US patent for a parallel lower extremity exoskeleton (LEE) model conferred to Nicholas Yagn in the year 1890 [6]. Since then and until present, various research groups have incessantly worked in this direction and many different forms of exoskeletons have been rolled out for multifarious applications. The General Electric company is credited for the development of the first known exoskeleton technology in 1965 [7]. In 2004, Berkeley Robotics and Human Engineering Laboratory developed a Berkeley Lower Extremity Exoskeleton (BLEEX), which was the first energetically autonomous and functional load carrying exoskeleton [8]. Apart from the aforementioned systems, various other exoskeletons have been developed, namely Human Universal Load Carrier (HULC), Hybrid Assist Limb (HAL) [9], RoboKnee [10], ReWalk [11], Onyx [12], H-WEXv2 [13], etc. A historical perspective and a comprehensive review of the exoskeleton is provided in [14], [15] and [16].

The efficacy and performance of a robotic exoskeleton in providing assistance to a user is dependent on the mechanical structure as well as the nature of control strategy incorporated in its design. The dynamics of a human exoskeleton system are coupled, highly uncertain and nonlinear in nature. For a seamless working of the exoskeleton system, it should move in parallel to the wearer and track the human gait accurately with a minimal time lag between the movement of human limb and the response of the exoskeleton to human limb movement. The range of motion (ROM) of exoskeleton should be within normal ROM of the human knee joint with mechanical and electronic safety mechanisms. Further, it should also match the anthropomorphic form of a wearer and exert an adequate magnitude of assistive torque on the limb joint of the person in a timely manner. Therefore, the problem of tracking human gait trajectory is a challenging one in the realm of systems and control engineering [17], [18].

To achieve the control objectives and ensure compliance of robotic exoskeleton with the wearer's intention, the existing approaches can be broadly classified broadly into three categories [19]. The first method is based upon the measurement of biological signals of human subject, which provide an indication about the locomotive intention of user. In this direction, the electromyography (EMG) and electroencephalography (EEG) signals have been measured and analyzed for detecting the walking intent of user. In [20], a EMG signals based adaptive torque estimator is proposed and integrated into the extended Slotine-Li approach, leading to the incorporation of a two step learning scheme into the controller. A multimodal human machine interface involving the incorporation of EEG and EMG signal modes to enable differentiation between the left and right leg movements is implemented in [21] for the control of lower limb exoskeleton. A hybrid control approach that employs EMG signals for determination of stair parameters and EEG signals for recognition of imagery tasks is formulated in [22] for augmentation of locomotion ability during climbing up and down a staircase. Various other control techniques based on EMG or EEG signals are elucidated in [23], [24] and [25]. However, the donning and doffing time for various exoskeletons based on biological signals are longer, leading to discomfort and inconvenience to the end user.

The second category of control techniques provide the use of variable stiffness actuators to provide assistance and achieve compliance. In [26], a total of fifty two lower limb exoskeletons are analyzed and compared with respect to the structure, actuation system and interfacing components. A cooperative control approach, wherein the actuator stiffness control loop works in collaboration with the impedance control loop is devised for the lower limb robotic system in [27]. Various other techniques with reference to this category are examined in [28], [29] and [30]. Such control methods require the customization of actuators to satisfy multifarious constraints on stiffness, power consumption, weight, available torque, etc., which is a formidable task. The final category of control techniques deals with the formulation of various control algorithms to ensure gait trajectory tracking and attain the desired performance. The adaptive fractional order nonsingular terminal sliding mode control based technique is proposed for the control of lower limb exoskeleton in [31] and corroborated via numerical simulations as compared with conventional and advanced control techniques. In [32], active disturbance rejection control technique, which is based on the concept of estimation and cancellation of the generalized disturbance is applied for the human trajectory gait tracking using a lower limb exoskeleton. The dragonfly optimization algorithm is employed to design a fuzzy logic control based proportional integral derivative (FLC-PID) controller for a two degree of freedom exoskeleton in [33]. Several other algorithms for the control of lower limb exoskeleton are given in [34], [35] and [36].

For the design and development of an industrial exoskeleton system, it is highly preferable that the control algorithm should not only track the human gait trajectory accurately in a timely manner, but also be simple to implement, robust, have a fixed control structure and fewer tuning parameters. To inherit the aforementioned desired features into the proposed exoskeleton system, a cascade control structure that incorporates a discrete incremental proportional integral – derivative (PI-D) control approach for position control is formulated in this paper. The foremost merit of the PI-D algorithm is that the derivative action is applied only to the output-controlled variable, which circumvents the issues corresponding to undesirable set-point kick behaviour when the reference variable changes suddenly. Further, the incremental form of PI-D algorithm also aids in avoiding the integral windup problem associated with the conventional PID control [37]. Moreover, the proposed exoskeleton with discrete incremental PI-D control strategy does not require repetitive retuning of controller parameters when users having different mass, height and inertia wear the exoskeleton. Therefore, the control mechanisms of the proposed exoskeleton are user-independent and does not entail the use of additional tuning and calibrations, when wore by different persons. Furthermore, the proposed exoskeleton is mechanically designed to be fitted on a human lower limb of the user and enhance locomotion dynamics while lowering metabolic expenditure for activities like lifting loads, squatting, and walking on stairs and inclined surfaces (upslope/downslope).

Hence, the primary contributions of the paper are enumerated as

- The design and development of a novel augmentative type active lower limb exoskeleton structure is undertaken in Defence Bioengineering and Electromedical Laboratory (DEBEL), India and explained in an elaborate manner in this paper.
- A fixed parameter discrete incremental Proportional Integral - Derivative (PI-D) controller is formulated and implemented on the proposed exoskeleton. The proposed controller works seamlessly when users having different mass, height and inertia properties wear the exoskeleton and no change in the parameter values of controller tuning variables is required.
- A comprehensive evaluation and four-phase testing of the proposed exoskeleton is undertaken on software, test bench, hanging dummy structure and the human subject.
- The performance of the discrete incremental PI-D control strategy implemented on the proposed exoskeleton is compared with the proportional - derivative (P-D) control approach.
- The time lag between the human and exoskeleton trajectories is assessed and ascertained to be minimal, thereby demonstrating the superior controller design and an improved mechanical structure of the proposed exoskeleton.

The remaining paper is divided into various sections as follows. The hardware configuration and the dynamic modelling of the exoskeleton system is undertaken in section II. The cascade control scheme for the gait tracking of exoskeleton is elucidated in section III. The results of four-phase testing of the proposed exoskeleton are provided and discussed in section IV. Finally, the conclusions are drawn in section V.

II. Hardware Configuration And Dynamic Modelling Of Exoskeleton

A. Hardware Configuration

A novel prototype of the proposed active exoskeleton is designed and developed at Defence Bioengineering and Electromedical Laboratory (DEBEL), India to provide assistance and strength at the knee joint of the wearer. The corresponding configuration is illustrated in Fig. 1. The proposed electrically powered knee exoskeleton is a two degree of freedom rigid structure consisting of thigh and shank links integrated with an electromechanical actuator at the knee joint. The electromechanical rotary type actuators with gear as transmission element are used to provide forward propulsive forces in tandem with each joint movement of both legs during locomotion.

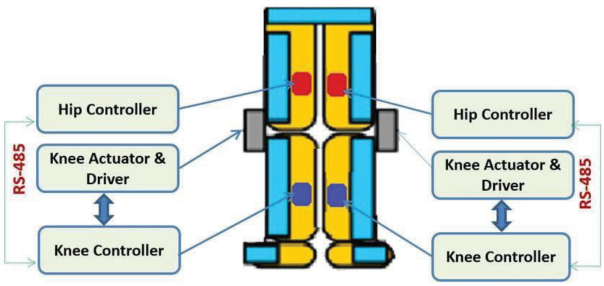


Figure 1. System Configuration

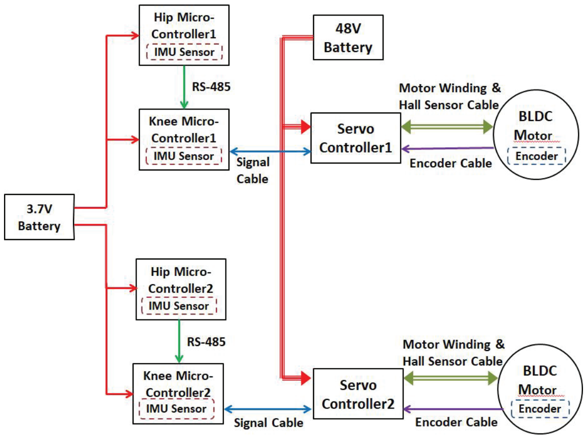


Figure 2. Electrical and Electronics Scheme of Proposed Exoskeleton

The hardware configuration of the proposed exoskeleton consists of five major subsystems, namely

1) Actuator subsystem
2) Power supply subsystem
3) Electronics subsystem
4) Control subsystem
5) Mechanical subsystem

Each of the aforementioned subsystems are described below.

Electronics subsystem: It comprises of sensors to provide feedback to the joint controller and joint driver board for the implementation of lower level control algorithm. The detailed electronics scheme of the proposed exoskeleton is described in Fig. 2. To capture the intent and kinematic data of wearer movements, inertial measurement unit (IMU) sensors and its data acquisition system are mounted on the wearer limbs. The purpose of the sensing system is to measure hip and knee sagittal plane joint angles in real-time, which shall serve as angle commands to the position control loop of exoskeleton joints to move them as per the subject's intent. Further, the incremental encoder mounted on actuators is used as feedback sensor. The encoder aids in the measurement of exoskeleton joint angle and angular rate of corresponding link. The acquired count from the encoder is used to estimate the corresponding joint angle, which is then fed back to the incremental PI-D controller. The joint Driver acts as an interface between the motor and joint controller. It comprises of ESCON 50/5 module, connectors and isolators for analog and digital signals which are required to be communicated between joint driver and joint controller PCB. The joint driver implements lower-level control using torque, current, and speed by getting input from the joint controller.

Control subsystem: The control subsystem comprises of discrete incremental PID tuned joint controllers for high level control and the graphical user interface to display the state of the Exoskeleton and its performance in real-time with onboard data logging capability. The control mechanism is the brain of exoskeleton system that receives inputs related to human limbs movements and phases of locomotion at all instances of the gait cycle and continuously provides command output for actuation through motors. A cascaded control architecture is applied in the proposed exoskeleton to control the exoskeleton joint based on the command from the corresponding human joint movement. The block diagram and a detailed description of the proposed control methodology is provided in section III.

Actuator subsystem: It includes a motor, gearbox and driver circuits coupled to exoskeleton knee joints for providing the requisite assistive torque (Refer Fig. 2). The actuators employed are flat type brushless DC (BLDC) motors with harmonic gear that acquires power from the power supply subsystem and facilitates locomotion of the exoskeleton. In the proposed exoskeleton structure, the BLDC motors are chosen due to high torque to weight ratio, long operating life, noiseless operation and lesser maintenance requirements as compared to the conventional brushed DC motors. Also, the torque delivered per watt is higher, making it useful in exoskeleton design applications where space and weight are critical factors.

Mechanical subsystem: It comprises of links, straps, and cushions to hold the exoskeleton onto the user and transmit the assistive force/torque via the actuator subsystem to the human limbs . The rotatable vertical links are connected to the joint links along with height adjustment mechanism to accommodate users having different heights. It also consists of locking mechanism in the waist strap to hold the exoskeleton onto the user. Straps are provided to attach the proposed exoskeleton to the thigh. Further, the shank plate with cushions aid in securing the device to the shank and enables it to transmit the requisite force generated by the actuator subsystem to the knee joint of the user.

Power supply subsystem: The actuators and the joint controller electronics are powered by a battery with an onboard Battery Management System (BMS). The Motor is powered through joint driver PCB by 48V battery. Joint controller electronics are powered by 3.7V battery (Refer Fig. 2). The joint driver is mounted the motor further on the mechanical wearable jig and the joint controller is mounted on the subject with IMU sensor integrated on it.

B. Dynamic Modelling

Both the legs of exoskeleton system are considered as independent and identical to each other. Since the exoskeleton is firmly attached to the lower limbs of the user, therefore, the wearer's limbs and the exoskeleton are together treated in the combined manner as a human-exoskeleton system (HES). According to Euler-Lagrange formulation, the governing equation for computation of torque in a HES is expressed as

$$\tau_{sys} = M(\beta)\ddot{\beta} + C(\beta, \dot{\beta})\dot{\beta} + G(\beta) \quad (1)$$

where, the corresponding matrices are defined in (2).

Here, $\beta = [\beta_h \quad \beta_k]^T$ denotes the joint angle matrix, $M(\beta)$ represents the inertial matrix, $C(\beta, \dot{\beta})$ signifies the centrifugal and Coriolis force matrix, $G(\beta)$ is the gravitational torque matrix and τ_{sys} denotes the total torque acting on HES. The total external torque comprises of the actuator torque, human torque and the torque exerted by the impact of ground reaction force when the feet of wearer touch the ground. Further, β_h and β_k denote the hip joint angle with respect to vertical and the knee joint angle with respect to the hip joint, respectively as shown in Fig. 3.

Furthermore, in (2), M, L, I and g represent the mass, length, inertia and acceleration due to gravity, respectively. The subscripts t, s, c and b denote the thigh, shank, body and centre of mass, respectively. The values of the aforementioned variables are associated with the human, exoskeleton system and are therefore dependent on each human subject. However, the incremental PI-D control algorithm formulated in this paper is model independent and applicable irrespective of the parameters of human subject.

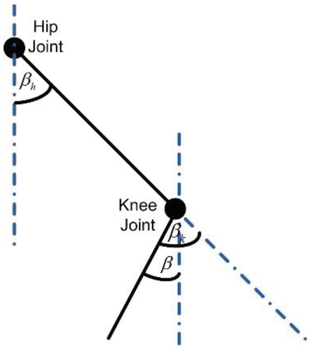


Figure 3. Joint angles

TABLE I. SPECIFICATION OF ESCON 50/5 MODULE

S.N	Parameters	Value
1.	Nominal Operating Voltage	10 − 50 VDC
2.	Maximum Output current	15A (f or < 20s)
3.	Continuous current	5A
4.	PWM Frequency	53.6 kHz
5.	Maximum Efficiency	98 %
6.	Temperature Operation	−30∘C to +45∘C
7.	MTBF	639'548 hours

III. CASCADE CONTROL OF EXOSKELETON

The exoskeleton control system is based on joint angle trajectory tracking control and employs a Cascaded control architecture. The block diagram of the cascaded control architecture for exoskeleton is shown in Fig. 4 and the overall diagram of the control system for exoskeleton is illustrated in Fig. 5. In the proposed cascaded control architecture, three controllers are applied in cascade to make the exoskeleton follow the knee joint trajectory in the sagittal plane. In this architecture, the outermost feedback loop is an incremental PI-D based position control, the middle loop is PI based speed control, and the innermost loop is PI based current control. Such a control architecture aids in enhancement of disturbance rejection capability for any disturbance that first disrupts the inner loops before impacting the primary control loop.

The ESCON module 50/5 from Maxon is chosen as the motor driver. The motor driver module implements the lower level control by controlling the motor speed and current. The brief specifications of the ESCON servo controller driver module are given in Table I. In the present work, the ESCON 50/5 servo driver drives the BLDC motors for actuation of the exoskeleton joints in speed control mode. The specifications of BLDC motor used are enlisted in Table II.

The objective of the controller is to ensure that exoskeleton has to follow the wearer's gait, which should be synchronous with all the joints of human lower limb while walking. Any delay in the response of the actuators will eventually cause walking instability which might result in severe joint injuries. For that, a position controller is implemented in the micro-controller and connected in cascade to the driver controllers. The joint position is calculated from the motor encoder and supplied as input to the discrete incremental PI-D controller, which is cascaded with the speed and current controllers of the motor driver. In the discrete incremental PI-D control scheme, instead of differentiating the error, only the output angle is differentiated. This alleviates the undesirable control action called derivative or set-point kick caused due to a change in setpoint of the reference signal

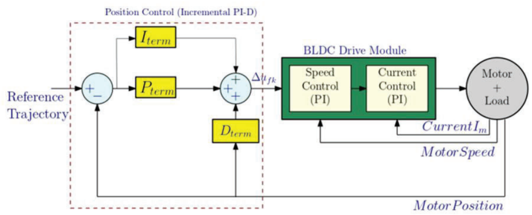


Figure 4. Cascaded Control Architecture for Exoskeleton Joint

Figure 5. Block Diagram of Control System for Exoskeleton

TABLE II: BLDC MOTOR DATA

Parameter	Unit	Value
Nominal voltage	V	36
No load speed	rpm	3070
No load current	mA	420
Nominal speed	rpm	2640
Nominal torque (max. continuous torque)	mNm	453
Nominal current (max. continuous current)	A	4.09
Stall torque	mNm	7580
Stall current	A	68.9
Max. efficiency	%	85
Terminal resistance phase to phase	W	0.523
Terminal induction phase to phase	H	0.554
Torque constant	mNm/A	110
Speed constant	rpm/V	86.8
Speed/torque gradient	rpm/mNm	0.412
Mechanical time constant	ms	13.7
Rotor Inertia	gcm2	3170

$$
\begin{aligned}
M(\beta) &= \begin{bmatrix} I_t + I_s + M_t L_{tc}^2 + M_s(L_t^2 + L_s^2 + 2L_t L_s \cos(\beta_{ts})) & I_s + M_s(L_s^2 + L_t L_s \cos(\beta_{ts})) \\ I_s + M_s(L_s^2 + L_t L_s \cos(\beta_{ts})) & I_s + M_s L_{sc}^2 \end{bmatrix} \\
C(\beta, \dot{\beta}) &= \begin{bmatrix} -M_s L_t L_{sc} \sin(\beta_{ts})\dot{\beta}_{ts} & -M_s L_t L_{sc} \sin(\beta_{ts})\left(\dot{\beta}_{ts} + \dot{\beta}_{bt}\right) \\ M_s L_t L_{sc} \sin(\beta_{ts})\dot{\beta}_{bt} & 0 \end{bmatrix} \\
G(\beta) &= \begin{bmatrix} (M_t L_{tc} g + M_s L_t g)\sin\beta_{bt} + M_s g L_{sc} \sin(\beta_{bt} + \beta_{tc}) \\ M_s g L_{sc} \sin(\beta_{bt} + \beta_{ts}) \end{bmatrix}
\end{aligned} \quad (2)
$$

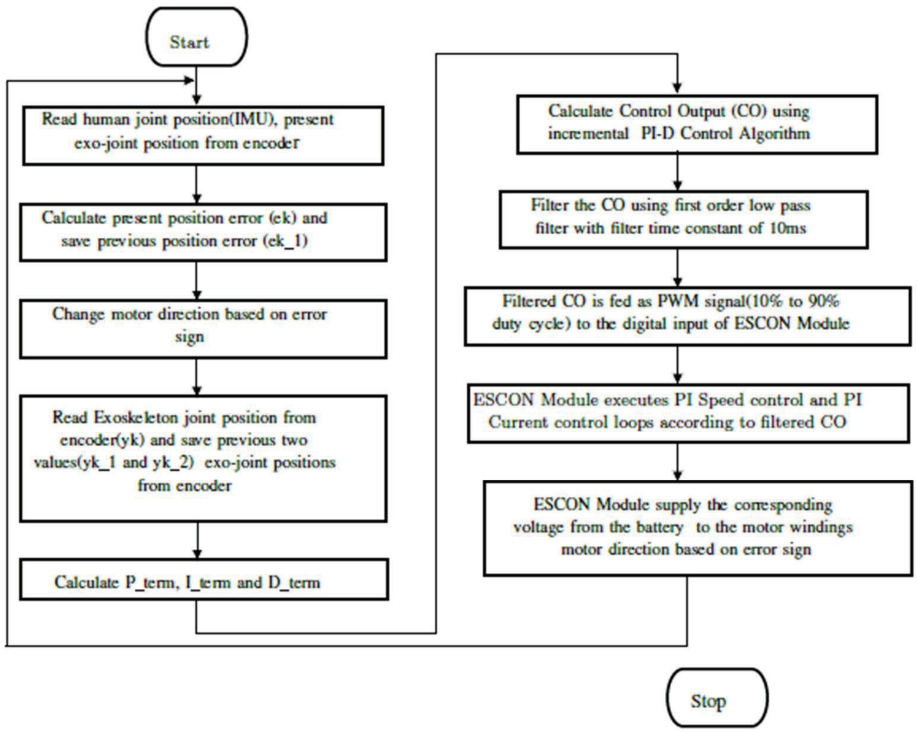


Figure 6: Software architecture design of Control Logic

The discrete incremental PI-D control law implemented in the current work is given as

$$\begin{aligned}\Delta u(k) &= k_p\big(e(k)-e(k-1)\big)+k_i e(k)\\ &\quad -k_d\big(y(k)-2y(k-1)+y(k-2)\big)\end{aligned} \qquad (3)$$

where, k_p , k_i and k_d denote the proportional gain, integral gain and the derivative gain, respectively. Further, y signifies the output position, y_r designates the human joint angle from the sensor, $e(k) = y_r(k) - y(k)$ represents the current position error, and $\Delta u(k)$ designates the current controller output. Using heuristic technique, the parameters of the discrete incremental PI-D controller are obtained as $k_p = 50$, $k_d = 50$ and $k_i = 12$, respectively. The control output of the PI-D controller in PWM (at 2.5 kHz) is fed to the ESCON module, where it is converted to the corresponding reference motor speed. Subsequently, the speed control and the current control take place in the ESCON driver.

The gain values of the inner PI controllers for the control of velocity and current are taken from ESCON studio after executing the in-built real-time system identification based auto-tuning of controllers as shown in Fig. 6.

The control system for a exoskeleton can operate in predefined mode as well as in sense and control mode. In the present work, the exoskeleton is operated in two modes:

1) **Predefined mode:** The gait patterns of many individuals are obtained and averaged. The gait cycle speed is adjusted accordingly and fed as reference trajectory. This mode is mainly used for medical purposes and while tuning the controller.
2) **Sense and Control mode:** The reference knee joint angles are obtained on-line as the user walks while

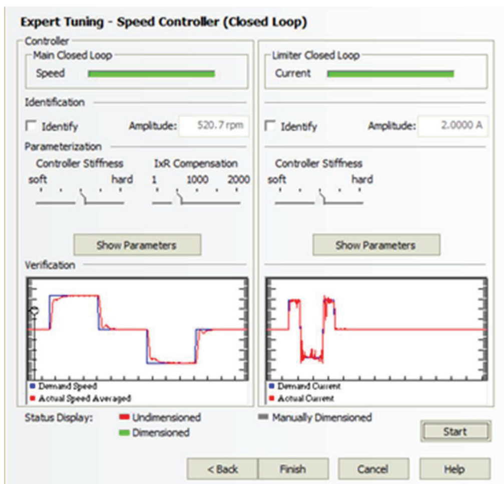


Figure 7. ESCON Studio Regulation tuning of Inner PI Speed and Current Control Loop

wearing the exoskeleton. IMU sensors are placed on the thigh and shank links and the knee ankle with respect to hip angle is fed as the reference input. The knee angle with respect to the hip is obtained from IMU sensor via the application of the following formula:

$$\beta_k = \beta_h - \beta \quad (4)$$

where, β_h= Hip joint angle (obtained from thigh segment sensor), β = inclination of shank segment with respect to vertical (obtained from shank segment sensor) and β_k= Knee joint angle. The sense and control mode enhances the motion and provides assistance to healthy subjects. It allows them to walk faster and for longer distances on different terrain with more load.

In addition, the Software Architecture Design (SAD) for implementing the control logic and the overall embedded software is presented in Fig. 7 and Fig. 8.

IV. Results and Hardware validation

In this section, various tests are conducted to evaluate the efficacy and robustness of the digital incremental PID algorithm for gait trajectory tracking using the proposed exoskeleton designed by DEBEL. The embedded software for Active Augmentative Exoskeleton is written using Atmel Studio IDE version 6.2. The embedded code is a stand-alone software written in C-language. The testing of the control algorithm was done in four phases:

A. Simulation

The initial testing of the proposed control algorithm is undertaken in MATLAB R2018a software environment. For this purpose, the motor and driver setup were simulated in Simulink. The driver has two PI controllers for speed and current control. The speed and current controllers operate on frequencies of 53.67 kHz and 5.367 kHz respectively. The position controllers are modelled with 1 kHz frequency. The control signal of the position controller is the duty cycle of a PWM signal of frequency 5 kHz. The Simulink block diagram of the overall system with discrete incremental PI-D controller is shown in Fig. 9. To analyze the controller performance, a Simscape model of a leg with thigh and shank link is created as shown in Fig. 10. To ascertain the capability of the proposed technique, a pre-defined gait trajectory is given and the corresponding results are obtained as shown in Fig. 11. The simulation results look promising with a very minor lag of only 13ms $(= (1.291 - 1.278)s)$ between the reference trajectory and the actuator response. The time lag of 13ms is very small as compared to the various existing exoskeletons, therefore, it exhibits a considerable improvement in trajectory gait tracking performance. Having demonstrated the efficacy of the discrete incremental PI-D control algorithm on the proposed exoskeleton, we proceed to undertake the bench testing of the proposed control algorithm.

B. Bench Testing

To test the efficiency of the control law, first the micro controller + driver assembly is connected to a motor on bench without load. The control was run on predefined mode and the results were obtained as delineated in Fig. 12. It can be observed that the time lag between the reference input and the actuator output is 23 ms $(= (5.665 - 5.642)s)$. The results

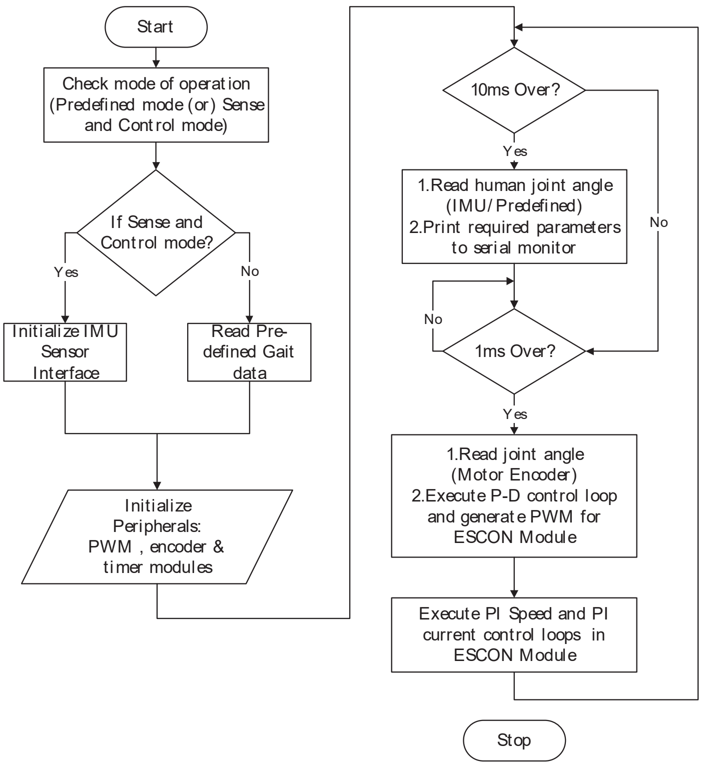


Figure 8: Software architecture design of complete system

are promising and the time lag during bench testing is only slightly greater than that obtained in simulations. The presence of a very small time lag in the pre-defined mode during bench testing also indicates that the proposed exoskeleton can be highly useful in medical and rehabilitation applications, where the patients have to follow a predefined gait trajectory defined by the exoskeleton. To ascertain the capability of the proposed incremental PI-D controller design approach, the performance is compared with the P-D controller. The control law for the P-D controller is given as $u(k) = k_p e(k) - \frac{k_d}{T_s}(y(k) - y(k-1))$, where $e(k)$ designates the error, T_s represents the sampling time, $y(k)$ is the current output and $y(k-1)$ signifies the previous output. The corresponding plot for position tracking is shown in Fig. 13. It can be deduced that the time lag for the incremental PI-D controlled knee joint (= 23 ms) is lower than that of P-D controlled knee joint, wherein the time lag is 46 ms $(= (5.389 - 5.343)s)$, thereby demonstrating the effectiveness of the proposed control scheme.

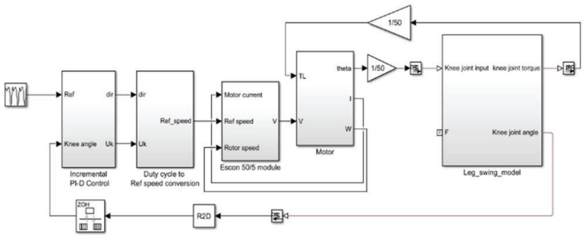


Figure 9; Implementation of Cascaded Joint Controller

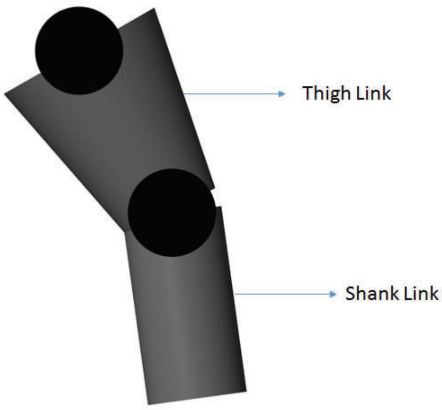


Figure 10: Simscape Leg swing model

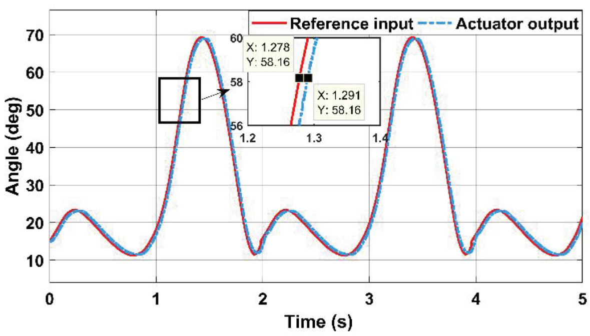


Figure 11: Simulation result for discrete incremental PI-D controlled knee joint

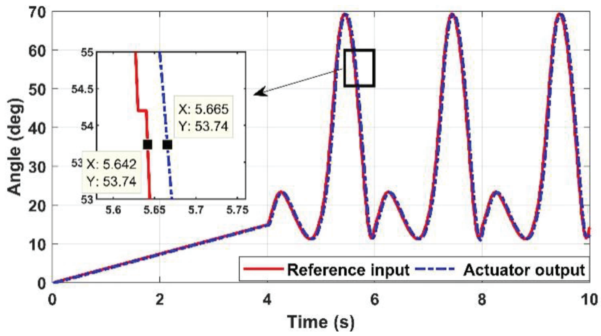


Figure 12: Bench test result for incremental PI-D controlled knee predefined Trajectory

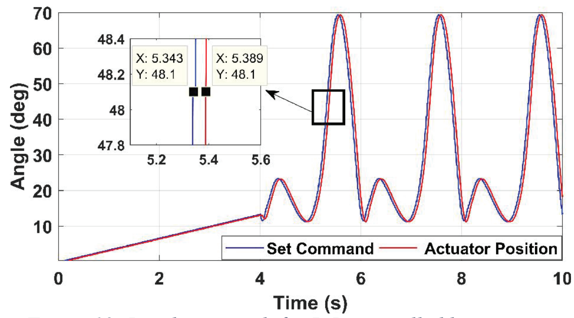


Figure 13: Bench test result for P-D controlled knee joint in predefined mode

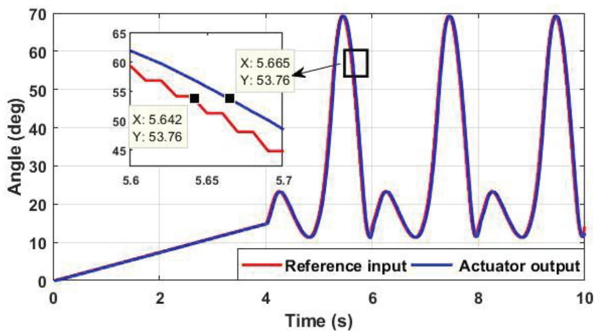


Figure 14: Test result on hanging structure for discrete incremental PI-D controlled knee joint of exoskeleton in predefined mode

C. Hanging Structure

The next step is to test the results with load. To accomplish that, the exoskeleton setup was attached to a dummy leg. Initially, the setup was run in predefined mode to investigate the performance of proposed digital incremental PI-D controlled system under load. It can be ascertained that the time lag between the reference input and the actuator output is 23 ms $(= (5.665 - 5.642)s)$, which is identical to the case of bench testing. Therefore, it can be deduced from the aforementioned analysis that the system performance under pre-defined mode does not exhibit variation when a load is applied.

Having undertaken the testing of exoskeleton setup on a dummy leg in the pre-defined mode, the next objective is to check whether the exoskeleton system is able to follow the user's gait trajectory. Therefore, the IMU sensors were attached to the human subject while the motors were attached to the hanging dummy leg. The corresponding response is illustrated in Fig. 15. The plot of the duty cycle and position error is shown in Fig. 16. To appraise the superiority of the proposed incremental PI-D controller, the gait trajectory tracking performance is compared with the P-D controller. The corresponding results for the control of knee joint exoskeleton via P-D controller are shown in Fig. 17. It can be inferred that the time lag between the reference input and the actuator output in the sense and control mode of exoskeleton operation for the incremental PI-D controlled system $(= (162.397 - 162.370)s)$ is 27 ms, which is lower as compared to the P-D controlled exoskeleton system having a delay of 50 ms $(= (44.53 - 44.48)s)$.

D. Human Trials

The excellent results of previous tests undertaken for the proposed discrete incremental PI-D controller in simulations, bench and hanging dummy gave confidence for the exoskeleton to be attached to a human subject. The complete exoskeleton system was worn by a healthy individual and the system response was logged dynamically while walking. The corresponding results are illustrated in fig. 18. The time lag when the exoskeleton was worn by the human subject is observed to be 30 ms $(= (19.21 - 19.18)s)$ and the human subject was able to walk on different terrains like level ground, stairs, grass and inclined plane without experiencing discomfort.

Hence, the successful four phase testing of the proposed exoskeleton affirms the efficacy of the proposed cascaded control logic. The minimal values of time lag also demonstrate the quick tracking ability of the human limb movement by the proposed exokskeleton.

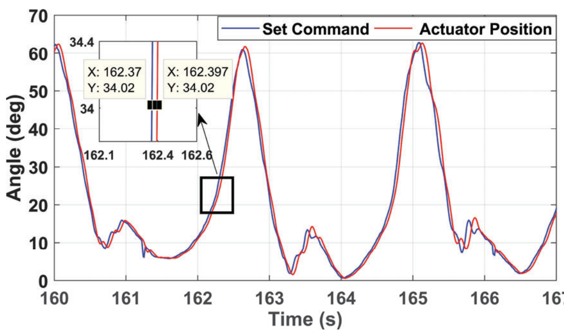
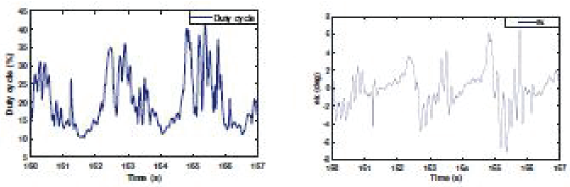


Figure 15: Test result on hanging structure for discrete incremental PI-D controlled Knee joint of exoskeleton in sense and control mode



(a) Duty cycle. (b) Position error

Figure 16: Duty cycle and Position error plot for PI-D controlled knee joint of exoskeleton in sense and control mode

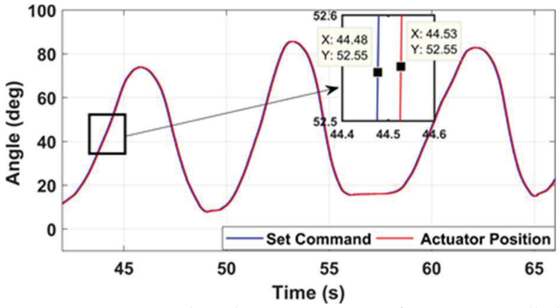


Figure 17: Test result on hanging structure for P-D controlled Knee joint of exoskeleton in sense and control mode

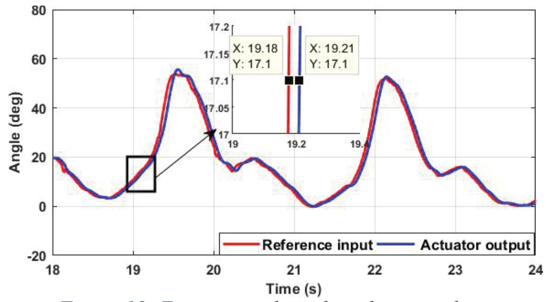


Figure 18: Experimental result on human subject

V. Conclusion

In this paper, the mechanical design and control logic implementation of a novel augmentative type active lower limb exoskeleton structure are described. The model independent cascade control scheme involving the implementation of a discrete incremental PI-D controller for position control and PI controller for velocity and current control is formulated for the accurate tracking of the human gait trajectory. It is observed from the four phases of testing that the proposed exoskeleton tracks the human gait accurately with a minimal time lag of only 30 ms, which is much lower as compared to various existing models of exoskeletons. The beauty of the discrete incremental PI-D control technique is that it circumvents the issues of set-point kick and integral windup of the conventional PID control, leading to an overall improvement in system performance. Further, the incremental PI-D technique also outperforms the P-D control approach for position tracking by exoskeleton. Thus, the aforementioned analysis and investigation provides conclusive evidence and corroborates the effectiveness of the proposed exoskeleton.

Acknowledgment

We would like to convey our heartfelt gratitude to the Dr. R Indu Shekar, Scientist G, Director, DEBEL, and Dr. K Mohanavelu, Scientist G, Project Director - Exoskeleton, for providing the permission, guidance & infrastructure to carry out this research work

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