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RESEARCH ARTICLE

A novel and advanced control method based on Fuzzy-PI for joint wear simulators

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Abstract

Background

This research presents a novel approach to improve the control performance of joint wear simulators that are used for testing prostheses. For this application, precise controller tuning and minimal tracking errors are essential to meet compliance standards like ISO 18192-1 or ISO 14242-3, and to test under realistic activities of daily living (ADL) scenarios.

Methods

To address these challenges, the authors propose employing a single-input-multiple-output (SIMO) fuzzy logic control system to augment the traditional proportional-integral (PI) tuning process for joint simulation. To facilitate the development and testing of potential controllers, we utilize a benchtop hardware-in-the-loop (HiL) simulation environment, which facilitated cost-effective rapid control prototyping (RCP). This HiL simulation mimicked joint motion and loading conditions akin to real spinal and hip wear simulators. The objectives of the study are to develop a robust controller for tribological applications and joint simulators and investigate the use of Fuzzy Logic as a possible enhancement of the control system. The Fuzzy-PI controller combines the conventional PI controller with Fuzzy Logic acting as a supervisor, enhancing overall control performance and robustness. The controller adapts to the system's operating range and performance characteristics through a combination of membership functions and control rules.

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Results

Results indicate that for ISO profiles with a fixed 1Hz frequency, both the traditional PI controller and the Fuzzy-PI controller perform equally well. However, as the frequency of the ISO profile increases or when handling ADL profiles with multiple frequency components, the Fuzzy-PI controller outperforms the PI controller. This was attributed to Fuzzy-PI's real-time adaptive capability to tune PI gains as frequency demands changed through a profile, providing a more robust and superior performance, particularly in challenging scenarios.

Conclusions

In conclusion, the Fuzzy-PI controller represents a promising advancement for joint wear simulators, offering improved control capabilities and better simulation of real-world physiological conditions.

Keywords
Fuzzy-PI controller, SIMO fuzzy logic control system, hardware-in-the-loop (HiL) simulation, joint wear simulators, activities of daily-living (ADL).



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Introduction

Recently, computational intelligence has been widely used to solve numerous complex problems by developing intelligent control methods. Fuzzy logic is one such control scheme that has proved to be very compelling for systems dealing with non-linear, non-sinusoidal, real-life data (Alavandar & Nigam, 2008; de Silva, 1995; Reznik *et al.*, 2000; Tian, 2005). Fuzzy sets were first introduced by Zadeh in 1965 (Zadeh, 1965) and have been implemented in various applications like railways, washing machines, air conditioners, auto-focusing cameras, robots, automobiles etc. (Er & Mandal, 2016). Fuzzy logic allows a system to transition gradually and continuously before reaching to a desired output as opposed to the traditional binary scheme that undergo an abrupt change and produce either a crisp 0 or 1 as the output (Chung *et al.*, 1998). The decision-making scheme of fuzzy logic uses simple If-Then rules helping it achieve effective control without the need of complex dynamic modelling (Carvajal *et al.*, 2000; Lee, 1990). Fuzzy If-Then rules are generated to describe the imprecise modes of reasoning that play a crucial role in the human ability to make decisions in an environment of uncertainty and imprecision (Hannan *et al.*, 2017). A fuzzy logic controller (FLC) aims to provide a model of approximate reasoning to produce a desirable output. The use of FLCs in industry is small when compared to PI controller designs. In the traditional proportional integral (PI) controller, the controller gains are initially determined based on the current system parameters and tuned manually to achieve the desired plant response (Hu *et al.*, 1999). Once the PI controller has been tuned, this static definition renders them incapable to control systems with additional complexities such as parameter variations within the system, non-linear and non-sinusoid control inputs (El_Mashade *et al.*, 2020; Li *et al.*, 2006). This is contrasted to deploying a Fuzzy-PI controller that can quickly adapt to sudden changes in linear and non-linear system depending upon the input profile that is used to control the process (Pan *et al.*, 2015).

The primary objective of this research is to design and assess an innovative control system, specifically a Fuzzy-PI controller, tailored for a joint wear simulator focused on the spine and hip. To achieve this, the study will leverage the previously developed benchtop hardware-in-the-loop (HiL) simulation environment, as documented in the study by (Iyer *et al.*, 2022). The HiL facilitated rapid control prototyping (RCP) (Glesner *et al.*, 2000; Hoyos-Gutierrez *et al.*, 2023) in the development, testing, and validation of various control algorithms, which represents an innovative approach in the field of tribology, particularly for wear testing of spinal, hip, and knee implants. The authors could find no previous research that has explored the use of FLC in this context, therefore this study serves as a valuable resource for researchers in the fields of tribology and medical engineering. It provides insights and knowledge on implementing sophisticated control algorithms in a straightforward, secure, and cost-effective manner, opening up new possibilities for advanced control strategies in joint wear simulation.

The hypothesis is that the Fuzzy element of the control system will provide intelligence to optimize the gains of the PI controller according to the changing demand profile. For comparison, the results are compared to an industry standard PI controller, which was tuned to provide good control to ISO-standard profiles at 1Hz. The PI controller's gains were then fixed throughout the measurements without any further tuning to evaluate its ability to control more challenging demand profiles. The study then compares the performance of the PI controller with the Fuzzy-PI controller in terms of their robustness and flexibility to control both a sinusoid and a real-life- activities of daily living (ADL) demand profile. The profiles were simulated for 100 cycles, and the robustness and flexibility of both controllers were tested based on their standard deviation at fixed PI gains for the PI controller and a fixed fuzzy membership function for Fuzzy-PI after tuning for optimal performance. ISO 18192-1 (ISO 18192-1, 2018) and ISO 14243-3 (ISO 14242-3, 2014) standards outline specific testing procedures for wear assessment of total spinal disc and hip prostheses. It involves using fixed and simplified sinusoidal motion profiles and load cycles. Performance criteria for the velocity-based controllers have been derived from the motion control tolerances defined in ISO 18192-1 as illustrated in Table 1-1

Table 1-2 illustrates the FE tolerance for the motion control as per ISO 14242-1 for the wear-testing of the hip (ISO 14242-3, 2014), and also defines the maximum and minimum tolerance of velocity control for the hip ADL walking profile. It is measured using the ISO tolerance in percentage for the hip motion profile.

Methods

Fuzzy logic controller (FLC)

Fuzzy logic controller (FLC) as a fundamental part of intelligent control, can deal with complex systems with relative ease. The basic architecture of an FLC is shown in Figure 2.1 It comprises of four fundamental elements: 1) fuzzification, 2) knowledge base/rule base, 3) the inference engine and 4) defuzzification.

Table 1-1. Cervical spine ISO 18192-1 tolerance for motion control parameters (ISO 18192-1, 2018).

ISO 18192-1 motion control parameters for flexion-extension (FE)				
Phase (%)	**Displacement (deg)**		**Tolerance**	
2	Max	+7.5°	+0.5°	6.7%
	Min	-7.5°	-0.5°	6.7%
Derived velocity control parameters for flexion-extension (FE)				
Phase (%)	**Velocity (rpm)**		**Tolerance**	
2	Max	+471	+31.08	6.7%
	Min	-471	-31.08	6.7%

Fuzzification. The first step of the FLC is the fuzzification of the controller inputs. In here, the crisp output data measured from the sensor is converted to some fuzzy values. These fuzzy values take the degree of memberships using a lookup table filled with linguistic rules that are written based on the system designer's understanding of the performance of the system under test (Khan & Rapal, 2006; Pratumsuwa *et al.*, 2010).

Knowledge base / rule base. Knowledge base is a repository of control rules written in the form of If-Then statements. The control rules are then applied on fuzzy values/sets to find their appropriate degree of membership (Mamdani & Assilian, 1975; Yamakawa, 1992).

The control algorithm has been developed throughout and implemented using LabVIEW 2017 Real-time (RT) graphical programming environment LabVIEW (RRID:SCR_014325), it may be possible to perform similar functions using the open source PyLab WORKS. Within the GUI, case structures were developed to enable rapid selection of joint simulation environment (spine or hip), controller choice (PI or Fuzzy-PI), as well as input profile to test on the HiL simulation over a defined range of frequencies that are usually experienced in real life by a human doing various daily-life activities.

Table 1-2. Hip ISO 14242-3 tolerance for the motion control parameters (ISO 14242-3, 2014).

ISO 14242-1 motion control parameters for flexion-extension (FE)				
Phase (%)	**Displacement (deg)**		**Tolerance**	
1	Max	+25°	+3°	12%
	Min	-18°	-3°	16.7%
Derived velocity control parameters for flexion-extension (FE)				
Phase (%)	**Velocity (rpm)**		**Tolerance**	
1	Max	+1402.35	+168.28	12%
	Min	-1282.89	-214.24	16.7%

A fuzzy membership function serves as a visual representation that quantifies the degree of membership for a given value within a defined fuzzy set. To create these membership functions, the Fuzzy System Designer tool within LabVIEW 2017 was employed. This tool facilitated the development of these functions through iterative trial-and-error processes, aiming to achieve optimal performance for the Fuzzy-PI controller.

Figure 2.2, Figure 2.3 Figure 2.4 illustrate the fuzzy triangular membership function. In this representation, the X-axis corresponds to the universe of discourse, which is the numerical range of fuzzy values established by the system designer based on controller specifications and requirements.

For Figure 2.2, the X-axis range was deliberately selected to encompass the maximum and minimum values of all profiles tested in this study. Similarly, the X axes of Figure 2.3 and Figure 2.4 encompass the complete range of proportional gain (K_p) and integral gain (K_i) values for all error values within the range indicated in Figure 2.2. However, the X axes ranges for Figure 2.3 and Figure 2.4 underwent numerous iterative adjustments. This process involved rigorous testing of each input profile until the Fuzzy-PI controller achieved optimal performance at 1 Hz and 2 Hz, respectively. On the Y-axis, values are represented on a scale from 0 to 1, indicating the degree of membership within this range.

The fuzzy membership functions were created using the fuzzy system designer feature within LabVIEW 2017 software,

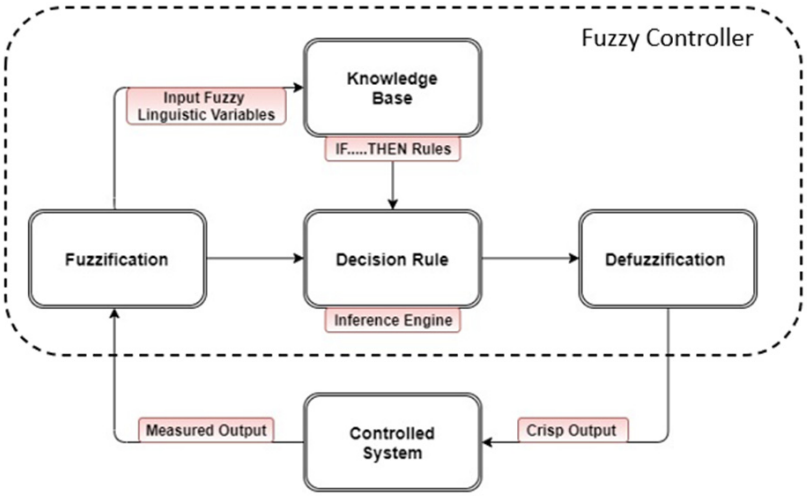

Figure 2.1. Fuzzy logic control architecture (Štefek *et al.*, 2021).

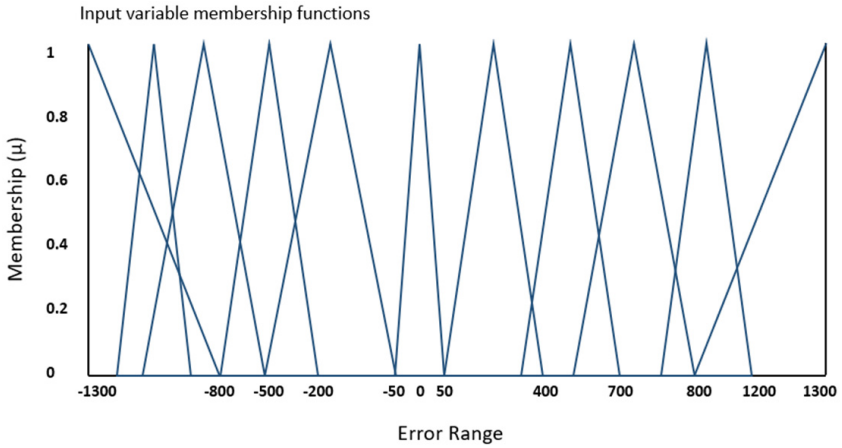

Figure 2.2. **Fuzzy membership function for error (e) for proportional-integral (PI) controller.**

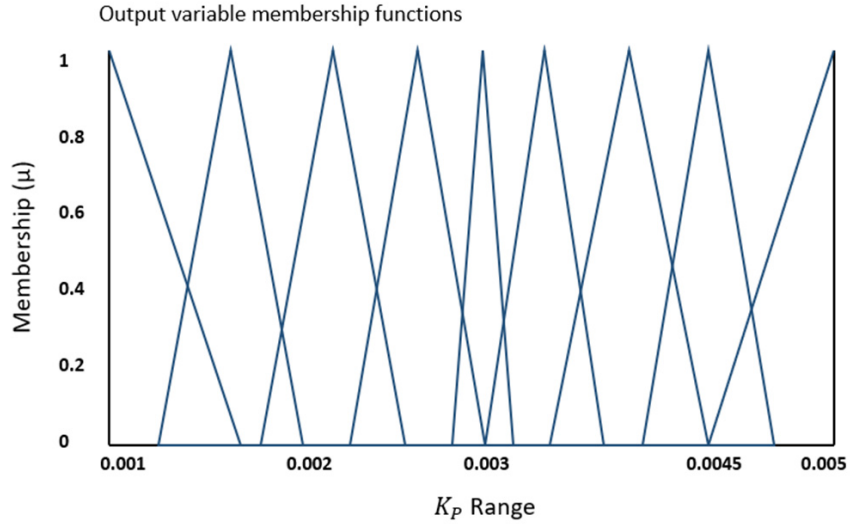

Figure 2.3. **Fuzzy membership function for proportional (K_p) gain.**

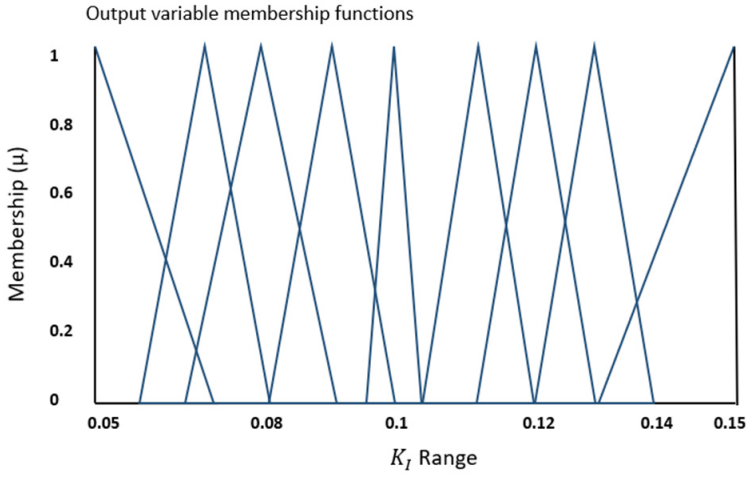

Figure 2.4. **Fuzzy membership function for Integral (K_i) gain.**

and the corresponding file has been uploaded to the GitHub repository with a .fs extension. (Iyer, 2023).

The inference engine. The inference engine is responsible for applying the decision rules to a fuzzy input from the feedback sensor in order to generate a fuzzy output. The decision rules are made using If-Then statements that contain the antecedents, for *e.g.*, error and change in error resulting out of the PI controller and the PI gains K_p and K_i are the consequent outputs based on the input.

Defuzzification. In defuzzification, the fuzzy output from the inference engine is mapped to a crisp value that provides the most accurate representation of the fuzzy set (Ebrahimnejad & Verdegay, 2018). Table 2-1 illustrates fuzzy rules which are linguistic expressions of the membership functions expressed in a bounded range for each variable that is used in the fuzzy system. The 11 fuzzy rules indicate 11 input triangular membership functions of Error illustrated in Figure 2.2.

In this application, the crisp output obtained in the fuzzy controller is by using the center of area method, also commonly referred as the centroid method which is defined below:

$$x = \frac{\sum_{x=1}^{n} x_i \mu_c(x_i)}{\sum_{x=1}^{n} \mu_c(x_i)} \quad (1)$$

It is represented as x, in a fuzzy output distribution to determine a single scalar value. The membership of the fuzzy sets is presented in μ_c, whereas the value of the membership is represented as x_i. Finally, the crisp output from the defuzzifier is an approximation that is used to state the PI gains K_p and K_i (Rizvi *et al.*, 2020). In this application, the derivative gain (K_d) is not used due to its aggressive reaction to the rate of change of the controlled process. Consequently, only a PI controller was tested on the HiL simulation as a comparison to a Fuzzy-PI controller.

A comparison between the PI and Fuzzy-PI controllers was conducted through simulations encompassing 100 cycles of the FE profile derived from the ISO-18192-1 standard and the hip ADL walking profile. The assessment of both controllers' robustness and flexibility involved evaluating their standard deviation. This evaluation was performed with fixed PI gains for the PI controller and a consistent fuzzy membership function for the Fuzzy-PI controller, as depicted in Figure 2.3 and Figure 2.4. These configurations were established after tuning for optimal performance, maintaining constant Kp and Ki gains.

The feedback data from the profiles employed in the HiL simulation was subject to analysis, involving the computation of both the mean and standard deviation over a span of 100 cycles using LabVIEW 2017. The outcome of this analysis produced an averaged waveform representing a single cycle. This averaged waveform was subsequently employed to evaluate the performance of both the PI and Fuzzy-PI controllers, with reference to the specified tolerances delineated in Table 1-1 and Table 1-2.

In the case of the PI controller, the experiment involved extensive trial and error testing of profiles for the spine FE and for the hip ADL profile. After thorough evaluation, the experiment selected the optimal Kp and Ki values of 0.003 and 0.11, which remained consistent throughout the testing process.

For the Fuzzy-PI controller, the range of Kp and Ki gains, represented as fuzzy membership functions in Figure 2.3 and Figure 2.4, was estimated based on the gains obtained for

Table 2-1. Fuzzy rules to evaluate error (e) using proportional (K_p), Integral (K_i) using linguistic form.

Sr no	Fuzzy rules
1	If Error is "Extremely Large Neg" THEN K_p is "Very Large" ALSO K_i is "Extremely Small"
2	If Error is "Very Large Neg" THEN K_p is "Large" ALSO K_i is "Very Small"
3	If Error is "Large Neg" THEN K_p is "Large" ALSO K_i is "Small"
4	If Error is "Medium Neg" THEN K_p is "Medium" ALSO K_i is "Medium"
5	If Error is "Small Neg" THEN K_p is "Medium-1" ALSO K_i is "Medium-1"
6	If Error is "Near Zero" THEN K_p is "Medium-2" ALSO K_i is "Medium-2"
7	If Error is "Small Pos" THEN K_p is "Medium-2" ALSO K_i is "Medium-3"
8	If Error is "Medium Pos" THEN K_p is "Medium" ALSO K_i is "Medium-3"
9	If Error is "Large Pos" THEN K_p is "Small" ALSO K_i is "Large"
10	If Error is "Very Large Pos" THEN K_p is "Very Small" ALSO K_i is "Large"
11	If Error is "Extremely Large Pos" THEN K_p is "Extremely Small" ALSO K_i is "Very Large"

the PI controller. Consequently, the values of 0.03 for Kp and 0.1 for Ki were chosen as the central values within the range depicted in Figure 2.3 and Figure 2.4.

Within the LabVIEW GUI, case structures were established to provide users with the option to select either ISO or ADL profiles for differentiation and utilize it as a set-point for the controller.

Fuzzy-PI velocity-based control method

Figure 2.5 illustrates the overall control structure of the HiL simulation used to test both PI and Fuzzy-PI controllers. It was originally developed to represent the motion and loading conditions of a spinal joint wear simulator; however, a secondary kinematic model has been derived to extend the testing capability of the HiL simulation to additionally represent the motion and loading of a hip joint. The objective of the controllers (PI and Fuzzy-PI) in a velocity-controlled system is to maintain a velocity set point at a given value and be able to accept new set point values dynamically. The fuzzy tuner shown in the figure below controls the real-time tuning of the PI controller. This particular fuzzy tuner is known as a fuzzy SIMO (single-input-multiple-output) system, whereby the error (e) generated within the PI controller is fed into the fuzzy system as the input variable. The inference engine of the Fuzzy controller then determines in real-time new K_p and K_i gains that are then used by the PI controller.

Results

The selection of test profiles was based on their complexity in terms of waveform shape, frequency components, and their relevance to human ADL. Based on this criteria, two profiles were chosen: 1) standard ISO-18192-1 (ISO 18192-1, 2018) profile for the spine and 2) a walking profile of the hip that was obtained from gait lab measurements (Lunn *et al.*, 2020) at Leeds Teaching Hospitals Trust. Results presented show the average response across 100 cycles simulated at 1 Hz and 2 Hz frequencies. The phase shift (PS) of the output response is measured using:

$$\mathrm{PS} = \frac{360 \times td}{T} \tag{2}$$

Where *td* is the time difference between the highest value of the input and the output profile at the end of the cycle, and *T* is the wave period *e.g.*, 1 second. Figure 3.1 illustrates the two controller's responses when following a flexion-extension (FE) velocity profile derived from the displacement profile in

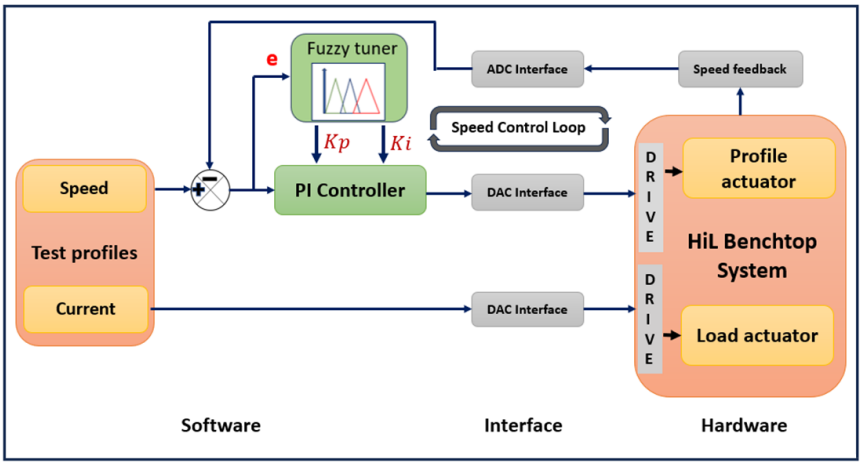

Figure 2.5. Fuzzy-Proportional-Integral (PI) control approach on the hardware-in-the-loop (HiL) simulation environment.

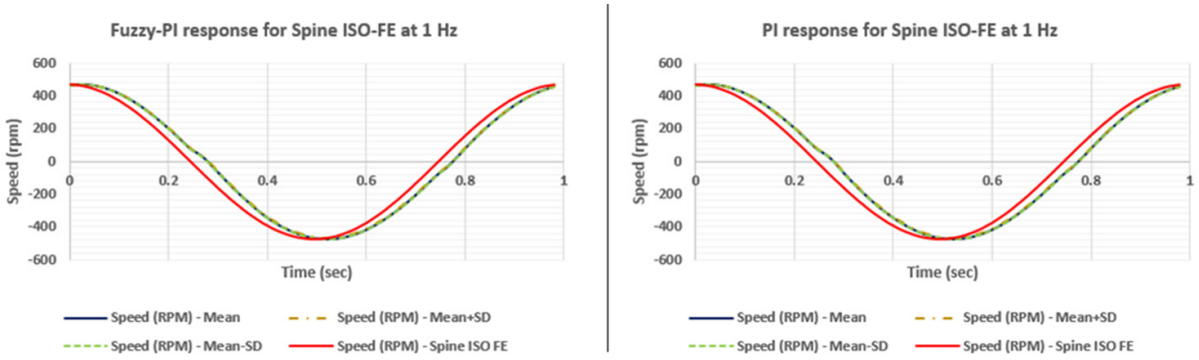

Figure 3.1. Fuzzy-Proportional-Integral (Fuzzy-PI) vs Proportional-Integral (PI) response of spine ISO flexion-extension (FE) at 1Hz.

ISO 18192-1. Both controllers showed similar performance and stayed within the tolerance limit of 2% phase lag and gain difference of 6.66% as specified in Table 1-1. This matched performance can be explained by the fact that the PI controller was manually tuned for this 1Hz profile and because the singular frequency of the profile did not require the Fuzzy-PI controller to adjust PI gains, hence both controllers performed equally well.

Figure 3.2 illustrates the same speed profile of the spine tested at 2Hz. The system response from both controllers demonstrates a clear difference in performance. Here, the Fuzzy-PI controller was able to adjust the PI gains to more robustly follow the 2Hz input profile with a phase shift of 14.4 degrees in comparison to the PI controller with a phase shift of 173 degrees and an amplitude gain of 5.4 decibels, thereby making the system highly unstable to control any further. In addition, the PI controller, due to its fixed gain values, took a number of cycles to find a steady state and hence this caused the standard deviation to be far greater.

Further, the amplitude max and min and the end-of-cycle phase shift for the Fuzzy-PI controller was within the tolerance specifications at 2Hz. Whereas the PI controller was out of tolerance for both amplitude and phase. Table 3-1 details the performance assessment for both controllers based on the ISO 18192-1 tolerances derived for speed control.

Figure 3.3 illustrates the changing PI gains in real-time when the Fuzzy-PI controller was active in controlling the spine ISO profile at 2Hz depicted above in Figure 3.2. This contrasts with the static gains of K_p = 0.003 and K_i = 0.11 used throughout the testing of all profiles for PI controller.

Figure 3.4 and Figure 3.5 show the response and auto-tuning of fuzzy gains in real-time of a hip walking profile for both controllers. The PI controller response had an average phase shift of 43 degrees in contrast to an average of 10 degrees for fuzzy-PI controller, as the phase shift is different in the peak and valley of the profile. Further, the standard deviation for PI controller is larger than Fuzzy-PI indicating that the range of Fuzzy gains allows the controller to be more stable and consistent.

The tolerance limits specified in ISO 14242-1 standards for the hip are ±12% for the amplitude gain and ±1% for the phase timing (ISO 14242-3, 2014). However, currently there are no international standard tolerances specified for ADL profiles. Therefore, Table 3-2 illustrates the performance assessment of both PI and Fuzzy-PI controllers for the hip

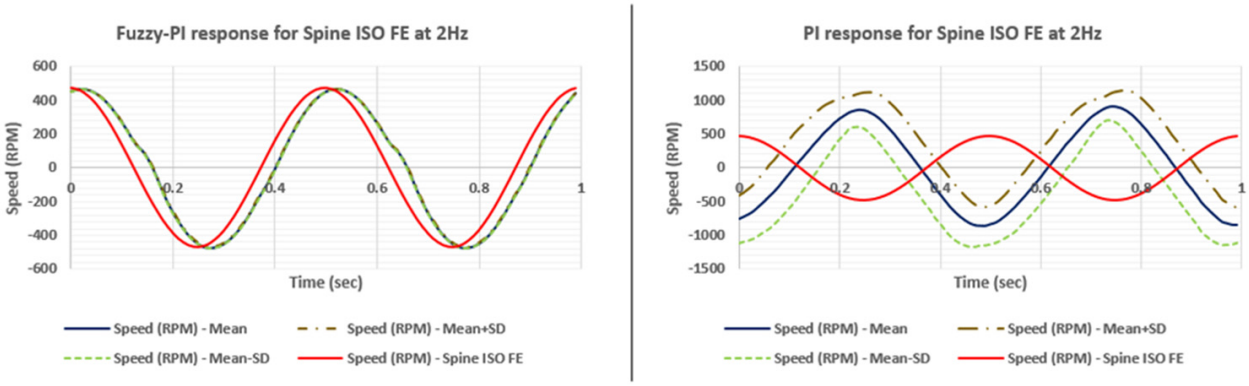

Figure 3.2. Fuzzy-Proportional-Integral (Fuzzy-PI) vs ProportionaI-integral (PI) response of Spine ISO FE at 2Hz.

Table 3-1. Controller performance assessment based on ISO 18192-1 tolerance specification.

Controller performance vs ISO 18192-1 tolerance			
Frequency	**Performance metric**	**Fuzzy-ProportionaI-Integral (Fuzzy-PI)**	**Proportional-Integral (PI)**
1 Hz	Amplitude (±6.66%)	-1.94%	-2.17%
	Phase (2%)	2%	2%
2 Hz	Amplitude (±6.66%)	2.43%	80.4%
	Phase (2%)	2%	26%

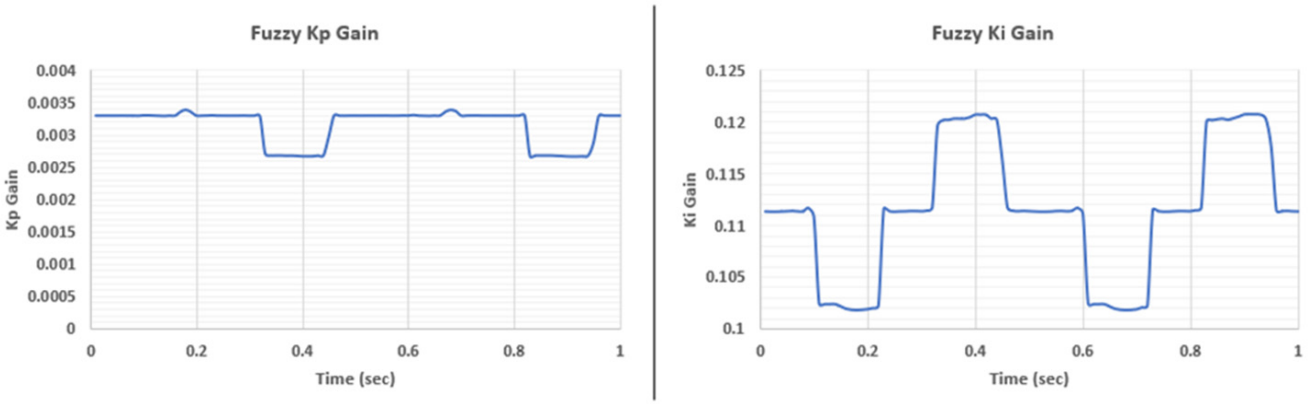

Figure 3.3. **Fuzzy gains for Spine ISO-FE profile at 2Hz.**

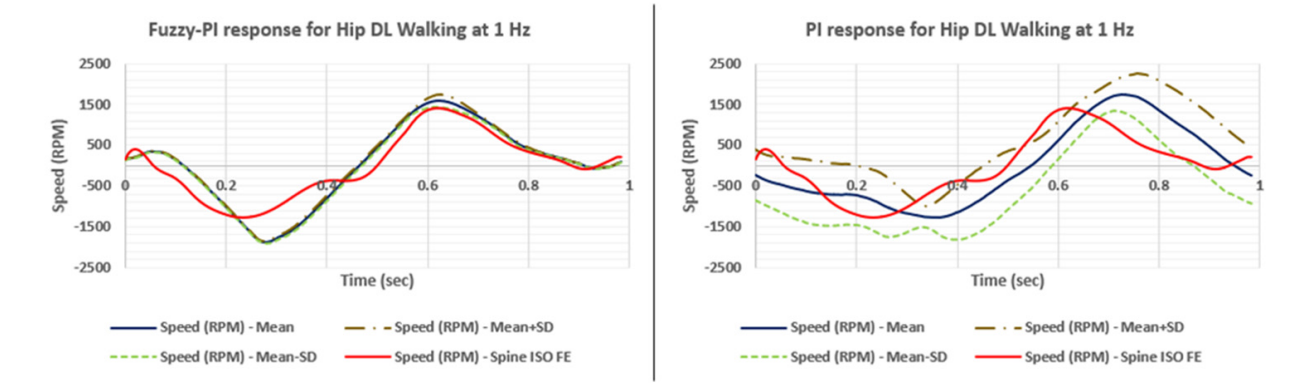

Figure 3.4. **Fuzzy-Proportional-Integral (Fuzzy-PI) vs Proportional-Integral (PI) response of Hip Daily-Living walking profile at 1Hz.**

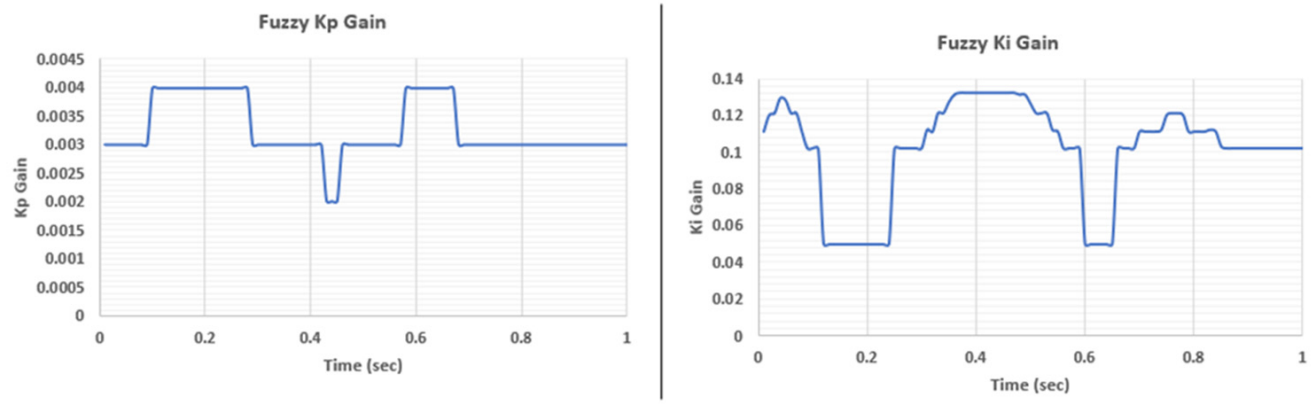

Figure 3.5. **Fuzzy gains for Hip Daily-Living walking profile at 1Hz.**

Table 3-2. Controller performance assessment based on the Daily-Living walking tolerance specification.

Controller performance vs ISO 18192-1 tolerance			
Frequency	**Performance metric**	**Fuzzy-PI**	**PI**
1 Hz	Amplitude (+12%)	+13.15%	+24%
	Amplitude (-16.7%)	-46.47%	-1.09%
	Phase (+1%)	+1%	-13.92%
	Phase (-1%)	-5.8%	-16.89%

daily living walking profile as per the tolerance limits of the ADL walking profile shown in Table 1-2.

Bode plot – frequency response

Figure 3.6 illustrates Bode plots for both controllers following the ISO FE profile over a frequency sweep from 0.5Hz to 2Hz. The Bode plots represent the amplitude gain, expressed in decibels (dB) and phase shift in degrees of a system as a function of frequency (Hz). The Fuzzy-PI controller demonstrated superior performance over the PI controller as the frequency increased and reached 2Hz.

Bode plot for the hip walking profile is not included in the paper as it was tested only for 1 Hz frequency and not for a range of spectrum like the ISO profile for the spine.

Discussions

The experimental setup, as discussed in this project and previously applied in the work by Iyer *et al.* (Iyer *et al.,* 2022), demonstrated the benefits of HiL simulation. For this work, the HiL simulation provided a robust and reliable platform for rapid development and testing of prospective controllers. The platform allowed verification and fine tuning of the prospective controllers in a low-risk environment before any potential deployment to a mechanical joint simulator. In addition, the testing platform was also capable of simulating both a mechanical spine simulator and a hip simulator *via* development of parallel software kinematics models, further demonstrating its value.

Throughout the approach, the Fuzzy element of the controller acted as a supervisor to the PI controller. Hence, key to the approach was to understand how the PI controller behaved across the desired frequency range. Following this system definition phase, membership functions could then be specified. With carefully defined membership functions in place, the complexity and setup time of running tests to follow a variety of profiles and frequencies is then greatly reduced. This is because the real-time adaptive nature of the Fuzzy supervisor can adjust the operating gains to optimally follow any profile that was part of the system definition phase. Traditionally, with PI control alone the operator would need to retune the controller (or enter pre-defined gains) before each test to ensure that the simulator would follow the test conditions (Chaudhary *et al.*, 2016; Ren & Bigras, 2017). Results illustrated on the Bode plot in Figure 3.6 clearly reveals that as the frequency of the input profile increases the gains of the PI controller initially set for 1 Hz could not control the actuator response especially during the change in the actuator's direction of rotation. This is where real-time auto-tuning using FLC provides better control with its wide range of PI gains. Also, when both controllers are tested against more challenging real-world waveforms such as the ADL walking profile of the hip the same PI gains used for the sinusoid profile did not provide better control as compared to its Fuzzy-PI counterpart as shown in the results. This is due to the higher frequency components present within the waveform.

This work has also shown how the Fuzzy-PI controller may be capable of controlling joint simulators to accurately follow daily-living profiles. Daily living profiles are typically non-sinusoidal and are composed of multiple frequency components, rendering them difficult for a traditional PI controller to accurately follow. The intelligent Fuzzy-PI controller presented in this study achieved this by utilizing real-time feedback to adapt PI gains and accurately follow the profile. The ability to accurately simulate daily living profiles has been a major limitation in pre-clinical testing of implants using traditional PI controllers, leading to numerous high-profile failures resulting in significant financial compensation (Abdelgaied *et al.*, 2022). Therefore, the adoption of intelligent controllers to improve pre-clinical testing is crucial for ensuring the effectiveness of joint implants in the future.

While Fuzzy Logic offers clear advantages, its use also has a significant drawback: engineers require a greater level of knowledge compared to using only PI controllers. Furthermore, the setup time to define the system with Fuzzy Logic is considerably longer than with traditional PI controllers. The HiL simulation environment allowed for the thorough evaluation of the experiments using a variety of ISO and ADL profiles, which enabled the rigorous testing of controllers and allowed engineers to develop effective fuzzy membership functions. A thorough understanding of system behavior is crucial in order to design effective membership functions. Additionally, testing the system with a classic PI controller remains the gold standard of feedback control systems as it provides an approximation of the system's optimum operating zone. This operating zone enables the design of the range of the fuzzy membership function, which is unique to each system based on its input conditions and external disturbances.

Conclusions

This work has presented a novel approach to improve the testing of prostheses on a joint wear simulator. The Fuzzy-PI controller represents a promising advancement for joint wear simulators, offering improved control capabilities and better simulation of real-world physiological conditions. Despite requiring extensive knowledge of the system and a comparatively high level of control expertise, the Fuzzy-PI controller has shown to have significant benefits over the traditional PI controller, such as: once implemented, no further retuning

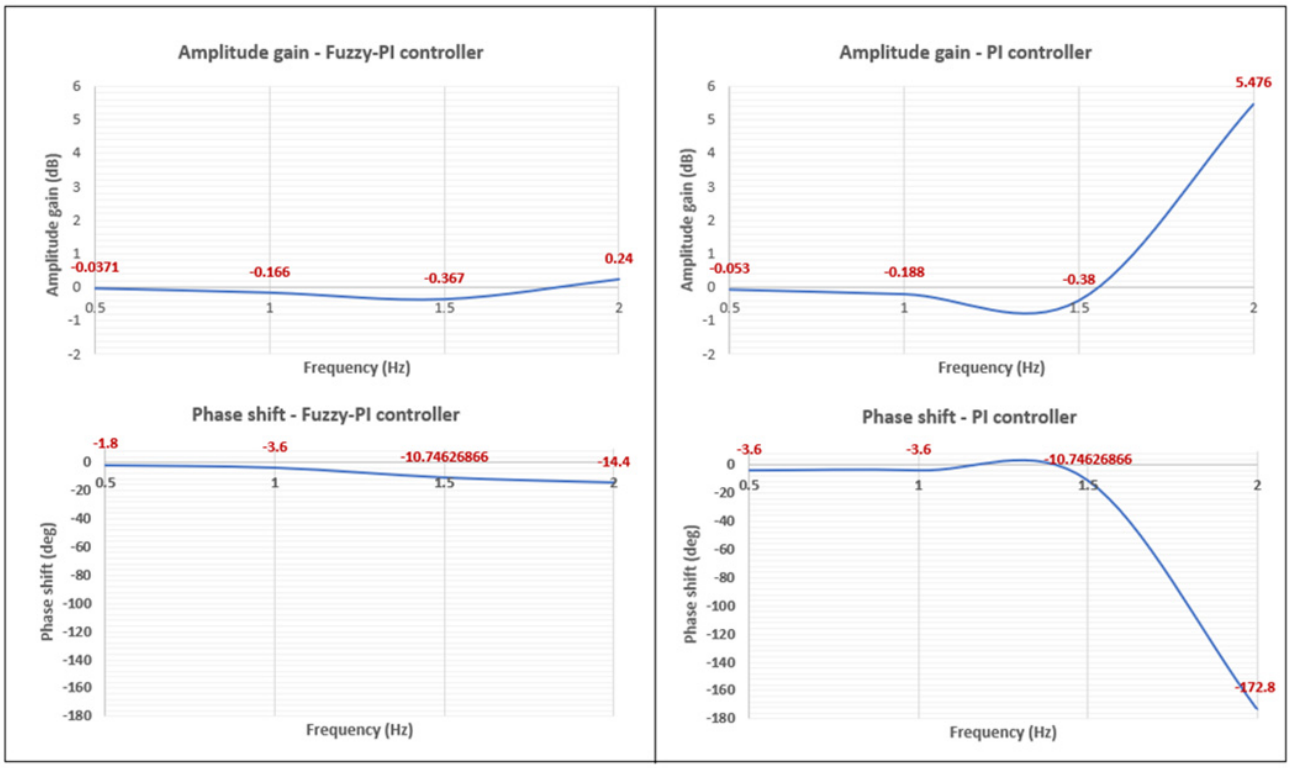

Figure 3.6. Frequency response of the hardware-in-the-loop (HiL) system for Fuzzy-ProportionaI-Integral (Fuzzy-PI) vs Proportional-Integral (PI) controller with ISO flexion-extension (FE) profile as the input signal.

is required and FLC is capable to ease the setup of such machines; potential to robustly run ADL profiles, because the FLC can adapt gains in RT.

The results obtained from the Bode plot analysis clearly reveal the limitations of the PI controller, originally tuned for a frequency of 1 Hz, in effectively controlling the actuator response as the input profile's frequency increases, especially during changes in the actuator's direction of rotation. However, real-time auto-tuning using FLC demonstrates superior performance for frequencies above 1 Hz, offering a wide range of adaptable PI gains to suit diverse operating conditions. In the case of more challenging real-world waveforms, such as the ADL walking profile of the hip, the same PI gains that worked well for the simpler sinusoidal profile prove to be inadequate compared to the Fuzzy-PI controller. The complexity of the waveform, with its higher frequency components, highlights the Fuzzy-PI's advantage in providing better control. Furthermore, the Fuzzy-PI controller displays remarkable robustness and flexibility throughout the testing process. Maintaining minimal standard deviation while utilizing the same membership function showcases its ability to effectively handle varying conditions and uncertainties. This emphasizes the Fuzzy-PI's potential as a reliable and adaptable control solution in joint wear simulation applications.

Future work

This paper has demonstrated the benefit of using HiL simulation in a tribological application to safely and rapidly advance controllers. Building upon this achievement, a crucial aspect of future work involves expanding the testing to encompass a broader range of ADL profiles on the joint wear simulator. This comprehensive evaluation will allow for rigorous testing and validation of the performance of both controllers under various demanding scenarios.

Additionally, further investigations may focus on optimizing the Fuzzy-PI controller to ensure its robustness and adaptability to a wide array of real-world waveforms and operating conditions. The controller's tuning parameters could be fine-tuned and adjusted based on specific performance requirements for different patient demographics or implant types. Moreover, conducting comparative studies between the Fuzzy-PI controller and other advanced control strategies could provide valuable insights into the most effective approach for joint wear simulation. This will aid in advancing the field of tribology and medical engineering, leading to improved prosthetic design and better patient outcomes.

Furthermore, the study could extend its scope to explore the potential benefits of applying the Fuzzy-PI controller to other

joint wear simulators beyond the spine and hip, encompassing knee and other joint replacements, or the combined testing of non-linear materials such as cartilage-on-cartilage. This could open up new avenues for innovative control solutions in the broader domain of joint prosthetics.

Data availability

Underlying data

Zenodo: Iyer03/HIL_Simulation: Initial release https://doi.org/10.5281/zenodo.8396924 (Iyer, 2023)

This project contains the following underlying data:

1. Feedback-response-of-100-cycles.zip (Zip folder containing sub-folders of Results obtained from FuzzyPI and PI controllers of Hip-ADL-Walking at 1 Hz and Spine ISO FE for 1 Hz and 2 Hz are as follows:

- Hip ADL Walking – folder with input and feedback data at 1 Hz for the following controllers:
    - Fuzzy-PI
    - PI results
- Spine ISO FE – folder with input and feedback data at 1 Hz and 2 Hz for controllers:
    - Fuzzy-PI results
        - 1 Hz
        - 2 Hz
    - PI results
        - 1 Hz
        - 2 Hz

2. MEAN_of_the Feedback_Response.zip (zip folder containing the mean feedback response of 100 cycles of Spine ISO FE with Fuzzy-PI and PI controllers at 1 Hz and 2 Hz. And Hip ADL Walking at 1 Hz with Fuzzy-PI and PI controllers).

Data are available under the terms of the Creative Commons Zero "No rights reserved" data waiver (CC0 1.0 Public domain dedication).

Software availability

Archived source code is available from: https://doi.org/10.5281/zenodo.8396924 (Iyer, 2023)

Source code is available from: https://github.com/Iyer03/HIL_Simulation/tree/main

License: CC0-1.0

Author contributions

Kaushikk Ravender Iyer: Conceptualization, Methodology, Software, Testing, Formal Analysis, Validation, Writing – Original Draft Preparation and Editing; **David Keeling:** Conceptualization, Funding acquisition, Supervision, Reviewing and Editing; **Richard M Hall:** Supervision, Reviewing and Editing.

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✗ **Chuanxin M. Niu**
Shanghai Jiao Tong University, Shanghai, China

This study formulated a control logic with fuzzy functions in the application of joint wear simulator. The feature of the solution was hardware-in-the-loop simulation. The authors claimed that using the algorithm in the context of wear testing of spinal, hip and knee implants, was innovative. However, this statement did not suffice to motivate the study.

Almost all control algorithms were designed to be a general mathematical tool, rather than a specific routine tailored to a narrow range of applications. Therefore, applying Fuzzy control in the field of wear testing did not exceed the initial purpose of this algorithm. As a result, it is a nice engineering attempt, but the research question remained unclear.

How would HiL + Fuzzy control expand our understanding of joint wear test, except that it provides a testbed? This was also not well articulated.

Also, at the very least, the Fuzzy-PI should be benchmarked, either against itself with different settings, or better off against competitors. Otherwise it is difficult to persuade the readers of the significance of the work.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
No source data required

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: robot control, biomedical engineering, human neuroscience

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Reviewer Report 11 May 2024

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Nasir awad
Mustansiriyah University, Baghdad, Iraq

The paper needs more improvement:
1- rewrite the abstract in classified and closed form.
2-All the references are old. You must provide a citation in a new reference.
3- You need to use other intelligent controllers, like adaptive control, neural control.
4- In fuzzy control, there are many approaches.I believe using type-2 fuzzy may improve the response.
5- You use a frequency response analysis? why. I believe the time domain is very accurate. Please give details about the system stability in frequency ananlysis, like gain margin and phase margin.
6-Please rewrite the conclusions and give the numerical results about the desired response.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
I cannot comment. A qualified statistician is required.

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: control engineering

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.