RESEARCH PAPER

I|J|A|M|B
INTERNATIONAL JOURNAL OF ADVANCES IN MEDICAL BIOTECHNOLOGY

Intelligent embedded system for physiological control of ventricular assist devices in health 4.0 background

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Abstract: The purpose of this study was to develop and evaluate a Physiological Control of Left Ventricular Assist Device (PC-LVAD) system within the Health 4.0 (H4) platform, using an Intelligent Embedded System (IES). The main aim was to personalize control systems and integrate medical devices into the treatment of Congestive Heart Failure (CHF) patients, specifically those who are not eligible for heart transplantation. The PC-LVAD system was implemented using the MyRIO® development platform, along with LabVIEW® FPGA and RT, Quartus II® EDA, and MATLAB®. Experimental tests were conducted to evaluate the system's performance with analyzing the Internet of Things (IoT) characterization and applying best practices for information security. The experimental tests demonstrated effectiveness of IES in storing and transmitting real-time data to graphical interface. The data collected by PC-LVAD system were consistent with external measuring instruments. This suggests that system successfully integrated with accurately captured and transmitted physiological data. The development of PC-LVAD system within the H4 platform, utilizing the IES, shows promise in personalizing control systems and integrating medical devices for treatment of CHF patients. The system's ability to capture and transmit real-time physiological data provides valuable insights into the patient's condition and allows for timely adjustments in treatment. By addressing the issue of constant flow in LVADs, the PC-LVAD system has the potential to improve quality of life and survival rate of CHF patients. Further research and clinical trials are necessary to validate the effectiveness and safety of system.

Keywords: Ventricle Assist Devices; Health 4.0; Physiological Control; Embedded system.

Introduction

Heart failure (HF) stands as a preeminent global health issue[1], wherein Congestive Heart Failure (CHF) represents its most incapacitating manifestation, distinguished by the heart's incapacity to effectively circulate blood to sustain a life of well-being[2]. While heart transplantation remains the quintessential therapeutic approach for advanced-stage CHF, its feasibility is confined by the dearth of suitable donors and potential contraindications[3]. Left Ventricular Assist Devices (LVADs) proffer an alternative remedy, serving as both a bridge to heart transplantation (BTT) and a modality of destination therapy (DT) for those ineligibles for transplantation[4].

Continuous flow LVADs (cfLVADs) function at a consistent pump speed, a parameter typically modulated by a medical practitioner. The healthcare professional evaluates both patient and pump variables to determine an appropriate setpoint within the control framework, thus ensuring the sustained operation at the designated speed, irrespective of any impedance encountered by the pump rotor[5]. The controller of the HeartWare cfLVAD (manufactured by Medtronic Inc., Dublin, Ireland) maintains comprehensive log files encompassing intricate operational data, which can be transmitted through electronic mail to facilitate treatment monitoring and enable timely identification of untoward incidents[6].

In order to enhance the efficiency of cfLVADs, the implementation of an active adjustment scheme becomes imperative, one that autonomously modulates pump speed in response to patient requisites, thereby obviating the necessity for manual intervention by medical professionals. Numerous methodologies have been postulated for the physiological regulation of cfLVADs (referred to as PC-LVADs), among which the Multi-Objective Control (MOC) system represents the zenith of sophistication[7]. This system takes into account a multitude of variables influencing the patient's condition and amalgamates the merits inherent in diverse control strategies to counterbalance the limitations observed in individual approaches. Nonetheless, this configuration can evolve into an intricate framework necessitating the incorporation of an artificial intelligence (AI) algorithm for guidance[5].

AI-driven MOC algorithms necessitate a controller endowed with elevated capacities in memory, data transmission, and computational processing. Fontana *et al.*[8] have formulated a portable and adaptable apparatus designed to interface with sensor-equipped cfLVADs within an environment of perpetual monitoring and self-regulation. This undertaking encompasses wireless administration and a wearable system interface. Furthermore, the integration of this controller with the SensorART platform stands imperative, as it

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Received 10 May 2023; Accepted 19 August 2023
https://doi.org/10.52466/ijamb.v5i2.112

augments the well-being of patients and streamlines the operational dynamics of medical practitioners[9]. The Health 4.0 (H4) paradigm heralds a transformative shift in healthcare, emphasizing the customization of therapeutic interventions[10]. Nevertheless, challenges endure in the creation of systems that possess the attributes of adaptability, appropriateness, energy efficiency, and safety, all aligned with the imperatives of healthcare requirements.

The innovation within this article resides in the implementation of an AI-driven MOC framework within the H4 paradigm, operationalized through an embedded system. This pioneering effort converges advanced artificial intelligence, healthcare, and technological integration to establish a dynamic and adaptable control mechanism that not only aligns with the personalized H4 ethos but also transcends conventional treatment modalities. By bridging these domains, the study advances knowledge by pioneering technological integration, potentially enhancing patient outcomes through adaptive treatment strategies, contributing to healthcare automation, and providing a substantiated exploration of AI and healthcare synergy, thus profoundly impacting the intersection of these disciplines.

The primary objective of this investigation is to effectuate the integration of an AI-driven MOC mechanism within the H4 framework, executed on an embedded system, subsequently subjecting it to empirical assessment based on initial criteria. Experimental tests were conducted to evaluate the system's performance with analyzing the Internet of Things (IoT) characterization and applying best practices for information security. The exposition is structured as delineated below: Commencement with the Introduction; Successive explication within Section II detailing the constituents pivotal to the formulation of the proposed methodology; Proceeding to Section III for the comprehensive presentation of the acquired findings, subsequently subjected to discourse within Section IV; Culminating in the summative deduction presented in Section V.

Materials and Methods

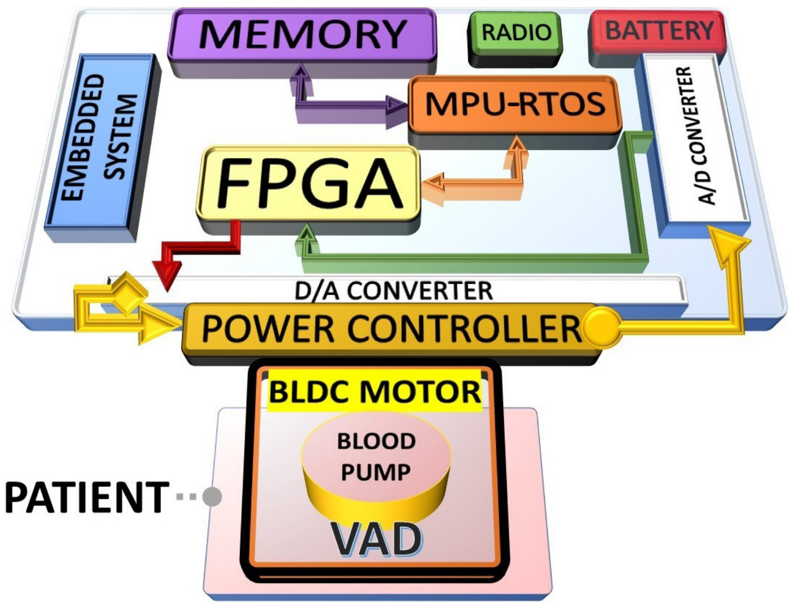
A. Intelligent Embedded System

The Intelligent Embedded System (IES) was meticulously conceived and compiled upon the MyRIO® development platform, an offering of National Instruments (Austin, USA), which incorporates the Xilinx Z-7010 Field-Programmable Gate Array (FPGA) alongside a dual-core ARM Cortex-A9 processor clocked at 2GHz, operating in conjunction with the MPU-RTOS (Microprocessor with Real-Time Operating System).

The realization of the proposed algorithms was methodically undertaken through a confluence of developmental tools, encompassing LabVIEW® FPGA and RT (Version 2018, National Instruments, Austin, USA), Quartus II® EDA (Version 9, Altera, San Jose, USA), and MATLAB® (Release R2018b, MathWorks, Natick, USA). The digital interfaces of the IES were seamlessly linked with the power controller (50/4 EC-S driver, Maxon, Sachseln, Switzerland) governing the EC45-N339281 BLDC motor (Maxon, Sachseln, Switzerland). The power controller underwent calibration and configuration via ESCON Studio (Version 18, Maxon, Sachseln, Switzerland) to enable the comprehensive acquisition of sensorless metrics, including voltage, current, and speed, from the motor.

The architectural schema of the IES, seamlessly engrafted into the power controller's framework, is visually explicated in Figure 1. Pivotal constituents of this architecture encompass: (i) a nucleus vested with the responsibility of data processing pertaining to actuation systems (facilitated through the D/A converter – Power Controller) and data assimilation (executed via the A/D Converter – Transducers); (ii) the MPU-RTOS, intricately entwined with

Figure 1 – Visual representation of the integration of Intelligent Embedded System (EIS) architecture into the power controller.



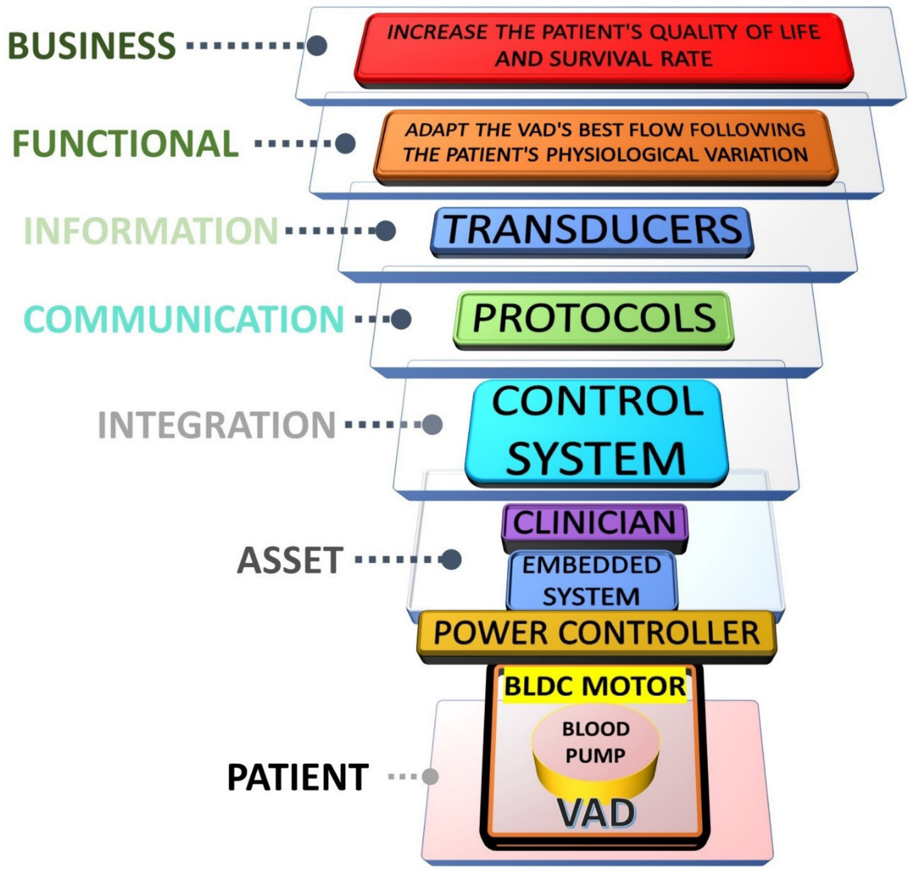
primary memory, operating as a computational nucleus for intricate algorithms and conditional variables, responsive to real-world stimuli; (iii) a radio interface, instrumental in the transmittal and reception of data pertaining to external modules and remote accessibility to a graphical interface; and (iv) a power source in the form of a battery, endowing requisite energy to the embedded system, power controller, and motor.

B. Selected H4 framework

The complexity inherent in the framework of intelligent medical devices arises from the dynamic exigencies and applications within the healthcare domain[12]. RAMI 4.0, a three-dimensional coordinate framework, delineates the pivotal facets of Industry 4.0 implementation, deconstructing intricate interdependencies into more manageable and coherent clusters[13]. In the work of Barboza *et al*. [14], a proposition emerged, suggesting the adaptation of RAMI 4.0 for collaborative integration within medical device control systems, coined as H4-RAMI4. This approach demonstrated its aptitude in modeling the local control architecture of a LVAD within the H4 paradigm [15]. Augmentation of the H4-RAMI4 construct is feasible through the integration of medical devices and the IoT within a secure and secluded cloud computing environment [16].

Illustrated in Figure 2 is the practical application of the H4-RAMI4 framework within the LVAD control system. The subsequent description highlights the distinct layers and constituents from an uppermost to basal perspective: (i) The Business layer encapsulates logic that governs the maintenance of functional integrity along the value chain, with the ultimate objectives of enhancing quality of life and elevating patient survival rates; (ii) The Functional layer executes business operations, optimizing LVAD value and/or operational regime to align with the patient's physiological requisites. This orchestration is facilitated by an intelligent and robust supervisory system seamlessly integrated with localized controls; (iii) The Information stratum structures data for processing, enacting event-driven rules, and transduces the physical attributes of treatment parameters through both tangible and virtual sensors; (iv) The Communication realm standardizes both internal and external information exchange, encompassing protocols for both wired and wireless data transmission to facilitate vigilant care; (v) The Integration domain orchestrates the seamless transition from physical to virtual resources; and (vi) The Asset layer represents the tangible elements of the operational reality, affording healthcare professionals platform resources that guide optimal treatment decisions for patients

Figure 2 – Visual representation of synergistic technological Integration in the application of the Health 4.0 (H4)-Reference Architectural Model for Industrie 4.0 (RAMI 4.0) Framework in the control system of Left Ventricular Assist Devices (LVADs).



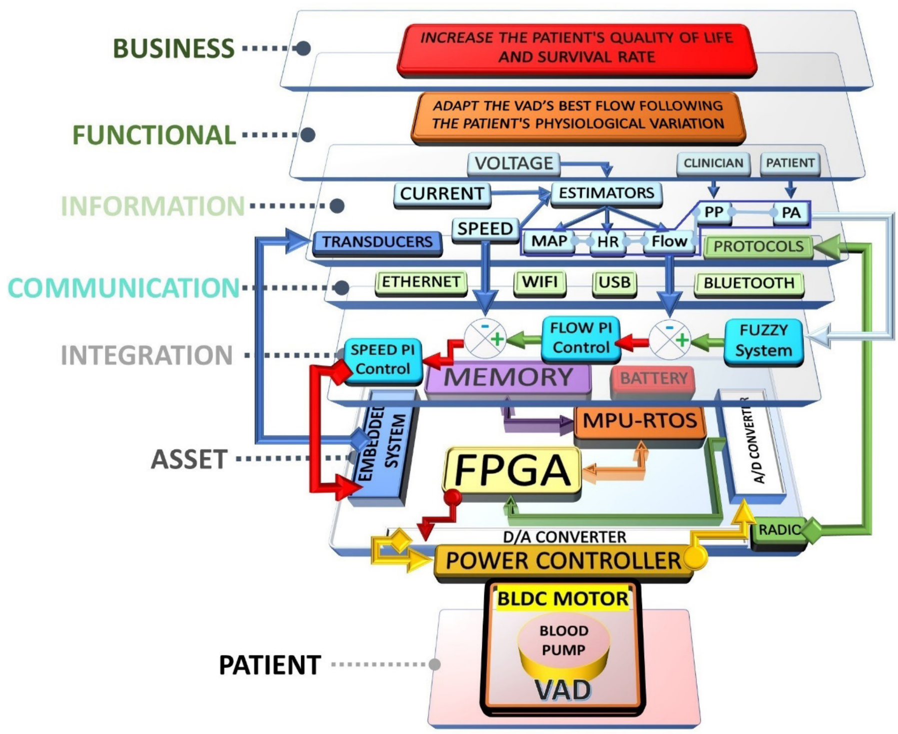
with LVAD implants.

C. Selected PC–LVAD

The chosen PC–LVAD for implementation within the IES is the Physiological MOC (MOPC) method proposed by Leão *et al*. [17]. The MOPC is meticulously devised to ensure the harmonious alignment of flow adjustment operations with the inherent physiological intricacies of patients bearing a LVAD. The rationale for this selection is founded upon its antecedent development within our research group and the empirically substantiated efficacy of MOPC operations, evinced by their congruence with the appropriate physiological parameters across various CHF scenarios, as simulated within a hybrid cardiovascular simulator [18].

Displayed within Figure 3, the MOPC, ensconced within the H4–RAMI 4.0 framework, is operationalized through the IES. Comprising a cascade of three sub-controls, the MOPC mechanism is constituted by an automatic control that modulates the manipulated variable governing flow control (flow rate). This variable, in turn, regulates the manipulated variable within the proportional–integral (PI) control (pump speed). The algorithms embodying the MOPC controls are seamlessly incorporated within the Integration layer of the H4–RAMI4 structure. Essential components encompassed by the MOPC encompass: (i) The autonomous control of the LVAD pump motor rotational speed, enacted through fuzzy logic, employing input parameters domiciled within the Information layer of H4–RAMI4. These parameters encompass fundamental aspects such as average heart rate (aHR), mean arterial pressure (MAP), minimum pump flow (mF), and patient–adjusted activity level (PA), as delineated by either patient–specific profiles or clinician–prescribed parameters (PP); (ii) The flow control module, grounded in the flow setpoint as defined by the clinician or governed automatically, leveraging the feedback value of flow obtained from the estimator; and (iii) The PI speed control facet, predicated upon the speed setpoint as stipulated by either clinical requisites or flow control dictates, utilizing the direct feedback value of speed extracted from the power controller.

Figure 3 – Visual representation of Synergetic Technological Fusion the Integration of the Physiological Multi–Objective Control (MOPC) Method within the Health 4.0 (H4)–RAMI 4.0 Framework, Executing on the Intelligent Embedded System (IES).



D. Evaluation of preliminary criteria in experimental tests

The assessment of preliminary criteria [18–20] was undertaken predicated upon an exhaustive scrutiny of the characterization of the H4 platform in its capacity as a medical IoT (MIoT) system, duly aligning with the cardinal tenets espoused by the General Data Protection Regulation (GDPR), specifically encompassing Accuracy, Integrity, and Confidentiality. The overarching framework finds delineation within the subsequent components [21–22]:

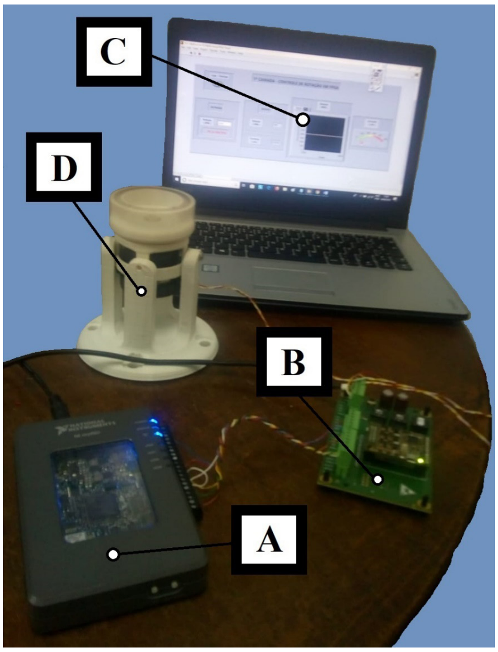
1. The Subscriber, vested with the onus of incessantly monitoring patient data that remains amenable to access and review (Availability criteria).

2. The Publisher, constituting an interconnected nexus of sensors and allied medical apparatuses, poised to either function independently or in concert, effectively capturing pivotal patient data (Identification, Sensors, and Communication criteria).

3. The Broker, assuming the mantle of processing and securely warehousing data within the cloud realm, adhering steadfastly to the imperatives of data precision, integrity, and confidentiality (Accuracy, Integrity, and Confidentiality criteria).

Depicted in Figure 4 is the assemblage of the IES for empirical experimentation, signifying the ensuing components: (i) A wired interlinkage spanning between the IES (Fig. 4a) and the power controller (Fig. 4b), facilitating digital initiation, analog speed designation, alongside analog acquisition of the motor's speed and current parameters; (ii) An interface for remote graphical access (Fig. 4c) resident upon a personal computing terminal, tethered via USB and wireless modalities to the IES; and (iii) The LVAD prototype (Fig. 4d), the propulsive mechanism of which embraces a Brushless Direct Current (BLDC) motor configuration. The nexus between the LVAD and its actuating agent is established through the instrumental medium of additive manufacturing.

Figure 4 – Assembled Configuration of the Intelligent Embedded System (IES) for Empirical Testing: (a) Implementation of the IES on the MyRIO platform, (b) The Power Controller (50/4 EC-S driver), (c) Graphical Interface for Remote Access to the IES, and (d) LVAD prototype with BLDC motor (EC45 N339281 BLDC).



Results

The incorporation of the MOPC was realized within the ambit of the H4-RAMI4.0 framework, constituting an integral facet of the H4 platform's instantiation upon the IES. To ascertain the algorithm's fidelity during the migratory testing phase, a functional executable program was formulated on a computing system. This validation entailed a meticulous juxtaposition of outcomes derived from the original proposition vis-à-vis the outputs generated by the novel rendition. Following the unequivocal validation of algorithmic consistency, the developed algorithm was seamlessly compiled directly into the IES architecture.

A. Preliminary criteria's experimental test – Subscriber

A Subscriber role, manifesting as a graphical remote access interface, has been devised for the IES to oversee the operational dynamics and data assimilation processes within the MOPC-H4-RAMI4.0 framework operationalized on the IES platform. The IES's "Home" interface is portrayed in Figure 5, prominently featuring buttons denoting: (i) "Stop," serving the purpose of instantaneously ceasing the physiological control's automatic adjustment regimen during exigent scenarios. In such cases, exclusive command over the closed-loop control of the LVAD rotation speed at the default setpoint is assumed; (ii) "Connection," facilitating the establishment of either USB or wireless linkage between the graphical interface and the embedded system; (iii) "WEB," ushering access to the data acquisition system through a designated web address; and (iv) "Record," empowering the recording of operational data into a log file situated within the internal or external memory of the system.

The IES's "Control" interface, depicted in Figure 6, showcases a pivotal "Control Mode" button, affording the choice of the principal closed-loop control mode within system operations. This entails the options of speed, flow, and automatic controls, complemented by the respective enabling setpoints for speed and flow parameters.

Figure 7 portrays the IES's "Patient" interface, spotlighting buttons inclusive of: (i) "Clock," serving to adjust the temporal schedule; (ii) "P.A.," enabling real-time selection of the patient's activity level from Soft, Mild, to Hard; and (iii) "P.P.," reserved for periodic clinician evaluations. During these assessments, the patient's clinical profile is determined in consonance with the INTERMACS classification (ranging from 1 [worst] to 7 [best]), or during instances indicative of potential recovery of systolic function (ranging from 8 to 10).

The IES's "Clinician" interface, featured in Figure 8, has been meticulously formulated to align with the specialist system governing automatic control over LVAD's demand. This involves structured input variables (aHR, MAP, mF, PA, and PP) replete with corresponding internal membership functions (smaller-bigger) and their attendant geometric configurations (triangular and trapezoidal) alongside defined range-points. Similarly, the output variable (Flow) is accompanied by its inherent internal membership functions (Decreases, holds, increases) embodied through geometric shapes (triangular and trapezoidal), in concurrence with stipulated range–points. The interface also comprises heuristic rules dictating the interplay among system variables. Pertinent details encompassing variables and heuristic rules have been chronicled in prior work concerning the migration of this stratum from MOPC to an embedded system [23].

Figure 9 reveals the IES's "Data" interface, where projected operational data (aHR, MAP, and mF) is portrayed, derived from the interpolation of experimental data incorporating the pump motor parameters (speed and current electrical). Additionally, an auxiliary network resource program has been devised within the IES, facilitating access to operational data through an Application Programming Interface (API), as illustrated in Figure 10.

In tandem with the ongoing research inquiry, an added module designated "Healthcare" has been developed within the IES framework. The IES's "Healthcare" module interface, delineated in Figure 11, culminates in the integration of an accelerometer with the MOPC, aimed at approximating steps and activity levels. This initiative seeks to supplant the limitation attributed to manual input in capturing patient activity levels. The module further facilitates real–time monitoring of ordinary states (standing, sitting, or lying down), event–based triggers (patient's sleep–wake transitions), and prospective life–threatening occurrences (patient falls, seizures, or loss of consciousness).

Figure 5 – Intelligent Embedded System "Home" graphical remote access interface.

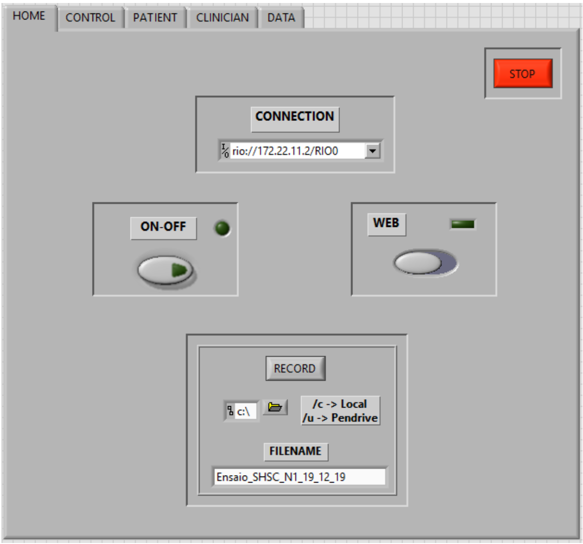


Figure 6 – Intelligent Embedded System "Control" graphical remote access interface.

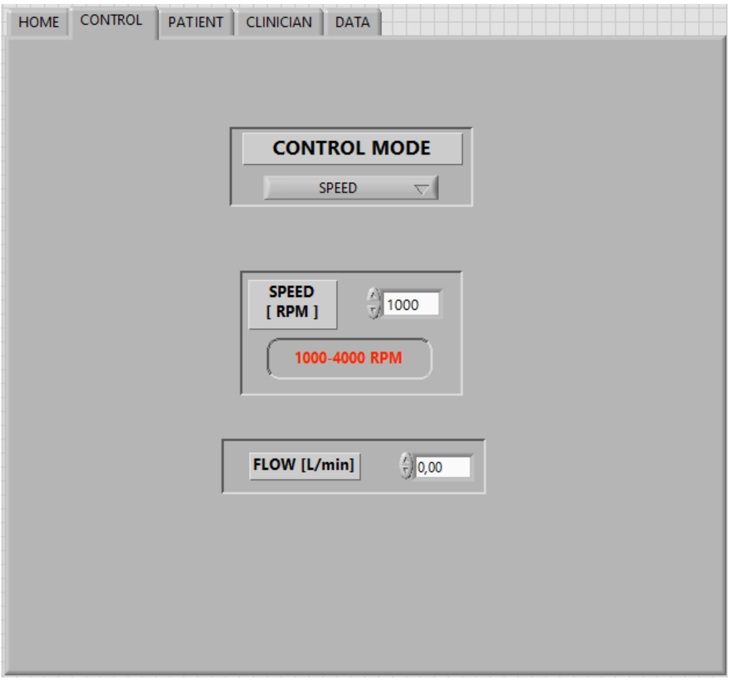


Figure 7– Intelligent Embedded System “Patient” graphical remote access interface.

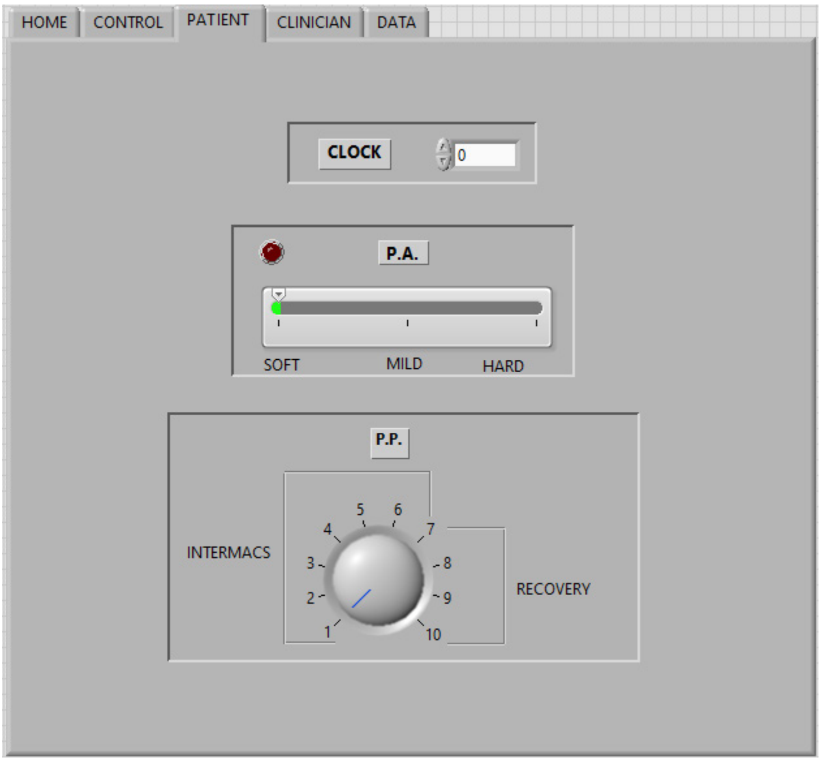


Figure 8 – Intelligent Embedded System “Clinician” graphical remote access interface.

Figure 9 – Intelligent Embedded System "Data" graphical remote access interface.

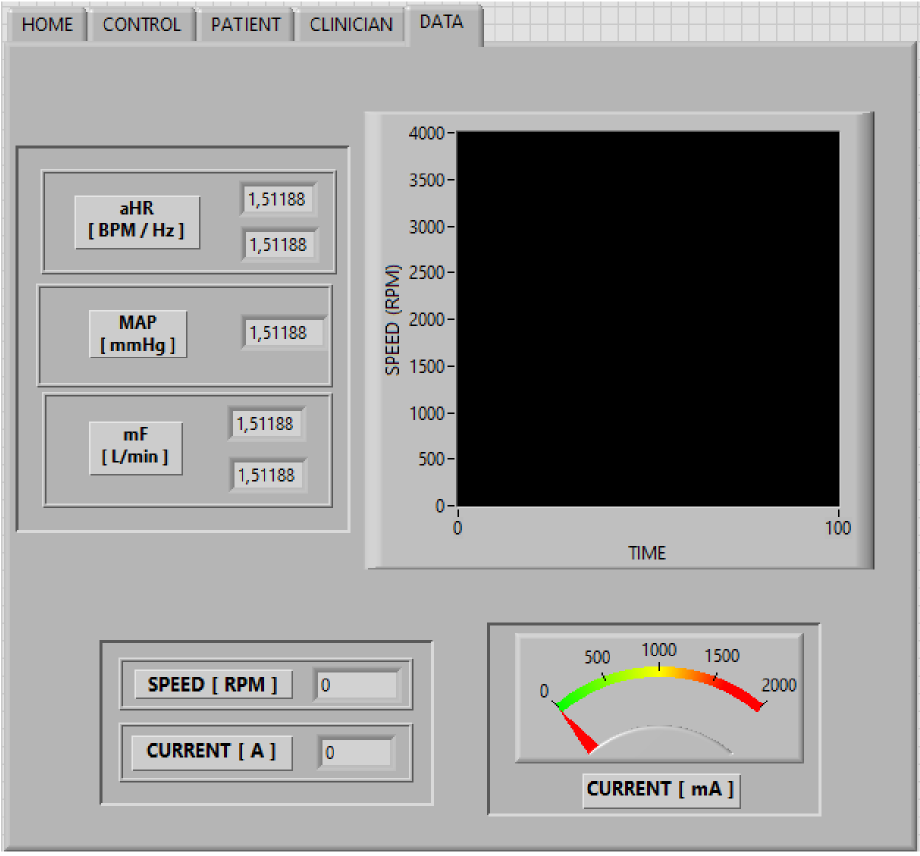


Figure 10 – Intelligent Embedded System "API" graphical remote access interface.

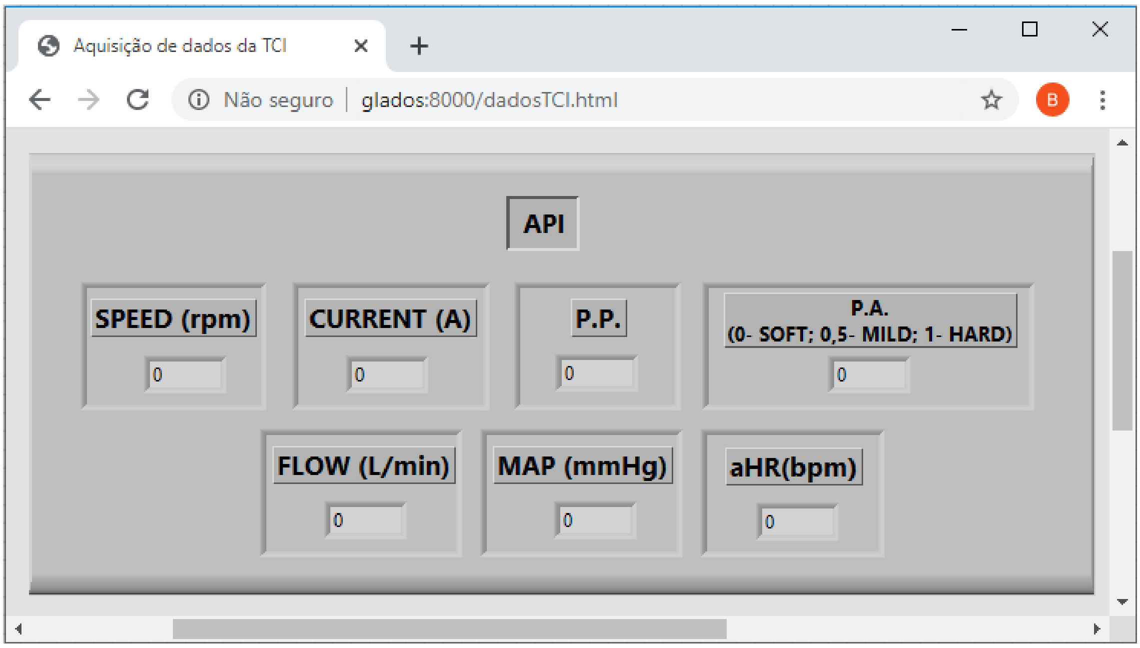
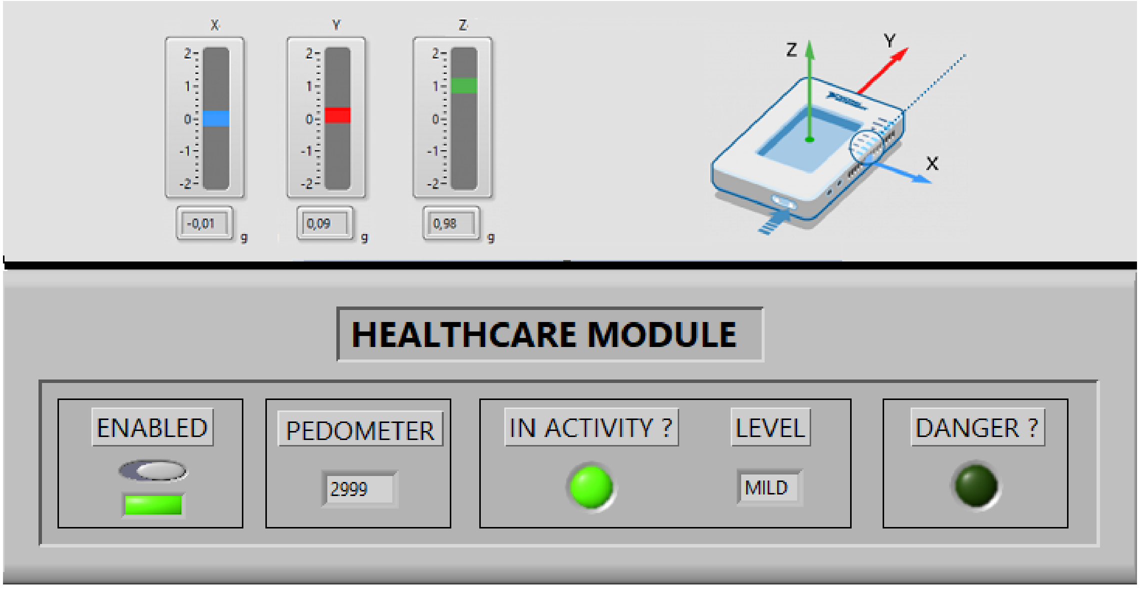


Figure 11 – Intelligent Embedded System "Healthcare" module graphical remote access interface.



B. Preliminary criteria's experimental test – Publisher

A variable named "ID" was introduced into the algorithm to fulfill the identification criterion. At the initial moment when the IES system begins operation, a one-time run function invokes the "ID" variable and assigns it a unique identification key consisting of a random set of letters (aA–zZ) and numbers (0–9).

The IES system has telemetry for data collection from the assist system and system operation as an essential routine to meet the sensor criterion. During all IES operations, a loop execution function calls the variables "motor speed" and "motor current" and assigns them processed values (0–4000 RPM; 0–2000 mA) derived from readings (0–5 V) at the respective analog input ports. The variables "motor speed" and "motor current" are processed internally within the estimation algorithm to calculate the LVAD's flow and differential pressure, as well as the patient's aHR and MAP, thus constituting a virtual sensor. Additionally, physical sensors with WiFi and Bluetooth (via dongle) radio capabilities can be integrated into the system.

In terms of communication, the IES system is compiled on MyRIO with resources for internet connection, including WiFi radio and RJ45 network cable, and has network features for remote operation control and real-time online data availability.

C. Preliminary criteria's experimental test – Broker

The An attribute designated as "ID" was introduced into the algorithm to fulfill the stipulated identification criterion. During the inaugural phase of the IES operation, an exclusive one-time runtime function is invoked to establish and assign the "ID" variable a distinctive identification code. This key is constituted by a random amalgamation of alphanumeric characters, encompassing both lowercase and uppercase letters (aA–zZ) and numerical digits (0–9).

Integral to the IES framework is the incorporation of telemetry mechanisms, essential for comprehensive data acquisition from the assist system, concurrently catering to the prerequisites of the sensor criterion. Across the entire spectrum of IES operations, a cyclic execution function engenders the invocation of the "motor speed" and "motor current" variables. These entities are subsequently endowed with meticulously processed values (ranging from 0 to 4000 rpm for motor speed and 0 to 2000 mA for motor current), extracted from readings obtained at the corresponding analog input ports. Notably, these values originate from the 0 to 5 V range. The "motor speed" and "motor current" variables undergo internal processing within the estimation algorithm to deduce significant metrics inclusive of the LVAD flow and differential pressure, alongside the patient's aHR and MAP. Consequently, they collectively form a virtual sensor. Furthermore, the possibility exists to seamlessly integrate physical sensors endowed with WiFi and Bluetooth capabilities, the latter facilitated through a dongle.

In the realm of communication paradigms, the IES structure is compiled within the MyRIO framework, bolstered by resources conducive to internet connectivity. These encompass WiFi radio and RJ45 network cable interfaces, thereby equipping the IES with comprehensive networking attributes. This architecture is inherently conducive to remote operational control and real-time online data accessibility.

V. Discussion

Left Ventricular Assist Devices (LVADs) have gained substantial utilization as a mechanism to ameliorate mortality rates while patients await heart transplantation, specifically addressing congestive heart failure (CHF) [4]. An ideal scenario entails the customization of these devices to harmonize with patient-specific flow requisites, contingent upon individual characteristics, care context, and contemporaneous conditions [7]. However, the establishment of a physiological control system for LVADs is presently situated within the developmental phase [5]. Presently, research endeavors are directed towards the Health 4.0 (H4) initiative, with the intention of augmenting the efficiency of healthcare services, enhancing the quality of life, prolonging patient survival, and fostering novel business paradigms within the sector [10–11]. This study's primary aim was the implementation of a physiological controller within the H4 framework, embedded within a proprietary system, and subsequently, an evaluation of the preliminary criteria for assimilating this entity within the broader H4 platform.

The prevailing control mechanisms for LVADs are underpinned by a closed-loop configuration governing blood flow pumping speed, adjudicated by clinicians during periodic assessments, coupled with insights stemming from sensorless methodologies grounded in actuator operational characteristics [5]. In the context of this investigation, a multi-objective control structure was formulated within the ambit of the H4 framework. This hierarchy encompasses a tier devoted to speed control (first layer), a subsequent stratum dedicated to device flow and pressure control (second layer), and culminating in an automatic flow adjustment control layer (third layer).

The realm of mobile and wearable digital health interventions (DHI) portends an avenue for post-surgery patient monitoring and support. Nonetheless, an exigency is perceived to enhance DHI reporting mechanisms, aimed at substantiating patient benefit, encouraging reproducibility, and advancing sustainability [24]. Remote health monitoring exhibits potential for ameliorating healthcare quality and cost-efficiency [25]. However, the amalgamation of wearable sensor data into electronic health records necessitates a harmonized consensus [26].

The bedrock of the H4 platform rests upon extensive online data acquisition, subsequently subjected to intricate algorithmic analysis to expedite comprehensive health optimization [10, 11]. The overarching thrust of H4 converges to bolstering the roles of both clinicians and patients within the treatment continuum [18]. A constellation of graphical interfaces has been curated (as elucidated in Figures 5–11) to enhance clinician-patient engagement with the LVAD system. This engenders augmented access to pertinent information for treatment strategies, alongside real-time presentation of operational and care data.

In line with regulatory and security prerequisites governing implantable biomedical devices, a graphical remote access interface has been formulated, encompassing facets of external security monitoring and local parameter surveillance of the LVAD system. The interface substantiates logs that mirror HeartWare logs, encompassing statistical data such as speed, energy consumption, LVAD flow, and pressure metrics. Moreover, historical event records, alarms capturing fault activations, and real-time logs to preemptively detect adverse events are pivotal attributes [6].

The advent of digital health devices mandates their integration within the broader context of precision medicine for effective cardiovascular health assessment [27]. The appraisal of preliminary criteria through empirical testing has been motivated by the characterization of an Intelligent Embedded System (IES), embedding Physiological Control (PC-LVAD), as a facet of the Internet of Things (IoT). This amalgamation is strategically harmonized with the H4 framework, inculcating information security as a paramount concern. The confluence of technology and medical applications through IoT imparts transformative impacts upon medical services [16].

Underpinning the H4 platform is the transposition of the Reference Architecture Model Industrie 4.0 (RAMI4) into the healthcare domain, encapsulating its application within the LVAD control system. Coincidentally, the Industrial Internet Reference Architecture (IIRA) exists in synergy with RAMI4, both possessing the overarching goal of industrial process digitization and optimization through technology infusion. Central to their architecture is a reservoir of stored data, often aligned with cloud computing adoption, and the advanced analysis of industrial data premised upon the tenets of big data. It is noteworthy that RAMI4's information domain axis parallels the functional information domain of IIRA [28].

The salient attributes of IES empower algorithmic programming and reconfiguration within PC-LVAD and supplementary enhancement modules. Existing propositions, such as the work by Satpathy *et al*. [29], contemplate data collation from IoT-oriented wearable devices, subsequently subjected to artificial intelligence processing via a field-programmable gate array (FPGA) system. This facilitates implementation of standardized communication protocols, accommodating diverse communication languages of varying LVADs through streamlined firmware updates [8]. Therefore, IES discerns the optimal hardware characteristics to manifest swift responses and refined control adjustments.

Derived from the outcomes thus garnered, should IES be effectively instituted as an LVAD controller, it stands positioned to perpetually collect usage data in a "24/7" cycle. The proliferation of data facilitates progressively sophisticated assistance to patients who have undergone implantation. Inherently structured, the data furnished by IES necessitates transformation into metadata or an equivalent unstructured format, accentuating the capacity for processing voluminous data streams within a potentially uninterrupted network constellation spanning multiple devices [30].

The integration of smart health devices is poised to generate a wealth of data, necessitating innovative processing techniques to derive actionable insights. Pioneering proposals, such as that by Taher *et al*. [31], advance an IoT-cloud-based framework tailored to batch and real-time processing of voluminous healthcare-centric Big Data. This infrastructure effectively caters to data migration mandates. In a similar vein, Mavrogiorgou *et al*. [32] advocate a holistic approach to foster data interoperability emanating from diverse devices fortified by IoT underpinnings.

The nexus of Software-Defined Network (SDN) intelligent controller-based edge computing accentuates efficient resource allocation within the confines of IoT devices' constrained resources. A post-processing regimen within IES emerges as an imperative, efficaciously enhancing communication and security facets. It is prudent to endorse the adoption of SDN controllers, as advocated by Badotra *et al*. [33] and Li *et al*. [34], thereby fostering load balancing, network optimization, and judicious resource apportionment within the healthcare ecosystem.

Elevating the discourse to security considerations, it is discerned that smart health monitoring systems invariably interface with wireless networks, inherently susceptible to security breaches [35]. Tang *et al*. [36] posit a privacy-preserving health data aggregation scheme, effectively harnessing health data from multiple sources with unwavering reliability. Further contributions, such as the two-stage bidirectional authentication protocol introduced by Alladi & Chamola [37], encapsulate hardware security primitives coined as non-clonable physical functions. Acknowledging the criticality of security in medical IoT devices, the IES configuration has been ingeniously architected to harbor ample processing capacity for security routines, leveraging sophisticated techniques such as end-to-end cryptography.

Throughout the assimilation of medical IoT technologies, two paramount considerations surface: firstly, the ramifications of human exposure to radiofrequency radiation technologies, possibly conferring adverse outcomes like cancer and compromised fertility [38]; and secondly, the paramountcy of security reliability within IoT integration, while mitigating vulnerabilities within medical devices [39-40].

The foregoing textual analysis underscores the imperative significance of addressing the intricate challenges entailed in the effective utilization of LVADs through the deployment of sophisticated PC-LVADs. The central thematic thread that pervades the discussion pertains to the burgeoning prominence of Artificial Intelligence (AI) and innovative control paradigms within the domain of cardiac support mechanisms, exemplified by the array of studies cited.

The comprehensive evaluation of the proposed Physiological Control System for LVADs (PC-LVAD) by Petrou *et al*. [41] serves as a foundational cornerstone in demonstrating the feasibility and safety of responding to variable flow dynamics in a controlled laboratory setting. This study contributes to the growing body of research aimed at enhancing LVAD functionality through responsive control systems. Similarly, the seminal insights provided by Al-Ani *et al*. [42] underscore the evolution of AI in the broader context of Mechanical Circulatory Support (MCS) complication screening. The succinct overview of the trajectory of AI integration into heart failure practice resonates with the envisaged future where the synergistic interaction of AI and clinical practice is poised to substantially transform patient care.

The pioneering contributions outlined in Fetanat *et al*. [43] and Magkoutas *et al*. [44] usher in novel paradigms in LVAD control systems. Fetanat *et al*.'s innovative utilization of a real-time deep convolutional neural network (CNN) to estimate preload aligns with the emerging trend of leveraging advanced computational techniques to enhance physiological estimation. The notion of a sensorless adaptive physiological control system exemplifies the convergence of machine learning techniques and medical device management. On a similar vein, Magkoutas *et al*.'s proposal of the Physiological Data-Driven Iterative Learning Controller (PDD-ILC) represents a promising advancement toward addressing the pulsatility concern in cfVADs. The meticulous tracking of predefined pump flow trajectories resonates with the imperative of physiological fidelity, a critical aspect in heart failure management. Lastly, the innovative work presented by Li *et al*. [45] introduces a new horizon in LVAD control systems by merging the realm of Deep Reinforcement Learning (DRL) and physiological estimation. The novel estimation of blood volume, integral to LVAD function, typifies the synergy between advanced computational frameworks and the intricacies of cardiovascular physiology. The cumulative insights gleaned from these studies affirm the pivotal role of cutting-edge technologies and innovative control strategies in shaping the landscape of LVAD utilization. The emergent theme of AI, machine learning, and advanced control paradigms showcases a trajectory toward patient-centric care characterized by improved responsiveness, adaptability, and physiological fidelity within the realm of heart failure management. In pursuit of these objectives, the imperative arises for the creation of a portable system endowed with the capability to harness the entire gamut of computational resources intrinsically intertwined with artificial intelligence. In this context, the essence of this endeavor is encapsulated in the present work, wherein an exposition is proffered, delineating a platform conducive to the conception and realization of such a system.

This investigation, albeit with valuable contributions, is not devoid of limitations. The IES archetype stands as a proof-of-concept real-time embedded LVAD, and its current status is ill-suited for medical deployment. The preliminary experimental tests, while rooted in the H4 background, predominantly pivot on qualitative analyses. Consequently, a broader and more extensive scope beckons, necessitating meticulous and standardized examinations to attain more precise quantitative insights. It is important to acknowledge that the outcomes arising from the bench tests, involving a controller actuating an LVAD prototype, bear demarcations, and do not encompass the encompassing milieu characteristic of actual utilization within an LVAD recipient's context.

Conclusion

This study delineates the proposition of implementing a Multi-Objective Physiological Controller (MOPC) within the Health 4.0 (H4) framework, operationalized on an Intelligent Embedded System (IES). The authors subsequently undertake an evaluation of preliminary criteria through empirical tests. The IES exhibits proficient data storage and real-time transmission capabilities to a graphical interface, consistently correlating with readings acquired via external instrumentation. Furthermore, the IES stands amenable to amalgamation with a multi-agent process fortified by sophisticated algorithms and artificial intelligence, which in turn furnishes a comprehensive comprehension of medical data encompassing diverse patients. This reservoir of insights becomes pivotal in informed decision-making pertaining to LVAD reconfigurations, culminating in ameliorated patient survival rates, elevated quality of life, and heightened productivity.

In forthcoming inquiries, the authors contemplate an expansion of the criteria attendant to the integration of the control system as a medical IoT device. Concurrently, the envisaged trajectory involves the scrutiny of this approach within simulated circulation loops, with the intent of extracting quantitatively robust and statistically significant performance outcomes for the MOPC ensconced within the H4-RAMI4.0 framework and operationalized on the IES.

Acknowledgments

The authors express their gratitude to the Institute Dante Pazzanese of Cardiology (IDPC), São Paulo Research Foundation (FAPESP), Higher Education Personnel Improvement Coordination (CAPES), University of Sao Paulo (USP), and Federal Institute of Sao Paulo (IFSP) for their partial support of this research endeavor.

References

[1]. Savarese G, Becher PM, Lund LH, Seferovic P, Rosano G, Coats AJ. Global burden of heart failure: a comprehensive and updated review of epidemiology. Cardiovascular Research. 2022.

[2]. Lilly LS. Braunwald's Heart Disease Review and Assessment E-Book: A Companion to Braunwald's Heart Disease. Elsevier Health Sciences. 2022.

[3]. Mantha A, Lee RO, Wolfson AM. Patient selection for heart transplant: balancing risk. Curr Opin Organ Transplant. 2022;27(1):36-44.

[4]. Yuzefpolskaya M, Schroeder SE, Houston BA, Robinson MR, Gosev I, Reyentovich A, D'Alessandro DA. The Society of Thoracic Surgeons Intermacs 2022 Annual Report: Focus on 2018 Heart Transplant Allocation System. Ann Thorac Surg. 2022.

[5]. Stevens MC, Stephens A, AlOmari AHH, Moscato F. Physiological control. In: Mechanical Circulatory and Respiratory Support. Academic Press; 2018. p. 627-657.

[6]. Consolo F, Pappalardo F. Real-time analysis of the log files of the heartware continuous-flow left ventricular assist device for the early diagnosis of pump thrombosis: a step forward toward clinical translation. J Cardiovasc Transl Res. 2022;15(2):408-415.

[7]. Tchantchaleishvili V, Luc JG, Cohan CM, Phan K, Hübbert L, Day SW, Massey HT. Clinical implications of physiologic flow adjustment in continuous-flow left ventricular assist devices. ASAIO J. 2017;63(3):241-250.

[8]. Fontana R, Tortora G, Silvestri M, Vatteroni M, Dario P, Trivella MG. A portable system for autoregulation and wireless control of sensorized left ventricular assist devices. Bio Biomed Eng. 2016;36(2):366-374.

[9]. Verbeni A, Fontana R, Silvestri M, Tortora G, Vatteroni M, Trivella MG, Dario P. An innovative adaptive control strategy for sensorized left ventricular assist devices. IEEE Trans Biomed Circuits Syst. 2014;8(5):660-668.

[10]. Poongodi T, Krishnamurthi R, Indrakumari R, Suresh P, Balusamy B. Wearable devices and IoT. In: A handbook of Internet of Things in biomedical and cyber physical system. Springer; 2020. p. 245-273.

[11]. Farahani B, Firouzi F, Chakrabarty K. Healthcare IoT. In: Intelligent Internet of Things. Springer; 2020. p. 515-545.

[12]. Pradhan B, Bhattacharyya S, Pal K. IoT-based Applications in Healthcare Devices. J Healthc Eng. 2021.

[13]. Hankel M, Rexroth B. The Reference Architectural Model Industrie 4.0 (RAMI 4.0). ZVEI. 2015;2(2):4-9.

[14]. Barboza M, de Sousa Sobrinho JR, Dias J, dos Santos Filho DJ. Supervisory and Intelligent Systems. In: Bioengineering and Biomaterials in Ventricular Assist Devices. CRC Press; 2021. p. 111-132.

[15]. Barboza M, Junqueira F, Bock E, Leão T, Dias J. Ventricular Assist Device in Health 4.0 Context. In: Doctoral Conference on Computing, Electrical and Industrial Systems. Springer; 2020. p. 347–354.

[16]. Kadhim KT, Alsahlany AM, Wadi SM, Kadhum HT. An Overview of Patient's Health Status Monitoring System Based on the Internet of Things (IoT). Wireless Personal Communications. 2020;114(3):2235–2262.

[17]. Leao TF, Utiyama B, Fonseca J, Bock EGP, Andrade A. In Vitro Evaluation of Multi-Objective Physiological Control of the Centrifugal Blood Pump. Artif Organs. 2020;44(8):785–796.

[18]. Fonseca J, Andrade A, Nicolosi DE, Biscegli JF, Leme J, Legendre D. Cardiovascular Simulator Improvement: Pressure versus Volume Loop Assessment. Artif Organs. 2011;35(5):454–458.

[19]. Samonas S, Coss D. The CIA Strikes Back: Redefining Confidentiality, Integrity, and Availability in Security. J Inf Syst Secur. 2014;10(3).

[20]. Ristevski B, Chen M. Big Data Analytics in Medicine and Healthcare. J Integr Bioinform. 2018;15(3).

[21]. Santos BJ, Leao TF, Bock EGP. Intelligent Control based on Fuzzy Logic Embedded in FPGA Applied in Ventricular Assist Devices (VADs). In: Proceedings of the 2019 4th International Conference on Robotics, Control and Automation. 2019. p. 138–143.

[22]. Oryema B, Kim HS, Li W, Park JT. Design and Implementation of an Interoperable Messaging System for IoT Healthcare Services. In: 2017 14th IEEE Annual Consumer Communications & Networking Conference (CCNC). IEEE; 2017. p. 45–52.

[23]. Islam SR, Kwak D, Kabir MH, Hossain M, Kwak KS. The Internet of Things for Healthcare: A Comprehensive Survey. IEEE Access. 2015;3:678–708.

[24]. Knight SR, Ng N, Tsanas A, McLean K, Pagliari C, Harrison EM. Mobile Devices and Wearable Technology for Measuring Patient Outcomes After Surgery: A Systematic Review. NPJ Digital Medicine. 2021;4(1):1–14.

[25]. Papa M, Mital M, Pisano P, Del Giudice M. E–Health and Wellbeing Monitoring Using Smart Healthcare Devices: An Empirical Investigation. Technol Forecast Soc Change. 2020;153:119226.

[26]. Azodo I, Williams R, Sheikh A, Cresswell K. Opportunities and Challenges Surrounding the Use of Data from Wearable Sensor Devices in Healthcare: Qualitative Interview Study. J Med Internet Res. 2020;22(10):e19542.

[27]. Leopold JA, Davis RB, Antman EM. Data from Digital Health Devices Informs Ideal Cardiovascular Health. J Personalized Med. 2021;11(3):189.

[28]. Velásquez N, Estévez EC, Pesado PM. Cloud Computing, Big Data and the Industry 4.0 Reference Architectures. J Comput Sci Technol. 2018;18.

[29]. Satpathy S, Mohan P, Das S, Debbarma S. A New Healthcare Diagnosis System Using an IoT–Based Fuzzy Classifier with FPGA. J Supercomput. 2020;76(8):5849–5861.

[30]. Kumar PM, Gandhi UD. A Novel Three–Tier Internet of Things Architecture with Machine Learning Algorithm for Early Detection of Heart Diseases. Comput Electr Eng. 2018;65:222–235.

[31]. Taher NC, Mallat I, Agoulmine N, El–Mawass N. An IoT–Cloud Based Solution for Real–Time and Batch Processing of Big Data: Application in Healthcare. In: 2019 3rd International Conference on Bioengineering for Smart Technologies (BioSMART). IEEE; April 2019. p. 1–8.

[32]. Mavrogiorgou A, Kiourtis K, Perakis S, Pitsios S, Kyriazis D. IoT in Healthcare: Achieving Interoperability of High–Quality Data Acquired by IoT Medical Devices. Sensors. 2019;19(9):1978.

[33]. Badotra S, Nagpal D, Panda SN, Tanwar S, Bajaj S. IoT–Enabled Healthcare Network with SDN. In: 2020 8th International Conference on Reliability, Infocom Technologies and Optimization (Trends and Future Directions)(ICRITO). IEEE; June 2020. p. 38–42.

[34]. Li J, Cai J, Khan F, Rehman AU, Balasubramaniam V, Sun J, Venu P. A Secured Framework for SDN–Based Edge Computing in IoT–Enabled Healthcare System. IEEE Access. 2020;8:135479–135490.

[35]. Butt SA, Diaz–Martinez JL, Jamal T, Ali A, De–La–Hoz–Franco E, Shoaib M. IoT Smart Health Security Threats. In: Proceedings of the 19th International Conference on Computational Science and Its Applications (ICCSA). July 2019. p. 26–31.

[36]. Tang W, Ren J, Deng K, Zhang Y. Secure Data Aggregation of Lightweight E–Healthcare IoT Devices with Fair Incentives. IEEE Internet of Things J. 2019;6(5):8714–8726.

[37]. Alladi T, Chamola V. HARCI: A Two–Way Authentication Protocol for Three Entity Healthcare IoT Networks. IEEE J Sel Areas Commun. 2020;39(2):361–369.

[38]. Miller B, Sears ME, Morgan LL, Davis DL, Hardell L, Oremus M, Soskolne CL. Risks to Health and Well–Being from Radio–Frequency Radiation Emit–

ted by Cell Phones and Other Wireless Devices. Front Public Health. 2019;7:223.

[39]. Longras, Oliveira H, Paiva S. Security Vulnerabilities on Implantable Medical Devices. In: Proceedings of the 15th Iberian Conference on Information Systems and Technologies (CISTI). June 2020. p. 1–4.

[40]. Graham. Fear of the Unknown with Healthcare IoT Devices: An Exploratory Study. Inf Secur J Global Persp. 2021;30(2):100–110.

[41]. Petrou A, Monn M, Meboldt M, Schmid Daners M. A novel multi–objective physiological control system for rotary left ventricular assist devices. Ann Biomed Eng. 2017;45:2899–2910.

[42]. Al–Ani MA, Bai C, Hashky A, Parker AM, Vilaro JR, Aranda Jr JM, Mardini MT. Artificial intelligence guidance of advanced heart failure therapies: A systematic scoping review. Front Cardiovasc Med. 2023;10:1127716.

[43]. Fetanat M, Stevens M, Hayward C, Lovell NH. A sensorless control system for an implantable heart pump using a real–time deep convolutional neural network. IEEE Trans Biomed Eng. 2021;68(10):3029–3038.

[44]. Magkoutas K, Arm P, Meboldt M, Schmid Daners M. Physiologic data–driven iterative learning control for left ventricular assist devices. Front Cardiovasc Med. 2022;9:922387.

[45]. Li T, Cui W, Xie N, Li H, Liu H, Li X, Wang Y. Intelligent and strong robust CVS–LVAD control based on soft–actor–critic algorithm. Artif Intell Med. 2022;128:102308.