Design of an Integrated Biomonitoring System for IVA/EVA Suits Using the Patient Assessment System (PAS)

Roberto C. Raimundi Rivera
Master of Science in Biomedical Engineering
Advisor: Rafael Nieves Castro, PharmD.
Polytechnic University of Puerto Rico
Graduate Project EXPO, May 2026

***Abstract*— *Advancing human spaceflight toward exploration-class missions requires autonomous health monitoring systems that operate without real-time support from Earth. This article presents the design and validation of an integrated hardware platform for biomonitoring in IVA/EVA suits. The system is based on the Patient Assessment System framework and integrates sensors for heart rate, oxygen saturation, respiratory rate, and temperature. A centralized embedded microcontroller performs local acquisition, signal processing, storage, and alert generation. Experimental and simulation results demonstrate acceptable accuracy, real-time response, and improved signal quality after motion compensation. The proposed design supports autonomous physiological assessment in constrained environments and provides a scalable foundation for future wearable biomedical systems for space and remote operations.*

Keywords *— Biomonitoring, Embedded Systems, EVA Suits, Wearable Systems.*

INTRODUCTION

Human space exploration is advancing beyond Earth orbit toward longer, more distant missions. As mission distances increase, astronauts cannot rely on immediate medical guidance from Earth. Communication delays can create a decision-making gap during medical emergencies, especially during extravehicular activities (EVAs), when the astronaut is enclosed in a spacesuit and under operational stress. For this reason, future IVA/EVA systems must include autonomous tools that monitor physiological status and enable rapid decision-making.

Traditional space biomonitoring has primarily focused on recording and transmitting data for later review. This approach is useful for research and tracking crew health trends, but it does not fully meet the requirements for real-time interpretation during emergencies. An integrated biomonitoring system must incorporate sensors, local processing, storage, communication, and feedback on a single wearable platform. In this project, the design aligns with this approach by placing the integrated processing unit at the core of the system, rather than relying on a smartwatch or external device.

The clinical concept guiding the decision logic is the Patient Assessment System (PAS). In emergency medicine and remote settings, the PAS facilitates rapid assessment based on general appearance, work of breathing, and circulation. Remote area medicine resources emphasize structured patient assessment to organize care in the field when resources and support are limited [1] [2] [3]. This project adapts this structured approach to a biomedical engineering design problem, translating selected physiological indicators into an integrated logic of thresholds and trends.

The project aims to design an integrated hardware system for biomonitoring in IVA/EVA suits. The system monitors heart rate, oxygen saturation, respiratory rate, and temperature while accounting for motion artifacts and power limitations. The work is based on the design documentation of a previous project [4] and focuses on creating an autonomous platform capable of operating under simulated conditions.

RELATED WORK

Current space biomonitoring systems demonstrate that wearable physiological monitoring is feasible in spaceflight environments. The Canadian Space Agency and NASA have evaluated systems such as Astroskin and other wearable

biosensor monitors for continuous health monitoring and crew readiness. NASA documentation describes the need for compact, interoperable biomedical sensors capable of measuring, storing, and transmitting physiological parameters during operational activities [5].

The same work also identifies data quality, usability, wireless communication, and the development of decision support systems as important areas for future exploration missions [5]. While existing systems provide valuable data, many are primarily designed for research or analysis on Earth. In a high-risk extravehicular activity (EVA), deferred analysis is insufficient. The system must identify relevant changes locally, generate alerts, and preserve data in case of communication interruption. This requirement justifies using an embedded microcontroller as the processing hub rather than a consumer device. Photoplethysmography is a common method for measuring heart rate and oxygen saturation using wearable devices. A Photoplethysmography (PPG) sensor optically measures changes in blood volume, typically using red and infrared light. Technical descriptions of optical cardiovascular monitoring emphasize the importance of Light-Emitting Diode (LED) selection, detector geometry, and signal quality for obtaining reliable readings in wearable devices [6]. Recent research on PPG sensors also demonstrates that sampling conditions, LED duty cycle, and signal processing affect accuracy and power consumption [7]. These factors are important in extravehicular activity (EVA) applications, where movement and battery life limitations are anticipated.

Respiratory monitoring can be performed using impedance pneumography, which estimates respiration from changes in thoracic impedance during lung inflation and deflation. A key advantage of this method is that electrodes can be integrated into a garment, reducing the need for external probes. Temperature monitoring is also important, as EVA suits use thermal control garments, such as liquid-cooling and ventilation garments, and sensor placement must avoid interfering with cooling tubes [8]. The literature on body-suit interaction also supports the need for monitoring beyond basic vital signs. Research on wearable sensor suits has examined pressure, movement, humidity, and temperature to quantify interactions between the body and the suit [9]. Musculoskeletal injury studies show that both suit components and operational activities can contribute to injury risk during spaceflight and extravehicular operations (EVA) [10]. Anderson's work on human-suit interaction further supports the need to assess fit, movement, and physical load in integrated suit designs [11]. Pressure perception research also provides context for why localized contact pressure is important in wearable systems [12].

SYSTEM DESIGN

System Design describes the engineering methodology for transforming physiological monitoring objectives into a wearable hardware system. It details the design specifications, sensor layer, processing approach, and validation techniques that underpinned the development of a self-sufficient biomonitoring platform for simulated IVA/EVA environments.

Design Requirements

The design requirements were based on the physiological parameters needed for basic health assessment and the physical constraints of integrating the IVA/EVA suit. The system must monitor heart rate, oxygen saturation, respiratory rate, and temperature while maintaining comfort, low weight, and stability during movement. NASA's standards for human systems and human-system integration guidance support the need to consider human factors, operational limitations, and safety requirements when designing wearable systems for crew [13].

Table 1 highlights the main monitoring requirements guiding the design process. These criteria are not a replacement for clinical validation but provide objective benchmarks for evaluating the prototype's engineering aspects.

Table 1

Physiological Monitoring Requirements

Parameter	Target Range	Sensor Method	Target Accuracy
Heart Rate	50-100 bpm	PPG optical module	+/-2 bpm
SpO2	93-100%	Dual-wavelength PPG	+/-2%
Respiration	9-20 breaths/min	Thoracic impedance	+/-1 breath/min
Temperature	36.1-37.9 C	IR non-contact sensor	+/-0.1 C

Architecture and Sensor Layer

The proposed architecture consists of a body area network composed of distributed sensors connected to an integrated microcontroller unit (MCU). The MCU collects and synchronizes sensor data, performs local processing, stores relevant records, and manages user feedback. This architecture reduces reliance on external communication and enables Earth-independent medical operations. The design also aligns with NASA's technology maturity level, which requires initial prototypes to progress from laboratory validation to testing in relevant environments [14], [15].

The sensor input layer includes a MAX30102 optical module for heart rate and oxygen saturation, an MLX90614 infrared sensor for temperature, an impedance pneumography system for respiration, and an inertial measurement unit (IMU) for motion detection. The IMU is not used as a vital signs sensor; its purpose is to provide motion information to identify or compensate for unreliable segments. Figure 1 summarizes the system architecture.

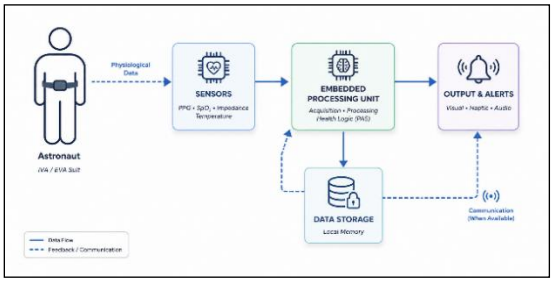

Figure 1

Embedded Biomonitoring Architecture for IVA/EVA Suit Integration

The hardware layout must be compatible with garment integration. The sensor's position affects both signal quality and user comfort. Optical detection requires stable contact with the skin or a uniformly reflective measurement area. Infrared sensors require a clear field of view of the skin, avoiding thermal interference from cooling lines. Textile electrodes for impedance pneumography must maintain uniform contact without adhesive gels. Figure 2 illustrates the general concept for sensor placement.

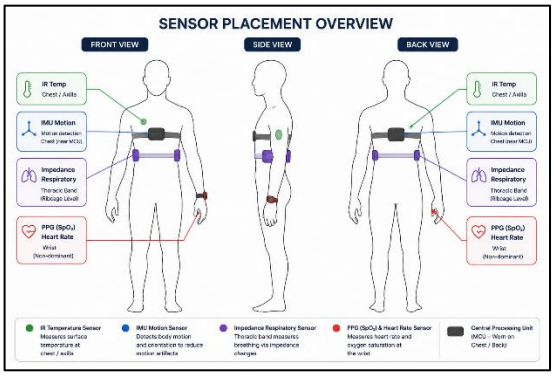

Figure 2

Sensor Placement Concept for the Wearable Biomonitoring Platform

Table 2

Sensor and Hardware Components

Component	Model/Type	Primary Function
PPG sensor	MAX30102	Heart rate and SpO2
Temperature sensor	MLX90614	Non-contact temperature
Respiratory sensor	Impedance system	Respiratory rate
Motion sensor	3-axis IMU	Motion context
Processing unit	ESP32/Cortex-M	Control and processing
Storage	microSD	Local data logging
Communication	BLE	External visualization

Signal Processing and Health Logic

The processing stage converts the raw sensor output signals into usable physiological parameters. Digital sensors, such as PPG and infrared temperature modules, provide directly sampled data, while the impedance-based breathing channel requires analog conditioning. The breathing signal is filtered to reduce baseline drift and high-frequency noise and then amplified before digital processing. These steps help maintain stable measurements under typical usage conditions.

Reducing motion artifacts is a major design concern, as extravehicular activities (EVA) involve arm movements, suit contact, and repetitive body movements. PPG signals are particularly sensitive to

sensor displacement. Therefore, the system uses IMU data to identify motion conditions and improve signal reliability. The IMU-supported approach does not eliminate all noise, but it reduces the likelihood of false alarms by identifying segments that require further correction or validation.

The integrated health logic compares measured parameters to predefined ranges and also assesses short-term trends. A low oxygen saturation value may indicate hypoxia; an elevated temperature may indicate heat stress; and a high heart rate during low physical activity may suggest cardiovascular strain. This logic is inspired by the PAS framework and is designed as a decision-support system rather than a complete replacement for the diagnostic system. Alerts are communicated via a color-coded interface, with green, yellow, and red statuses, and with haptic feedback in critical conditions.

Validation Methodology

The system was evaluated through controlled tests and in a software simulation environment. Controlled tests compared sensor outputs with reference values at rest, during movement, and under simulated abnormal conditions. The goal was to confirm that the prototype could capture each selected physiological parameter within the target accuracy range defined during the design phase.

As part of the project, a software simulation was developed to evaluate the behavior of continuous monitoring before proceeding to more realistic physical tests. The simulation generated real-time values for heart rate, oxygen saturation, respiratory rate, temperature, battery level, and stress index. It was used to verify data flow, user interface behavior, alert generation, and system response under dynamic conditions. This step was useful because it allowed testing anomalous scenarios, such as low oxygen saturation or elevated temperature, without putting the user at risk.

A second validation approach involved motion artifact analysis. Signal quality was compared across static, walking, and arm-swing conditions, both before and after IMU-based compensation. This test assessed whether the motion context improved measurement stability during simulated operational activity.

Results

In summary, the main results of the experimental and simulation validation. The findings are categorized by sensor accuracy, motion artifact behavior, and system response to assess if the prototype achieved the design goals for real-time biomonitoring.

Sensor Accuracy

The prototype demonstrated acceptable accuracy across all monitored parameters. Heart rate showed only minor deviations from baseline, with the largest error occurring after exercise. Oxygen saturation remained within the expected range and accurately reflected reductions associated with mild hypoxia and simulated low perfusion. Temperature and respiratory rate measurements were stable and showed minimal error. Table 3 summarizes the measured performance.

Table 3

Experimental Performance Summary

Parameter	Reference Condition	Measured Error	Result
Heart Rate	Rest to post-exercise	+1 to +3 bpm	Acceptable
SpO2	Normal to low perfusion	-1 to -2%	Acceptable
Temperature	Baseline /elevated	+0.1 C	Acceptable
Respiration	Rest/stress	+1 breath/min	Acceptable

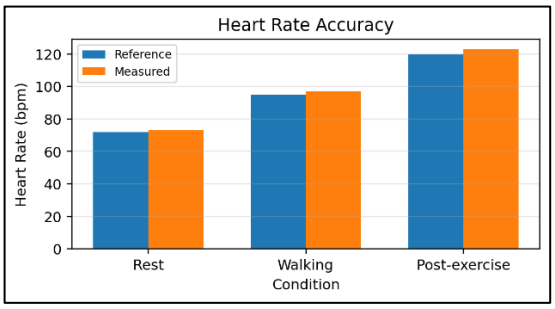

Figure 3

Heart Rate Comparison Between Reference and Measured Values

Figure 3 compares reference and measured heart rates across rest, walking, and post-exercise

conditions. The measured trend closely aligns with the reference data, supporting the use of optical sensing for real-time heart rate monitoring.

Figure 4 compares oxygen saturation across normal, mild hypoxia, and low-perfusion conditions. The measured values were slightly lower than the reference values but remained within the target range for this prototype. The ability to detect a reduction in oxygen saturation is important because hypoxia is one of the most critical risks in a pressurized suit.

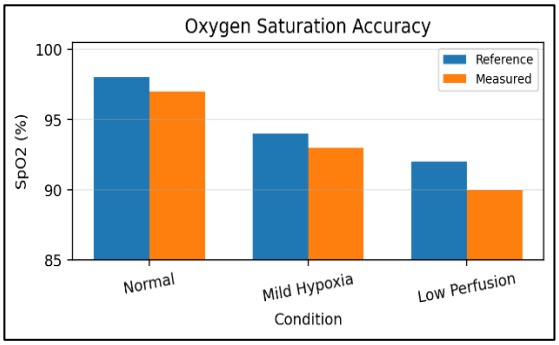

Figure 4
Oxygen Saturation Comparison Between Reference and Measured Values

Motion Artifact Reduction

Motion artifacts were introduced to evaluate the system's behavior under dynamic conditions. The results show that signal degradation increased during walking and arm movement. After applying motion compensation using IMU data, signal quality improved by approximately 40 percent in the highest-motion condition. Figure 5 compares raw and compensated signal quality.

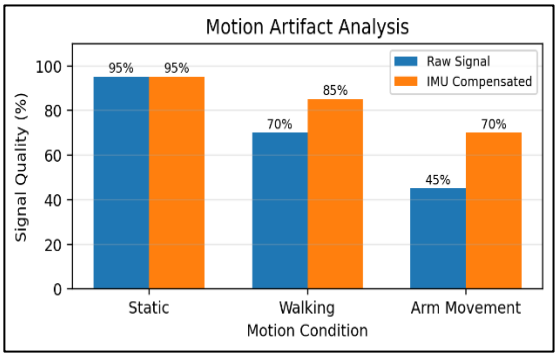

Figure 5
Motion Artifact Analysis Comparing Raw and IMU-Compensated Signals

Simulation and System Response

The simulation interface confirmed that the system could process continuous physiological data and update the user display in real time. Simulated abnormal conditions included reduced oxygen saturation, elevated temperature, and gradual physiological drift. In each case, the system generated the expected warning or critical alert based on its threshold logic. Figure 6 shows the Real-Time simulation interface developed for this project, which supports the system's response and visualization results.

These results align with previous findings that wearable biosensor systems are feasible for long-duration monitoring but require attention to data quality, user comfort, and wireless communication reliability [5]. They also support the need for sensor fusion and motion-aware processing in wearable systems operating in dynamic conditions [7] [9].

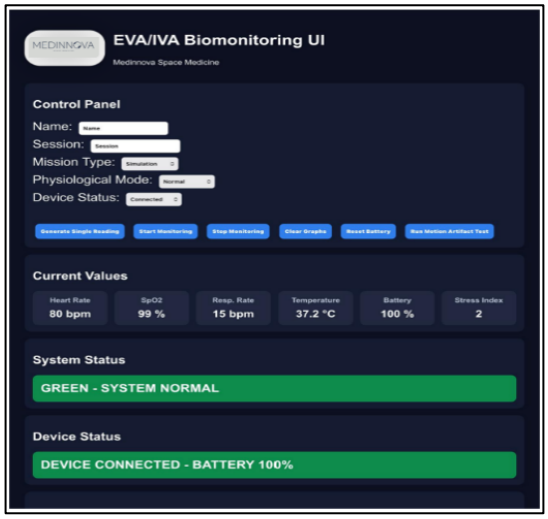

Figure 6
Simulation Interface Showing Real-Time Physiological Monitoring and Alert Status

The simulation interface was built as a Google Apps Script web application. This enabled real-time visualization of physiological parameters and alert conditions during simulated testing.

The code in Figure 7 illustrates the software logic for generating simulated physiological data and evaluating alert conditions against predefined thresholds.

Figure 7

Google Apps Script Code Segment Used for Real-Time Physiological Simulation and Alert Generation

DISCUSSION

The results support the feasibility of an integrated biomonitoring platform for IVA/EVA applications. The selected sensors measured the required physiological parameters with acceptable accuracy under simulated conditions. Because this is a prototype design project, the results should be viewed as proof-of-concept validation rather than final clinical validation. The central MCU architecture provided a clear advantage by enabling local data processing and maintaining system functionality even when external visualization devices were unavailable.

Motion artifacts remain the primary technical limitation. This is expected because wearable optical and impedance sensors are sensitive to displacement and contact variability. However, the IMU-based compensation strategy improved signal quality and offered a practical path for future development. Additional filtering, adaptive thresholds, and multi-sensor validation could further reduce false alerts.

The health logic in the prototype is intentionally simple. It doesn't replace medical diagnosis but shows how physiological data can be converted into practical operational feedback. This distinction is crucial because the project's aim is to promote early awareness, not to replace physicians or flight surgeons. In an EVA environment, alerts need to be straightforward, quick, and easy to interpret under workload. Color-coded feedback and haptic alerts help lower cognitive load and provide instant awareness of the system's status.

From a design perspective, the project integrates biomedical engineering, embedded systems, and human factors. Space suit integration requires more than precise sensors; it also demands adaptable hardware, reliable signal pathways, power management, and compatibility with garment layers. Future enhancements should include analog-suit testing, thermal-vacuum testing, extended battery assessments, and broader human-subject validation. These steps are essential to advance the system toward readiness for the target environment, consistent with TRL-based development planning [14] [15].

IMPLEMENTATION CONSIDERATIONS

Several practical considerations shaped the final design. The first was maintaining a clear separation between core processing and user visualization. A smartwatch or external display may present information, but the MCU must remain responsible for acquisition, processing, storage, and alert logic. This improves reliability because the system can continue operating even if the external display is unavailable.

The second consideration was garment compatibility. IVA/EVA monitoring hardware must conform to movement, avoid pressure points, and remain stable during repeated suit motion. To this end, the design emphasizes flexible substrates, textile electrodes, simple alert states, and simulation-based verification before more realistic analog testing [9] [11].

LIMITATIONS AND FUTURE WORK

Although the prototype met the project objectives under simulated conditions, additional validation is still required. The system has not yet been tested in an actual EVA suit or in a thermal-vacuum chamber, and the current health logic is threshold-based rather than patient-specific. Longer

endurance testing is also needed to confirm battery performance.

Future work should integrate the sensor modules into a real garment layer and evaluate durability, comfort, and signal stability across repeated movement cycles. Following TRL development practices, the system should progress from laboratory-prototype validation to relevant environmental testing before operational consideration [14] [15].

CONCLUSION

This article presents the design and validation of an integrated hardware platform for biomonitoring in IVA/EVA suits. The proposed system integrates PPG, infrared temperature sensing, impedance pneumography, IMU-based motion detection, local storage, wireless communication, and embedded health logic into a single wearable architecture.

Experimental and simulation results demonstrated acceptable accuracy for heart rate, oxygen saturation, respiration, and temperature. Motion artifact analysis showed that IMU-based compensation improved signal stability by about 40 percent under dynamic conditions. The simulation environment further confirmed that the system can process continuous data streams and generate alerts in response to abnormal physiological scenarios.

Overall, the proposed design offers a functional and scalable approach to autonomous physiological monitoring. Although additional validation is needed before operational use, the project represents a practical step toward Earth-independent medical support for future space exploration and other remote environments.

USE OF AI

As stated in the "Graduate School Guidelines for the Ethical and Responsible Use of Artificial Intelligence," the following disclosure statement is included:

"This work used an AI tool (Chat GPT) for: brainstorming, research ideas or outlines, grammar, structure, or stylistic editing, and drafting tables, visualizations, or code templates. All interpretations, arguments, and conclusions are the author's own and have been verified for accuracy".

REFERENCES

[1] NOLS. (2026). *9 Wilderness Medicine Acronyms You Need to Know* [Online]. Available: https://www.nols.edu/blog/9-wilderness-medicine-acronyms-you-need-to-know/.

[2] NOLS. *Case Study 34* [Online]. Available: https://www.nols.edu/case-studies/case-study-34/.

[3] NOLS. (2026). *Wilderness First Aid - Patient Assessment System Demonstration (YouTube)* [Online]. Available: https://www.youtube.com/watch?v=N67g_M6LDHw.

[4] M. Soto, Development of an Integrated Biomonitoring System for IVA/EVA Suit Based on Pat, International Institute for Astronautics Science, 2025.

[5] W. Toscano et al., "Wearable Biosensor Monitor to Support Autonomous Crew Health and Readiness to Perform," in NASA Technical Reports Server, ARC-E-DAA-TN38722, 2019. [Online]. Available: https://ntrs.nasa.gov/citations/20190001996.

[6] Clinical Leader. (2026). *Wearables for optical cardiovascular monitoring: Designing the PPG sensor in the ActiGraph LEAP* [Online]. Available: https://www.clinicalleader.com/doc/wearables-for-optical-cardiovascular-monitoring-designing-the-ppg-sensor-in-the-actigraph-leap-0001.

[7] F. A. Jhuma et al., "A hybrid photoplethysmography (PPG) sensor system design for heart rate monitoring," in *Sensors*, vol. 24, no. 23, Art. no. 7634, Nov. 2024, DOI: 10.3390/s24237634.

[8] NASA, "Liquid Cooling and Ventilation Garment (LCVG)," in *NASA Human Integration Design Handbook (HIDH)*, NASA, 2010.

[9] Y. Y. Shen, A. Boppana, K. Arquilla, and A. P. Anderson, "Wearable sensor suit system for quantifying human-spacesuit interactions," in *Proc. IEEE Aerospace Conf.*, Big Sky, MT, USA, 2018. DOI: 10.1109/AERO.2018.8396681

[10] R. A. Scheuring, C. H. Mathers, J. A. Jones, and M. L. Wear, "Musculoskeletal injuries and minor trauma in space: Incidence and injury mechanisms in U.S. astronauts," in *Aviat. Space Environ. Med.*, vol. 80, no. 2, pp. 117-124, Feb. 2009, doi: 10.3357/ASEM.2270.2009.

[11] A. P. Anderson, *Understanding human-space suit interaction to prevent injury during extravehicular activity*, Ph.D. dissertation, Massachusetts Institute of Technology, Cambridge, MA, USA, 2014.

[12] E. S. Dellon, K. Keller, V. Moratz, and A. L. Dellon, “The relationship between skin hardness, pressure perception, and two-point discrimination in the fingertip,” in *J. Hand Surg.*, vol. 20, no. 1, pp. 44-48, Feb. 1995. DOI: 10.1016/s0266-7681(05)80015-4.

[13] NASA, *NASA-STD-3000: Man-Systems Integration Standards*, NASA Johnson Space Center, Houston, TX, USA, 1995. https://ntrs.nasa.gov/citations/19960021764

[14] NASA, *NASA Systems Engineering Handbook*, NASA/SP-2016-6105 Rev2, Washington, DC, USA: NASA, 2016.

[15] NASA. (2023, Jan. 11). *Technology Readiness Assessments Using NASA’s Best Practices Guide* [Online]. Available: https://science.nasa.gov/wp-content/uploads/2023/11/tra-tech-showcase-2023-beauchamp-copy.pdf.