International Journal of Reconfigurable and Embedded Systems (IJRES)
Vol. 14, No. 3, November 2025, pp. 855~876
ISSN: 2089-4864, DOI: 10.11591/ijres.v14.i3.pp855-876

Reconfigurable embedded systems for remote health monitoring: a comprehensive review

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Article Info

Article history:

Received Jun 3, 2025
Revised Oct 11, 2025
Accepted Oct 25, 2025

Keywords:

Data integrity
Field programmable gate array
Low-power design
Real-time responsiveness
Reconfigurable embedded systems
Remote health monitoring
Telemedicine

ABSTRACT

The rapid expansion of telemedicine and wearable health devices has intensified the demand for energy-efficient and adaptable embedded systems capable of supporting real-time, reliable remote health monitoring. This review provides a comprehensive survey of reconfigurable embedded platforms—focusing on field-programmable gate arrays (FPGAs), coarse-grained reconfigurable arrays (CGRAs), and heterogeneous system-on-chips (SoCs)—deployed for monitoring critical physiological parameters such as electrocardiogram (ECG), oxygen saturation (SpO_2), and body temperature. We analyze co-design methodologies that integrate artificial intelligence (AI-driven) neural accelerators, quantization strategies, and runtime adaptability to address the competing requirements of low power consumption, data integrity, and latency minimization in diverse telemedicine contexts. The paper highlights the strengths and limitations of conventional versus reconfigurable approaches, reviews case studies in wearable and implantable health devices, and underscores key design trade-offs in performance, scalability, and security. By systematically mapping current innovations and identifying unresolved challenges—including standardization, clinical validation, and secure edge integration—this review positions reconfigurable architectures as a cornerstone for next-generation, patient-centric remote health monitoring. Future directions emphasize AI-enabled adaptability, sustainable and carbon-aware device design, and personalized healthcare through adaptive embedded systems, charting a pathway toward scalable and resilient telemedicine ecosystems.

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1. INTRODUCTION

Telemedicine's swift advancement has ushered in a truly transformative era for healthcare provision, most notably via wearable tech enabling remote health oversight. With the increasing clamour for healthcare solutions that are both effective and efficient, reconfigurable embedded systems are proving to be absolutely critical. Their adaptability and energy efficiency are key, significantly boosting the lifespan of health monitoring devices. These integrated systems enable the continuous and effortless monitoring of essential physiological indicators–think electrocardiogram (ECG), oxygen saturation (SpO_2), and body temperature–guaranteeing precise, real-time data transfer. This review strives to offer a thorough analysis of the present state of play regarding embedded platforms in wearable health devices, showcasing their contributions to both data integrity and responsiveness within telemedicine. By examining existing approaches and charting potential future pathways, this work aims to further knowledge and practices that could serve as the bedrock for the next generation of remote health monitoring solutions, as emphasised by [1], [2]. Visual aids such as will, in most cases, further clarify the importance of integrating wireless technologies into this field.

The landscape of healthcare delivery is undergoing a profound transformation driven by technological advancements, particularly in telemedicine and wearable health trackers. These innovations enable continuous health monitoring, easing the burden on hospitals and clinics while enhancing patient management. Modern portable health devices, powered by internet of things (IoT) technologies, track vital physiological parameters such as heart rate (via ECG), SpO_2, and body temperature, delivering real-time updates to both patients and healthcare providers [3]. The growing demand for remote monitoring—especially among individuals with chronic conditions or those in remote areas—has spotlighted the importance of reconfigurable embedded systems, valued for their flexibility and energy efficiency in sustaining long-term telemedicine operations [4]. This shift toward tech-enabled, patient-centric care is mirrored in market trends: the UK digital patient monitoring devices market, for instance, generated USD 10,091.9 million in 2023 and is projected to reach USD 51,134.9 million by 2030, growing at a CAGR of 26.1%. Wearable devices led revenue generation in 2023, while mHealth is expected to be the fastest-growing segment. As illustrated in Figure 1, the UK is poised to lead Europe's digital health market, underscoring the rising significance of telemedicine and wearable technologies in shaping the future of healthcare.

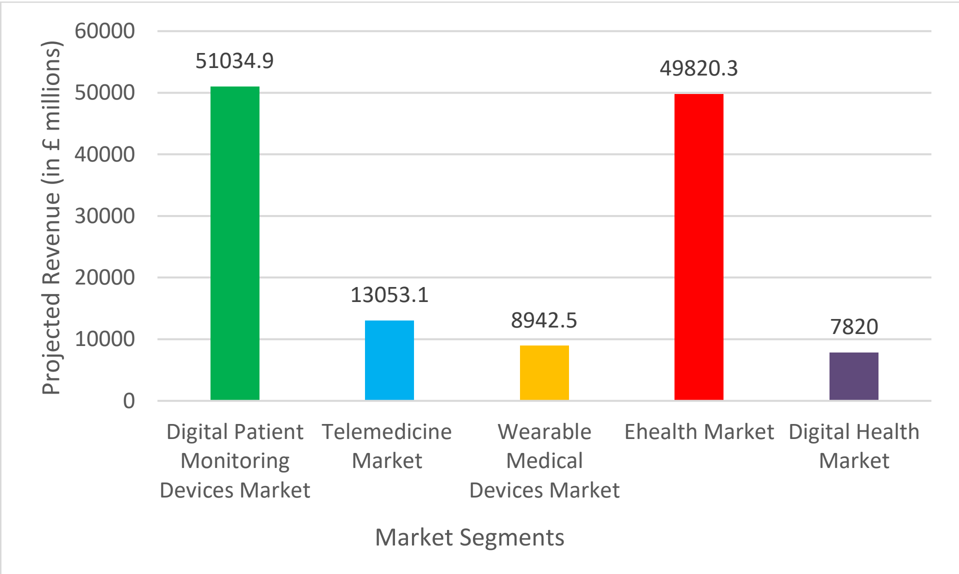

Figure 1. Projected UK market revenues in healthcare technologies by 2030

The way embedded systems have grown really shapes how they're used in healthcare, especially when it comes to keeping an eye on health remotely. Because we're leaning more and more on systems that can change to fit different needs, being reconfigurable is turning out to be a key thing that makes them work better and last longer. Systems that use field-programmable gate arrays (FPGAs) show this off, allowing system parameters and functionalities to be updated dynamically from a distance. This can tweak how well they work as things are happening, boosting how patients are looked after and keeping data safe [5]. What's more, these systems are flexible enough to fit right into important healthcare setups, where keeping things secure and being able to adapt is super important because of the growing risk of cyberattacks [6]. By making sure systems can keep up with new tech and changing health monitoring needs, reconfigurability doesn't just help save energy, it also helps us reach the big goal of having telemedicine that can keep going, which advancement is reflected in the development of modern wearable health devices.

The merging of ECG, SpO_2, and temperature monitoring is rather important for health monitoring at a distance, which helps to keep an eye on patients constantly in different healthcare scenarios. Each of these contributes in its own way to understanding a patient's overall health. It helps to spot serious problems by getting and analysing data as it happens. For example, ECG monitoring setups, making use of adaptable embedded structures, can change how they process signals. This improves how well they can spot irregular heartbeats while using power in the best way possible. Likewise, SpO_2 sensors use fancy optical methods along with low-power FPGA solutions to reduce errors caused by movement, making sure readings are reliable in various situations. Temperature monitors add to these technologies by giving key information about metabolic states, particularly when they are in wearable or implantable forms. Overall, these systems highlight how important adaptability is to meeting the changing needs of telemedicine, which ultimately improves patient results and how well healthcare is delivered [7].

The integration of reconfigurable embedded systems into contemporary healthcare infrastructure represents a significant advancement in remote health monitoring technologies. These systems contribute to enhanced patient care delivery and the long-term sustainability of digital health solutions [7]. This review presents a systematic synthesis of current reconfigurable architectures and their applications in continuous physiological monitoring—specifically, electrocardiography (ECG), SpO_2, and body temperature. Emphasis is placed on critical design attributes such as low-power consumption, data fidelity, and real-time responsiveness, all of which collectively reinforce the robustness and scalability of telemedicine frameworks. A key contribution of this work lies in its forward-looking perspective, highlighting the emerging potential of AI-driven platforms capable of autonomous adaptation to individual patient needs. Such developments signal a paradigm shift toward personalized, intelligent health management. The comprehensive analysis offered herein serves as a foundational reference for future research and innovation in the evolving domain of wearable healthcare technologies.

2. FOUNDATIONS OF REMOTE HEALTH MONITORING

The growing complexity of healthcare needs has spurred the development of remote health monitoring systems, essentially moving us away from traditional face-to-face appointments towards newer telemedicine solutions. This shift underlines the need for devices that use little power, keep data safe, respond quickly, and work well together. Reconfigurable embedded systems have become a key answer to these needs, allowing for adjustments as healthcare itself changes. Using technologies like FPGAs and coarse-grained reconfigurable arrays (CGRAs), these systems boost the performance of monitoring devices. This ensures data is sent efficiently whilst keeping energy use low, which is vital for wearable tech. Also, they tackle the differences often seen between what patients say about their recovery and how well they're actually doing, as pointed out in research [8]. As [9] has shown, using wireless technologies really improves what these monitoring systems can do, highlighting their important role in pushing remote healthcare forward.

2.1. Evolution of wearable and remote health systems

The incorporation of reconfigurable embedded systems in remote health monitoring marks quite a step forward for wearable gadgets and telemedicine. With healthcare increasingly favouring remote solutions, old-fashioned medical practices are giving way to proactive, data-informed methods, which boost patient involvement and improve results. The flexibility of reconfigurable systems, especially in gadgets monitoring ECG, SpO_2, and temperature, means data can be analysed in real-time and adapted to the patient's specific needs, thus promoting energy conservation and ensuring long operational lives. This progress is supported by wireless health systems, which allow for smooth data transfer and improve access to vital sign monitoring. As a result, the coming together of these technologies not only improves the trustworthiness of patient data but also tackles important requirements like low power usage and being able to work with other systems, encouraging a sustainable future for healthcare [10].

2.2. Key requirements for effective health monitoring

The progress of remote health monitoring rests on a few key things that really affect how well it works. First off, they need to use very little power because these gadgets need to keep running without needing to be charged all the time. This makes sure we can reliably collect data for a long time. And alongside that, keeping the data safe and sound is super important. We need strong systems to protect patient info and make sure the readings are spot-on when they're sent over [3]. Plus, they need to respond in real-time, especially when things get urgent–quick analysis can make a big difference for patients. It's also vital that these systems can talk to each other and grow as needed; they should fit in nicely with different healthcare tech and handle more and more users, as recent studies have pointed out [11]. Generally speaking, this comprehensive view ensures remote health monitoring not only does the job now but also gets ready for what's coming, which helps create healthcare solutions that last and work well.

2.2.1. Low-power consumption

In the ever-shifting world of remote health monitoring, how little power something uses is incredibly important. It really affects how practical and useful embedded systems are. These systems need to be efficient so they can last a long time, especially in wearable tech that keeps an eye on things like ECG, SpO_2, and temperature. New ideas in low-power designs, like the low-power wide-area networks (LPWAN) setup someone came up with, help send important health info far away while using as little power as possible. This makes the system last longer and work better [12]. Plus, putting clever machine learning stuff into these systems means they can change how they work to use even less power without losing accuracy, or so the existing literature says [4]. This sort of progress is vital to ensuring that remote health monitoring is accessible and does what it's supposed to, which should improve things for patients and the way healthcare is delivered. Integrating these ideas is therefore key to creating health monitoring solutions that are efficient and sustainable.

2.2.2. Data integrity and security

Within the ever-shifting world of remote health monitoring, guaranteeing both data integrity and robust security stands as necessary, crucial for keeping patient confidence high and ensuring the system works properly. Reconfigurable embedded systems are becoming increasingly central to telemedicine, and as they do, they've got to be effective at protecting sensitive health information, particularly given the vulnerabilities that naturally come with transmitting data wirelessly. Integrating encryption alongside secure reconfiguration techniques creates a valuable protective shield against possible cyber threats, thus boosting how resilient the system is as a whole [13]. Furthermore, decentralised strategies, blockchain for example, could strengthen security protocols and make data management more transparent, dealing with those major worries about data integrity. This multi-faceted emphasis on security is, crucially, vital, particularly as systems interact with a range of interconnected devices, which of course increases the opportunities for attacks (as evidenced by the rising risks illustrated in). In the end, strong security measures are fundamental when it comes to progressing the deployment and broad acceptance of reconfigurable systems in remote health monitoring environments, which paves the way for all sorts of innovative healthcare solutions.

2.2.3. Real-time responsiveness

Reconfigurable embedded systems are getting better all the time, and this has really changed how we can monitor health remotely, especially when it comes to how quickly they can react. These systems use things like the IoT and artificial intelligence (AI) to constantly collect and look at health data. Because of this, doctors can step in straight away if there's an emergency. For example, real-time analytics help us spot unusual things in patient data quickly. This makes diagnoses much more accurate and improves things for patients, compared to what we used to do [14]. What's more, because reconfigurable setups can adapt easily, these systems can change how they work to fit different diagnostic needs. This is really important when things are changing quickly in healthcare. This ability also helps with predicting when equipment needs fixing and deciding how to use resources in healthcare properly [15]. Generally speaking, being able to react quickly not only makes remote monitoring systems work better, but it also shows how important advanced embedded technologies are for the future of telemedicine and looking after patients. Ultimately, responsiveness remains a cornerstone of successful health monitoring solutions.

2.2.4. Interoperability and scalability

To boost system effectiveness, the swift progress of remote health monitoring technologies demands a strong framework for both interoperability and scalability. As healthcare provision depends more and more on interconnected devices, the capacity of reconfigurable embedded systems to integrate smoothly with different healthcare protocols–Health Level Seven International (HL7) and fast healthcare interoperability resources (FHIR), for instance–becomes truly vital. This integration doesn't just enable real-time data exchange between various devices, but also lets healthcare professionals scale solutions efficiently, without risking functionality or data integrity. Furthermore, the adaptability these reconfigurable architectures offer means systems can evolve alongside emerging technologies, like 5G and the internet of medical things (IoMT); these could significantly enhance existing healthcare infrastructures. Implementing low-power designs boosts these systems' longevity and operational effectiveness, paving the way for sustained, flexible healthcare advancements [16], [17]. So, the importance of interoperability and scalability cannot be overstated when we're trying to fully realise the potential of reconfigurable embedded systems in remote health monitoring.

2.3. Conventional embedded systems vs. reconfigurable systems

The evolution of health monitoring has underscored a significant shift from conventional embedded systems toward more flexible and reconfigurable architectures, particularly in remote applications. Although traditional embedded systems are known for their reliability, their rigid structure often limits adaptability and efficient resource management. This can be a problem when healthcare environments are constantly changing. Reconfigurable systems, on the other hand, offer a real boost because they can be adjusted in real-time. This means they can optimise how well they work and how much energy they use, which is super important for devices that monitor things like ECG and SpO_2. Things like LPWAN are being combined with these adaptable designs, which allow for smooth data collection and transmission–vital for good health management [2]. Plus, we're seeing the development of sophisticated image and video processing methods that help these systems interact with what is going on around them. This, in turn, improves how they make decisions when monitoring health [18]. So, all in all, moving towards reconfigurable embedded systems is a big step forward in telemedicine, making sure it's sustainable and improves the care patients receive.

3. RECONFIGURABLE EMBEDDED ARCHITECTURES

A key consideration affecting how reconfigurable embedded architectures evolve in remote health monitoring is how well they adapt to differing healthcare needs without sacrificing energy efficiency. These architectures utilise technologies such as FPGAs and CGRAs, offering the fine-grained adaptability that is vital for applications like ECG and SpO_2 monitoring. Heterogeneous system-on-chip (SoC) designs, which combine microcontrollers (MCUs) with AI accelerators, further boost the ability of these systems to carry out complex processing in real-time, as discussed in [19], [20]. For instance, the design of these systems is geared towards ensuring data integrity is preserved through effective signal filtering and artifact removal, which is crucial for accurate health assessments. Generally speaking, reconfigurable architectures not only optimise performance but also extend the life and usability of health monitoring devices, reinforcing their significance in the evolving world of telemedicine and remote patient care. Among the visual aids utilised, it effectively demonstrates the application of wireless health systems, highlighting the integration of such reconfigurable technologies in practical health monitoring scenarios.

3.1. Overview of reconfigurable hardware in healthcare

The progression of healthcare tech has signalled quite a shift in remote health monitoring, largely down to advances in reconfigurable hardware. These systems, particularly FPGAs and CGRAs, provide great flexibility and efficiency, tailored for particular medical uses, such as ECG and SpO_2 monitoring. The ability to dynamically reconfigure hardware allows real-time adjustments to processing algorithms; this greatly improves data integrity and also reduces energy use, vital for wearable health devices used in different settings. Moreover, integrating these systems with new platforms makes it easier to interoperate with current medical setups, crucial for thorough patient monitoring and care. So, reconfigurable hardware is a cornerstone in the continued quest for responsive and sustainable healthcare solutions, and it's shaping how telemedicine advances in various clinical contexts [21].

3.1.1. Field-programmable gate arrays (fine-grained adaptability)

The use of FPGAs offers a genuinely transformative route to embedded architectures within the developing sphere of remote health monitoring systems. Consider their fine-grained adaptability. These devices enable dynamic reconfiguration, allowing processing tasks to be precisely tailored to specific application requirements, such as ECG and SpO_2 monitoring. This adaptability, quite frankly, leads to better energy efficiency. They're able to run complex algorithms–vital for real-time data analysis–while keeping power consumption down, which is pretty important for wearable tech that needs to keep going without constantly needing a recharge. Furthermore, integrating FPGAs helps maintain robust data integrity and responsiveness, which is definitely paramount in telemedicine. And that aligns with the challenges we see in real-world situations, as some recent papers have shown [22], [23]. Ultimately, this versatility inherent in fine-grained FPGA configurations not only keeps performance up to scratch, but also, and perhaps more importantly, it opens up possibilities for new and innovative approaches in remote health monitoring.

3.1.2. Coarse-grained reconfigurable arrays (balance between efficiency and flexibility)

Within the developing field of remote health monitoring, CGRAs play a crucial role; they help to balance both efficiency and adaptability. These architectures allow for processing capabilities that can be tailored, meaning devices can adapt to applications like ECG and SpO_2 monitoring without using too much energy. By using CGRAs, embedded systems can see notable performance gains while keeping power consumption low, which is very important in wearable tech [24]. Furthermore, CGRAs are inherently flexible, which allows quick reconfiguration, so computing tasks can be dynamically adjusted as patient needs evolve, ensuring real-time responsiveness. As can be seen in the development of integrated health-monitoring platforms, this adaptability is key to improving patient care and data integrity [25]. The effective balance that CGRAs strike is therefore a cornerstone in the progress of reconfigurable embedded systems in telemedicine, helping to shape the future of personal health management.

3.1.3. Embedded FPGAs and heterogeneous SoCs (integration with MCU/CPU/AI accelerators)

The ongoing progress in electronics has significantly altered what reconfigurable embedded systems can do, most notably in remote health monitoring scenarios. Integrating embedded FPGAs (eFPGAs) into diverse SoCs gives a real boost to flexibility. It allows MCUs, central processing units (CPUs), and AI accelerators to be incorporated smoothly. With this kind of setup, real-time processing of important parameters like ECG, SpO_2, and temperature becomes possible, which helps with monitoring patients effectively and making diagnoses. The adaptability of reconfigurable platforms means devices can adjust to different workloads, keeping energy use down and extending their lifespan–both vital in telemedicine where constant operation is a must. Furthermore, the successful use of hardware in AI acceleration really highlights how these systems can transform data security and privacy, all while handling the increasing amount of health data produced, reinforcing how crucial they are in modern healthcare solutions [26]–[28]. The incorporation further illustrates the relevance of these technologies in advancing wireless health systems.

3.2. Energy-efficient design strategies in reconfigurable health devices

The development of reconfigurable health devices has really highlighted the need for energy-efficient design approaches, especially now that remote health monitoring systems are trying to meet increasingly complex patient requirements. By, for instance, using architectures like single-instruction multiple-data (SIMD) processors, such systems can preprocess data even in environments where energy is limited. This considerably boosts power efficiency and lowers bandwidth usage, as demonstrated in several models that have been proposed [29]. Moreover, the use of FPGAs allows a level of fine-grained adaptability. This, in turn, allows devices to adjust to very specific patient profiles and different application demands, and thus ensures good performance and reliability over a long period [29]. These innovations do not just make real-time responsiveness easier in health monitoring; they also emphasise the possibility of scalable solutions inside the telemedicine sphere. With these strategies, reconfigurable systems are likely to have a noteworthy effect on patient care while, at the same time, tackling key limitations of more traditional embedded architectures, which makes them vital in future healthcare progress.

3.3. Software-hardware co-design and reconfiguration granularity

For reconfigurable embedded systems in remote health monitoring, the convergence of software-hardware co-design and reconfiguration granularity proves vital in boosting effectiveness. These systems, by facilitating dynamic adaptability, are able to optimise performance contingent on diverse patient needs and environmental contexts, thereby assuring real-time responsiveness and energy efficiency. Such adaptability is particularly critical when considering applications such as ECG and SpO_2 monitoring, where the accurate capturing and processing of physiological data takes precedence. What's more, the granularity offered by reconfiguration capabilities empowers developers to fine-tune hardware to carry out particular tasks, keeping resource expenditure minimised whilst output quality is maximised. As fine-grained architectures have explored, this approach is in line with the pressing requirement for integrated solutions in telemedicine, where operational efficiency has a direct impact on patient outcomes [30]. Furthermore, a more cohesive health monitoring ecosystem can be fostered through the promotion of interoperability among devices via configurations of this nature [31].

4. APPLICATIONS IN REMOTE HEALTH MONITORING

The way we keep tabs on health from afar has seen some clever new approaches that mean healthcare isn't just stuck within the four walls of a doctor's surgery. Reconfigurable embedded systems are particularly worth mentioning, as they make monitoring devices more adaptable and effective for things like ECGs, SpO_2, and temperature. These systems make good use of things like wearable sensors and smartphone apps, which help collect data in real time and get patients more involved, also boosting how well they stick to rehab plans and how happy they are with their care. For example, new wearable motion sensors give us solid measurements of how well someone's recovering, highlighting shortcomings in how much we've traditionally relied on patients telling us how they feel [8]. On top of this, using drones to get medical supplies where they're needed shows how advanced tech can spread medical services to areas that don't get enough attention, by making the delivery of essential supplies a whole lot easier [32]. All these developments point to a big move towards healthcare that puts the patient first, with the potential for care that's not only smarter but also more tailored to the individual. Table 1 shows remote health monitoring applications and impact.

Table 1. Remote health monitoring applications and impact

Application	Description	Impact
Remote patient monitoring (RPM) [33]	Continuous collection of physiological data (e.g., blood pressure and glucose levels) to manage chronic conditions.	Reduced hospital readmissions and improved medication adherence.
Remote therapeutic monitoring (RTM) [33]	Monitoring of non-physiological data (e.g., pain levels and therapy adherence) to manage conditions like arthritis and asthma.	Enhanced patient engagement and timely interventions.
Digital biomarkers [34]	Utilisation of data from wearables and smartphones to monitor disease progression and treatment response.	Provision of valuable insights into various diseases, aiding in early intervention.
Telemedicine apps [35]	Platforms facilitating RPM and communication between patients and healthcare providers.	Improved communication and higher adherence to treatment plans.
IoT-based remote health monitoring [36]	Integration of IoT devices for continuous health data collection and analysis.	Enhanced patient care through real-time monitoring and data-driven decisions.

4.1. Electrocardiogram monitoring: embedded platforms and signal processing

The evolution of embedded platforms designed for ECG monitoring is, generally speaking, changing how remote health care works at its core. These systems, which utilise low-power designs coupled with clever signal processing, make continuous, real-time heart monitoring possible–something especially important given the increasing number of cardiovascular diseases linked to lifestyle choices, as some studies have shown [37]. Reconfigurable systems, when integrated, improve how adaptable and efficient ECG devices can be, letting them handle complicated things like spotting arrhythmias while using as little power as possible. What's more, using wireless communication like Bluetooth makes it easier to send data to healthcare professionals, which improves results for patients [38]. As the need for useful telemedicine increases, depending on new technologies, like AI algorithms for signal processing, will be key for providing correct and quick heart assessments, and for encouraging proactive health management.

4.1.1. Embedded platforms for electrocardiogram acquisition and processing

The incorporation of embedded platforms into ECG data gathering and analysis marks a significant leap forward in remote health monitoring setups. These platforms, through the use of adaptable designs, can effectively adjust to differing ECG signal features, which improves diagnostic accuracy and patient well-being. To illustrate, the implementation of AI and machine learning within these embedded systems not only helps in arrhythmia detection with notable precision–said to reach approximately 92% when processed from ECG data–but also makes power usage more efficient, considerably lengthening device lifespan [39]. Moreover, designs such as MPSoCs exemplify the mutually beneficial link between high-performance computing and low-energy consumption, enabling real-time processing capabilities essential for successful remote diagnostic measures [40]. Generally speaking, these developments highlight the potential for portable, personalised health devices that interact smoothly with telemedicine systems, ultimately encouraging improved health management amongst various populations.

4.1.2. Reconfigurable electrocardiogram signal filtering and feature extraction

Reconfigurable embedded systems are increasingly important in remote health monitoring, particularly where ECG signal processing is concerned. Crucially, effective filtering and feature extraction from ECG signals are vital for diagnosing and monitoring heart conditions accurately. By using reconfigurable architectures, such as FPGAs, these systems can adapt dynamically to changing signal conditions. This enhances the detection of specific waveform features–such as the QRS complex and arrhythmias–while minimising power consumption, a particularly critical factor for wearable devices [41]. What's more, integrating innovative algorithms can markedly improve data integrity and real-time processing capabilities, addressing the challenges presented by noise and motion artefacts [42]. Such advances highlight just how important reconfigurable systems are to improving the functionality and accuracy of ECG monitoring solutions. Ultimately, this leads to better patient outcomes in telemedicine applications. For visual context, it provides insight into the integration of wireless technologies central to these systems.

4.1.3. Energy-efficient field-programmable gate array/system-on-chip implementations for arrhythmia detection

Energy-efficient technologies have significantly advanced the capabilities of remote health monitoring, particularly in the early detection of arrhythmias. Reconfigurable platforms such as field- FPGAs and SoC designs enable programmable, low-power operation—an essential feature for wearable devices. These architectures offer dynamic adaptability, allowing rapid and efficient processing of ECG signals to identify abnormal heart rhythms in real time, which is critical for timely intervention. Optimizing power consumption not only extends battery life but also ensures consistent data integrity, thereby enhancing patient trust in wearable health solutions. Furthermore, the reconfigurable nature of these systems supports iterative updates based on clinical feedback, aligning with the evolving demands of modern healthcare [4]. As such, energy-efficient FPGA/SoC-based solutions are at the forefront of innovation in remote health monitoring, driving improvements in diagnostic accuracy and system sustainability.

4.1.4. Case studies: wearable electrocardiogram patches, Holter monitors

Wearable health tech has really shaken up how we keep an eye on patients, especially when it comes to heart health. Think ECG patches and Holter monitors–they're prime examples of how we're using clever, adaptable tech to boost what these devices can do and how well they connect with users. ECG patches let us constantly track heart rhythms, grabbing data in real-time. This means fewer trips to the hospital as doctors can diagnose and keep a close watch on patients remotely. Holter monitors, which used to be a bit of a pain to wear, are now smaller and use less power, making them much easier for patients to stick with. This allows for a proper look at arrhythmias over longer stretches. It's worth noting that this tech is always improving, especially when it comes to signal quality. Dodgy data can make things tricky when diagnosing, so clever algorithms that cut down on noise are really important [43]. What's more, the latest versions often use all sorts of sensors to make sure they're reliable and work well for everyone, tackling accuracy issues that studies have pointed out [44].

4.2. Oxygen saturation monitoring: architectures for optical sensing and analysis

The development of optical sensing technologies has markedly improved the functionality of SpO_2 monitoring systems, boosting their importance in remote healthcare. The incorporation of complex frameworks enables real-time assessment and improved precision, which is particularly vital for patients suffering from respiratory or cardiovascular ailments. A key component of this progression is the use of adaptive signal processing methods that cleverly reduce movement-related distortions, thus keeping data reliable in diverse scenarios. Low-power, FPGA-based systems have become a favoured option for constant SpO_2 monitoring, capable of delivering dependable operation without sacrificing power usage. These advancements not only add to the dependability of pulse oximeters but also ease their inclusion in multiparameter devices, thereby promoting a comprehensive overview of patient well-being [45]. Generally speaking, the continuous improvement of these frameworks is essential for advancing telemedicine, as they tackle both the requirement for precision and the rising need for wearable tech in healthcare contexts.

4.2.1. Architectures for optical sensing and real-time analysis

Optical sensing technologies, when integrated into remote health monitoring, considerably improve our ability to analyse data in real-time and care for patients. For instance, SpO_2 monitoring uses optical sensors that incorporate sophisticated algorithms, adapting to different situations to provide accurate readings despite movement. This kind of adaptive signal processing is rather important because it tackles typical problems encountered in the ever-changing settings where health monitoring devices are used. Low-power reconfigurable architectures, often FPGA-based, also play a role here. They enable continuous monitoring while extending battery life, which encourages users to keep using the device and makes the device last longer. These architectural improvements not only enhance efficiency but also safeguard the integrity of the data gathered, vital for trustworthy health assessments. Overall, the progress of these optical sensing architectures is a key step forward in telemedicine, helping to improve health outcomes for patients monitored remotely [46].

4.2.2. Adaptive signal processing for motion-artifact removal

The enhancement of data accuracy in remote health monitoring, most notably with wearable technologies, has become incredibly important recently. Motion artifacts present a real problem and adaptive signal processing is key to ensuring the reliability of physiological data, SpO_2 readings, for instance. This method cleverly separates genuine signals from noise caused by movement, which improves the reliability of diagnoses and treatment decisions that clinicians make. Reconfigurable systems boost how efficiently this processing works. They allow for easy integration of algorithms–low-power, high-performance–which are designed for particular situations. As a result, developing adaptable tech like this not only boosts performance, it also meets the tough demands of telemedicine. It's a vital move towards dependable health monitoring solutions that support patient care. As shown, these sensors are crucial for ensuring overall data integrity and usability in healthcare applications [41].

4.2.3. Low-power field-programmable gate array-based solutions for continuous SpO_2 monitoring

The integration of low-power FPGAs into systems that continuously monitor SpO_2 serves as a very good example of progress in wearable health tech. These solutions use the flexibility that FPGAs have, which makes real-time adaptation and optimisation of signal processing algorithms possible; this is crucial for measurements of SpO_2 that are accurate. Via utilising architectures that are energy-efficient, such systems are able to run for longer periods without needing to be recharged all the time, a feature that is vital for continuous health monitoring. Moreover, adaptive algorithms–which can mitigate motion artefacts–contribute towards better data integrity, improving the reliability of readings in dynamic settings. The iterative reconfigurability that FPGAs possess enables updates and improvements without needing a complete hardware replacement, which promotes cost-effectiveness and longevity. Low-power FPGA-based approaches not only address current health monitoring challenges, but also make future innovations in remote patient care easier to do [47].

4.2.4. Integration in pulse oximeters and multiparameter devices

The swift progress in remote health monitoring has highlighted the need for smooth integration of different physiological measurement tools, notably pulse oximeters and multiparameter devices. As healthcare leans towards less invasive and more efficient monitoring approaches, innovations that use the IoMT are becoming crucial in boosting patient care. For instance, incorporating real-time data transmission abilities can greatly improve the handling of conditions such as cardiovascular problems or respiratory diseases. Indeed, findings suggest continuous pulse oximetry is effective at capturing vital signs with good accuracy [12]. Moreover, the inclusion of advanced machine learning methods in these devices has revealed potential in predicting key health metrics, permitting proactive healthcare interventions [48]. Therefore, the fusion of these technologies not only enables thorough health monitoring but also fits with the growing requirement for versatile, low-power solutions in telemedicine, reshaping patient management frameworks in the process. It's important to note the adaptability required for these integrations, generally speaking, to ensure compatibility across diverse patient needs and technological infrastructures.

4.3. Temperature sensing: reconfigurable systems for thermal monitoring

Within the field of remote health monitoring, improvements to patient care are reliant on progress in sensor technologies, with a particular focus on temperature sensing. Reconfigurable embedded systems offer a notable benefit, permitting adaptable thermal monitoring solutions in both wearable and implantable devices. These systems not only enable ultra-low-power operation–crucial for prolonged monitoring–but also facilitate real-time data processing, vital for proactive medical interventions. This adaptability is highlighted by developments in energy-efficient design methods, making such systems capable of fulfilling demanding health monitoring requirements whilst ensuring dependable performance. Moreover, the incorporation of reconfigurable architectures with advanced data management protocols ensures the resilience and security of health data transmission, boosting patient confidence and safety in telemedicine applications. Generally speaking, temperature sensing within these reconfigurable frameworks represents a transformative approach to health monitoring, able to respond effectively to dynamic healthcare environments [49], [50].

4.3.1. Embedded systems for body and skin temperature sensing

The incorporation of embedded systems within health monitoring gadgets has markedly altered how we handle physiological data, most notably when it comes to gauging body and skin temperature. Researchers are suggesting novel temperature sensors, built using sophisticated materials like laser-synthesised graphene, which demonstrate both high sensitivity and a decent level of robustness. It's worth noting how the electrical conductivity of laser-reduced graphene oxide is cleverly employed to fashion temperature-sensitive resistors. These are then encased in polydimethylsiloxane to boost linearity and fend off humidity, making them rather appealing options for wearable tech designed for constant monitoring [51]. Furthermore, on top of that, the latest strides in low-power wide-area networks are making it easier to remotely gather health information, thus improving how well monitoring systems work, specifically for those more at risk, like older folks [12]. All of these techy leaps forward underscore the significance of reconfigurable embedded systems. These systems hold the potential to be adapted for a variety of uses, ensuring both energy efficiency and trustworthy real-time data within telemedicine.

4.3.2. Reconfigurable thermal monitoring systems in wearable/implantable devices

The progression of sophisticated thermal monitoring systems is decidedly key to improving the functionality of health-oriented wearable and implantable devices, suggesting notable advancements in both patient care and health management. These systems facilitate the ongoing surveillance of body temperature, which proves vital for the prompt identification of diverse medical issues, encompassing infections and inflammatory reactions. Through the employment of reconfigurable embedded architectures, such systems possess the ability to modify their functions according to particular health monitoring demands, thus optimising power usage whilst preserving elevated data integrity and reaction times–a crucial necessity for impactful telemedicine [4]. Moreover, the incorporation of lightweight substances and miniaturised parts bolsters the practical application of these systems across varied situations, assuring adequate biocompatibility and patient ease [52]. Consequently, reconfigurable thermal monitoring setups signify a considerable leap forward in remote health monitoring technologies, presenting a route towards bespoke healthcare resolutions amidst an ever more digital epoch.

4.3.3. Ultra-low-power designs for long-term monitoring

The push towards ultra-low-power designs has become a rather crucial part of remote health monitoring systems, really boosting how practical they are for using them long-term. By cutting down on energy use, these designs let devices run non-stop for longer stretches, which in turn helps patients stick to using them and makes data collection more accurate. Putting in place dynamic power management methods, like voltage scaling and adaptive reconfiguration, is a key part of getting good energy efficiency whilst keeping performance robust. On top of that, these systems often make use of reconfigurable architectures, letting them adapt in real-time to suit the particular needs of individual patients; this is vital in telemedicine situations where being responsive is incredibly important [53]. Plus, incorporating efficient data processing algorithms optimises how well these devices can monitor, as shown by ongoing research looking to strike a balance between power needs and precision and user experience. These advances really highlight how important ultra-low-power designs are in changing remote health monitoring for the better.

5. CROSS-CUTTING DESIGN CONSIDERATIONS

The crucial foundation when developing reconfigurable embedded systems for remote health monitoring is the intricate dance between various design choices. As telemedicine develops further, the focus on techniques that minimise power consumption-think voltage/frequency scaling and dynamic reconfiguration-becomes ever more important for extending battery life, all while keeping things running efficiently. At the same time, keeping data safe and sound is paramount, meaning robust encryption and secure reconfiguration methods are a must to protect sensitive health data. Real-time responsiveness is also a big factor; latency constraints need careful management to guarantee timely diagnostics and delivery of care. Strategies such as adaptive scheduling, for example, can help prioritise critical signals during urgent situations. Taken as a whole, these interwoven design considerations not only boost the reliability and robustness of the systems, but they also cement their usefulness in actual healthcare environments, pushing forward advancements in remote health solutions [4], [54]. Furthermore, the uptake of wireless communication protocols, as seen in highlights how these systems can slot into healthcare ecosystems, expanding the range of potential uses.

5.1. Low-power design techniques: voltage/frequency scaling, dynamic reconfiguration, and approximate computing

In the ever-expanding world of remote health monitoring, it's becoming clear that low-power design techniques are essential. These techniques enhance both the effectiveness and the longevity of embedded systems. Techniques such as voltage and frequency scaling–not to mention dynamic reconfiguration–really help cut down on energy use. This lets devices run efficiently, even when the battery is low, which is especially important for wearable tech. Also, approximate computing gives us some serious performance gains. Of course, there's a balance to be struck between accuracy and efficiency. However, it means devices can handle complex health data without draining the power too much. Being able to recalibrate systems on the fly is a real boon, as it allows the systems to adapt to different contexts and the way people use them. This makes sure vital health data is consistently monitored and processed with the least amount of fuss. As highlighted in [18], [55], embedding intelligent processing directly addresses the performance needs. This reinforces why energy-efficient methods are so important in the growth of telemedicine, generally speaking. Table 2 shows low-power design techniques in embedded systems.

Table 2. Low-power design techniques in embedded systems

Technique	Description
Dynamic voltage and frequency scaling (DVFS) [56]	A power optimization technique that dynamically adjusts the processor's operating voltage and clock frequency in response to workload intensity. By scaling down these parameters during low-demand periods, DVFS significantly reduces energy consumption while maintaining system performance. It also contributes to memory power management by aligning memory access rates with processor activity, enhancing overall efficiency in embedded systems.
Dynamic reconfiguration [57]	A design strategy that enables system components to be modified or reallocated at runtime, allowing embedded platforms to adapt to changing performance and power demands. In heterogeneous SoC environments, dynamic reconfiguration enhances energy efficiency by selectively activating or reprogramming hardware modules based on workload intensity, application context, or user behavior. This approach supports adaptive computing, reduces idle power consumption, and extends operational lifespan—making it especially valuable for resource-constrained systems like wearable health monitors and IoT devices.
Approximate computing [58]	A low-power design technique that intentionally introduces controlled inaccuracies into computations to reduce energy consumption. By relaxing precision in non-critical operations, approximate computing enables aggressive voltage over-scaling and simplified circuit design, resulting in substantial power savings. This approach is particularly effective in error-tolerant applications such as multimedia processing, wearable health analytics, and machine learning inference, where minor deviations in output quality are acceptable and do not compromise overall functionality.

5.2. Data integrity and security: encryption, secure reconfiguration, and blockchain/federated edge health data management

In the sphere of reconfigurable embedded systems designed for remote health monitoring, data integrity and security stand as paramount considerations, essentially underpinning the system's reliability. To safeguard sensitive health data effectively, robust encryption protocols coupled with secure reconfiguration techniques are, quite simply, essential, enabling healthcare providers to shield patient information. The integration of blockchain technology further bolsters these security measures; it facilitates federated edge health data management, ensuring, in most cases, that only authorised personnel can access or modify the data, thereby preserving its integrity. As the importance of real-time responsiveness in telemedicine escalates–and it most certainly is–these security frameworks must operate seamlessly so as to avert potential vulnerabilities, and to ensure that essential health information is transmitted without any delay or compromise. This intricate interplay of encryption, secure reconfiguration, and blockchain solutions truly exemplifies the advancements within this field, all aligning with the overarching goal of creating safe, efficient, and responsive remote health monitoring systems, ultimately transforming patient care [59]–[61]. The adoption of such innovative technologies signals a lasting evolution, generally speaking, in how we approach health data management in an increasingly interconnected world.

5.3. Real-time responsiveness: latency constraints in remote diagnosis, adaptive scheduling, and prioritization of critical signals

For remote health monitoring, reconfigurable embedded systems are essential for better real-time responsiveness, most notably concerning latency when diagnosing patients remotely. These systems need to competently handle critical signal prioritisation alongside adaptive scheduling; this ensures crucial health data is transmitted and processed promptly. Advanced architectures make this possible, using dynamic algorithms that adjust to changing network conditions and specific user needs. For example, studies have shown that dual-large language model (LLM) frameworks can improve data routing, but also drastically cut latency by optimising network performance in telemedicine. These improvements can increase user experience and responsiveness by as much as 52.5% compared with older methods [62]. Furthermore, such systems highlight how important telecommunications are for smooth health data exchange, underscoring the necessity for efficient resource allocation to manage growing demands [63]. Generally speaking, these advancements are pushing remote health monitoring towards a future where providing timely and reliable patient support is no longer just a goal, but an actual reality.

5.4. Reliability and robustness: fault-tolerance in reconfigurable devices and handling sensor noise

For remote health monitoring to truly shine, we need systems that can handle sensor noise without faltering, especially in reconfigurable devices. It's crucial that these devices keep working, even when things get tricky operationally, and that they adapt to faults without letting the data quality slip. Recent research points to the importance of layered fault-tolerance strategies–thinking about fault detection, recovery and containment all together. This not only makes devices tougher but also gives users more faith in telemedicine, knowing their vital signs, like ECG and SpO_2, are being watched accurately and without interruption [64]. Also, designing these embedded systems means being smart about power use, particularly when devices are running on low battery in constrained environments [65]. Generally speaking, tackling sensor noise with solid, reconfigurable architectures is key to pushing remote health tech forward, paving the way for health monitoring solutions that are reliable and real-time. Such methodologies, generally speaking, ensures continuous, and accurate monitoring.

6. INTEGRATION WITH TELEMEDICINE ECOSYSTEMS

To improve how we look after patients, healthcare tech is always changing, and it really needs to work well with telemedicine. This is about making patient monitoring and care much better. Reconfigurable embedded systems that are high-tech are key to this; they help swap and work with data in real-time. These systems are really good because they can change to fit different health needs. So, they can help with things like checking ECGs or body temperature, which is super useful. Also, we're getting better networks like 5G that have low latency, which helps these embedded systems to work in the IoMT. This means everything works smoothly with healthcare standards like FHIR and HL7 [66]. We've also seen that adaptive technologies can really help when there's a health crisis, making our digital health systems stronger [67]. Basically, using all this tech together is super important for making telemedicine even better.

6.1. Edge–cloud continuum for remote health data processing

The convergence of edge-cloud infrastructures is becoming rather important within remote health data processing; it's a key step forward, really, in boosting telemedicine's effectiveness. Essentially, this setup links local edge computing–that's processing data near its origin–with the considerable power of cloud computing. By spreading out data analysis, we not only get quicker reactions but also keep data sound during crucial medical moments. Recent talks bring up the point that different sorts of devices, coupled with the need to act fast, pose tricky problems we've got to sort out to truly tap into these technologies for health monitoring [68]. Furthermore, adding Edge AI can greatly improve real-time health checks, leading to better results and smarter use of resources [69]. This partnership between edge and cloud tech is vital in making strong, flexible platforms. These platforms can deal with what modern telemedicine asks for, while also ensuring data is managed well, generally speaking.

6.2. Interoperability with healthcare standards (HL7, FHIR, and IEEE 11073)

Within the complex domain of remote health monitoring, interoperability plays a critical role, particularly in aligning healthcare standards such as HL7, FHIR, and IEEE 11073. These standards provide a foundational framework that facilitates seamless data exchange across diverse healthcare systems, ensuring consistency and accuracy in communication. HL7 enhances clinical and administrative data exchange, while FHIR, as a modern web-based standard, promotes interoperability via its user-friendly setup, which supports mobile apps and cloud integrations. IEEE 11073, meanwhile, deals with the specifics of medical device comms, defining protocols that allow devices to share vital information effectively. Generally speaking, the collective impact of these standards is quite profound; they bolster the development of reconfigurable embedded systems. These systems can adapt to diverse monitoring needs whilst maintaining data integrity and security, thus paving the way for more responsive and efficient telemedicine solutions [70]. Incorporating insights from technological advancements, such as those depicted in, enhances the understanding of these standards' practical implications in real-world applications.

6.3. Artificial intelligence-enabled reconfigurable platforms for predictive healthcare

The merging of AI with reconfigurable embedded systems has, in recent years, opened up some genuinely exciting avenues in predictive healthcare. These AI-driven platforms are generally crafted to meet differing healthcare demands, which they do by way of dynamic hardware tweaks, thus optimising both how well they work and how much power they use. This kind of adaptability can be incredibly valuable for monitoring health remotely, where using little power and reacting quickly are vitally important. It's worth noting, too, that incorporating explainable AI (XAI) frameworks into these systems improves user trust and understanding–something crucial for getting telemedicine applications widely adopted. Furthermore, new materials being developed alongside adaptive algorithms driven by AI look set to enhance how secure and intact data remains within patient monitoring environments. This ensures robust solutions that, generally speaking, continue to evolve alongside technological advances [71], [72]. As these innovations gain more traction, they are very likely to transform the healthcare delivery landscape, making predictive models both more accessible and more effective for all sorts of patient populations.

6.4. Role of 5G/6G and internet of medical things in enabling scalable solutions

The convergence of 5G/6G technologies alongside the IoMT is, generally speaking, quite crucial in the ever-developing sphere of remote health monitoring. These developments help make real-time data transmission from a variety of medical devices easier, which in turn improves the scalability and indeed the efficacy, of health monitoring solutions. The ultra-low latency and high bandwidth that are provided by 5G/6G networks, in most cases, enable seamless communication between wearable sensors and healthcare systems, which improves patient responses and also care outcomes significantly. Furthermore, IoMT builds a framework, quite a cohesive one in fact, that allows a good number of devices to interconnect and deliver comprehensive health analytics. This ensures data integrity is greater, as well as security, in patient monitoring environments. The integration of these technologies is illustrated further in various applications, particularly in the development of embedded systems that are adaptable and can respond to shifting healthcare demands promptly. Therefore, the combined effect of 5G/6G and IoMT heralds what might be considered a transformative era for telemedicine, permitting a healthcare delivery paradigm that is more responsive and, crucially, more efficient [73].

7. COMPARATIVE ANALYSIS OF PLATFORMS

The continued development of reconfigurable embedded systems is opening up fresh possibilities for remote health monitoring, demanding a key comparison of available platforms. A range of architectures, including application-specific integrated circuits (ASICs), MCUs, and FPGAs, each offer different benefits and drawbacks regarding energy use, precision, and adaptability–all vital for ECG, SpO_2, and temperature monitoring applications. For example, FPGAs generally provide a good compromise between adaptability and performance, and importantly, enable real-time responses crucial for telemedicine applications [4]. Furthermore, the rise of biosensor tech has increased the need for portable, cost-effective platforms suitable for on-site diagnostics. This, in turn, highlights the necessity for devices that are both efficient and robust [74]. This comparison both sheds light on current tech paradigms and encourages the investigation of future paths in personalised healthcare, designed to fit neatly into current telemedicine setups. The importance of these results is shown in, which illustrates the deployment of wireless health systems, furthering the debate on platform capabilities.

7.1. Comparative: ASIC vs. microcontroller vs. FPGA/SoC for ECG, SpO_2, and temperature

Enhancing remote health monitoring through emerging technologies requires a careful comparison of embedded platforms such as ASICs, MCUs, and FPGAs/SoCs to determine the most suitable option for applications like ECG, SpO_2, and temperature sensing. ASICs are widely recognized for their exceptional energy efficiency and minimal power consumption, making them ideal for battery-operated devices [75].; however, their limited flexibility can pose challenges when telemedicine requirements evolve. In contrast, MCUs offer moderate performance, ease of design, and robust operation, enabling rapid deployment in health monitoring systems with reliable functionality. FPGAs and SoCs, due to their reconfigurability, support real-time adaptation and are capable of executing complex signal processing algorithms essential for accurate physiological measurements, thereby improving system responsiveness [76]. Selecting the appropriate platform involves balancing energy efficiency, computational accuracy, and architectural flexibility—underscoring the need for a tailored approach in designing reconfigurable health monitoring solutions. A comparative table outlining these attributes can clarify the operational trade-offs and guide platform selection in the dynamic landscape of remote healthcare. The significance of these technologies is reflected in their integration into wireless health systems aimed at delivering optimal patient care.

7.2. Energy consumption vs. accuracy vs. flexibility

The incorporation of reconfigurable embedded systems within remote health monitoring presents a rather complex challenge, one requiring a delicate balance between energy consumption, accuracy, and, indeed, flexibility. Given the evolving nature of healthcare demands, especially within telemedicine, systems must optimise their energy usage without sacrificing the precision of physiological measurements; acquiring accurate data is, of course, paramount for patient monitoring and effective diagnosis. For instance, the utilisation of FPGAs and CGRAs allows for adaptable signal processing, tailored specifically to particular medical applications, thus facilitating real-time responsiveness whilst managing energy expenditure quite effectively. However, the inherent trade-offs–flexibility versus energy consumption–become rather evident when recalibrating these systems for varying clinical requirements, as demonstrated in both operational and design contexts [77]. Furthermore, the inclusion of machine learning techniques can enhance the accuracy of health diagnostics, albeit with a consequential increase in computational demands, which complicates the energy-accuracy-flexibility balance [78]. The critical consideration, generally speaking, remains how to enhance these reconfigurable systems so they meet the dynamic needs of remote health applications while striving for what one might call optimal performance. The efficacy of systems like these is illustrated by those designed for ECG and SpO_2 monitoring, providing somewhat insightful case studies in energy-efficient, accurate health data acquisition.

7.3. Commercial solutions vs. academic prototypes

The ongoing pursuit of innovation in remote health monitoring is highlighted by how commercial solutions and academic prototypes intersect. Systems developed commercially tend to focus on user-friendly interfaces and smooth integration into current healthcare structures, delivering immediate, useful applications. Conversely, academic prototypes often showcase the newest technologies, such as those examined in [79], and concentrate on complex energy harvesting and reconfigurable architectures that push the boundaries of embedded systems. Although these innovative academic methods, which might involve advanced algorithms for power extraction, offer several theoretical benefits, their real-world scalability is still a major concern. Moreover, biometric technology insights, as noted in [80], illustrates the difficulties encountered when moving from laboratory settings to real-world applications, stressing elements such as sample quality and security. Generally speaking, this dynamic interaction between commercial practicality and cutting-edge research supports the development of reconfigurable systems that are crucial for remote health monitoring.

8. CHALLENGES AND RESEARCH GAPS

The evolution of reconfigurable embedded systems designed for remote health monitoring brings to light a range of challenges, alongside substantial research gaps that certainly deserve closer scrutiny. Power, performance, and security trade-offs remain critical considerations; ensuring optimal energy efficiency while meeting stringent security standards for medical-grade devices is a complex undertaking. Moreover, the absence of robust standardisation across platforms raises concerns about interoperability and scalability in diverse healthcare environments. Existing research underscores the growing need for secure edge computing frameworks to address evolving data privacy regulations [81]. In parallel, clinical validation and regulatory approval processes present formidable barriers that can delay the deployment of innovative solutions in real-world settings [82]. These concerns are further illustrated in Figure 2, which presents the percentage of healthcare organizations reporting key vulnerabilities. Notably, 73% are influenced by FDA cybersecurity guidance, 52% express concern over regulatory changes, 48% of medical devices are unable to run security software, and 39% contain critical unpatched vulnerabilities. Such statistics highlight the pressing security challenges embedded within healthcare technology. Tackling these issues is essential not only for improving device reliability and user trust but also for laying the groundwork for adaptive systems that can be seamlessly integrated into telemedicine. The insights gleaned from these findings enrich the ongoing discourse, emphasizing the importance of practical, secure, and scalable wireless health solutions in shaping the future of patient care.

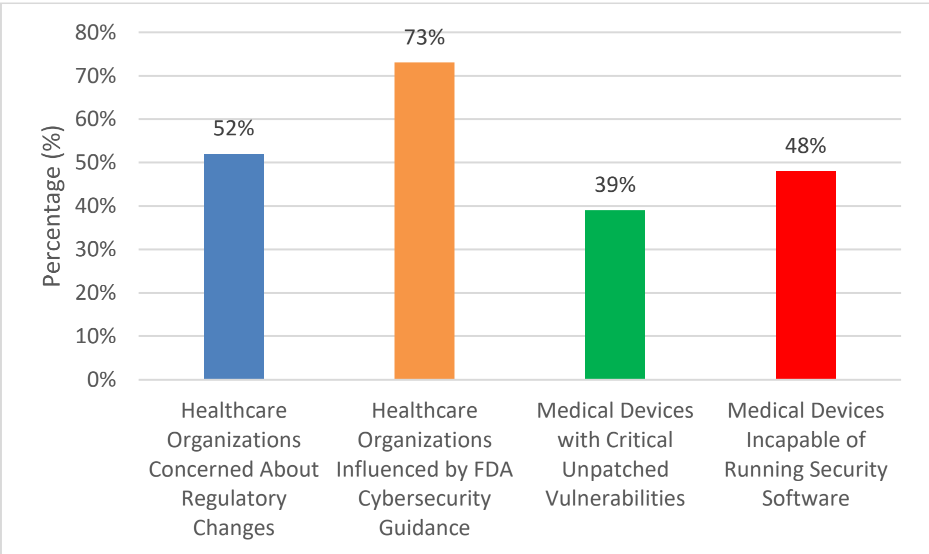

Figure 2. The percentage of healthcare organizations reporting various concerns and vulnerabilities

8.1. Power-performance-security trade-offs in medical-grade devices

The delicate balance between power usage, effective performance, and security provisions presents considerable hurdles in medical devices, specifically when it comes to remote health monitoring. With healthcare's growing dependence on wearable tech, we find it ever more vital to juggle these factors. Boosting power efficiency can often risk undermining the strength of security measures, potentially leaving patient data vulnerable to threats. For example, when reconfigurable embedded systems are designed for minimal power usage, the challenge of maintaining data integrity grows, particularly under the dynamic conditions we see in telemedicine applications. Moreover, implementing advanced algorithms could heighten the computational burden, potentially affecting real-time responsiveness [49]. These trade-offs demand a careful calibration of system parameters. It is vital that devices not only work well but also protect against cybersecurity risks, mirroring current discussions around merging innovation with safety in medical technology [83]. Generally speaking, it's a complex issue, and finding the right balance is key.

8.2. Standardization issues for reconfigurable health monitoring platforms

The swift advancement of telemedicine, coupled with the increased availability of adaptable health monitoring setups, presents several standardisation issues that need resolving to enable smooth interoperability. These setups, vital for uses like ECG and SpO_2 monitoring, require a joined-up framework to bring different devices together and encourage easy data sharing across varied healthcare systems. The mixing of diverse designs–it is anticipated that IoT devices will reach 30 billion by 2030, remember–calls for a strong standardisation method. This is to make certain of compatibility and security, mainly focusing on communication across platforms and the integrity of data, as detailed in recent looks at segment routing technologies [84] and new IoT innovations [85]. Dealing with these points is crucial, not just for boosting how devices work, but also for growing trust and dependability in telemedicine, which is key for patient results and how well healthcare works.

8.3. Data privacy regulations and secure edge computing

In these times, with digital health technologies popping up all over the place, keeping personal data safe is really important for people to trust them. The way data privacy rules and edge computing work together shows a big step forward in protecting sensitive health info that's processed remotely. Edge computing spreads out data processing, meaning sensitive info can be analysed closer to where it comes from, which cuts down on the chances of breaches when it's being sent. This setup fits well with the rules that insist on strong privacy measures, as we've seen in chats about using blockchain in edge systems to make them more secure [86]. Also, using federated learning in edge AI means models can be trained locally. Thus, this further keeps data safe and sticks to the legal requirements [69]. These improvements really show how crucial secure edge computing is for remote health monitoring, making sure patients' privacy is respected, and that we're following all the rules.

8.4. Scalability of reconfigurable platforms in real-world deployments

Reconfigurable platforms are particularly promising due to their adaptability to different operational requirements, a vital attribute for practical deployments, especially in remote health monitoring contexts. These systems, through the incorporation of advanced design approaches—as evidenced by several recent investigations—exhibit enhanced scalability, directly tackling the escalating data volumes inherent in health monitoring tasks. Indeed, innovative frameworks that harmonise both hardware and software resources can optimise overall performance, effectively diminish energy usage while preserve that all-important real-time responsiveness [87]. Furthermore, practical implementations in industrial settings have highlighted the adaptive qualities of such systems, enabling seamless integration with a wide array of monitoring technologies, thus boosting their scalability even further [88]. In most cases, these attributes ensure that reconfigurable embedded systems are capable not only of satisfying present healthcare needs but also of developing in tandem with ongoing technological progress, embodying the resilience and adaptability that are so crucial for future telemedicine applications.

8.5. Clinical validation and regulatory approval barriers

Integrating reconfigurable embedded systems for remote health monitoring presents complexities, further compounded by clinical validation and regulatory approval challenges. These hurdles are particularly important in making certain that devices not only adhere to technological standards, but also address real-world healthcare needs. Take, for example, the German Digital Health Care Act; it highlights the need for a strong framework covering societal acceptance, clinical efficacy, and economic viability. This underscores the multifaceted nature of assessing digital health applications, such as DiGAs [89]. Furthermore, innovative technologies like radio frequency (RF-based) sensing systems encounter environmental reliability and regulatory compliance problems, both crucial for accurate health monitoring [22]. Consequently, successfully navigating these validation processes necessitates comprehensive assessment frameworks. These frameworks must balance technical performance with real-world applicability, thus ensuring that remote health solutions are both effective and widely accepted. To encourage such advancements, collaboration amongst healthcare, technology, and policy stakeholders is essential.

9. FUTURE DIRECTIONS

The ongoing evolution of remote health monitoring suggests a future increasingly shaped by self-optimising and AI-driven reconfigurable health devices. These innovations promise to enhance the adaptability of monitoring systems, enabling personalised, context-aware responses tailored to individual patient needs. The integration of neuromorphic and in-memory computing is widely recognised as a potential catalyst for major advances in biosignal processing, paving the way for more efficient and responsive health monitoring architectures. Furthermore, next-generation sensors—engineered with inherent reconfigurability—are set to transform healthcare delivery by ensuring that devices not only react to real-time health data but also operate sustainably and with carbon awareness [90]. However, as these technologies advance, ensuring robust device security remains a critical challenge. Figure 2 highlights the primary concerns of healthcare organizations regarding vulnerabilities in medical devices. It underscores the ongoing tension between innovation and security, emphasizing the need for reconfigurable systems that can adapt over time without sacrificing performance or regulatory compliance. Together, these trends mark the emergence of a new era in telemedicine—one that blends technological sophistication with personalized care, while navigating the intricate challenges of cybersecurity and regulatory oversight.

9.1. Self-optimizing and artificial intelligence-driven reconfigurable health devices

The ongoing advancement of health tech demands fresh solutions that improve both patient care and how well things run. One particularly interesting development involves self-optimising, AI-powered health devices that can be reconfigured, adjusting on the fly to different patient requirements and surroundings. AI's inclusion in these devices helps process data in real time, but also supports predictive analysis, making it easier to step in with medical help when needed. These improvements are especially useful for keeping an eye on health remotely, where devices have to work dependably in all sorts of situations. By using adaptable designs, these devices are able to tweak their operations to keep power usage down, all while making sure the data gathered is sound. This tactic really boosts the life span of health monitoring options, which in the end leads to happier patients and better results in telemedicine setups [91]. Generally speaking, the effects of these technologies point to a pretty big shift towards healthcare that's both more personal and more effective.

9.2. Integration of neuromorphic and in-memory computing for biosignal processing

The evolving terrain of remote health monitoring sees neuromorphic and in-memory computing as a rather promising route to boost biosignal processing efficiency. This blending streamlines the handling of complex data from wearable tech, often hampered by energy and latency issues. Neuromorphic computing, generally speaking, mirrors the brain's efficient neural networks and presents a noteworthy advantage over standard designs. It enables concurrent calculation and data storage, cutting down on the power drain from data transfers [92]. Moreover, using in-memory computing methods can, in most cases, simplify data processing. This allows for the swift and efficient management of large amounts of biosignals captured in real time [93]. The ultimate goal isn't just enhanced performance, though; it also tackles vital needs such as energy conservation and responsiveness in real-time. This, in turn, paves the way for more cutting-edge, reconfigurable embedded health monitoring systems.

9.3. Next-gen sensors with built-in reconfigurability

The increasing reliance on adaptable sensor technologies is really driving the evolution of health monitoring solutions. We're seeing next-generation sensors, with built-in reconfigurability, offering flexibility like never before. These allow for real-time adjustments to cater to diverse patient needs and changing environmental conditions. Now, this capability markedly improves the performance of remote health monitoring systems–especially in scenarios demanding rapid response and continuous data acquisition. Innovations in reconfigurable architectures, like FPGAs, generally foster an environment where energy efficiency and longevity are really important [16]. Healthcare providers, by incorporating these advanced sensors, are able to optimise patient monitoring, making sure that data integrity and responsiveness are maintained within the telemedicine framework [94]. What's more, the integration of these technologies within platforms really enhances interoperability, allowing seamless communication across various healthcare systems. Consequently, these next-gen sensors, generally speaking, are at the forefront of a transformative shift in remote health monitoring practices, reinforcing their pivotal role in the clinical care of the future.

9.4. Sustainable and carbon-aware design in health internet of things systems

The progress of health-focused IoT demands a move toward designs that are sustainable and mindful of carbon emissions, giving environmental impact the same importance as patient well-being. With telemedicine becoming more widespread, particularly through wearable tech, it's essential to weave energy-efficient methods into these devices to reduce their ecological impact. By concentrating on strategies that use little power–like adaptive signal processing and dynamic reconfiguration–designers can improve how long health monitoring tools last and how well they work, all while keeping performance and data accurate [95]. What's more, using renewable energy in reconfigurable embedded systems helps this effort, encouraging a complete method for healthcare tech that fits with global sustainability aims. Committing to eco-friendly health IoT solutions shows an ethical duty and equips healthcare with strong, flexible tech ready for what's ahead, improving results for people and the planet.

9.5. Personalized healthcare through adaptive embedded systems

The integration of adaptive embedded systems with personalised healthcare has emerged as a transformative paradigm in remote health monitoring. This convergence enables real-time data acquisition and analysis, supporting timely and informed clinical decision-making tailored to individual patient needs. Advanced reconfigurable embedded architectures—such as those examined in ECG and SpO_2 system analyses—significantly enhance both flexibility and energy efficiency, attributes that are critical for the performance and longevity of wearable health devices [4]. Moreover, we're seeing innovations like the dual-LLM framework, which demonstrate just how much potential there is in embedding AI into these systems. This fosters responsive healthcare environments that can adapt to the specific conditions faced by users [62]. As the demand for healthcare that is truly personalised continues to grow, the ability of these adaptive systems to ensure integrity, security, and real-time responsiveness will be absolutely paramount. This will solidify their role as keystones in the future of telemedicine and, of course, patient care.

10. CONCLUSION

The advancement of reconfigurable embedded systems represents a critical step toward enabling scalable, efficient, and patient-focused remote health monitoring within modern telemedicine. By combining adaptability, flexibility, and energy efficiency, these platforms can address diverse healthcare requirements such as ECG, SpO_2, and temperature sensing, while ensuring low power consumption, robust data integrity, and real-time responsiveness—capabilities essential for dependable wearable and implantable medical devices. The integration of hardware–software co-design, optimized digital signal processing, and FPGA-based neural accelerators further strengthens their role in supporting continuous health monitoring, reducing latency, and extending device lifetimes in resource-constrained environments. At the same time, reconfigurable architectures are evolving to incorporate AI-driven adaptability, making it possible to tailor processing pipelines to specific workloads or patient needs, thereby enhancing the personalization and effectiveness of healthcare delivery. Despite these advantages, challenges remain, including the trade-offs between energy consumption and performance, the complexity of design methodologies, and the absence of standardized frameworks that can guarantee interoperability and regulatory compliance across diverse platforms. Security and privacy also stand as major concerns, with runtime reconfiguration introducing new vulnerabilities that must be addressed through trustworthy architectures and secure data-handling mechanisms. Addressing these challenges requires a multidisciplinary approach that unites expertise from electronics, biomedical engineering, computer science, and healthcare policy, ensuring that technical innovations are matched with clinical validation and safe integration into healthcare ecosystems. Looking ahead, reconfigurable embedded systems have the potential to become a cornerstone of telemedicine, fostering sustainable, low-cost, and widely accessible solutions that not only improve health outcomes for individuals but also provide scalable monitoring capabilities at the population level, ultimately reshaping how healthcare is delivered in an increasingly connected and data-driven world.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the institutional support provided by Universitas Ahmad Dahlan (UAD) and Universiti Teknikal Malaysia Melaka (UTeM), which was instrumental in facilitating this research. Special appreciation is extended to the Embedded System and Power Electronics Research Group (ESPERG) for their sustained technical contributions, collaborative engagement, and domain-specific

expertise. The ESPERG team's involvement significantly enriched the methodological rigor and practical relevance of the study, particularly in the areas of embedded system design and power optimization.

FUNDING INFORMATION

The research was funded by PT. Intelektual Pustaka Media Utama (IPMU) under contract number 07/RST-E/IPMU/I/2025, which supported the facilitation of this work.

AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
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Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

Data availability does not apply to this paper as no new data were created or analyzed in this study.

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