
SMART SPACE HEALTHCARE MONITORING SYSTEMS

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ABSTRACT

With the quick progress in space exploration by humans, there is a need for efficient and autonomous systems to monitor the health of astronauts. Healthcare methods used in current space missions depend on the delayed data analysis and support from earth, which cannot be effective for deep space missions. This paper provides a detailed discussion about health monitoring technologies used in astronaut missions, including wearable biosensors, IoT technology, AI analytics, PHM, and multimodal sensors. Latest advancements made between 2024 and 2025 are also highlighted in this study. A comparison among the discussed methods is provided with respect to their capabilities, challenges, and future scope.

KEYWORDS: Astronaut Health Monitoring, Edge AI, Wearable Sensors, PHM, Sensor Fusion, Space Healthcare.

INTRODUCTION

Individuals exist close to the globe of Earth at one point, but soon those individuals find themselves many hours away from assistance. Mars missions that travel beyond the low orbit make the quiet time become very long periods of silence. Experts claim that Mars missions involving humans toward the planet Mars require messages to travel through the void for 24 minutes in a single direction. Because this time delay exists, the way medical treatment functions undergo a complete transformation. Assistance from ground control cannot arrive when a response requires half an hour of waiting. It has been observed that choices must be made by the crew alone when they are located far from their known supporters. This separation causes a total modification of procedures because the Mars missions are isolated. This issue demands today's aerospace medicine shift toward self-sufficient space health

systems. Such systems rest on three foundations

A. Autonomous Monitoring

Beyond Earth's orbit, health information transmits in segments, reviewed afterward by specialists on Earth. As distance grows toward Mars, communication falters - responses from ground teams arrive too late. When delays stretch across minutes, self-reliance emerges not by choice but by necessity. Signals crawling through space reshape how decisions unfold aboard spacecraft.

B. Data Streaming

Embedded within flight suits, smart textiles relay crew health metrics directly to onboard computers rather than ground stations. During flight, such materials monitor vital functions continuously. Because communication stays internal, information avoids interplanetary delays. Within the cabin, processing units register changes in real time. Threads woven into garment strata carry biometric impulses with near-invisibility. Onboard systems retain data, directing it solely to adjacent computing units. Never sent downward, it remains distant from remote operational stations.

C. Latency Zero

Instant signals emerge when oxygen levels change - response time is zero. Should the heartbeat behave unusually, feedback follows at once, not afterward. In case radiation rises sharply, reaction occurs ahead of awareness. Without pause, adjustments prompt immediate replies. At the exact needed second, each warning reaches its target.

D. Ambient Monitoring:

During sleep, movement inside the living space is monitored by embedded sensors. Changes in vocal patterns emerge through subtle audio tracking over time. Technology built into furniture or walls replaces the need for wearable devices. Motion detection equipment lines the perimeter, capturing shifts without intrusion. Background processing handles speech cues without drawing attention. Presence alone activates observation within the area. Motion captures automatically, free of wearable aids.

EVOLUTION OF ASTRONAUT HEALTH MONITORING

A. Traditional Monitoring Systems

First were the checks on vital signs. The doctors then looked at the blood samples. Afterward

was the physical examination. The laboratory results were delivered through courier service. Manual inputting of the data to spread sheets happened afterwards. Weekly discussions of the results were done by specialists. Finally, paper records kept the results.

1. *Periodic testing:*

Halfway into the journey, the astronauts were doing tests according to schedules made even before the journey had

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started. Such arrangements meant that changes in physiological processes could go unnoticed.

2. *Sampling:*

In the vast reaches of space, sampling was an action that took a great deal of time. At times, they would review their findings right then and there; at other times, they would leave everything to check later on.

3. *Active reporting:*

Back on Earth, mission teams waited for updates from spacewalkers checking in by voice. Each report came through slowly, shaped by how they felt at that moment - tired, alert, hungry - no sensors, just words spoken into a mic.

Back on Earth, doctors often check blood, run scans, then review what they see - that kind of routine happens up in space too (NASA). Messages between orbit and ground control crawl instead of race, so waiting becomes the only option when answers matter most.

B. Transition to Ongoing Monitoring

Modern technologies employ wearable devices to monitor:

A. *Heart Rate*

Out in the open, tiny sensors built right into watches or skin patches keep an eye on how the heart behaves over time. When something shifts - like a heartbeat that stumbles or rising tension - the device knows before it becomes obvious. These signals travel quietly, feeding live updates without anyone having to schedule a single doctor visit.

2. *Physical activity:*

The sensors within the machine always monitor the movements of the astronauts. Bones lose strength rapidly in space; hence, physical activity is essential. Motion sensors document all their exercise sessions. Muscles grow weaker without exercising; hence, exercise becomes a

continuous process. The machines document all the movements, ensuring nothing is overlooked.

Watching things closely over time helps spot odd changes fast - so care can start before problems grow. A steady eye means issues rarely sneak through unnoticed, catching small signs shifts how support unfolds later on.

WEARABLE SENSOR TECHNOLOGIES

The flexible wearable technology has become the bedrock of Worn close to the skin, astronaut health sensors replace heavy equipment once standard in space travel. Instead of rigid devices, flexible systems move with the person inside. Because floating disrupts fixed instruments, adaptability becomes critical during flight. With these updates, tracking vital signs continues quietly alongside daily tasks.

A. Allows continuous physiological tracking:

Worn like patches on skin or built right into clothes, these devices stay out of the way while tracking vital signs nonstop. Because data flows constantly, crew doctors see patterns unfold hour by hour across full days. Subtle shifts - like slight rises in body heat or changes in breath rhythm

during rest - show up clearly over time. Unlike quick checkups at fixed times, continuous observation captures what brief visits miss entirely.

B. Provides non-invasive monitoring:

Most flexible wearables shine by tracking body functions - no needles needed. Through skin-level scanning, new light-based tools follow blood flow quietly. Meanwhile, tiny channels inside the device capture sweat, revealing shifts in stress markers, salts, and energy use. These updates come without pricking or tubes, just steady contact.

C. Enable real-time analysis:

Because these devices contain tiny processors handling edge computing, immediate analysis of gathered information becomes possible. Should an astronaut's body show sudden shifts, alerts appear right away - no need to wait for ground-based systems or the spacecraft's main computer. Processing happens locally, cutting delays that could matter in emergencies.

D. Point-of-Care Diagnostic Systems in Space Communication delays with Earth create a situation

where immediate access to clinical health checks becomes mandatory during long-duration space missions. Experts claim that Point-of-care testing (POCT) systems address this challenge by allowing space travel professionals to conduct medical examinations directly onboard spacecraft. While customary methods require that biological samples are returned to Earth for scientific assessment, Point-of-care testing (POCT) devices provide rapid and reliable results within the spacecraft itself. Because lateral flow immunoassay (LFIA)-based biosensors require small amounts of supplies and operate without complex instrumentation, lateral flow immunoassay (LFIA)-based biosensors are particularly suitable for such applications in microgravity environments. Autonomous healthcare and timely medical decision-making in deep space exploration are assisted by Point-of-care testing (POCT) systems.

Recent 2025 research highlights:

Bone density decreases alongside muscle weakening during extended periods of inactivity. Meanwhile, changes occur in heart-related functions under similar conditions. Physical systems adapt differently when movement is reduced over time

Now equipped with sensors, today's wearable devices capture exact levels of electrical activity via EMG alongside three-dimensional motion data from targeted muscles. Because these tools track how hard the body works, they help monitor astronaut exercise routines designed to fight muscle loss in space. Instead of guessing effort, scientists rely on real-time signals showing muscular load during resistance training in weightless conditions.

- Stability and data integration issues (CoLab):

Even though these systems are highly developed, working in space brings serious engineering hurdles. Studies show keeping sensors firmly attached proves difficult because skin constantly sheds while humidity shifts. On top of that, combining vast streams of varied data from multiple crew members into a single clear analysis platform remains a stubborn coding challenge.

Among findings, wearable tech proves useful during spaceflight by tracking heart behavior under microgravity conditions (Nature). When weightless, liquids inside the body shift toward the head and upper torso - this alters both blood pressure and how much blood the heart pumps. Evidence confirms these devices detect changes accurately, capturing data like

heart rate variability and trouble maintaining upright posture without delay. Their ability to deliver immediate physiological feedback positions them as practical tools for health oversight beyond Earth. Real-time metrics emerge clearly through consistent sensor performance in extreme environments.

New progress in electronic tools that people wear goes further than watching how the physical body works. These electronic tools now measure chemical substances inside the person because measuring chemical substances gives better data about health when medical professionals want to understand the body. Current academic works show that biological signal detectors are joined together to identify cortisol. Experts claim that cortisol is a primary signal for long-term mental pressure and how the body protects itself from illness. One tool which uses light from chemical reactions was built by researchers for use in outer space missions. This specific tool allows the measurement of cortisol found in the water of the mouth without causing any body injury to the person. Space travelers can see the cortisol levels immediately while they perform their working duties outside the earth. Those electronic tools maintain high precision when they are used in places with very low gravity even though the environment is difficult. Scientists have observed that medical checking is moving away from simple pulse monitoring toward looking at the complete chemical state of the body.

ADVANCED BIOSENSORS AND FLEXIBLE WEARABLE TECHNOLOGIES IN SPACE

A. Extended stays in space subject crew members to severe physical effects: muscles weaken under weightlessness, bones lose mass, heart function shifts, radiation levels rise. Because of this, new kinds of biological detectors are now in development - meant to track well-being constantly, spot illnesses sooner, allow treatment directly in orbit. Real-time analysis happens inside the vehicle, needing little material input; thus fitting situations far from ground-level hospitals. Even so, samples come without needles most times - using spit, perspiration, tiny blood drops instead. Accuracy remains high even when gravity nearly disappears around them.

B. Wearable tech bends easily, fitting astronauts' bodies without resistance. From heartbeat rhythms to shifts in brain signals - each detail moves through silent networks below the skin. Instead of rigid casings, soft materials hold sensors close, reading changes moment by moment. Data flows outward not just when asked, but constantly, like breath. Even

motion patterns reveal strain; tiny voltage spikes from muscles tell hidden stories. Oxygen saturation dips appear early, caught before symptoms form. Because wires vanish into thin air, movement stays unblocked across long stretches of time. Signals leap toward Earth, landing in quiet rooms where doctors observe silently. No bulky frames press against shoulders or limbs during sleep cycles. Each sensor type works apart yet blends results into one clear picture. Thought fluctuations register alongside body tremors, linked only by timing. Health becomes less guesswork, more steady stream of measured facts. Ground crews receive updates even mid-sentence in conversations from space. Comfort does not fade after weeks because pressure points never build. Electrical impulses from nerves join temperature trends in shared logs. Nothing shouts urgency unless thresholds cross invisible lines set long ago.

C. Even with major progress in technology, problems still exist when using biosensors and wearables in space. Because gravity is nearly absent, liquids do not move as they do on Earth - this causes bubbles to form, flow becomes uneven, and substances mix poorly, interfering with sensor readings. Devices need careful engineering to operate within tight limits for energy use, physical dimensions, resilience, and safety, all while protecting sensitive biological materials from cosmic rays. Another layer of difficulty arises from combining information across platforms, maintaining consistent function, and handling personal health details securely. Without resolving these barriers, dependable, self-running medical tracking cannot work reliably during extended travel beyond low orbit.

Figure 1: Integrated architecture of biosensors and wearable technologies for astronaut health monitoring in space.

IOT AND TELEMETRIC HEALTH SYSTEMS

Remote monitoring becomes possible when sensors link with communication tools through IoT systems. Information travels automatically across interconnected devices toward a single hub, eliminating the need for people to manage data transfer. Centralized collection relies on these connections, forming the backbone of today's land-based telemetry operations.

1. Advantages

A. Remote accessibility:

From any place on Earth, health workers and mission teams access live data feeds without delay. Because signals travel instantly, constant oversight happens even when patients are far from medical staff. Distance fades as a barrier once information flows nonstop across

continents. Watching vital signs unfolds in real time, linking caregivers to distant scenarios seamlessly. Wherever someone needs attention, responders stay informed through continuous updates. Live transmission turns isolation into connection for treatment purposes.

B. Unified storage of data:

From every sensor, information flows into a shared storage space - sometimes local, sometimes online. Because everything lands in one place, spotting patterns across weeks or months becomes straightforward. What once sat separate now connects, allowing clearer views over time.

C. Scalability:

When missions evolve, or fresh tools appear, IoT adjusts just as fast. Adding extra sensors? No need to start over - fitting them in works smoothly. Each upgrade slots into place without tearing anything down first.

2. Limitations

A. Over-reliance on connectivity:

Should the signal break, face disruption, or be obstructed by celestial bodies, data flow stops. A steady wireless connection shapes every part of how the system operates.

B. Latency:

Even vast streams of live data move with delay across network systems. When alarms trigger at sensors, the brief gap before headquarters acts on that signal can matter greatly during crises.

C. Security threats:

Because signals travel through air, they can be intercepted, disrupted, or manipulated by attackers.

Protecting sensitive data demands encryption - yet achieving strong security here involves complex hurdles.

IOMT-BASED AND EMBEDDED BIOMEDICAL MONITORING SYSTEMS

Health tracking in space now relies increasingly on connected medical devices that operate nonstop. These systems gather data without interruption, using networked sensors across spacecraft environments. Instead of isolated tools, they function as linked units sharing information constantly. Such setups allow precise observation of bodily changes during long

missions. Rather than periodic checks, assessments occur steadily through automated feedback loops. Integration into daily routines happens naturally, avoiding disruption to crew activities.

From wearable sensors, IoMT setups gather live data on vital signs. These systems track essential body metrics continuously. Physiological measurements flow directly into digital networks. Live updates come through small devices worn by individuals. Key health indicators are recorded without delays. Information moves automatically from sensor to system. Monitoring happens as bodily functions change

1. Oxygen saturation (SpO₂)
2. Heart rate variability (HRV)

From here, information travels toward cloud-hosted systems offering:

1. Scalable data storage
2. Real-time analytics
3. Remote accessibility for medical experts

Where medical staff are scarce, these tools enable steady observation along with prompt care when needed. Though oversight is remote, health responses still occur without delay through automated alerts and consistent tracking across isolated settings.

At the same time, small medical sensors have been built into space suits to track astronaut health during work outside vehicles. While these systems operate, they gather body data without interrupting movement. As missions extend beyond the craft, monitoring becomes essential for safety. Because conditions change rapidly, real-time feedback supports timely decisions. Though lightweight, the devices maintain accuracy under extreme stress. Where traditional gear fails, new materials allow flexibility and durability. Since power is limited, energy efficiency shapes design choices. With every mission, refinements improve reliability across environments.

Among these setups are various sensing devices. Some include thermal detectors. Others feature motion trackers. A few rely on light-based instruments. Each uses different components depending on function

1. Pulse oximeters (SpO₂ monitoring)
2. Skin temperature sensors
3. Galvanic skin resistance sensors (stress detection)

Sensor information gets handled directly by internal hardware, then sent onward through secure channels. From local analysis it moves without delay toward centralized nodes. Processing occurs at source before transfer begins in sequence. Data flows first through embedded circuits prior to external relay. Only after on-device interpretation does transmission proceed accordingly

1. Spacecraft computers
2. Mission control centers

Visualization of bodily functions occurs instantly through this setup, making it possible to spot irregularities sooner. Early warnings emerge because data appears without delay, supported by continuous monitoring capabilities.

Integrated systems of this kind enable ongoing, self-reliant tracking of health - crucial when journeys extend far into space and last for extended periods. Though automatic oversight may seem routine, its role grows critical under isolation where medical aid is beyond reach.

ARTIFICIAL INTELLIGENCE IN SPACE HEALTHCARE

Among tools available today, artificial intelligence stands out when managing vast volumes of astronaut physiological data. Because these systems assist with handling specific challenges. One such challenge involves detecting subtle changes in vital signs over time. Where patterns might escape human observation. Though machines process inputs continuously. As conditions shift during long missions. Which makes real-time analysis critical. Since delays could affect outcomes. When early warnings are necessary. Even minor anomalies gain significance under extreme conditions. While traditional methods struggle with scale. Given how much information accumulates daily. So adaptive models become essential. If accuracy must be maintained. Until mission objectives conclude

a. Detection of anomalies:

Among streams of information flowing each second, subtle shifts - like slight variations in breathing patterns - are quietly isolated. These tiny deviations often escape human observation entirely. Through continuous examination, machines detect what eyes might

overlook. Precision emerges where attention fades. Rare signals rise into view only through persistent sorting. Attention focuses on what seems insignificant at first glance.

b. Forecasting health problems:

Future health problems - such as viral outbreaks, weakening muscles, or cardiac events - may show early signs

when past and current data are examined together. Patterns emerge before symptoms appear, given careful review of accumulated records alongside live inputs. Insights arise not just from volume but from timing, sequence, occasional outliers. One moment reveals little; a series over time tells more. Detection improves when silence between signals is also considered. What happens weeks prior often matters as much as what occurs seconds before onset

c. Providing decision-making support:

Operating independently, this system supports astronauts lacking medical training during emergencies by guiding initial assessments. When immediate contact with doctors on Earth is unavailable, it directs essential diagnostics. Steps for intervention follow based on real-time analysis. Decisions emerge from embedded protocols tailored to acute scenarios. Assistance unfolds without reliance on external communication. Procedures adjust according to observed conditions. Inputs shape subsequent actions systematically. Clarity forms through structured response patterns. Safety gains arise via consistent internal logic. Outcomes depend on preloaded clinical pathways.

In 2025, research revealed artificial intelligence improved detection of health irregularities in space travelers by roughly 22 percent through data gathered from body-worn sensors. Because newer algorithms focus on spotting bodily changes in weightless environments, today's models reduce incorrect alerts much more effectively.

Breakthroughs built on key techniques

A. Deep Learning:

Processing intricate streams - such as unfiltered ECG outputs, environmental sensor readings, alongside subtle shifts in facial behavior - is handled through layered computational models. These structures uncover patterns otherwise invisible within an astronaut's physiological state. Hidden links emerge when diverse inputs interact across deep frameworks. Complexity becomes traceable once signal types are unified under non-linear transformations. Insight arises not from volume but from structure-sensitive analysis.

B. Time-series Modeling:

Among tools suited for time-based patterns, certain algorithms handle bodily signals best. A case in point: recurrent neural networks track shifts in an astronaut's vitals across extended periods without pause.

C. Personalized Health Modeling:

A digital twin forms for every astronaut, shaped by individual physiology rather than broad norms. Because of this, baseline health metrics shift per person, guided by personal data patterns. Uniqueness in these references allows detection of anomalies at finer levels. Precision rises when expectations follow one's own rhythm, not group averages.

Even so, reliance on cloud-based AI introduces lag in data exchange, which demands the shift toward edge AI solutions. Communication lags of several minutes in deep space render ground-based supercomputing ineffective; real-time warnings become unfeasible under such conditions. As a result, aerospace specialists now lean heavily on localized computation - running advanced algorithms directly through hardware embedded in spacecraft or even within sensors of portable gear.

BIG DATA AND CLOUD-BASED HEALTH ANALYTICS

Among large-scale data platforms stands Artemis - a system designed for immediate handling of medical data streams. This framework responds to intense flows generated through continuous patient monitoring. Built specifically for velocity and volume, it processes live signals without delay. Its full name reveals purpose: A Real-Time Environment for Medical Information Systems. Operation occurs under demanding conditions where timing affects outcomes.

- ***Enable***

- a. Real-time analytics**

While processing constant flows of information from multiple detectors simultaneously, such systems execute advanced health computations instantly. A drop in circulation strength combined with an unusual respiratory rhythm becomes meaningful through their ability to connect separate physiological signals, identifying serious bodily events precisely as they arise.

b. Handling large amounts of health information:

Large-scale data platforms excel in gathering extensive, complex datasets over long durations. As a result, health professionals may link current crew vital signs with vast archives of past records. With time, patterns emerge across layers of stored information. When examined closely, these connections support deeper understanding of physical responses. Over months or years, such storage reveals subtle trends otherwise missed. Because detail accumulates steadily, comparisons grow more meaningful. From this foundation, assessments gain depth through reference to earlier cases.

- ***However***

High bandwidth becomes necessary under these conditions. Despite carrying live patient signals - uncompressed vital signs, real-time ultrasound streams, or molecular test results - a vast amount of spectrum space becomes essential. Owing to inherent constraints in interplanetary links, available throughput remains too narrow to support dense analytical systems.

c. Need communication networks:

Heavy computations today rely on ground-based supercomputers or cloud platforms. Because of this, uninterrupted links through space communications become essential. Take NASA's Deep Space Network - it supports critical functions needed for stability. When signals fail, even briefly, medical systems tied to them stop working entirely.

PROGNOSTIC HEALTH MANAGEMENT (PHM)

Beginning before symptoms arise, RePHM shifts focus from delayed responses to forward-looking care. Rather than responding only after crisis occurs, it emphasizes continuous readiness under intense conditions. Through early detection methods, health tracking becomes a steady presence, not an occasional reaction. Monitoring systems anticipate strain before breakdowns happen, especially where risks are high. In such settings, prevention takes shape via consistent observation and adaptive support. This approach relies on data patterns that signal change well ahead of failure points

a. Early detection of problems:

Weeks prior to symptom onset, PHM identifies initial biological shifts through continuous observation. Radiation-induced cell changes appear gradually; these are captured promptly by the system. Infections reveal themselves quietly

- detection occurs at first measurable shift. Bone density loss, though slight, registers clearly under active tracking methods.

b. Provision of early warnings:

If PHM identifies a declining physical condition in astronauts, a warning activates to alert them of potential health issues. Consequently, measures may be taken to avoid worsening states - adjustments to food intake might occur, specific strength-based exercises could begin, or medicine may be used when needed.

c. Decision-making tool:

Should an emergency arise, PHM provides clear and impartial data. When predictions regarding astronaut health are precise, choices around readiness for spacewalks gain clarity through PHM insights. Mission adjustments follow logically when such foresight supports them.

This result comes by including:

d. Sensor information:

From flexible wearables to intelligent garments and vehicle environmental monitors, information flows without pause - capturing elements such as pulse fluctuations, chemical makeup of perspiration, alongside levels of oxygen within the crew compartment. Streamed continuously, these varied measurements emerge through interconnected sensing platforms designed for dynamic conditions. Rather than pausing between inputs, updates arrive in constant succession, each tied to physiological or surrounding changes. Heart-based rhythms shift into digital records just as air quality values feed into broader observation sequences. Data types differ widely, yet transmission follows a uniform rhythm across devices.

e. Machine learning:

From streams of relentless data, complex algorithms draw patterns using advanced AI methods. Where shifts occur, predictive systems adjust the individual astronaut profile through adaptive modeling. Hidden links - like those connecting rest cycles to mental strain - are mapped without human guidance. Over time, these models evolve alongside their subjects, shaped by fresh inputs at every turn.

f. Past medical history:

Analysis happens alongside past records. Context shapes how live information is interpreted.

Before launch, health details are recorded - genetic tendencies included. Reactions to low gravity form part of that background. Interpretation relies on these stored patterns. Past behavior guides present assessment. Information flows into a framework already built. History becomes structure for current decisions.

Still, putting PHM systems into real-world use brings notable difficulties. Processing highly complex, data-heavy models without pause calls for significant computational capacity. Given that operation must occur locally through edge computing - necessary to avoid delays caused by vast distances in space travel - the burden grows heavier. Operating under strict limits on mass, energy use, and heat dissipation makes meeting those intense processing needs a central hurdle in current aerospace medical engineering.

MULTIMODAL SENSOR FUSION

Facing complex data, systems combine sensor inputs to improve precision by relying on diverse measurements. Unlike single-parameter analysis - prone to errors due to variability - a multi-sensor approach mirrors medical diagnosis where conclusions emerge from multiple observations. Resulting clarity comes not from volume but from cross-verified signals gathered independently.

Techniques

A. Kalman Filtering:

Though measurements from wearable devices often suffer distortion due to movement or electromagnetic disturbances, the Kalman filter offers a structured mathematical approach. Because space environments introduce irregular disruptions, such precision becomes critical. Instead of accepting raw data at face value, this method estimates actual bodily conditions - like real-time heart rate - by refining assumptions over time. With every new input, adjustments occur subtly, reducing inaccuracies without abrupt shifts. Despite external chaos, consistency emerges through iterative correction. Thus, reliability improves naturally, not by force.

B. Bayesian Inference:

When analyzing health data, one approach adjusts likelihoods as new information arrives. A sudden rise in heartbeat measured by wearable fabric might seem unimportant early on, given its isolated nature. Yet should environmental sensors also record falling oxygen levels inside the vehicle, assumptions shift. Probability shifts upward when both signals align, guiding

reassessment. Such combined inputs prompt revised conclusions through structured reasoning methods. The weight of dual indicators alters initial judgments significantly. Earlier doubts fade once multiple streams suggest similar outcomes. This form of evaluation responds dynamically to layered observations. Conclusions evolve only when supporting signs accumulate gradually. Initial uncertainty gives way under consistent patterns emerging over time.

C. Machine learning:

Though large neural models handle intricate patterns well, they excel when linking diverse data types through nonlinear logic. Because of deep learning methods, correlations emerge across imaging from handheld ultrasound devices, chemical markers in perspiration collected by wearable sensors, and movement tracked by three-axis accelerometers. These combined inputs reveal bodily changes missed by standard statistics due to system-wide interactions hidden beneath surface metrics. Only layered network structures uncover such subtle cross-domain shifts without relying on linear assumptions.

Recent studies indicate fusion improves system dependability yet introduces greater processing demands (arXiv). Because information comes from separate sensing units, incorrect alerts grow rare - monitoring continues even when one sensor stops working or loses contact with the body. Still, aligning several ongoing data flows while filtering and analyzing them requires strong computation power. Handling this volume of tasks under tight onboard computing conditions aboard a space vehicle remains a central hurdle for uninterrupted health tracking.

ADVANCED DIAGNOSTIC TECHNOLOGIES

Approaches now available involve techniques such as these Molecular Testing

A. Genomic analysis:

Out beyond Earth's shield, radiation floods through cells while weightlessness alters internal rhythms - gene activity shifts under such strain. Monitoring unfolds aboard station labs where tools track RNA behavior and protein creation as they happen instead of relying on delayed analysis from ground centers. Signals emerge showing cellular stress, markers shift across genetic controls, sometimes revealing damage within DNA strands that could lead to illness years later.

B. Personalized testing:

A single genetic blueprint defines every astronaut, reacting in distinct ways beyond Earth's atmosphere, so tracking molecules becomes necessary for custom healthcare. Because of this, artificial intelligence aboard can shape individual regimens - meals, defenses against cosmic rays, medications - aligned precisely with each person's biological state.

Nanoscale Monitoring

A. Detection of ocular health:

Occasionally seen in space environments, SANS arises when bodily fluids shift under altered gravitational conditions, often leading to visual disturbances. Detection becomes possible through advanced contact lenses embedded with microscopic sensors capable of measuring eye pressure along with trace compounds found in tear fluid.

B. Non-invasive approaches:

Because of progress in tiny-scale technology, highly responsive miniaturized detectors now identify trace amounts of biological signals down to one in a billion. Breath, sweat, or saliva alone might reveal early signs of viral activity, heart irregularities, or tension markers - matching accuracy once requiring blood analysis.

New progress in tools for diagnosing health in space focuses on small devices made from paper and tiny channels that guide liquids. Instead of complex machinery, these rely on natural wicking to move samples through the system - a trait useful when gravity is weak. One method drawing interest uses immune reactions on strips that show results without power sources. Because they require minimal handling, such formats suit long missions far from Earth. Adding light-producing chemical reactions improves the ability to detect subtle signs of stress hormones like cortisol. With this combination, real-time tracking becomes possible inside spacecraft during extended travel. Such designs prove practical solutions exist for maintaining crew well-being beyond our planet.

ECOSYSTEM FOR SMART WEARABLES

Components of Integration:

a. Wearable:

Here lies the individual piece inside the system. While functioning separately, it connects through shared structures. Not isolated, yet distinct in role. Its presence supports balance across parts. Through interaction, influence moves both ways. One element shifts, others

respond silently.

Among these are smart textiles with high adaptability, capable of responding to subtle changes. Biometric devices worn on the body form another part, tracking real-time physical data. Skin-based sensors add further detail by measuring biochemical shifts and muscular function. Electrocardiogram readings emerge continuously from such systems. Flexibility defines much of this technology, allowing close interaction with human physiology. Constant oversight extends to heartbeat patterns and metabolic signals alike.

b. Ambient intelligence:

A network of interconnected systems transforms the living environment into a silent observer for health monitoring. Using advanced air-quality detectors, it captures subtle shifts in breath composition. Voice analysis occurs through sound-based instruments tracking vocal strain linked to psychological load. Movement evaluation happens via light-sensitive devices studying walking patterns and physical exhaustion.

c. AI systems:

Processing occurs within the ecosystem through a dedicated unit. From wearable sensors, biological signals emerge alongside environmental inputs gathered by ambient systems. While one stream captures body metrics, the other records surrounding conditions. Despite differences in origin, both feeds converge into unified analysis. Through structured computation, raw numbers transform into meaningful indicators. With continuous flow, assessment keeps pace with changing states. Real-time output reflects current well-being of personnel onboard.

COMPARATIVE ANALYSIS

prediction systems may capture noise rather than patterns. Limited samples increase the chance models fail when applied beyond known cases.

e. Environmental concerns:

Deep space creates challenges for constant observation. Radiation damages tiny electronic parts. Microgravity alters skin shape, so sensors lose contact. Background disturbances disrupt quiet tracking methods.

Table 1: Comparative Analysis.

Approach	Real-Time	AI Support	Accuracy	Dependency	Limitation
Biosensors	No	No	Medium	Low	Limited Scope
Wearables	Yes	Partial	Medium	Medium	Reliability
IOT Systems	No	Yes	High	High	Latency
AI Systems	Partial	Yes	High	High	Cloud Dependency
PHM Systems	Yes	Yes	High	High	Complexity
Sensor Fusion	Yes	Yes	Very High	Medium	Computation
Molecular Monitoring No	No	Limited	High	Low	Experimental

RESEARCH CHALLENGES

Some of the key difficulties include:

a. Systems that decide without human guidance do not exist here

Despite existing practices relying on human oversight, medication choices today remain under the authority of ground-based flight surgeons. When traveling beyond near-Earth orbits, an independent artificial intelligence framework becomes necessary - one that operates without constant external input.

b. Power limitations with wearable devices:

Constantly capturing, handling, or sending data on bodily functions demands significant energy. Designing wearable devices becomes difficult when internal power sources are used - these increase the mass of a flight outfit. Though lightweight materials help, added battery bulk remains an obstacle during movement. Equipment meant to monitor health must balance function with physical strain, especially where every gram counts.

c. Challenges regarding the data integration process:

Among emerging tools, a high-level tracking platform generates vast amounts of varied information - one moment numeric pulse readings, the next raw audio signals showing voice stress. Handling these diverse inputs requires alignment, sorting, correction, and integration; yet doing so within tight processing limits complicates development. Unexpected bottlenecks arise when blending formats under minimal hardware capacity, pushing design boundaries in

subtle ways.

d. *Insufficient data on real astronauts:*

High accuracy in machine learning depends heavily on large datasets. Yet human exposure to extended space travel remains minimal. Because of this scarcity, astronaut health records are too sparse for reliable modeling. As a result,

FUTURE DIRECTIONS

Future work needs to investigate:

A. *Edge AI-based monitoring:*

In order to conclusively address the issue of latency associated with massive distances in space, future developments will require compression of complex neural networks to enable them to operate fully on the "edge." This implies conducting all sophisticated diagnostic algorithms on the wearable chips or onboard spacecraft computer servers to ensure instant alerts to medical concerns without relying on Earth.

B. *Energy-efficient wearable devices:*

Research is now leaning towards medical wearables that can sustain themselves. This entails designing extremely low-power microchips and incorporating innovative power-generation technologies, such as piezoelectric materials capable of producing electric energy through the astronaut's bodily movements or thermoelectric generators fueled by body heat, to avoid carrying heavy and finite batteries.

C. *AI + PHM hybrid systems:*

Future designs will be based on a seamless fusion between AI technology and Prognostic Health Management (PHM). Rather than responding reactively to immediate sensor inputs, the AI+PHM system would dynamically forecast the astronaut's health status several weeks ahead by simulating possible missions to suggest preventive actions in terms of diet, physical activity, or scheduling.

D. *Healthcare using digital twin technology:*

In aerospace medicine, the development of digital twins, which are highly accurate, continuously refreshed virtual representations of each individual member of the crew, is progressing rapidly. By inserting telemetry data into these highly detailed and constantly changing models, onboard AI will simulate the progression of a particular illness or the effect

of a medication in billions of iterations within seconds, all without touching the astronaut.

E. Models of astronaut health:

The idea of the "baseline human," which applies to every astronaut, is already outdated in space exploration. Models for future missions will have to be highly personalized, incorporating the results of genetic sequencing before the flight and other relevant information about the astronaut, including his or her biological response to microgravity.

CONCLUSION

In this survey, astronaut health monitoring systems were thoroughly analyzed. The vital development in health monitoring is described – transition from the reactive type of medicine that used regular testing with manual samples' taking to the present stage, when wearable devices are employed along with IoT telemetry framework.

Despite all innovations, current methods are far from perfect. Current solutions utilize the cloud infrastructure, and cannot be considered autonomous. Modern technology allows gathering continuous and highly precise physiological information; however, analysis requires supercomputer resources back on Earth. Continuous reliance on Earth-based computer and "human-in-the-loop" controllers is critical for safety; however, communication latencies associated with physics of space create significant risks. Inability of physicians to intervene remotely means that deep-space travel is not viable under the current system.

Development of AI, multimodal sensors, and edge computing marks the way to go forward. For successful completion of a mission to Mars and other long-term flights, autonomous medical care systems will be needed. With the help of multimodal sensors collecting all types of physiological information, edge computers processing it instantly regardless of bandwidth, and artificial intelligence that performs tasks of a doctor, it is possible to gain the necessary independence.

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