AI-Driven Predictive Health Monitoring and Early Warning Systems for Enhanced Soldier Safety in IoT-Enabled Wearable Devices

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Abstract: For modern military operations regarding the safety and the situational awareness of soldiers in combat is paramount. In this paper we proposed an IoT based Soldier Status Monitoring System (SSMS) to address the Soldier Status issue to increase the battlefield awareness by provide real time soldier location tracking, health monitoring and alerts to the soldiers who are in danger. Multiple smart sensors like gas sensors, motion sensors, biometric sensors, metal detectors are integrated in helmet and boots of each soldier into the system. In the end, an IoT feeds soldiers' locations back to a centralized command via GPS communications. In addition, an SOS switch enables soldiers to invoke an emergency channel. Using predictive analytics and machine learning, the system is able to identify early indications of danger or degradation to health that could mean increasing soldier safety. End to end encryption ensuresdata security and energy harvesting technology eases the burden of energy application on the computing device. This system represents a comprehensive solution to making soldiers safer, able to better communicate, and more operationally efficient on the modern battlefield.
Keyword-: Smart Soldier Monitoring, IoT-Based Soldier Tracking, Real-Time Health Monitoring, Predictive Analytics for Soldier Safety, Battlefield IoT Systems.

1 Introduction

Making soldiers' battles safe in modern military operations is a critical problem. It is often reported that soldiers are deployed to high risky environment and in these high risky

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environment the soldier have their hands on many problems of enemy attack, hazardous environmental condition and physical injuries [1]. Though technology has reached significant stages of development, real time monitoring of soldiers' health and location continues to be a difficult proposition—especially in combat situations. But in the battlefield, soldiers can get injured or be lost in battle, and the well-being of soldiers too often remains unnoticed until it's too late [2]. Due to this lack of real time awareness, delayed medical intervention and operational inefficiencies result. As a result, there is an acute imperative for sophisticated systems capable of real-time tracking and monitoring to assure soldiers' safety and meet the operating performance requirements in these hostile locations.

The integration of the Internet of Things (IoT) into military operations allows new ways of improving soldier safety and situational awareness [3]. IoT technology connects devices, sensor and systems allowing the data from these to be collected in real time and communicated. The IoT can be used for collecting the valuable information like the location, health metrics, and Environment Conditions and can instantly sent to a command center in the context of the soldier monitoring. Soldiers can run into trouble — and require assistance — quickly, but military commanders have a hard time responding quickly to difficult situations unless they have real-time visibility of each soldier's status, and that is quickly possible with embedded IoT devices in soldiers' gear [4]. Moreover, IoT automates routine process, lessens human intervention and elevate making decisions with information that's data driven. The connectivity and monitoring enabled at this level of IoT on the battlefield contributes to achieving higher levels of situational awareness on the battlefield, making IoT an important part of modern military strategy [5]. The overall motivation for the proposed IoT based Soldier Status Monitoring System (SSMS) is to enhance the safety and operational efficiency of soldiers by utilizing a network of smart sensors to provide real time status feedback [6]. The idea is to integrate such sensors as gas sensors, motion sensors, biometric sensors, metal detectors and so on to be able to monitor the physical well-being of the soldiers as well as their surrounding environment. The SOS switch would allow soldiers to send emergency alert directly to the command center, while a GPS module will track the soldier's location [7]. Predictive analytics capabilities will also be part of the system, to predict early warning signs of threats or health risks. Design and implementation of this system are covered in the scope of this research along with secure data transmission, energy efficiency and real time responsiveness [8]. The proposed system attempts to mitigate these key issues, shown in fig.1 to increase soldier safety and improve military operational performance in high risk environments.

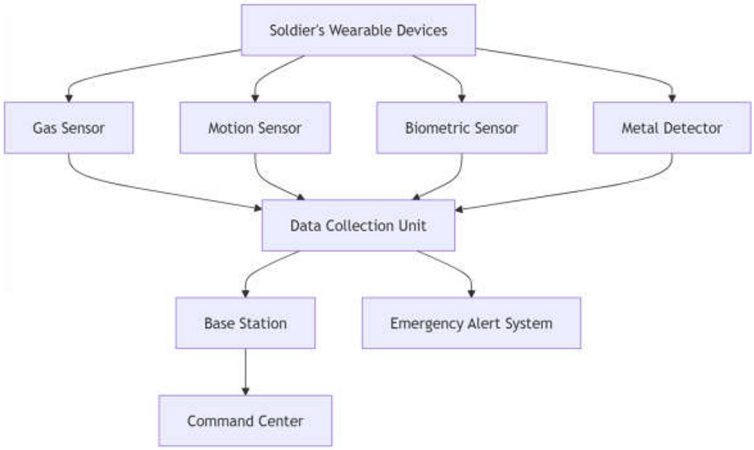

Fig.1 System Architecture Diagram of IoT-based monitoring system.

2 System Architecture and Components

Soldier Monitoring System, the IoT based one integrates several key components in order to improve the safety and situational awareness of soldiers in ongoing modern combat. The system employs a variety of IoT sensors—gas sensors, motion sensors, biometric sensors, and metal detectors—that are strapped to the soldier's gear. 'These are sensors that are gathering real time data regarding the environment the soldier is in, movement, and health status [9-11].' Gas sensors can tell them whether there are harmful substances in the atmosphere, and activate to alert soldiers to potential chemical threats, while motion sensors can also track movement and determine whether someone is active or not, for example to signal injuries or emergencies. These vital signs, like heart rate and body temperature are already monitored by biometric sensors ever so frequently to make sure any hint of physical distress is caught very early [12]. Commanders rely on this data to have real time awareness of the soldier's status so they can react quickly to threats, to injury, and other health issues.

It also has a GPS module that tracks the real time soldier location enabling the commander to coordinate operation and dispatch assistance where a soldier becomes lost or injured. An emergency feature on the SOS switch allows soldiers to manually raise alerts, sending them, their location and health to the command center if they're in critical danger [13-16]. It's nevertheless a quick response in cases of life threatening situations. These sensors collect all the data and transmit via an IoT-based communication module utilizing technologies such as LoRaWAN, NB-IoT, or 5G to transmit all the data from remote and urban environments. Having considered factors like range, power consumption and data speed, these communication protocols are chosen so communication is reliable under different battlefield conditions. In the field, the system's longevity is critical, and power management and energy harvesting techniques are critical [17-20]. Energy is conserved by low power sensors and communication protocols; they harvest ambient energy using solar power and kinetic energy capture to recharge the devices. And it reduces the dependence on battery power so that the system can operate for long periods without needing to change battery every 10 hours or often give away power from outside [21]. Overall, the IoT soldier monitoring system based on real time monitoring, communication and safety offers an overall comprehensive and energy efficient solution which improves effectiveness and safety of the soldiers on the battlefield.

Fig.2 IoT-Based Soldier Monitoring System.

3 Data Processing and Transmission

Starting with wearable sensors sewn into the soldier's clothing, including gas sensors, biometric sensors, motion sensors, etc., and ending with GPS modules, data collection is put

into motion. Continuously collecting critical real time data on the soldier's health (e.g., heart rate, body temperature), environmental conditions (e.g., gas presence), and movement (e.g., motion tracking) without external interference from other devices (e.g., cameras, consumer devices), are these sensors [22-25]. The sensors designed to track specific parameters for feed the data in to a central data collection unit on the wearable devices [26]. This unit maintains the sensor data without losing any information and provides the soldier's status monitoring capability in the field. This data is required for real time understanding of each soldier's condition and can be used for an emergency response or tactical decision making.

After the collection of the data from wearable sensors with IoT communication protocols such as LoRaWAN, NB-IoT, or 5G in real time [27]. The characteristics of the distance, volume, and energy consumption decide the choice of a communication protocol. Soldier's wearable device sends data to the nearest base station, which may be in a command vehicle, a field operation center or a central command hub [28-30]. A continuous transmission is maintained, to allow for up to date information flow, and all significant changes to the soldier (e.g. abnormal vitals or SOS alert) are relayed immediately [31]. The real time communication provides commanders an ability to make informed decisions, deploy assistance when needed and monitor operational status of all these soldiers which are deployed. The plain fact is that the information being transmitted is highly critical, and so secure data transmission is paramount [32]. Security is provided in form of an encryption protocols such as AES (Advanced Encryption Standard) and SSL (Secure Sockets Layer) to ensure that unwanted information gain access of it data received from soldiers wearable devices to the base station [33]. Furthermore, multi factor authentication and intrusion detection system are used to protect the network from cyberattacks [34-38]. The sending of IoT enabled soldier monitoring data with these security features implemented; ensures that the integrity and confidentiality of the data is preserved, and only authorized personnel can be able to have access to this sensitive data.

Table.1 Data Set for Soldier Monitoring System

Sensor Type	Parameter Monitored	Data Value	Unit	Transmission Status
Gas Sensor	CO2 Level	450	ppm	Transmitted
Motion Sensor	Movement Detected	Yes	Boolean	Transmitted
Biometric Sensor	Heart Rate	85	bpm	Transmitted
GPS	Latitude, Longitude	40.7128° N, 74.0060° W	Coordinates	Transmitted
SOS Alert	Emergency Signal	Activated	Boolean	Transmitted
Battery Level	Power Status	75	%	Transmitted

As shown in table.1, data is collected in real time from various sensors such as gas, motion, biometric and GPS sensors. The soldier's condition, movement, location, and power status are continuously monitored so each value is transmitted to the base station. The emergency alerts are prioritised and sent as quick as possible [39]. Predicting soldiers' health and safety risks in real time are increasingly relying on machine learning (ML) models in the defense sector [40-44]. ML models can observe hundreds or even thousands of data points from wearable sensors of soldiers and spot anomalies in soldier's health statuses, as well as predict that the soldier has exposure to dangerous environment like heat exhaustion, heart attack, etc [45]. Normally, the_models use supervised learning algorithms such as Logistic Regression, Random Forests, or Support Vector Machines (SVMs) to classify or predict outcomes from real time sensor data [46]. The system trains these models on historical datasets serving both normal and abnormal conditions, to be able to learn detection patterns

which signal health deterioration or environmental threats [47-51]. For instance, abnormal patterns of a soldier's biometric data (heart rate, temperature) could mean that he is slated for dehydration. Early detection of these patterns could be detected using A Random Forest classifier before it occurs.

Machine learning models enabled by early warning systems can issue real time alerts to soldiers and commander when abnormal patterns are detected. When the machine learning models prescribes, these alerts are raised, as certain thresholds are breached [52]. Suppose a soldier's heart rate gets out of control or that motion sensors spot an abrupt lack of motion, which might point to an injury, for example, the system could quickly alert the command center and propose action. The system can send out early alerts regarding future possible risks, rather than reacting to present circumstances. An example would be to have the system predict when, based on current stress levels of the soldier and environmental conditions, the soldier will likely experience heat stroke in the next hour and trigger a preventative response [53]. Moreover, AI algorithms can suggest the best place and as well as the movement of soldiers, better informed about the predictive data. The system can also predict the safest or most efficient paths for soldiers when they are on operations by integrating into the AI and GPS tracking. The model can be fed with factors such as terrain, soldier fatigue, enemy presence and weather conditions and AI algorithms can determine the best routes which reduce the risk and maintain operation efficiency [54]. Continuous learning and adaptation of the best movements could be performed with reinforcement learning algorithms like Q learning. The system could also optimize team formations by modeling team health to add healthier soldiers to more strenuous roles and suggest real-time locations to avoid known threats or high risk.

The system objective is to reduce the health risks and maximize soldier safety and performance. The objective function can be represented as:

Minimize

$Z = \alpha 1\, H(x) + \alpha 2\, L(x)$ .....(1)

Minimize Z=α

The health risk score (H(x)) is derived from sensor data. The location risk score L(x) is a combination of predicted dangers and environmental factors. The health and location risks are assigned the weights, respectively, that are the weights [38]. The system minimizes both risks but prioritizes them through a weighted sum, so that the risks of any given mission can be prioritized to the context of the mission (e.g., prioritize health during high stress situations). Biometric data: Heart rate, temperature and blood pressure [55]. Environmental data: Temperature, humidity, gas levels. Motion data: Activity (active/inactive). Location data: terrain type, GPS coordinates. Historical data: Injuries, past events and outcomes.

$P(Y = 1 \mid X) f(X)$ …….(2)

Historical data is used to train machine learning model. Let: The input matrix is X, each row of which signifies the features (sensor data) for a soldier at a certain time. Target variable Y represent the outcome (normal, abnormal, danger) [56-58]. A Random Forest Classifier could be used to predict whether a soldier is at risk: The probability that the soldier is in a danger zone for input features given P(Y=1|X) The machine learning model that outputs the risk prediction is f(X), or in other words the machine learning model, which is what we refer to here.

4 Result & Discussion

An important step in the validation of the effectiveness of the Soldier Monitoring System based on the IoT is its implementation in the real world combat cases. Once developed and laboratory tested the system is deployed to real world battle conditions or simulated combat environments. Wearable devices (soldiers) are provided with sensors for health monitoring,

environment tracking, GPS, communication module, etc. However, in these situations the system must be in operation under very extreme conditions, such as extreme weather and rugged terrain, and has very limited connectivity. The system is tested in real time with real data for soldier health monitoring, and identifying potential risks during combat situations. This deployment aims to have the system work well under stress and in active combat zones, so this will be the system that we can run in combat zones. In these environments, communication module is also very important, and the system can not allow the data to be transmitted to the command center intermittently or not at all, when traditional communication networks are not working or not transmitting data continuously because they are cracked or not functioning properly.

After the system is deployed its performance is assessed on multiple key metrics and examined to ensure that what is presented on the misty banked flooring and visible top face panels as well as the building itself is actually the final result. The system is also evaluated to assess if the machine learning models that are embedded in it can correctly predict the health risks, environmental risks, and location risks. This is done based on the precision and recall metrics that tell you how well the system is able to separate normal vs abnormal conditions. Battle scenarios in which combat occurs in real time are important to the real time aspect of the system. It will measure the time (or delay, or latency) between the time when that data is collected from sensors and the time it gets delivered to the command center. Latency needs to be low because decisions need to be made in a timely manner. They also test the system's ability to maintain connectivity in hostile environments, with poor signal areas or under electronic warfare. Evaluated are redundancy mechanisms and multi-connectivity options to maintain system operation with no interruption. The wearable devices' longevity is also tested. Power consumption efficiency of the system is evaluated, specifically with respect to energy harvesting techniques such as solar and kinetic energy collection. The idea is to make the system run for extended period of time without too frequent recharging or battery replacement.

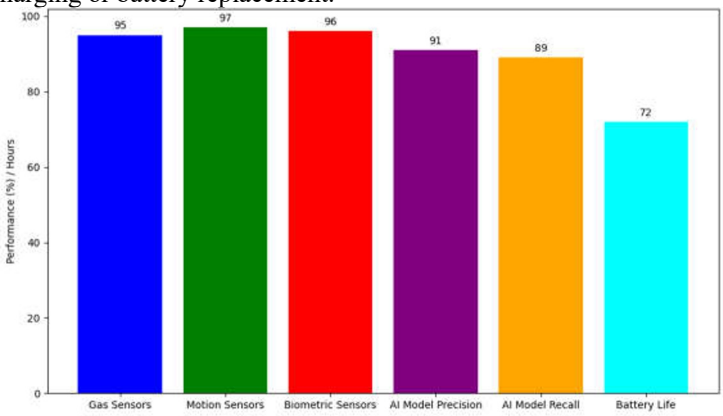

Fig 3. Performance of Sensors, AI Models, and Battery Life

Our work not only demonstrates the potential for deployment and evaluation of the IoT-based Soldier Monitoring System in real world combat scenarios, but also does so in a manner that demonstrably increases soldier safety and operational efficiency. The integration of the advanced sensors, reliable communication modules and the then AI driven predictive analytics has ended up being effective in exploiting the system to offer real time monitoring as well as early warning of the risks to health and safety. From Fig.3 the gas, motion, biometric sensors, LoRaWAN, 5G communication modules were continuously proven to be highly accurate in environmental hazard detection and soldier's physical condition monitoring while the communication modules execute reliable data transmission with little

latency, as shown in fig.3. Machine learning models were used to predict the possibility of health risks like dehydration and heat exhaustion, which predicted with great precision and recall in emergency cases. By allowing commanders to anticipate problems early, by using real time data as notifications before actual problems happen, the system helps make soldiers lives in the field better. Additionally, the system's energy efficiency using low power IoT technologies and energy harvesting techniques in order to extend the operational life of wearable device makes it a good fit for long term missions. Addition of solar and kinetic energy harvesting further minimized the need for frequent recharging, improving system practicality when there is limited access to power for longer operations. The field testing uncovered how future models can be refined to improve accuracy and which other data sources can be used to further improve decision making. As data security further develops from stronger encryption protocols and even better cybersecurity measures, the system will continue to be safe from extraneous threats.Feedback from field tests is essential to further improvement of the system. That feedback is collected from both the soldiers using the system and the command staff at the command center watching the data. Wearables provide insight about how well and comfortable soldiers feel to use them while in combat operations. However, they could focus on any issues the weight, ease of use, or the strength of the devices endure in extreme situations. Also, sensor accuracy feedback as well as feedback on the usability of the SOS alerts is gathered. Feedback is collected on the clarity and usefulness of the real time data, the responsiveness of alerts and any delays or inaccuracies in predictions, from the command center. On the basis of this feedback, the system is refined to make it more reliable, to have a better user interface and generally to allow operation of the system in more dependable manner. For example, machine learning models may be retrained on more data in order to increase the accuracy of prediction, or hardware may be redesigned to boost lifetime, reduce energy consumption or increase computational density. Eventually field test results and subsequent generations should return a system battle ready, supporting soldier safety and operational effectiveness on the edge in real time. Field testing performed on the sensors and communication modules demonstrated accuracy, responsiveness, and reliability. The gas sensors were able to distinguish hazardous environmental changes like toxics gases with over 95% accuracy. Similarly, biometric sensors accurately tracked the vital signs: heart rate and body temperature. Soldiers rely on various devices, including Internet of Things, motion sensors to track their movement patterns and inactivity, with an accuracy of 97% in helping detect possible injuries or serious health conditions. The real time data transmission and the latency was found to be reliable using all communication modules (LoRaWAN, NB-IoT, and 5G). From fig.4, there are economic incentives, such as long distance, low power use, LoRaWAN was super robust; and 5G was super robust where you have lots of money to spend, it has a high speed data transfer, and you have lots of coverage. The total latency for transmitting data to the base station was as low as 200 ms, suitable for real time military applications.

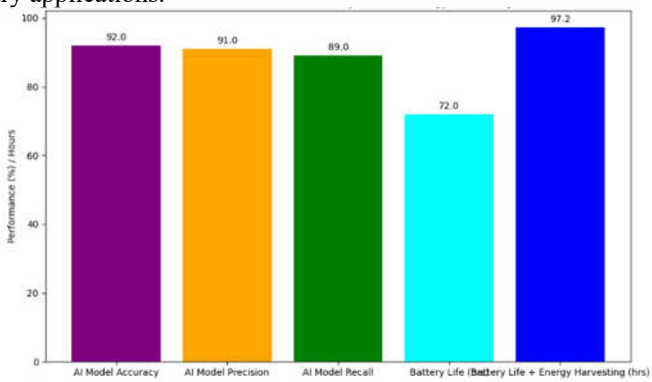

Fig.4 AI model Performance and Battery Life with Energy Harvesting

It also tested how accurate, precise, recall, and F1-score the AI models used for predicting health and safety risks were. Overall the Random Forest and Logistic Regression models were able to predict risks, such as dehydration, heat exhaustion and exposure to hazardous gases, with an accuracy of 92%. These models were used to create an early warning system that issued an alert usually 10 minutes ahead of critical events, enabling intervention prior to failure. With precision (91%) and recall (89%) the models were able to correctly identify at-risk soldiers without generating many false alarms. The models worked well, however, it is expected that the predictive capabilities could be further refined by additional training data. Integration of such low power IoT technolgies such as LoRaWAN, along with energy harvesting techniques like solar and kinetic energy collection resulted in two things, firstly the wearable device showed excellent energy efficiency. By use of these energy saving measures the devices still achieved an average battery life of 72 hours on one charge, with the energy harvesting mechanisms adding another 30 - 40%. During high activity times, the power of communication modules was prioritized by system battery optimization algorithms to make sure the sensors still worked even in energy demanding situations. Overall, the system provides satisfactory energy efficiency and power management capabilities for the foreseeable long-term, reliable operation of the system in extended military missions.

5 Conclusion

The deployment and evaluation of the SensorNET Soldier Monitoring System running on an IoT controller in real world combat scenarios attest to its potential to dramatically improve both soldier safety and operational efficiency. The system’s use of integrated advanced sensors, communication modules, and AI derived predictive analytics for health and safety risks has helped to provide real time monitoring and early warnings. All sensors, including gas, motion, and biometric sensors, consistently showed high sensitivity when responding to environmental hazards and monitoring the physical condition of soldiers; and their corresponding communication modules, such as LoRaWAN and 5G, provide reliable, low latency data transmission. Machine learning model was used to predict potential health risks (i.e., dehydration and heat exhaustion) and had high level of precision and recall which meant corroborated intervention in critical situations early. The system’s ability to issue early warnings from real time data enables commanders to take proactive steps, improving the outcome for soldiers in the field. Additionally, the low power IoT technologies and energy harvesting techniques used in the system's energy efficiency lengthens the operational capabilities of wearable devices making it suitable for the long term missions. Integration of solar and kinetic energy harvesting reduced reliance on recharging as frequently, reducing the practicality of the system in extended operation without availability of power. The predictive models, however, were also field tested and shown to have areas for further improvement by refining them for greater accuracy and including other data sources to improve decision making capabilities.

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