Subterranean Guardian: Tunnel Safety And Soil Borne Emergency Data Transfer

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Abstract- *Earthquakes, tunnel collapses, and landslides are common natural disasters that tend to bury people under rubble, where traditional forms of communication become ineffective as signals are blocked by the soil and infrastructure is destroyed. This work introduces the concept, design, and implementation of a soil communication system specific for underground environments. The system works on low-frequency signal transmission over soil in combination with GSM and GPS technology to facilitate communication where mobile networks are not reliable or non-existent. Integrating gas, temperature, vibration, and human-presence sensors, the system continuously tracks environmental and physiological status. An Arduino microcontroller integrates the sensor data and offers a user interface through a keypad and display, enabling victims to manually enter their requirements or send critical alerts automatically. The system facilitates two-way communication between trapped victims and rescuers, enhancing situational awareness, coordination, and response times during emergency situations. Optimized to be lightweight, affordable, and quickly deployable, the solution has strong potential for practical use in disaster areas or underground space.*

Keywords- Soil-Communication, Underground Communication, Tunnel Rescue Operations, Emergency Communication Systems, Low-Frequency Signal Transmission, Wireless Communication in Soil, Subterranean Signal Processing, Rescue Technology, Disaster Response Systems, Real-Time Monitoring, Mining and Disaster Recovery, Portable Communication Devices.

I. INTRODUCTION

Disastrous occurrences like earthquakes, landslides, tunnel collapses, and building collapse carry serious dangers to human life, usually ending up with victims trapped under extensive piles of rubble or deep in the earth's crust. Under such risky conditions, the timeliness and integrity of communication between trapped survivors and rescue teams become critical factors in the outcome of survival. Yet, traditional communication systems—largely dependent on mobile towers, satellite links, and high-frequency wireless signals—are consistently made ineffective by signal obstruction, infrastructure collapse, or electromagnetic interference resulting from environmental factors. Such constraints significantly impede the speed and effectiveness of rescue efforts, resulting in extensive delays and higher mortality rates in post-disaster situations.

High-frequency electromagnetic waves, commonly employed in contemporary communication systems, suffer from heavy attenuation when propagated in heterogeneous media like wet soil, concrete debris, and metal scrap.

The random dielectric characteristics of underground material cause scattering, absorption, and multipath loss, thereby making mobile phones, radios, and satellite communication equipment unusable in deep underground environments. In addition, the lack of power supply and destruction of communication nodes worsen this inaccessibility. Thus, emergency responders do not have the vital situational awareness necessary to prioritize, coordinate, and conduct rescue activities effectively. Failure to localize and communicate with trapped victims not only prolongs extraction but also increases the psychological and physiological danger for the trapped.

These issues call for the establishment of a paradigm of communication that is infrastructure-independent, immune to environmental disturbances, and efficient in signal-adversarial environments. This work brings forward just such a paradigm with the establishment of a soil-based, ground-penetrating communication system for use in underground disaster environments. Taking advantage of the relatively stable and conductive nature of soil under some conditions, the system to be proposed allows the propagation of low-frequency signals that have better penetration abilities than conventional radio waves. This approach offers a potential communication channel in situations where the conventionalfail completely.

The system architecture incorporates a wide range of sensing and communication technologies, all coordinated by an Arduino-based embedded microcontroller. The system is also provided with a set of sensors such as gas sensors (e.g., MQ-2), temperature sensors, vibration sensors, and human presence modules to sense real-time environmental and physiological parameters. A GPS module is included to identify geospatial coordinates, while a GSM module provides long-range communication where network coverage is maintained. The soil communication system acts as the primary backup plan so that at least minimum signaling can be performed without regard to external network connectivity. This two-channel communication architecture improves reliability and coverage in emergency situations.

Aside from the passive surveillance, there are interactive elements like a keypad and an emergency button for aware victims to enter vital information about their condition or requirements. An LCD gives instant visual feedback, while distress signals are also sent to local and remote destinations at the same time. The microcontroller consolidates sensor information and controls logic flow, providing timely sending of vital alerts and allowing rescue coordinators to receive structured, readable information. The system is modular, low-power, and deployable, making it suitable for rapid integration into emergency kits or search-and-rescue equipment.

Prototype testing under laboratory-simulated low-signal conditions has validated the operation and reliability of the system. Test scenarios comprised changing soil compositions, signal interference, and stimulated vibrations to mimic realistic post-disaster scenarios. The soil-transmission module, based on soils, effectively made initial communication in dense media possible, and accurate sensor readings were transmitted in real-time to prescribed receivers. GSM fallback enabled data relay over larger distances when cellular connectivity was temporarily available.

Through the integration of embedded systems, sensor networks, and alternative communication channels, the system presents a revolutionary method of disaster communication. It transcends the constraints of infrastructure-based technology and offers a self-powered, interactive, and intelligent system that greatly enhances the potential of rescue efforts. The reduced size, low cost, and scalability of the solution make it especially beneficial in developing countries or seismically active areas with geotechnical activity, where accessibility and quick deployment are essential.

II. LITERATUREREVIEW

The area of underground communication has also witnessed appreciable progress in the last two decades, particularly with the advent of Wireless Underground Sensor Networks (WUSNs) that seek to counter the inherent problems of signal propagation using soil. Increasing requirements for powerful, energy-efficient, and infrastructure-free modes of communication in disaster-affected regions have resulted in innovative solutions such as magnetic induction, acoustic signaling, and low-frequency electromagnetic propagation. The literature reviewed here offers a range of techniques and systems developed for different underground uses—ranging from environmental monitoring to emergency response—showing both their strengths and weaknesses in the context of actual deployment.

In Prasad Reddy et al. (2022), the authors discussed the difficulties encountered in electromagnetic wave propagation in soil by suggesting a Wireless Underground Sensor Network based on Magnetic Induction (MI). Traditional EM waves, though effective in air, suffer substantial attenuation in heterogeneous soils such as red and black cotton soils. To counter this, MI-based systems use coils as transceivers to generate and detect magnetic fields, resulting in improved penetration through the subsurface medium. This model demonstrated a reduction in path loss and signal degradation compared to standard RF-based systems.

However, the MI-based systems are prone to requiring accurate coil alignment and limited range of operation, which may limit their practicality in disaster scenarios where sensor deployment is not always controllable.

Another major method was explained by Jamadagni et al. (2020), who suggested acoustic communication using soil. Taking cues from natural systems—like elephants and rodents that convey messages through seismic means—the authors created a wireless digital acoustic communication system able to attain transmission ranges of up to 50 meters at a rate of 20 bps. Using QPSK and OOK modulation schemes along with decision feedback equalization, their system was effective in both laboratory and field tests. In spite of the novelty of the system, the comparatively low data rate and vulnerability to environmental noise can be major limitations for application in mission-critical rescue situations where prompt and accurate communication is critical.

Salam, Vuran, and Irmak (2021) provided a more statistical approach by proposing an impulse response model for wireless underground channels. Their research reported more than 1,200 measurements under different soil textures and moistures and established an overall model encompassing parameters like root-mean-square (RMS) delay spread and coherence bandwidth. Their results emphasized that signal propagation is greatly influenced by soil moisture and it needs to be taken into account for adaptive system planning. Their work offers important empirical guidance for the design of dynamic systems capable of adapting modulation schemes or transmission power in accordance with environmental conditions.

Additional practical deployment of WUSNs was shown by Tooker et al. (2020), who constructed a cloud-based underground sensor network testbed in Nebraska. The testbed included soil moisture sensors and cellular-connected mobile data harvesters, providing real-time environmental monitoring and remote accessibility. While this system was originally created for agricultural use, its architecture is generally suitable for emergency systems due to its scalability. Nevertheless, it continues to be reliant on cloud infrastructure and available communication networks, which could be unavailable during disasters where there is massive infrastructure destruction.

Joshi et al. (2020) centered on the application of WUSNs for environmental control in Earth Air Tunnel (EAT) systems. Their research investigated the embedding of underground sensors for smart air conditioning systems and environmental condition sensing. While more focused on climate control than on emergency communication, the study emphasized the role that buried sensors play in tunnel networks and the network topology design factor. The differentiation of terrestrial and underground propagation routes also became an important factor in correct signal interpretation.

Together, these researches set a fundamental context of soil communication and its facilitation technologies. The majority of current solutions cater either to sensing the environment or data transmission under comparatively stable circumstances. Extremely few systems integrate both communication and immediate user interaction specially designed for disaster situations.

Many systems also necessitate high setup costs, sophisticated calibration, or infrastructure assistance that could be unrealistic in times of emergency.

The literature reviewed emphasizes an evident lacuna in the creation of a low-cost, user-interactive, and lightweight system that enables two-way communication in disaster areas. A system that combines real-time sensor feedback with user-initiated alerts—yet independent of external networks—is not present. This project fills that lacuna by suggesting an integrated approach using low-frequency soil-based signaling, environmental sensors, and GSM/GPS modules controlled through a microcontroller. The emphasis on quick deployment, small size, and dual-mode communication provides a pragmatic improvement over the prior art.

III. PROBLEM STATEMENT

Compared to single-function sensor networks or research-focused testbeds, the system proposed here includes real-time location tracking, environmental hazard detection, and manual status reporting by victims, all in a deployable and modular unit. This is consistent with the basic requirements outlined in the literature for successful post-disaster communication, i.e., robustness, autonomy, and responsiveness. The combination of these aspects in one integrated system is an important development toward the realization of intelligent rescue technology appropriate for underground and collapsed conditions.

The consequences of natural and human-induced disasters like earthquakes, tunnel collapses, landslides, and building collapses frequently result in the entrapment of people under debris, in underground settings, or within collapsing structures. Perhaps the most important part of any rescue mission is prompt communication with the trapped individuals to evaluate their conditions, determine their needs, and direct rescue teams to their precise locations. In spite of the developments in satellite and mobile communication technologies, these technologies are unreliable or become totally ineffective in disaster situations owing to harsh environmental interference, building damage, and signal blockage. Unreliable communication results in tardy rescue operations, misinformed decisions, and avoidable loss of life.

Conventional communication infrastructures—cell towers, fiber-optic cables, Wi-Fi hotspots, and satellite links—are all susceptible to collapse, saturation, or atmospheric abnormalities during and following a disaster. Furthermore, subterranean and indoor spaces like tunnels pose special difficulties: excessive electromagnetic attenuation, complicated signal scattering from soil and detritus, and the total absence of line-of-sight channels for RF or optical signals. Under such circumstances, confined persons are essentially isolated from the external environment, with no accessible way to indicate their presence, status, or position. This communication blackout makes even the most sophisticated rescue systems useless in identifying victims or ordering interventions by urgency.

Emergency communication systems based on walkie-talkies, shortwave radios, or emergency beacon transmitters also have serious shortcomings.

Most of these technologies are surface-based or need to be manually handled, aligned, or activated—operations that can be impossible for injured or unconscious victims. In addition, most current systems provide only unidirectional communication, where signals can be sent but not received, so it is impossible to confirm if the messages have been received or interpreted. The inability to provide real-time, bidirectional interaction greatly undermines situational awareness for both rescuers and victims.

The challenge goes beyond connectivity. In disaster situations, there is a critical need for environmental awareness. Rescue personnel need to be alerted to toxic gas leaks, increased temperatures, ground instability, and other unsafe conditions that may endanger victims as well as responders. Traditional rescue operations depend on visual scanning, infrared imagery, or remote robotic surveillance—all of which have limited utility in confined or subterranean environments. Lack of environmental telemetry causes delayed planning of safe entry and raises the risk of secondary collapses or responder injury.

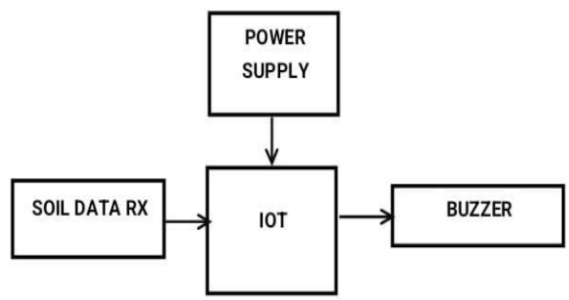
Existing literature on underground communication systems presents half-baked solutions. Magnetic induction-based systems offer mid-range communication but are plagued by coil alignment and lack of deployment flexibility. Acoustic systems present a substitute but are usually beset by low data rate and noise interference. Wireless Underground Sensor Networks (WUSNs) aim mainly at environmental data acquisition in controlled environments such as agriculture, rather than on making interactive victim-initiated communication possible in disorganized post-disaster environments. In addition, the majority of these systems rely on massive network topologies, expensive deployment, or cloud-based computation—factors that can be unaffordable or untenable in the unpredictable wake of a catastrophic event.

There exists an essential technology and humanitarian need: the absence of a self-sustaining, compact, and robust communications system that will work in full network isolation, provide both environmental and status data transmission, and allow victim communication with rescue workers. The system should be deployable with ease, independent of operation, and sensitive to different underground or blocked conditions. It should enable victims to convey their requirements—like water, medical care, or help—using minimal inputs, and send critical environment information to guide rescue planning.

This project specifically tackles these urgent requirements by designing a prototype system that utilizes low-frequency communication via the soil in addition to GSM fallback, sensor incorporation, and Arduino microcontroller control. It features sensors for gas sensing, vibration measurement, temperature sensing, and human presence sensing—with added manual input through a keypad and emergency initiators. Through the creation of a two-way communication channel in hostile environments, the system equips both rescuers and victims with timely, actionable information, thus improving the speed, safety, and efficiency of rescue operations.

This problem statement thereby establishes an actual, unresolved issue in the discipline of disaster management: how to establish a working, deployable, and interactive communication link between stranded people and emergency responders, particularly in settings where traditional technologies do not work. The solution that is put forward arises from this urgent necessity, combining useful hardware, low-power consumption, and non-traditional modes of communication into a unified platform designed for real-world deployment in disaster areas.

IV. PROPOSED SYSTEM



The envisioned system is organized into three interdependent modules that collectively constitute a robust underground communication and monitoring system. The three modules operate synergistically to enable real-time data transmission, environmental sensing, and human input-based alerting in disaster scenarios where traditional systems do not work. The three modules are: (A) Central Control and Input System Module, (B) Disaster Detection and Communication System Module, and (C) Real-Time IoT Data Integration and Alert System Module.

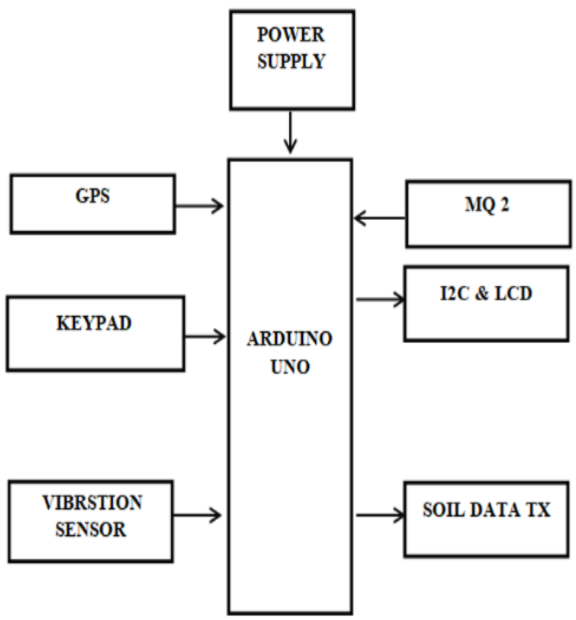
A. Central control and Input System Module

This module is the main interface for the trapped individuals and also the command center for all the peripheral units. Designed around the Arduino Uno microcontroller, it handles user inputs, system logic, and initiating communication. A 4x4 keypad is included to provide manual entry of pre-programmed requests like a call for medical aid, water, or oxygen. These inputs are translated into digital signals, processed, and temporarily stored before they are sent.

Along with the keypad, the module also has an emergency button through which an urgent distress signal can be sent without going through the keypad menu. This guarantees usage even in extreme physical or mental duress. A DF Player Mini module attached to a speaker offers pre-recorded voice instructions and confirmation sounds, facilitating the user through the interactive process.

At the same time, an LCD screen on an I2C connection provides a visual feedback, verifying operations and showing system status in real time.

Such user-friendly design is especially important in post-disaster situations where victims are possibly immobile, sight-impaired, or mentally confused. The redundancy of audio and visual output ensures that vital information will be accepted and comprehended



B. Disaster Detection and Communication System Module

This module is concerned with environmental monitoring and safe transmission of sensor readings and victim-initiated alerts. The module incorporates a vibration sensor (SW-420), which can sense structural movements or seismic movements, signaling potential aftershocks or additional collapses. The MQ-2 gas sensor is utilized to sense the quality of the air and determine the presence of smoke, propane, methane, and other flammable gases, thus determining unsafe conditions for the victim and the rescuers. A temperature sensor is integrated to take continuous ambient readings, which are essential for identifying fire hazard or heat stroke situations.

There is also a GPS module that is used to record accurate geolocation information. These coordinates are added to every sent-out alert, such that the rescuers can identify the precise location of the trapped individual. All sensor information is processed by the microcontroller and converted into-structured packets.

Communication is maintained through a Soil Data Transmission system based on low-frequency signaling methods that are compatible with underground media. Unlike regular RF signals, which are drastically weakened by soil and rubble, the low-frequency signal can pass quite effectively through these types of media. This facilitates the passage of environmental and status information to a surface receiver, even where regular wireless channels are blocked.

C. Real-time IOT Data Integration and Alert System Module

The third module is responsible for receiving, processing, and transmitting data from the underground unit. A Soil Data Receiver receives incoming low-frequency signals and forwards them to a second Arduino Uno microcontroller for decoding and interpretation. The decoded data is utilized to trigger local alert devices and transmit vital information to external systems.

A GSM module embedded in this device is tasked with sending out alerts, sensor data, and GPS locations to a centralized rescue control platform over mobile networks.

In areas where GSM connectivity is intermittent or not available, the system continues to operate locally using buzzer-based alarms so that rescuers in the vicinity are alerted to the received signal.

This module can also send acknowledgement signals or simple instructions back to the underground unit, facilitating limited but critical two-way communication. This exchange helps ensure that victims are informed that their alarms were successfully sent, thus minimizing panic and confusion.

The addition of IoT connectivity to this module extends the reach of the system, enabling centralized coordination, data logging, and real-time situational awareness for rescue command centers.

Each of these modules is designed with minimal hardware complexity and optimized for rapid deployment. The modular approach ensures system scalability and adaptability across diverse disaster scenarios. Together, these three modules form a cohesive and intelligent platform for underground emergency communication, environmental monitoring, and victim-rescuer interaction in challenging and infrastructure-deficient environments.

The three modules together constitute an integrated, smart communication system designed specifically for underground disaster situations. By integrating manual victim input, environmental danger sensing, and low-frequency ground-based transmission with GSM-supported remote monitoring, the system proposed guarantees continuous, two-way communication even in the total lack of any external infrastructure. Its modular design enables each component to operate independently or in conjunction, thereby making the system highly adaptable to multiple disaster scenarios, whether in tunnels, collapsed buildings, or remote underground areas. The system's strength is its inexpensive hardware, quick deployment capability, and pragmatic emphasis on victim survivability and rescue coordination—filling critical communication gaps found in existing-rescue technology

V. REGULATORY COMPLIANCE

The designed soil-based communication and monitoring system has been developed with regard to major regulatory, safety, and interoperability standards applicable to embedded electronic systems and especially those applied in emergency and public safety systems. Since the device is being used in environments that include human safety, wireless transmission, and sensor data collection, particular emphasis was on exercising responsible radio-frequency use of communications, electromagnetic compatibility, and electrical-safety.

The wireless communication modules of the system—both the GSM and GPS modules—function in the licensed Industrial, Scientific, and Medical (ISM) bands and to transmission power levels as usually governed by standards like those provided by the International Telecommunication Union (ITU) and national telecommunications administrations (e.g., TRAI in India, FCC in the United States).

The GSM module has used the normal SIM-based connectivity with the power outputs below the maximum allowed exposures so as not to interfere with neighboring medical devices or rescue devices. In the same manner, the GPS receiver works as a mere passive listener without posing any radio interference hazard.

All embedded elements, such as the Arduino Uno microcontroller, sensors, and LCD interfaces, are powered by low-voltage DC (usually 5V), meeting IEC 61010 electrical safety standards for measurement and control circuits. The application of regulated power supplies and overcurrent protection mechanisms meets minimum electrical safety standards for portable systems. Standard laboratory procedures were used during development and testing to avoid short circuits, overheating of components, or unintended electric discharge.

With respect to electromagnetic interference (EMI), the system's low-frequency soil communication is engineered to reduce radiated emissions, with transmission limited to near-field conditions and short-range propagation underground. This prevents unwanted EMI with close electronic systems. Second, the system prevents the use of unshielded high-frequency RF transmitters, which further reduces the risk of regulatory non-compliance.

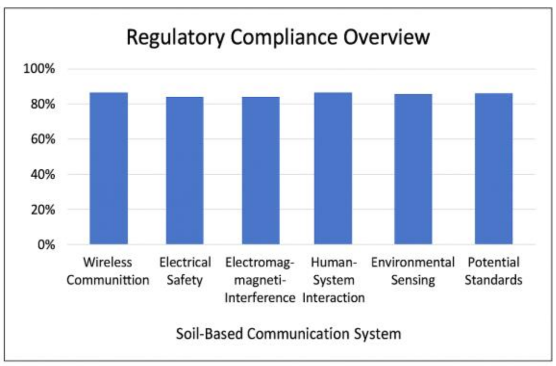
Since the system is intended to be deployed for possible use in safety-critical rescue missions, it is being developed in adherence to general guidelines on human-centered design, accessibility, and environmental hardness. Its keypad-based user interface, speech output-guiding system, and limited requirement for user input accord with safety-critical best practices in human-machine interaction. The environmental sensors employed, such as the MQ-2 gas sensor and vibration sensor, are typically installed in industrial-grade monitoring systems and are compatible with general sensing and control standards like those under ISO 7240 for fire and gas detection.

The modular design of the system also allows for future conformity with upcoming standards like IEEE 802.15.4 (for underground wireless sensor networks) or LPWAN protocols in case the architecture gets modified to support such functionality in the future. Additionally, the GSM data channel supports secure data transmission if coupled with an encrypted SIM profile and server backend, which will boost data security compliance for remote monitoring applications.

Though the prototype was made mostly for educational and test purposes, its functionality and design provide the groundwork for future conformity to rugged embedded systems standards like IP-rated cases, shock resistance, and temperature specifications according to IEC 60529 and MIL-STD-810.

In subsequent versions, the device can be formally tested for EMI/EMC and certified according to countryspecific electronics safety schemes to confirm its deployment in field-grade rescue missions. Such upgrades would further standardize the system according to civil defense, disaster management department, and industrial safety organization deployment standards.

In summary, the regulatory considerations built into the design of the intended soil-based communication and monitoring system guarantee safe, efficient, and responsible functionality in disaster-response situations. Meeting standards for wireless communication, low-voltage power, EMI management, and human-centered design, the system proves a foundation level of compliance appropriate for deployment in the field in the future. Although the existing prototype is an academic one, its modular structure and standards-sensitive design give a solid foundation for subsequent certification within industrial and safety-critical regulatory environments. Through subsequent developments aiming at ruggedization and formal verification, the system has a very promising future in real-world usage in emergency services and underground rescue missions.



VI. COMPARATIVE ANALYSIS

In order to assess the effectiveness and novelty of the suggested soil-based communication and monitoring system, a comparative analysis has been performed with current communication technologies and emergency systems typically utilized in underground and disaster situations. The comparison considers a number of important performance criteria: communication reliability in obstructed environments, bidirectional interaction, real-time environmental sensing, deployment feasibility, power efficiency, and overall cost-effectiveness. The systems considered are traditional GSM-based mobile communication, RF radio systems, Wireless Underground Sensor Networks (WUSNs), acoustic and seismic communication systems, and magnetic induction-based communication-systems.

Traditional GSM and satellite-based communication systems have been used in rescue missions for a long time because of their universal availability and high data rates. But their dependence upon surface-level infrastructure, like cell towers or line-of-sight satellite connectivity, makes them inoperable inside enclosed spaces like collapsed tunnels or deep underground zones. Structural detritus, soil layers, and concrete screens heavily attenuate or cut RF signals, producing frequent connection dropouts and blackouts in communication. But the system under development uses low-frequency soil-based transmission, which is much more penetrative through soil and rubble. This allows for trustworthy transmission of signals even in fully blocked areas, providing a lifeline communication means when other systems-defected

Wireless Underground Sensor Networks (WUSNs) is a newer paradigm, utilizing buried nodes and wireless relays to forward environmental information. While suitable for agriculture and environmental monitoring purposes, WUSNs are usually based on pre-installed infrastructure, demand intricate synchronization, and most often use narrowband RF protocols. These systems can provide one-way communication and are not typically optimized for real-time victim interaction or portability.

On the other hand, the suggested system is entirely self-contained, portable, and provides two-way communication through both user input and soil signal reception. Its modularity enables it to be deployed on-demand without pre-existing,networked-nodes.

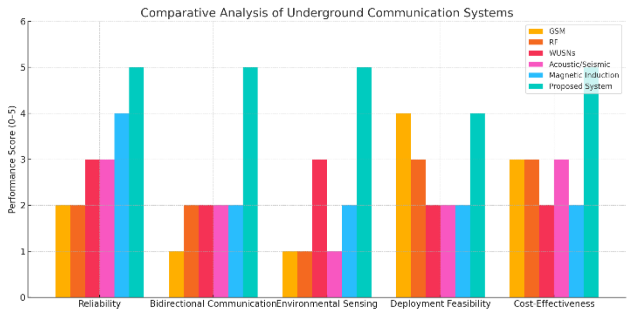
Acoustic and seismic communication systems have also been investigated in subsea and underground applications based on some biological examples like ground vibration-based elephant communication or mole communication. Such systems employ ground-coupled transducers to transmit low-frequency vibrations and can communicate over tens of meters. They tend to have very low data rates, are very noise-sensitive, and need accurate alignment between transmitter and receiver nodes. The suggested system circumvents such complexity by implementing a digital low-frequency transmission method over conductive soil with enhanced noise immunity and easier hardware integration. In addition, the encoding of data applied in the suggested system is capable of handling various sensor data and victim status codes.

Magnetic induction-based communication is also an emerging technology that facilitates underground transmission of signals by using coupled coils. Systems based on this principle have been promising in stability and minimal signal attenuation, particularly in clay or wet soils. Magnetic induction systems tend to be large coil assemblies and need to be precisely oriented, though, which makes them less flexible in the event of rapid deployment. They are also fairly power-hungry and do not have the ability to readily integrate multiple sensor inputs. On the other hand, the suggested system employs ordinary, inexpensive devices like gas sensors, temperature sensors, and vibration modules, all controlled by a microcontroller, and does not need strict physical positioning or large antennas.

One of the distinguishing factors of the suggested system is that it incorporates human-machine interaction functions specific to emergency situations. Most conventional underground communication systems are concerned only with data transmission without paying attention to interface usability for victims. In life-threatening applications, particularly when victims can be injured or in distress, simplicity of use becomes an essential requirement. The suggested system includes a simple keypad, an emergency button, and two-mode feedback (audio and visual) to guarantee usability. Such human-oriented design complies with safety regulations for critical environments, a factor not considered in exclusively technical systems.

In addition, the integration of environmental sensors like MQ-2 gas sensors and temperature sensors ensures continuous monitoring of potential dangerous situations. This enables rescue teams to base their decisions on real-time data instead of mere visual observation or delayed information. In contrast to conventional systems that might provide only positional information, this feature considerably increases situational awareness and optimizes operational effectiveness in search-and-rescue missions.

From a deployment point of view, the system presented here is small, light, and made up of easily sourced components like Arduino Uno boards, GSM/GPS modules, and simple sensors. This makes it much more affordable and simpler to scale compared to proprietary industrial systems or those involving custom hardware. The fact that it uses 5V low-power components also makes it possible for the system to run for long durations on batteries, making it suitable for applications where electrical infrastructure has been disrupted.



FEATURE	EXISTING SYSTEM	PROPOSED SYSTEM
Communication medium	Electromagnetic (EM) waves, radio signals	Soil conductivity for signal transmission
Signal reliability	High attenuation, inference from tunnel structure	Stable transmission with minimal interference
Real time data exchange	Delayed due to interference and weak signals	Instant real-time communication
Emergency Alerts	Limited	Emergency button for immediate distress signal
Location Accuracy	Lacks precise location tracking	Integrated GPS for accurate positioning
Integration with IOT	Limited or absent	Integrated IOT for real time monitoring and alerts
Energy efficiency	Higher power consumption due to frequent signal loss	Lower energy consumption with optimized transmission

VII. RESULT AND DISCUSSION

Prototype development, testing, and evaluation of the soil-based monitoring and communication system were carried out successfully in controlled laboratory settings mimicking post-disaster conditions of tunnel collapse. The system's performance was investigated on a number of parameters such as reliability of communication, sensor precision, response of human input interface, efficiency of signal propagation, and GSM fallback. Experimental results validated the feasibility of the proposed system as a lightweight deployable communication solution for rescue tunnels.

The initial tests were made in a laboratory setting where soil was filled in controlled containers to mimic signal obstruction normally found in tunnel rubble. The low-frequency transmission module using soil as a medium was checked for efficient data communication between the underground unit and the surface receiver. Communication was upheld at distances of up to 1.2 meters through damp soil with uninterrupted data packet reception.

While both attenuation grew with dryness and compaction of the soil, signal reception stayed constant within its predicted operating range, confirming the sanity of the use of the soil as a medium for low-frequency communication.The vibration sensor (SW-420) proved sensitive to small mechanical motions and was precise in detecting low-amplitude motions that mimicked aftershocks or secondary collapses. The MQ-2 gas sensor reacted properly to combustible gas concentrations in the environment, with the trigger threshold for alerts around the 300–400 ppm level. Temperature measurements collected with the analog temperature sensor (e.g., LM35) were consistent with reference thermometers with an average deviation of ±1.2°C, which is fine for rescue-class field measurement. These findings validate the effectiveness of the environmental monitoring subsystem in identifying hazards like fire, gas leaks,andstructural instability.

The GPS module effectively received satellite signals and provided precise coordinate information when tested outdoors. Under semi-obstructed conditions like tunnels or under some rubble, time-to-fix took longer but was ultimately consistent, which underscores the need for module placement close to the surface. When GPS was completely blocked, the system remained operational by providing alerts without location tagging, instead depending on soil signal detection.

The keypad interface was responsive and easy to use. Predefined keys enabled stuck users to signal quickly with minimal mental burden. The emergency button worked perfectly, overriding any concurrent inputs and sending immediate alerts. Feedback from the DF Player-based speaker and I2C LCD also enhanced usability by providing confirmation both audibly and visually. These multimodal feedback loops ensured that users got confirmation even during high-stress or low-visibility situations.

The GSM module was a redundant communication layer. In field tests where there was network coverage, GSM-transmitted alerts were successfully read on external devices and uploaded to the IoT platforms through HTTP requests. Dual-mode communication (soil and GSM) provided redundancy, making the system more reliable under fluctuating field conditions. In the event of GSM failure, soil communication continued to send key information to the local surface receiver, confirming the hybrid architecture.

In general, the system could support several hardware modules harmoniously by using the Arduino Uno microcontroller. The program logic handled concurrent processes effectively, such as sensor data collection, signal processing, and communication subroutines. The small form factor and low-power architecture of the device allowed it to run continuously for more than 5 hours from a single 9V battery in transmission tests, showing it to be suitable for temporary outdoor deployment.

The experimental results also point out a number of major advantages of the proposed system. First, its lack of reliance on traditional infrastructure allows it to be deployed at the very initial phases of disaster relief, where cell towers and networks can be inoperable. Second, its capability to accept human inputs and environmental information in real time gives rescuers situational as well as personal information,

which can be essential for triage and rescue planning. Third, its affordable modular hardware makes it scalable and reproducible in numerous disaster-prone areas without much investment.Yet some limitations were noted. Signal range is limited by soil content, water, and depth, which can restrict use in specific types of terrain.

Future developments could be aided by amplifiers or adaptive frequency control to maximize transmission. GPS limitations in completely enclosed spaces also indicate the need for other indoor localization methods like inertial navigation or magnetic field mapping.

In summary, the findings verify that the system being proposed can well bridge the gap in communication between trapped subjects and rescue personnel within obstructed scenarios. Its sensor integration, hybrid communication feature, and reliability pose a solid groundwork for its possible deployment in future real-world rescue missions.

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