13th International Defense and Homeland Security Simulation Workshop
20th International Multidisciplinary Modeling & Simulation Multiconference

2724-0363 © 2023 The Authors.
doi: 10.46354/i3m.2023.dhss.002

The Rover Module for emergency management: A technical description, crowd simulation, and battery experiment

Dean Reed[1,*], Jonathan Hurter[1], Devyn Dodge[1], Alexander Mompoint[1] and Travis Hillyer[2]

[1]Institute for Simulation and Training, 3100 Technology Pkwy, Orlando, FL 32826, USA
[2]U.S. Army Combat Capabilities Development Command Soldier Center (DEVCOM SC), 12423 Research Pkwy, Orlando, FL 32826, USA

[*]Dean Reed. Email address: dean.reed@ucf.edu

Abstract

Providing critical information on human and object states during an emergency (such as the geolocations of rescuees, as well as urgently needed resource information) is limited for current devices, in terms of battery longevity, physical embodiment, and a reliable connection to a network, given an ad hoc interim with degraded communication infrastructure and lack of basic services. To break this limitation, the multifunctional tool of the Rover Module is proposed and presented through a technical description, crowd-simulation analysis, and battery experiment. Recent world events underscore a need for defense and homeland security to invest in such a device for emergency response. The Rover Module, which integrates various sensors in a small form-factor and body-wearable system, is an internet-of-things device that can use haptic feedback for navigating (e.g., to a missing person) based on GPS data, send out location pings, and produce audible cues. The crowd simulation results show the ability of first responders outfitted with the Rover Module to reduce chaotic behavior and improve overall regional stability via clear details on resource location and availability. In relation, the battery experiment supports real-world usage based on the simulation; we leveraged simulation results to extend the Rover Module operational time.

Keywords: Search and rescue; Emergency management; Internet of things (IoT); Crowd simulation; Command and Control (C2)

1. Introduction

In an emergency, there are major factors that decide what can be done and how quickly a response can be made, two being information and time. An emergency requires that a response is planned and enacted within a short span of time to have the highest chance of a positive outcome. In disaster situations, where the major concern is to save lives, one of the most influential pieces of information a disaster response team can have is information on the disaster team personnel and victims in real-time. If those on the receiving end of the aid have some sort of device that can inform the rescuers of their position in some capacity, the victim can be found and saved quicker. In the case in which the victim does not have a device to provide some information about them, the rescuers can have a device to aid in coordination. This device can be extended beyond disasters, such as a lost hiker in a national park (i.e., a person partaking in an activity with a known risk, leading to the need for rescue). This device would be the Rover Module, a multifunctional module designed to provide an increased chance of success when dealing with emergency situations. The Rover Module would also function in emergency situations wherein other locations of valuable interest may be broadcasted, such as the location of urgently needed resources (e.g., food and water) and healthcare as basic services.

The Rover Module has the capability of providing accurate GPS geolocations, information on the person, tactile feedback, auditory stimulation, and more (such as a single-button SOS, or emergency alert) to aid in efforts to mitigate losses in an emergency. Capabilities are provided in a small form-factor as to be minimally intrusive when on a person, and the device has an extended battery life with the intent of preparations for prolonged use (i.e., days without a need for recharging). The Rover Module comes with the intention of modularity and ease of integration with other devices across short-range communication methods, such as Bluetooth, and long-range communication methods, such as radio. A Rover Module, as worn by an individual, is shown in Figure 1, along with a CAD rendering of the Rover Module (in two variations).

Figure 1. View of a physically worn Rover Module (top) and CAD renderings of Rover Module variations (bottom).

The data being produced or rerouted by the Rover Module can be relayed to sister Rover Modules or to a device that allows a user to view the data in a digestible form. This form can be as simple as an interface that allows the raw data to be read and combed through or in a more complex interface of simulation software inputting the real-life location, as well as additional information, of an individual.

The present study's proposed Rover Module is sought as an addition to the repertoire of existing and potential techniques of future search and rescue efforts, ranging diversely across emergency scenarios of natural and man-made causes. Traditional methods of victim-detection searches, albeit containing limitations, include visual exploration through unaided physical void search, audible callout (i.e., calling out, requesting victims to perform the sound of knocking, and locating victims via a grid-pattern of listeners), electronic viewing (e.g., mini search-cameras, infrared imaging, and fiberscopes), electronic listening (i.e., a probe array of acoustic-seismic devices), and canine search (Wong & Robinson, 2004).

Given the purpose of supporting an emergency scenario's response through the Rover Module functionalities, the goal of this study is to analyze a crowd simulation comparison (of settings with and without the Rover Module implementation), determine the real-world Rover Module's related battery life, and provide a technical description of the current system.

The rest of the document provides supporting information for understanding the Rover Module: Section 2 provides background information on the defense and homeland security context, an internet-of-things (IoT) context, the state of the art, a technical description of the Rover Module, and the research questions. Section 3 holds the study method, including the simulator aspects and equipment used. Section 4 combines the study results with discussion points. Finally, Section 5 provides a conclusion, which points out limitations and next steps.

2. Background

2.1. Defense and Homeland Security Context

To better cognize how the Rover Module functions, we consider the role of humans who may be augmented with its capabilities for natural and man-made emergencies, including disasters. Namely, victim localization (for search and rescue) and supplies tracking. Emergency management here is one piece of a loop, considering mitigation and preparation (occurring before an emergency event) and response and recovery (occurring after an emergency event; Alexander, 2002). Within a soldier typology, this emergency support has its root in a humanitarian type (Kaspersen, 2021), supporting a role for soldiers to identify with. Both civilian first responders and the military may benefit from ways to improve current systems, whose urgency dictates a swift and concerted effort. In this way, the tool falls under dual-use, supportive of military and non-military users. The Rover Module response systems could be integrated for a litany of inciting incidents, such as floods, earthquakes, volcanoes, wildfires, tsunamis, hurricanes, heatwaves, blizzards, landslides, capsizes, wars, lost hikers, and trapped miners. First, the Rover Module can be utilized to set off an audible cue to indicate human (or other) presence, which may be useful in conditions wherein a visual search is limited (e.g., by rubble occlusion). Second, the Rover Module can provide a vibrotactile indication to support movement towards a goal (e.g., a lost hiker) using GPS and potentially dead reckoning.

Military assistance for disaster response is not a new practice. For example, in 2010, Haiti suffered an earthquake, a disaster which sparked a U.S. military response for supportive aid. Specifically, military humanitarian assistance and disaster relief were provided—with the military taking on aspects of initial response (e.g., saving lives), relief operations, restoration, and recovery—coordinating with a variety of government and nongovernmental organizations (helping the latter with aspects including medical facilities and shelter distributions), and supporting a cluster system (a regular gathering of experts for problem-solving among various clusters; Cecchine et al., 2013).

Although the 72 golden hours have been suggested as a response time to find survivors, a more lucid view is against a rigid universal time-for-rescue, abandoning any heuristics in favor of a decision-support tool: Macintyre et al. (2011) listed many earthquake-related factors to consider (with a primary ordering believed as void spaces, ventilation, and water [and food to a lesser extent], before other considerations) for search-and-rescue time, of which an interplay between the factors is an ultimate determinant; yet, such a tool required more reliable data-sources for vetting against. Note, the transfer of considerations to other disasters is possible.

From an account of search-and-rescue after the Haiti 2010 earthquake, Macintyre et al. (2011) showed rescue times ranged from 1.61 to 7.22 d (as part of their method, rescuees required equipment that was beyond bystander ability via hand or tool, and some rescuees required medical intervention while entrapped). In a media report of a recent earthquake hitting Turkey and Syria, a boy was rescued almost 10 d after the earthquake hit (Chavez, 2023). The segue to reduce or remove personnel from search-and-rescue operations is a critical pivot, given the need to find victims in response and shift to supporting recovery, providing further support of the Rover Module to help reduce awareness fog through a detection capability.

However, large-scale natural disasters are only one use-case expected to benefit from the Rover Module. The device also offers a means to increase the safety of soldiers and first responders during training exercises by improving leadership's ability to track and manage units; and by offering improved tools to identify and locate lost individuals. Force-on-force and land navigation training often place inexperienced individuals into unknown environments involving potential dangers, including extreme heat, cold, and rigorous terrain. For a somewhat recent example, a National Guard soldier performing navigation training at Camp Blanding went missing and died, despite a giant search covering over 1000 acres (over 4 million m^2) by multiple means (e.g., by helicopter and on foot), with flight searches in a grid pattern (Scanlan, 2018a); the soldier's death was declared an accident and resulted from environmental heat exposure (Scanlan, 2018b). This microcosm narrative underscores a motivating emergency example of how the proposed Rover Module could have been integral to the trainee's apparel or equipment, providing location status to improve the search-and-rescue team's efforts.

The facility of providing initial, rapid, and low-cost information in response to a disaster in densely populated areas is critical. Prevention of large, disorderly crowds and providing an ability to communicate the available resources (Keating, 1982) will assist in alleviating panic, reducing casualties due to resource competition and stampeding due to major bottlenecks and undue crowd pressures (Helbing et al., 2005).

2.2. Internet-of-Things Context

The Rover Module's envisioned emergency implementation operates within an IoT paradigm. Within IoT, there is an interconnected network of things, the latter being virtual or physical identifiable objects that can communicate across said network. The network may be wired or wireless. The titular things may change or describe their state. Contributors to realizing IoT are microelectronics, wireless communication, data storage capabilities, data elaboration capabilities, and data processing software and platforms (Bognar, 2018). In the domain of disaster relief, if degraded communication infrastructure occurs (i.e., network congestion or loss of network connection) then a more reliable interim ad hoc system is required as wireless communication.

2.3. State of the art

Since the Rover Module is partly sound-driven for search and rescue, it parallels the use of unmanned aerial vehicles (i.e., drones) for victim localization via audio, such as seen in Basiri et al. (2018). These drones can cover areas that may be arduous for humans to reach, can act as a force multiplier, and can help in environments wherein visual cues are less pronounced (e.g., fog, smoke, forests, and rubble). The Rover Module approach may act complementary to such a remote-sensing system, providing aural cues and perhaps backup systems through GPS in situations wherein drones are missing or ineffective (e.g., due to extremely noisy surroundings).

A system for coordination and situational awareness has been in place for the military and emergency responders: blue force tracking. Work by the Space and Naval Warfare Systems Center Atlantic (2014) provided an overview of blue force tracking, paraphrased hereinafter in this paragraph. Blue force tracking allows tracking personnel and resources, with a system having (at minimum) a GPS tracking unit integrated with a software package (usually providing a mapping application). Such GPS tracking units can be active or passive; they can be dedicated primarily to GPS or be GPS-enabled (such as tablets, cameras, and smartphones); they can be part of a system leveraging GPS and wireless technology; and they may use a mesh network. Variation in formats exchanged from a GPS tracking unit is also possible, such as by email, short message service (SMS), and audio communications. Example blue force tracking uses are navigation, visual identification, biotelemetry, equipment status, a button-press SOS (i.e., emergency alert), and a geo-fencing notification.

Blue force tracking and the Rover Module share a similar general outlook on state information, but the Rover Module is progressive by increasing battery longevity and employing only a set of skeleton capabilities (i.e., a minimal but critical set) for an emergency-response interim, while retaining a small physical embodiment. Still, the Rover Module's ability to interoperate with blue force tracking may prove synergetic in emergency response.

Some smartwatches are similar in the sense they can track movement, have two-way communications, provide user feedback, and monitor functions based on battery life. However, the commercial smartwatch product generally relies on wireless communication to a synced cellphone or a linked cellular data plan. The Rover Module relies on a set of long-range radios and mesh networking radios to communicate. When compared to cellular data, the radio methodology appears superior primarily due to its ability to run for a long duration on its own battery and non-reliance on cellular networking, perhaps extending to places where a cellular signal can't reach.

One of the most recent smartwatches claims to have the ability to last 60 h (about 2.5 d) on low power settings (Apple, n.d.). Another example, one that requires a smartphone connection, claims to have 18 d of battery life but is unable to communicate with other devices without an established Bluetooth connection. Furthermore, its battery life is reduced to an expected 57 h if left in GPS mode (Garmin, n.d.), a feature that would be critical for the proposed emergency response approach. The Rover Module design has the potential to last months in a low power state while maintaining an ability to activate networking and location functions, as determined in a preliminary in-house study.

An example of another system that combines multiple sensors (e.g., gas, dust, and temperature) is found in a mining safety context (Adjiski et al., 2019). The multiple sensors are embedded in personal protective equipment and connect to a smartphone through Bluetooth, with the smartphone communicating via a Wi-Fi network. The sensor data is interpreted by a network, with the possibility of human input, before instructions are sent to a user's smartphone. Their system shares some behavior with the Rover Module since their system aids the user in making decisions based on a multitude of sensor inputs. However, their system differs by relying on a smartphone as an interaction method and a connection to a network, leaving users at the mercy of the battery life of the smartphone and the requirement of an established network to allow communication to the smartphone.

2.4. Rover Module Technical Description

The purpose of the Rover Module is to provide ample information regarding the location, state of the module, user, and environment. This information is relayed over a Long Range Wide Area Network (LoRaWAN) capable radio. LoRaWAN can provide networking over long distances, as far as 2 km under ideal conditions. Acoustic transducers, haptic actuators, and buttons (e.g., SOS) are also components of the current design. These features are complemented with a dual-core IoT capable chip array with local Bluetooth Low-Energy (BLE) that emphasizes an ad hoc IoT feature set.

The user position is provided through a GPS receiver that, when combined with an optional source of Radio Technical Commission for Maritime Services (RTCM) correction data, can provide up to 1 cm accuracy of the Rover Module. This ability is provided through a real-time kinematic (RTK) enabled multi-band global navigation satellite system (GNSS) receiver. This ability can aid in accurately locating a user who has the device in their possession for search-related purposes, coordination in search efforts, and tracking other valuable locations. The user state information can be gathered by the interaction of the Rover Module with external devices via BLE 5.0, radio communications, Wi-Fi, and direct connections; these methods all function off of a standardized communication protocol intended to allow easy integration into the Rover Module. The technology used to achieve the module incorporates an embedded system consisting of a microprocessor with the capability of Bluetooth, Wi-Fi, and the multi-band GNSS receiver. The current Rover device also includes a wide variety of sensors, such as MEMS-based inertial localization sensors and environmental sensors (e.g., barometric pressure and temperature sensors).

This system enables a low-power device to last about 50 h on a relatively small battery (as found in this study's results), with physical space available to increase battery size. The combination of the information able to be retrieved from the Rover Module and incorporated into simulation software provides the capability of simulating the user in a virtual environment. The Rover is currently used in an effort, funded by the U.S. Army, geared to support the E-Bullet's live-training ensemble solution.

The Rover Module has the potential to be a lifesaving device. To fulfill that potential, the module needs to monitor and maintain the internal battery status for long periods of time, as the Rover Module's battery life allows consistent location messages to be sent out and audible cues to be produced at regular intervals.

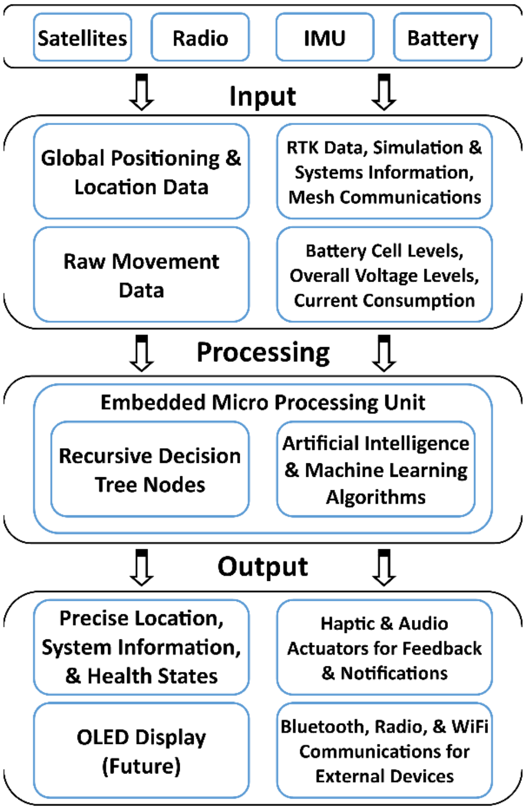

Figure 2. Diagram of the Rover Module architecture.

This longevity is achieved by following a few decision trees embedded into a Rover Module's processing algorithm. As the battery degrades, decisions are made on how often to ping out location data and audible cues. If one Rover Module picks up a response from an additional nearby Rover Module, another decision can be made to increase how often location messages are sent out. Thus, a battery management algorithm ensures the availability of a crucial response enabler. A diagram of the Rover Module architecture is given in Figure 2.

2.5. Research Questions

As has been shown, the Rover Module intends to fill a gap in emergency response by improving on current devices, in terms of providing a system that can operate in an ad hoc interim with degraded communication infrastructure (while maintaining battery life and a small form-factor) and provide locations of rescuees and urgently needed resources. Overall, three main research questions were determined for this study:

1. Can first responders with the Rover Module be effective when implemented in a crowd simulation?
2. If they can be effective in 1, how long in real-world time does it take for the simulated Rover Module condition to reach effectiveness?
3. If they can be effective in 1, can the real-world Rover Module's battery power realistically meet the time-to-effectiveness given in 2?

3. Methodology

3.1. Crowd Simulation: Overview

To implement the crowd simulation, the authors selected a publicly available crowd simulation software called jCrowdSimulator (Fraunhofer IVI, 2023). The jCrowdSimulator software was chosen as the simulation platform because it is free, has an open-source license, is easily extensible, and supports common geospecific terrain formats (e.g., Shapefile). As a drawback, crowd elements called pedestrians had to be specialized to be individualistic and behave in an agent-based process. The pedestrian model was specialized to include individual goals. The individual agents were enhanced to be able to respond to the crisis: a major earthquake that removed all traditional infrastructure for the crowd (e.g., electricity).

3.2. Crowd Simulation: Agents

The software was also enhanced to include simulated first responders, implemented as agents equipped with simulation capabilities provided by the Rover Module. We developed individualistic agent goals based on a set of agent types: Average Citizens, First Responders (i.e., locals), Rover-Equipped First Responders, Looters, Rioters, and Roamers. Average Citizens had goals of obtaining resources for fundamental living: water, food, and shelter. Resources were distributed at key areas of the simulation and dedicated routes were used by the agents to access the resources. Rioters were programmed with desires to randomly cause damage and congregate at waypoints marked as riot areas. Looters were designed to loot designated merchant areas and potentially try to steal from other agents when conditions presented an opportunity. All agents could interact with each other due to an "agent x meets agent y" event implementation that was driven by the locale of an agent and the crowd force model used, called the HelbingBuznaModel, which is a software implementation of the Helbing-Buzna Crowd Model (Helbing et al., 2005). Components of the emergent agent behaviors are consistent with a local crowd normalization effect in levels of calmness (Mawson, 2005). As individual agents encounter other crowds, they may join or share relative emotional weights.

3.3. Crowd Simulation: Approach

For the simulation component, the time to reduce natural hysteria as a direct response to the simulated disaster was measured. Using Maslow's hierarchy of needs for individual agent goals, we attempt to show that a simulated crowd in a chaotic condition will reduce levels of aggression and disorder by distribution of high quality and accurate information provided by agents that contain a simulation of the Rover Modules' functionality. Within the simulation, the behavioral goal of the agents composing the crowds was to seek relevant resources. A geospecific environment was used. First responders were placed in the simulation to disperse and re-direct the crowds towards the necessities by providing information accessible from the Rover Module, since the timely dispersion of resource information promotes positive cohesive reactions and increased information gathering (Cocking et al., 2009). Dense milling crowds were spread across multiple waypoints, the latter varying in attributes (e.g., a storefront), resembling the potential disruption and clustering of people incited by a disaster. A Command and Control (C2) software component was implemented to act as a communications manager, handling message routing and providing management of resources (human and materials). Figure 3 shows the framework of the simulation.

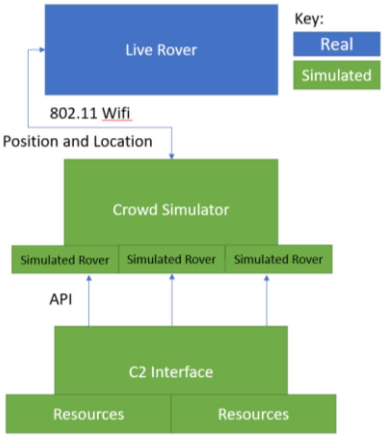

Figure 3. Framework of the crowd simulation.

3.4. Crowd Simulation: Location and Environment

The vicinity of İbrahimli, 27560 Şehitkamil/Gaziantep, Türkiye (Turkey) was represented within the simulation, since it was recently hit by an earthquake and was impacted by the real-world aftermath of the lengthy disaster. Our process was to use an open-source series of tools to import the shapes of the buildings, streets, and various obstacles within the Gaziantep region; and to serve as a base map for the simulation. The QGIS software (QGIS Project, 2023) was used to import base map data (provided by an OpenStreetMap provider, Geofabric) and then project it to the usable Universal Transverse Mercator (UTM) coordinate system. Afterward, OpenJUMP (OpenJUMP Volunteers, 2023) was used to create a variety of crowds using attributed point features (see Figure 4).

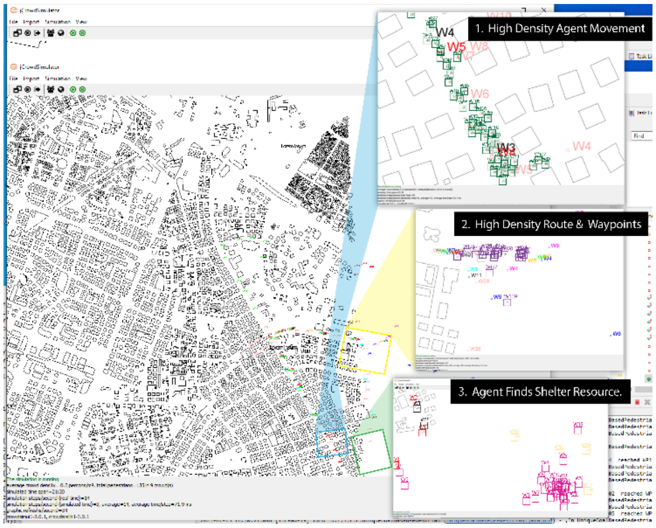

Figure 4. The jCrowdSimulator with agent activity.

In addition, we created a series of valid initial routes through the city that were created using another set of attributed vector data (or routes) in OpenJUMP. The routes were essentially a file containing waypoints with provisioned attributes as follows: NORMAL, POLICE_CHECKPOINT, MERCHANT_AREA, FOOD_RESOURCE, WATER_RESOURCE, SHELTER_RESOURCE, CHAOS_ZONE and a default value of UNDEFINED. Each route was associated with a crowd software construct, which was generated as a loose set of attributed point data in its own Shapefile and represented a cluster of individual point features with an individual enumeration mapping to each of the aforementioned agent types (e.g., Average Citizens and First Responders). On execution, the crowd simulator moved the agents according to the logic of the agent goals and the application of crowd model forces. Our system was configured to run for 10 h of real-time at a 5x simulation speed and represented 50 h (about 2 d) of total simulation time.

3.5. Crowd Simulation: Equipment

One of the benefits of using jCrowdSimulator is that it is cross-platform and written in a lightweight thread model that scales well over common computing equipment. The measurements for this experiment were initially collected on an ASUS gaming laptop as the host machine. Furthermore, the system was executed in a VMWare Workstation Pro 16.2.5 virtual machine client, with its configuration shown in Table 1. To drive the number of simulation instances higher and increase the number of samples, a high-end server was leveraged to scale multiple instances of the jCrowdSimulator simultaneously. A VMWare ESXI system was used to create and execute four instances, each having slightly different conditions (see Table 2). Table 2 contains averaged values from over 16 sessions.

Table 1. Configuration of the virtual machine client.

OS	Microsoft Windows 10 Education
System Model	VMware7,1
Processor	AMD Ryzen 7 4800H with Radeon Graphics, 2895 MHz, 4 Core(s), 4 Logical Processor(s)
Installed Physical Memory (RAM)	5.00 GB
Hard drive	1 TB dynamically allocated

Table 2. Configuration of the virtual machine server.

OS	VMware ESXI 7.03.2
System Model	SuperMicro Superserver SYS-8048B-TR3F
Processor	4x Intel(R) Xeon(R) CPU E7-4820 v3 @ 1.90GHz (80 logical processors)
Installed Physical Memory (RAM)	512 GB
Hard drive	11 TB shared cluster

3.6. Battery Experiment: Equipment

Figure 5 gives a bird's-eye view of the Rover development board used during the battery experiment. The board displays the current and future components of the Rover Module.

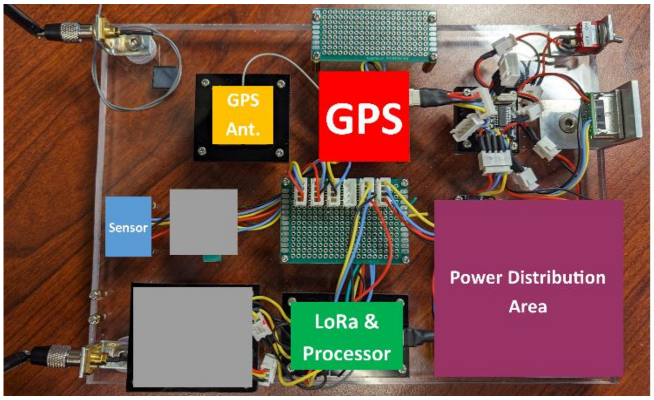

Figure 5. Rover development board for battery experiment.

Various testing equipment included battery monitoring devices, such as a voltmeter and load tester. A message receiver was used for counting and verifying received transmissions. Additional wireless communication devices that interacted with the Rover development board were used. A high-end PC for data and video recordings was also used.

3.7. Battery Experiment: Intelligent Conservation

A few different practices are used for our dynamic and intelligent battery conservation methodology. One of the methods we used is called a decision tree. The paths, or branches, of the tree create the direction of the decision-making process. The path in which the module decides to take is based on live and dynamically changing values from a specific sensor suite inside the Rover. If the system decides accuracy is more important, based on the sensor suite, the system will continue down such a branch; but if battery life is decided as more important, a different branch is selected. This is a simplified version of a method used to intelligently conserve the Rover Module battery life.

3.8. Procedure for Optimizing Battery Usage

We have developed a first-step power-saving algorithm called the Medium Power Saving system; this system and a non-restricted power-consumption baseline will be the conditions described in the following experiment. It was desirable to translate the decision trees into rules that could be applied to a single step of our simulation so that we could use it as a basis for projected battery expenditure. We determined that our lifecycle of the power-saving condition consists of four states, each corresponding to a sub-condition. The highest power-consuming state is when every part of our system is on simultaneously. We further decomposed our system to identify lower consuming combinations. Ultimately, we defined power draw measurements for each of the states (see Table 5). Finally, we applied the power values against the simulation, and computed the required power for a 50 h scenario. The required power was then used to determine the final values for the power cost versus accuracy and timing of the production of geolocation messages.

4. Results and Discussion

4.1. Crowd Simulation

Our simulation shows that first responders with Rover Module capabilities can help restore order faster in areas hit with natural disasters. Furthermore, the results support that long duration operation of agents using Rover Module enabled services are beneficial to a more symbiotic instance of crowd management. In our simulation, we use a group of Average Citizens and attempt to coax them into obtaining food and water, and then settle in a provided shelter area. Once encountered, the Rover agents equipped with the Rover Module assisted with providing the latest information on the location and routes to the resources. In contention are a large group of agents that are simply moving through the environment and impeding progress. Other smaller groups of looters and rioters are causing disturbances and general mayhem. Responders without Rover equipment in other simulation instances can calm local groups. Results from the crowd simulation are shown in Table 3. Rover-enabled first responders led to a significantly faster time for agents reaching provisional shelters, with an average of about 44 min in response to Research Question 2. The data provided in Table 3 shows first responders with the Rover Module can be effective in simulation, in response to Research Question 1.

Table 3. Results from the crowd simulation.

Quantum	No First Responders	First Responders without Rover	First Responders with Rover
Riot/Damage Incidents per sim trial (Per city block)	64/40	47/31	35/21
Looting incidents per sim trial	164	54	46
Average Citizens reaching provided shelters	8 of 24	17 of 24	24 of 24
Average time until agents reached shelter (s)	34,344	25,065	2,623

A powerful component of the C2 simulation interface is the ability to keep track of the ingoing and outgoing simulated Rover messages. We counted the position traffic and heartbeat messages that were generated during the simulation conditions that contained the Rover-equipped first responders, in turn providing guidelines for best-case and worst-case network traffic requirements. Unsurprisingly, First Responders that were in the constant patrol state used significantly more bandwidth than the Rovers that were stationed at checkpoints.

Table 4. Message tracking of Rover-equipped first responders.

Rover status	Number of Messages	Network bytes transmitted
Stationed at Waypoint	7489	32434
Constant Patrol	347,777	5,564,493

In Table 4, we see that Rovers that stay in the vicinity of a post, or a known checkpoint, can conserve the number of messages and, by extension, how often they should post a position update. The simulation was configured to produce a position message whenever a Rover agent had moved 1 m and to post a heartbeat radio message every 30 s if idle. This configuration allows us to calculate the estimated battery use in mA; then we can quickly reduce the number of position messages and power used by increasing the distance between position reports as mission parameters dictate.

4.2. Battery Experiment

The intent behind the battery experiment was to precisely collect the current battery-power draw at different conditions the Rover is put under in live scenarios. This data allows the Rover to operate with improved decisions and potentially train future machine learning algorithms to prolong battery life, while still being in a serviceable state. Table 5 depicts the common states the Rover device may be in during an emergency response. Each condition was tested numerous times, for varying durations, ranging from 7 min to 22 min. Only the components specified in the table were powered on and active during the data collection. This allowed for an extremely accurate representation of the current draw for each condition. Upon the completion of the run, the current consumption data was saved.

Table 5. Common condition states the Rover may be in.

Medium Power Saving Condition	
Sub-Condition 1D (Trial 1-3)	-Accelerometer polling every 20 ms (50 Hz) -Voltage sensor polled every 30 s -No other sensors, GPS, or heartbeats
Sub-Condition 1C (Trial 4-8)	-Accelerometer polling every 20 ms (50 Hz) -LoRa sending heartbeat w/ ID every 30 s -LoRa Transmit Power set to 13 dBm (default) -Voltage sensor polled every 30 s -No other sensors or GPS active
Sub-Condition 1B (Trial 9-13)	-Accelerometer polling every 20 ms (50 Hz) -Voltage sensor polled every 30 s -LoRa Transmit Power set to 13 dBm (default) -LoRa Location messages synced with GPS freq. -GPS rate 0.33 Hz (once every 3 s)
Sub-Condition 1A (Trial 14-17)	-Accelerometer polling every 20 ms (50 Hz) -Voltage sensor polled every 30 s -LoRa Transmit Power set to 13 dBm (default) -LoRa Location messages synced with GPS freq. -GPS RTK rate 0.33 Hz (once every 3 s)
Non-Restricted Power Consumption Condition	
Baseline (Trial 18-21)	-Accelerometer polling every 20 ms (50 Hz) -Voltage sensor polled every 30 s -LoRa Transmit Power set to 23 dBm (max) -LoRa Location messages as fast as possible -GPS RTK rate 3 Hz

The experiment produced positive results. As expected, current consumption increased as the accuracy and the number of communication transactions increased. Figure 6 depicts the average milliamps (mA) consumed during each trial per condition. By dynamically adjusting the load on the battery, based on movement patterns and their surroundings, each module can cater to an individual's necessities. Whether it be a longer duration of increased accuracy, or a message needing to be broadcasted at a greater distance, the scenarios of a first responder might be endless, so the Rover needs to be adaptable.

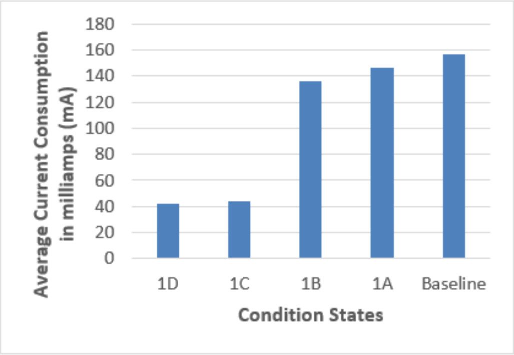

Figure 6. Current consumption by conditions.

From the data collected, a cost function variable for each sub-condition of the Rovers' battery cost function can be calculated. This cost function can tie directly into the crowd simulator and predict the levels of accuracy for a scenario, the frequency of communication messages, and how long an agent with a Rover Module is in each sub-condition. Table 6 portrays an example of a cost function used during one of the crowd simulation trials; the results are applied to answer Research Question 3.

A posted Rover in the crowd simulator describes an agent wearing a Rover stationed in a designated, known location, with minimal movement, where minimal C2 interactions or communication is necessary. A roaming Rover in the crowd simulator describes an agent wearing a Rover, actively moving, seeking individuals that may need assistance, with moderate levels of communication to C2, obtaining up-to-date information.

Table 6. Cost function breakdown.

	Posted Rover	Roaming Rover
Seconds in Sim.	180000	180000
Seconds in Sub-Con. 1B	166.304	34777.7
Seconds in Sub-Con. 1C	2912.971	20.333
Seconds in Sub-Con. 1D	176920.717	145201.966
Cost of Sub-Con. 1B (mA)	6.287	1314.790
Cost of Sub-Con. 1C (mA)	35.441	0.24739
Cost of Sub-Con. 1D (mA)	2049.333	1681.923
Subtotal (mA)	2091.060	2996.969

5. Conclusion

The aim of the Rover Module is to improve the effectiveness and efficiency of the emergency-response process. The crowd simulation model reflects the calming benefit of ground truth that the Rover enables during the early stages of emergency response. The Rover-enabled first-responder agents alleviated notional panic, the latter known to occur during catastrophes and perceived dwindling resources (Keating, 1982). Furthermore, the simulator provides a basic guideline for the data and power required for tracking with the Rover Module. The aligned power savings algorithms employed during the Medium Power Saving condition demonstrated that the Rovers could sustain C2 throughout the delicate but turbulent efforts to restore initial order and basic logistics after a large disaster. Additional power exists for additional operations (such as status updates and individual queries).

We were able to demonstrate that the simulation can be used as a tool to ascertain the number of messages required to operate for long periods of time. Additionally, the battery testing under different sub-conditions allowed us to create an adjustment for the scenario so that we could meet the prolonged battery use required. As a result of the initial simulation results, we were able to adjust the reporting rate to increase the Rovers' operational time to meet the scenarios' demand.

5.1. Limitations

As stated, the Rover Module is part of the E-Bullet system and provides a highly accurate location service for force-on-force training. The logistics of the E-Bullet training can tolerate a train-charge-train-again cycle. However, for emergency scenarios, the Rover Module will need to be specialized into a unique variation of its own to increase battery capacity; we would likely substitute a lower-powered GPS implementation. The current iterations of the Rover Module lack a comprehensive visual display to support text-based input and output. Thought needs to be given to the best input mechanisms that support the operational modality of first responders.

5.2. Next steps

A series of incrementally improved Rover Modules will be generated, with quality displays and input systems integrated and retested. Near-term evolutions of the Rover Module will harness additional IoT sensors, such as downward- and forward-facing cameras, to assist in GPS-denied environments and provide visual odometry functions. Carriage of short voice-messages for English-to-local on-the-fly translations are being studied and are near-term enablers for first responders deployed into non-English-speaking regions. Such a translator can be readily added to the crowd simulation. On the horizon, LED lights, infrared sensors, and atmospheric gas sensors are either in a prototypical stage or on the Rovers' milestone planning.

Additionally, integrating an efficient and reliable dead-reckoning algorithm for when GPS communication is scarce is non-trivial. A mature and dynamic battery management process will require effort to improve Rover Module longevity. The optimization of battery capacity, size, and duration with respect to mission parameters deserves future research. Keeping wireless communication between Rover Modules is a necessity for our system, therefore choosing the right method among a plethora of options can prolong battery life and guarantee reliable transmissions; adding a second wireless interface may be a method for improved throughput.

The crowd simulation can be augmented and improved by incorporating incident responses by the first responder agents (Solis et al., 2019). Our simulation reports incidents as they occur, but we can easily extend and improve fidelity by assigning incident reports to the closest available first responder. Furthermore, this will allow us to improve the network traffic estimates, since responders will be prone to additional communication and bidirectional reporting.

Funding

This research was funded by the U.S. Army Combat Capabilities Development Command Soldier Center

(CCDC SC), grant number W912CG-21-C-0010.

Acknowledgments

This research was funded by the SFC Paul Ray Smith Simulation and Training Technology Center (STTC) Soldier Effectiveness Directorate (SED) U.S. Army Combat Capabilities Development Command Soldier Center (DEVCOM SC). However, the views, findings, and conclusions contained in this presentation are solely those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the U.S. Government.

References

Adjiski, V., Despodov, Z., Mirakovski, D., & Serafimovski, D. (2019). System architecture to bring smart personal protective equipment wearables and sensors to transform safety at work in the underground mining industry. *Rudarsko-geološko-naftni zbornik*, *34*(1), 37-44. https://doi.org/10.17794/rgn.2019.1.4

Alexander, D. E. (2002). *Principles of emergency planning and management*. Oxford University Press.

Apple. (n.d.). *Apple Watch Ultra*. Retrieved April 14, 2023, from https://www.apple.com/apple-watch-ultra/

Basiri, M., Schill, F., U. Lima, P., & Floreano, D. (2018). Localization of emergency acoustic sources by micro aerial vehicles. *Journal of Field Robotics, 35*(2), 187-201. https://doi.org/10.1002/rob.21733

Bognar, E. K. (2018). Possibilities and security challenges of using IoT for military purposes. *Hadmérnök*, *13*(3), 378-390. https://folyoirat.ludovika.hu/index.php/hadmernok/article/view/3858

Cecchine, G., Morgan, F. E., Wermuth, M. A., Jackson, T., & Schaefer, A. G. (2013). The US military response to the 2010 Haiti earthquake: Considerations for Army leaders. Rand Corporation.

Chavez, J. (2023, February 18). How 'extraordinary' survivors are still being pulled from rubble 10 days after massive earthquake. CNN. https://www.cnn.com/2023/02/18/health/turkey-quake-rescues/index.html

Cocking, C., Drury, J., & Reicher, S. (2009). The psychology of crowd behaviour in emergency evacuations: Results from two interview studies and implications for the Fire and Rescue Services. *The Irish Journal of Psychology*, *30*(1-2), 59-73.

Fraunhofer IVI. (2023). *jCrowdSimulator* [Computer software]. GitHub. https://github.com/FraunhoferIVI/jCrowdSimulator

Garmin. (n.d.). *Garmin fēnix 7 – Standard Edition*. Retrieved May 02, 2023, from https://www.garmin.com/en-US/p/735611/pn/010-02540-00#specs

Helbing, D., Buzna, L., Johansson, A., & Werner, T. (2005). Self-organized pedestrian crowd dynamics: Experiments, simulations, and design solutions. *Transportation Science*, *39*(1), 1-24. https://doi.org/10.1287/trsc.1040.0108

Kaspersen, I. S. (2021). New societies, new soldiers? A soldier typology. *Small Wars & Insurgencies*, *32*(1), 1-25.

Keating, J. P. (1982). The myth of panic. *Fire Journal, 76*(3), 57-61, 147.

Macintyre, A. G., Barbera, J. A., & Petinaux, B. P. (2011). Survival interval in earthquake entrapments: Research findings reinforced during the 2010 Haiti earthquake response. *Disaster medicine and public health preparedness, 5*(1), 13-22.

Mawson, A. R. (2005). Understanding mass panic and other collective responses to threat and disaster. *Psychiatry, 68*(2), 95-113.

OpenJUMP Volunteers. (2023). *OpenJUMP (Version 2.2.1)* [Computer software]. Github. https://github.com/openjump-gis/openjump

QGIS Project. (2023). *QGIS (Version 3.30.2)* [Computer software]. https://www.qgis.org/en/site/index.html

Scanlan, D. (2018a, June 22). *Massive Camp Blanding search ends with missing soldier found dead*. Jacksonville.com | The Florida-Times Union.

Scanlan, D. (2018b, July 10). *Autopsy: Heat exposure caused Army reservist's death at Camp Blanding*. Jacksonville.com | The Florida-Times Union. https://www.jacksonville.com/story/news/crime/2018/07/10/autopsy-heat-exposure-caused-army-reservists-death-at-camp-blanding/11504907007/

Solis, A. O., Nosedal-Sánchez, J., Asgary, A., Longo, F., Rizzi, D., Plested, K., Briga, A., Castagna, A., & Zaccaro, B. (2019). Agent-based simulation of a fire department's response to emergency incidents: An updated model. *Proceedings of the 9th International Defense and Homeland Security Simulation Workshop (DHSS 2019)*, 39-46. https://doi.org/10.46354/i3m.2019.dhss.007

Space and Naval Warfare Systems Center Atlantic (2014). *GPS blue force tracking systems application note*. U.S. Department of Homeland Security. Retrieved June 2023, https://www.dhs.gov/publication/blue-force-tracking-systems

Wong, J., & Robinson, C. (2004). Urban search and rescue technology needs: Identification of needs. *Federal Emergency Management Agency (FEMA) and the National Institute of Justice (NIJ)*. Document, 207771.