Cable Installation Robot for Contested Environments (CIRCE) Project Proposal

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Abstract—**Modern military operations increasingly rely on secure communication networks. However, in contested environments where radio frequency and electromagnetic interference are present, wireless communication systems are often unreliable or compromised. To address this, the Cable Installation Robot for Contested Environments (CIRCE) operates as a semi-autonomous robotic system to deploy physical ethernet cables in high-risk zones. Unlike existing aerial or manual solutions, CIRCE utilizes a ground-based platform to navigate GPS-denied environments utilizing on-board sensors and algorithmic path planning. The purpose of this paper is to establish an outline of CIRCE's system architecture and reliability to operate as intended.**

Index Terms—**Sensor Fusion, SLAM, GPS Denied Autonomous Systems**

I. Introduction

Modern military operations rely heavily on network-centric warfare, but this dependency creates a vulnerability: adversaries can jam up radio frequencies to deny wireless communications in contested environments. When wireless systems fail, hardwired ethernet cables offer a reliable alternative that cannot be jammed remotely. The problem is that deploying these cables currently requires soldiers to physically lay them through hostile environments, putting personnel directly in harm's way. The Cable Installation Robot for Contested Environments (CIRCE) eliminates this risk by autonomously deploying communication cables in dangerous zones, allowing units to establish secure connections without exposing anyone to enemy fire.

This proposal outlines the design and development of CIRCE to meet requirements specified by the U.S. Army Combat Capabilities Development Command (DEVCOM). The robot must navigate autonomously through contested terrain, even when GPS is jammed, all while deploying ethernet cable that meets TIA/EIA-568 installation standards. It shall communicate back to C2 through the cable it lays and run for at least 20 minutes on the power supply. Making this work requires bringing together several complex systems: autonomous navigation that doesn't rely on GPS, sensors that detect obstacles in real time, and efficient power management to keep everything running in the field.

II. Formulating the Problem

The establishment of reliable communication networks is a cornerstone of modern military operations. In conventional scenarios, wireless radio frequency (RF) communications provide flexibility and speed for effective coordination. However, adversaries are actively developing capabilities to intercept and jam these signals, creating a "silent battlefield" where command and control (C2) capabilities are degraded, and units lose the ability to coordinate operations, share intelligence, or maintain situational awareness [1]. To combat this degradation in frequency-contested environments, hardwired ethernet cable becomes the necessary alternative to establish jam-resistant communication that cannot be interfered with by adversaries. However, establishing these hardwired connections currently requires personnel to manually lay communication lines through contested zones, exposing military personnel to enemy fire, improvised explosive devices (IEDs), and unnecessary combat danger. Based on the needs of the U.S. Army Combat Capabilities Development Command (DEVCOM), the Cable Installation Robot for Contested Environments (CIRCE) system addresses this critical capability gap by autonomously deploying communication cables in hostile environments, eliminating personnel risk while restoring reliable C2 communications.

The U.S. Army requires unmanned systems capable of entering high-risk zones to remove personnel exposure during communication infrastructure deployment. The CIRCE system must operate independently to keep military personnel out of danger while traversing contested areas and deploying hardwired communication cables. The system must navigate to designated waypoints in GPS-denied environments where satellite navigation is unavailable due to jamming or physical obstructions. Because the robot operates in high-risk zones where human intervention is dangerous, it will encounter physical challenges including rough terrain, uneven hills, and obstacles that require robust mobility systems to maintain traction and reach designated locations. The soil's ability to provide traction is limited for small, unmanned ground vehicles (UGVs), and wheel slip can minimize mobility, causing the robot to become immobilized in certain terrain conditions.

The CIRCE system must deploy physical communication lines while traversing complex environments where cables are susceptible to catching on natural or man-made objects. The system requires a spool mechanism capable of deploying communication lines at controlled speeds synchronized with the robot's forward velocity and slack conditions to minimize cable entanglement. If cable deploys too rapidly, it creates excessive tension and slack that the robot must overcome by increasing acceleration, resulting in higher battery consumption and potential cable damage. Conversely, insufficient deployment speed causes the robot to drag cable, increasing pulling tension beyond acceptable limits, and risking cable jacket damage or conductor breaks. The cable management system must maintain proper tension—typically 25 pounds maximum for Cat5e/Cat6 ethernet—while adhering to minimum bend radius specifications of 4-8 times cable diameter to ensure signal integrity [2].

While other robotic solutions exist, they lack critical factors necessary to complete this mission. Unmanned aerial vehicles (UAVs) and drones commonly deployed in similar situations face fundamental payload limitations when carrying the substantial weight of communication cables designed to withstand rough environmental conditions. The physical weight of cables restricts how far and how long UAVs can travel before battery depletion forces mission termination [3]. Additionally, when UAVs begin unwinding cable during flight, the aerodynamic forces and shifting center of gravity caused by the trailing cable can destabilize the aircraft, making it difficult to control and potentially causing crashes [4]. Ground-based commercial robots, while offering superior payload capacity, are not purpose-built for cable deployment and lack integrated cable management subsystems, requiring extensive modification that essentially duplicates the engineering effort CIRCE demands.

Both UGVs and UAVs offer distinct advantages and disadvantages in their operational approaches, but the critical requirement is designing and implementing a robust robotic system capable of overcoming the unique challenges of autonomous cable deployment in contested environments. The challenge necessitates a dedicated engineering team to achieve complex integration of an autonomous ground-based navigation system operating in GPS-denied conditions with the dynamic physical demands of deploying a communication tether while maintaining cable installation standards, all within the constraints of limited onboard power and hostile operational conditions. This multi-disciplinary integration requirement—spanning electrical engineering, mechanical engineering, computer science, and systems engineering—justifies the capstone project scope and demonstrates the technical complexity that existing commercial solutions cannot adequately address.

III. Background

Several technical and operational factors were considered in the development of CirceBot. A closely related system is the cable deployment system for unmanned ground vehicles (UGVs) developed by Michigan Technological University [5]. In their system, a UGV departs from a fixed power source and traverses terrain while deploying an electrical cable to establish connections between nodes within an autonomous mobile microgrid. The platform integrates navigation and environmental awareness technologies, including inertial measurement units (IMUs), global positioning systems (GPS), Light Detection and Ranging (LiDAR), and vision-based sensing to survey the environment and ensure accurate cable placement between grid nodes [5].

A key subsystem in this design is the Adjustable Cable Management Mechanism (ACMM), which prevents cable twisting, snagging, shunting, or entanglement during deployment [5]. This mechanism enables controlled payout and mitigates mechanical failure due to environmental obstacles.

The integration of cable management hardware with autonomous navigation demonstrates the feasibility of mobile infrastructure deployment using ground robotics. CirceBot adopts similar foundational principles in mapping, navigation, and cable deployment. However, CIRCE is intended to operate in more unpredictable environments [5]. While the system described in [5] supports microgrid infrastructure, CirceBot is designed for deployment in GPS-denied and RF-jammed environments, where traditional wireless communication may be unreliable or unavailable. In such environments, establishing a physical communication backbone becomes critical.

The primary objective of CirceBot is to autonomously route and deploy Ethernet cable across irregular, hazardous terrain to establish a secure communication link between forward units and a base location. To accomplish this, CirceBot will integrate multi-sensor navigation, including LiDAR, infrared sensors, depth cameras, and additional environmental perception systems to continuously monitor terrain conditions and adjust its trajectory accordingly [6], [7]. These sensors will enable real-time obstacle detection, hazard avoidance, and adaptive path planning in unpredictable operational environments.

Unlike conventional autonomous systems that rely heavily on GPS, CirceBot must operate effectively in GPS-denied conditions. Therefore, sensor fusion techniques combining LiDAR, inertial measurements, odometry, and vision-based localization will be implemented to provide reliable positioning and mapping [7]. The onboard processing architecture will include an embedded computing platform capable of handling perception, mapping, and path planning algorithms. A single-board computer may be used for high-level data processing and communication between subsystems, while a dedicated microcontroller will manage low-level motor control and real-time sensor interfacing.

A critical design consideration is the onboard cable management system. The deployment mechanism must regulate cable tension to prevent tangling, excessive drag, or mechanical failure during traversal [8]. The system must also support controlled retraction if route adjustments are required. This functionality draws conceptual inspiration from the ACMM described in [5], while adapting it to Ethernet deployment.

In contrast to many autonomous systems that rely primarily on wireless communications and GPS navigation, CirceBot will utilize the physical Ethernet cable it deploys as its primary data communication medium. This architecture increases resistance to RF interference and electronic jamming while enabling high-bandwidth and low-latency connectivity. The successful implementation of CirceBot requires the integration of robotics, embedded systems, mechanical design, sensor fusion, and resilient communications engineering to develop a reliable autonomous cable-deployment platform suitable for operation in unpredictable and hostile environments.

IV. Specifications

CirceBot shall be designed to receive and execute commands while transmitting telemetry data in the format supplied in the CirceSoft2CirceBot.proto spec from CirceSoft. CirceSoft shall accept planned paths in the specified format and follow those paths to its objective.

CirceBot shall dispense cable according to installation guidelines, including proper curve radiuses, strain relief, and tension tolerances.

CirceBot shall be equipped with an independent power source capable of at least 20 minutes of operation in Tennessee environments.

CirceBot shall transmit real-time data, including current position, current velocity, meters of cable left, heading, battery life percentage, and error codes if any occur.

CirceBot shall receive Next Position waypoints and navigate to the next waypoint.

CirceBot shall carry up to 100 meters (approximately 10 lbs) of Ethernet cable and report error codes via self-diagnosis.

CirceBot shall be rechargeable, send and receive commands at a minimum frequency of 10 Hz, and communicate with CirceSoft using the WebSocket protocol.

CirceBot shall have a switch to simulate GPS-denied environments and will communicate using the deployed Ethernet cable.

CirceBot shall stop once the specified destination is reached and allow for easy reloading and quick replacement of Ethernet cable reels within 2 minutes, without the use of external tools.

CirceBot shall use minor obstacle avoidance to avoid collisions.

V. Constraints

The material cost of CirceBot shall remain within the established budget, and any remaining or unused funds shall be retained by or returned to Tennessee Tech University.

The construction and operation of CirceBot shall comply, as applicable, with OSHA, ANSI/RIA, and ISO robotics safety standards [9].

The manufacturing, testing, and eventual deployment of CirceBot shall not adversely affect the general public on the Tennessee Tech University campus or within the surrounding Cookeville, TN area.

The design and construction of CirceBot shall also adhere to any additional standards or requirements provided by the client or the university, if applicable.

VI. Survey of Existing Resources

In recent years, autonomous robots have been developed that can navigate complex terrain using various sensors. One example of this is the GE Autonomous Robot ATVer developed by General Electric's (GE) Research Lab team. The robot can navigate unstructured environments, such as forests, using GE's Humble AI technology. Humble AI uses algorithms to assess risks when traversing uncertain areas [10]. Although this robot is an excellent option for navigating rugged environments, the robot would not meet the specifications and constraints set for this project. Another example of autonomous robots that can traverse difficult territories is the CLAWbot developed by the Adaptive Robotics and Technology Lab. The CLAWbot uses wheels and claw-like components to traverse both smooth land and potential barriers. While the CLAWbot can easily travel across obstacles, the robot has a fixed axis which would make navigation more difficult [11].

Clearpath Robotics has designed a few autonomous robots of varying sizes that are suitable for rugged environments. One example is the Warthog, which can navigate tough environments such as soft soils, vegetation, mud, steep grades, and small amounts of water. The robot can run unmanned and can use sensors, such as LiDAR, for obstacle detection. The Warthog includes easy accommodation of accessories including sensors, lights, and robotic arms to suit a wide range of needs. The robot also includes a Robot Operating System already installed for easy setup. This robot can hold up to 600 pounds and can travel at 11 miles per hour. The battery has a nominal runtime of 2.5 hours, which is sufficient for most applications. Although the Warthog would be a great option for navigation, its heavy price tag makes this option unfeasible. While the other models developed by the company are less expensive, they are designed for smaller applications and would not work effectively in rugged territory [12].

UAVs are an excellent option for navigation in GPS denied environments. UAVs such as drones have exceptional flexibility and maneuverability, which makes navigating complex environments much easier. Drones collect data on the environment and its position using sensors such as LiDAR, cameras, and IMUs. The data collected is then processed using advanced algorithms, including SLAM, to map the drone's position and the environment. The drone can then use that data to make decisions based on what the optimal path would be and update the path as more data is collected and processed [13]. One example of a UAV that can navigate GPS denied environments was made by Andrew Bernas. Bernas used VSLAM on a NVIDIA Jetson Orin Nano to navigate areas without the use of GPS. The drone uses visual-inertial sensing and onboard mapping to accomplish this [14]. While drones are accurate, independent, faster, cheaper, and less likely to take damage, the drones have many disadvantages that ultimately would not fit the constraints and specifications for this project. Drones need complex algorithms, sensor limitations, powerful computing systems, government regulatory barriers, issues with integration, and would not be able to hold heavy equipment. These issues and disadvantages ultimately make drones unideal for this project [13].

Reviewing other environments autonomous systems can operate in, autonomous underwater vehicles (AUVs) pose transferrable aspects despite maneuvering via unique propulsion system compared to terrestrial systems. One such robot has been deployed by Japanese researchers to aide in deploying fiber optic cable. Despite the remote operated vehicle (ROV) having sub systems pertaining to buoyancy control, one such sub system most applicable to the terrestrial environment is the cable installation sub system. The AUV cable sub system utilizes a sheave and bobbin system, each independently driven by motors, to guide the cable while reducing the risk of cable entanglement during deployment. This combination may open avenues for further research for cable feeding feedback when measuring cable tautness and varying cable dispensing speed [15].

VII. Measures of Success

Measures of success of the CIRCE system will be based on whether CirceBot has the capability to communicate with CirceSoft, complete its intended mission without external intervention, and lay cable efficiently as outlined in the specification sheet. The CirceBot shall successfully navigate to specified waypoints provided by CirceSoft while operating in both normal and GPS-denied modes. Success will be measured by the robot reaching all waypoints within the expected path tolerance and without requiring manual correction. The CirceBot shall deploy up to 100 meters of Ethernet cable while maintaining proper installation practices, including acceptable bend radius, strain relief, and tension control. The installed cable will be inspected after deployment to verify that it meets the guidelines and remains fully functional. The system shall operate for a minimum of 20 minutes on its independent power source while carrying the required an approximated 10 lbs. of cable load. Success will be measured by continuous operation without power failure during the test period. The system shall transmit and receive commands at a minimum rate of 10 Hz using the deployed Ethernet cable and WebSocket protocol. Success will be measured by verifying consistent telemetry updates and command acknowledgment throughout operation. The CirceBot shall operate without physical assistance during mission execution, including obstacle avoidance, path following, cable deployment, and stopping at the final destination. Overall success will be determined by the system's ability to restore a communication link between the simulated C2 location and the asset while meeting the defined specifications.

VIII. Resources

Each team member must utilize a diverse range of engineering skills to properly and successfully design, build, and implement each segment of this project. The team must also stay within the boundaries set before them, either by the buyer, supervisor, etc. Each team member must contribute to the tasks set before them, utilizing their unique expertise in the concentration, ensuring each aspect of the project is addressed effectively.

A wide range of sources are required to ensure successful completion of this project. Each team member holds valuable skills that are necessary in the design and implementation of the robot. Such skills include 3D design, programming, soldering, troubleshooting, power systems, and hardwiring. Design software's such as AutoCAD, SolidWorks, and KiCad are imperative for creating schematics and the layout for the components. Expertise in programming languages such as C++ and Python are vital for the development of the software used to control and automate the robot, as well as the integration between the hardware and software subsystems. Knowledge in power systems is requisite in ensuring the optimization of power supply and preventing potential issues related to power connections. Skills in troubleshooting, hardwiring, and soldering are essential for ensuring proper connections and preventing or fixing issues that may arise. As the need for more skills necessary in the completion of this project arises, the team will continue to learn new skills and expand upon their current skills.

This project will require the use of various materials to ensure the proper design of the robot. Such materials include sensors, microcontrollers, a robot base, an ethernet cord, and a power supply. Sensors are required to guarantee that the robot can autonomously navigate complex environments. Microcontrollers are necessary to ensure precise control of the robot and accurate measurements from the sensors. A robot base is vital for the navigation and movement of the robot. A strong and lengthy ethernet cable is necessary to ensure proper connection and stable communication while navigating harsh environments. A reliable power supply is essential in ensuring the robot can accomplish the tasks it has been given.

Proper documentation and trustworthy sources of information are necessary in ensuring the proper design and completion of this project. GitHub will house important documents regarding the design and testing of the robot. Effective communication via Teams and email among team members is crucial to ensure the fulfilment of the requirements for this project. Advisement from faculty such as Dr. Storm, Dr. Van Neste, Dr. Rizvi, and Mr. O'Conner is key to guaranteeing the success of this project, as well as assure the design follows the specification and constraints set by DEVCOM.

IX. Budget

The development of the CIRCE system requires a maximum budget of 1070. The team will rely on a combination of commercial off-shelf electronics and custom manufacturing. The chassis and cable management mechanism will be 3D printed using highly durable filament. The hardware architecture will utilize a microcomputer, like a Raspberry Pi 5, to process LiDAR and camera data. And microcontrollers, such as an STM32, to control motors and process telemetry information. The robot will utilize high-torque DC motors to traverse its environment and stepper motor to help unwind the communication cable. Power will be supplied by high-capacity batteries capable of sustaining at least 20 minutes of continuous operation. Additionally, the budget will account for software development tools, including licenses and simulation software and a contingency fund to account for part replacement, design changes, or unforeseen expenses.

X. Personnel

Instructor:

Supervisor/Advisor: Dr. Rizvi will serve as the primary supervisor for the CirceBot project, bringing experience in control theory, autonomous systems, and robotics.

Gerardo Ramirez: Experience in system integration and project coordination, with proficiency in embedded programming (C/C++), Python, and hardware-software interface design.

Brady: strong areas are in troubleshooting and wiring and is also familiar with power and programming.

Summer: Proficient in 3D design software's such as AutoCAD and SolidWorks, programing languages including C/C++, Python, and MATLAB, and soldering

Nick: Proficient in SOLIDWORKS, additive manufacturing, soldering, microcontrollers, and hardware troubleshooting, with additional experience in programming languages including C, Python, and MATLAB.

Sharif Zahra: Knowledgeable in C/C++ for microcontrollers and integrating systems. Also knowledgeable in power and control systems.

Daniel Davis: Proficient in embedded programming using C/C++ and microcontroller development, with experience in MATLAB and soldering.

Category	Item	Quantity	Unit Cost ($)	Total Cost ($)
Materials & Components				
	Raspberry Pi 5	1	100	Already Have
	STM32	1	30	30
	LiDAR & Camera	1	250	Already Have
	DC Motors &Wheels	2	40	80
	Stepper Motor	1	75	75
	Battery	1	190	190
Subtotal				375
Software Tools				
	Software Licenses	2	100	University Provided
	Simulation Software (3D Modeling)	1	200	University Provided
Subtotal				0
Prototyping & Testing				
	3D Printing Materials	4	50	200
	Custom PCB	3	50	150
	Miscellaneous Hardware (Fasteners, wiring, etc.)	1	50	50
	Cat5e Cable (100 m)	1	40	40
Subtotal				440
Contingency Funds				255
Total Budget				1070

Fig. 1. Table 1: Development Expenses

Alongside the EE Capstone team personnel, there will be a Mechanical Engineering team working on developing a custom chassis and robot to carry CIRCE through the terrain. To mitigate unforeseen issues in integrating the two sub-assemblies, the EE team will have a subgroup serving as liaisons between the ME and EE teams to answer any concerns.

XI. Timeline

As mentioned in Section I, the project's scope for the EE Capstone team involves developing an autonomous rover for US Army DEVCOM. As such, there are several internal and external milestones the team must meet as they are listed below. To accomplish and meet these deadlines, the team plans to set realistic stretch deadlines to ensure goals are met ahead of schedule.

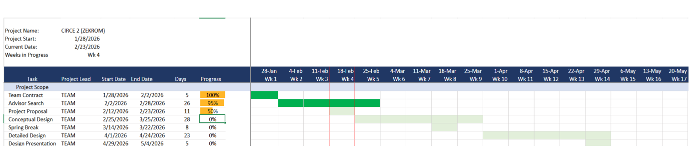

Fig. 2. Proposed Gantt Chart

Conceptual Design (Internal milestone): March 25th, 2026, from figure 1.

Detailed Design (Internal milestone): April 24th, 2026, from figure 1.

Design Presentation (Internal milestone): April 29th, 2026, from figure 1.

Maintaining a clear, coordinated timeline across electrical and mechanical subsystems is critical to the project's success. To support this, the EE team will work closely with the mechanical engineering team to minimize integration issues and ensure both subsystems remain on schedule for integration and testing.

XII. Specific Implications

Implementing the CIRCE system provides several significant benefits that directly address the challenges encountered in tactically contested environments:

Restoration of Reliable Communications:

By deploying a dedicated hardwired Ethernet link, the system maintains a continuous connection between the stationary asset and centralized Command and Control (C2) even when RF communications are disrupted by jamming or interference. This uninterrupted data link is crucial for ensuring the proper functioning of mission-critical operations.

Enhanced Safety for Personnel:

Rather than exposing personnel to high-risk scenarios—such as manually laying cables through contested areas, the autonomous CirceBot performs cable installation. This approach minimizes human exposure to enemy threats and hazardous conditions, thereby enhancing overall operational safety and reducing the risk of injury. Furthermore, the autonomous project attribute reduces human personnel taken away from reestablishing control over the contested environment.

Precision and Efficiency in Cable Deployment:

The integrated CirceSoft application leverages real-time telemetry and field imagery to compute an optimal cable route that adheres to best installation practices. By considering factors such as proper curve radii, strain relief, tension tolerance, and potential environmental hazards, the system minimizes installation errors and delays, ensuring that the cable is deployed accurately and maintains its operational integrity.

Operational Adaptability:

Equipped with advanced navigation algorithms that function in GPS-denied environments, the CirceBot can reliably operate across a range of terrains and conditions. This versatility allows the system to be effectively deployed in various tactical scenarios, increasing its overall utility.

Cost Efficiency and Reduced Risk:

Automating the cable installation process decreases the reliance on manual labor in high-risk settings, which not only cuts labor costs but also minimizes the financial and operational risks associated with personnel injury or mission failure. With each solider costing on average $50,000$–100,000 to train and maintain, these savings contribute to improved operational readiness and reduced long-term expenditures [16].

Overall, CIRCE provides a reliable and practical way to restore communication. By improving operational control, reducing risk to personnel, accelerating deployment, and lowering long-term costs, the project supports the mission needs while offering a safer option to cable installation.

XIII. Broader Implications

The implementation of CIRCE carries implications that extend far beyond its immediate military application in contested environments, affecting global security dynamics, economic considerations, environmental sustainability, societal technological advancement, and the ethical responsibilities of engineers developing autonomous systems.:

Global and Economic:

From a global perspective, CIRCE represents a shift toward autonomous systems that reduce human exposure in high-risk military operations. As near peer adversaries develop increasingly sophisticated electronic warfare capabilities, nations that can maintain communications in contested environments gain significant strategic advantages. The proliferation of autonomous cable deployment technology may influence international military doctrine, potentially reshaping how forces establish and maintain command networks in hostile territory. This technological capability could affect the balance of power in regions where communication infrastructure determines operational success.

Economically, CIRCE offers substantial cost benefits beyond the initial development of investment. The United States military spends approximately $50,000to$100,000 per soldier for training, equipment, and annual maintenance, not accounting for medical costs, benefits, or the incalculable human cost of casualties [1]. Deploying CIRCE instead of personnel for cable installation missions reduces these recurring costs while eliminating casualty related expenses including medical treatment, disability compensation, and survivor benefits. Over the system's operational lifetime, even accounting for maintenance, repairs, and eventual replacement, the economic advantage of autonomous deployment becomes clear. Furthermore, reducing personnel exposure to combat operations decreases the psychological toll on service members and their families, reducing long term costs associated with post-traumatic stress treatment and veteran healthcare.

The development of CIRCE also stimulates economic activity in the robotics and autonomous systems sectors. Manufacturing these systems creates jobs in engineering, production, quality assurance, and technical support. As military procurement drives technological advancement, commercial applications emerge, expanding the market for autonomous cable deployment beyond defense applications. This may create potential opportunities for private sector growth in telecommunications infrastructure, disaster response, and industrial automation markets.

Environmental:

CIRCE's environmental impact requires consideration across its lifecycle, from manufacturing through operation to eventual disposal. The system's design should prioritize environmentally responsible material selection, utilizing recyclable components where feasible and avoiding hazardous materials in battery systems and electronic assemblies. During operation, CIRCE's electric propulsion system produces zero direct emissions, contrasting favorably with diesel-powered alternatives or vehicle-based cable deployment methods. The autonomous system's optimized path planning reduces unnecessary terrain traversal, minimizing soil compaction and vegetation disturbance compared to manual deployment where personnel may take indirect routes or make multiple passes to correct installation errors.

Cable deployment itself presents environmental considerations. Ethernet cables contain copper conductors and plastic insulation materials that, if damaged or abandoned, persist in the environment. CIRCE's adherence to proper installation guidelines, maintaining appropriate bend radii, tension, and strain relief, increases cable longevity and reduces the likelihood of premature failure and environmental contamination. The system's precision reduces cable waste by optimizing deployment routes and minimizing excess cable use. However, the engineering team must consider end of life cable recovery and recycling procedures, particularly for military applications where cables may be deployed in contested areas and subsequently abandoned.

The manufacturing process for CIRCE components, particularly battery systems and electronic assemblies, carries environmental costs including resource extraction, energy consumption, and potential pollution. The team bears responsibility for specifying components from manufacturers with responsible environmental practices and designing eventual disassembly and component recovery. Battery disposal requires particular attention, as lithium ion and other advanced battery chemistries contain materials requiring specialized recycling processes to prevent environmental contamination.

Societal:

Beyond military applications, CIRCE's technology addresses communication challenges in numerous civilian contexts where RF communication is unreliable or impossible. Mining operations frequently require communication infrastructure in GPS-denied, RF-contested underground environments where manual cable installation exposes workers to collapse hazards, toxic atmospheres, and equipment dangers. CIRCE derived systems could establish communication networks in active mines, abandoned mine rescue scenarios, or exploratory tunneling operations, enhancing worker safety and operational efficiency.

Urban infrastructure maintenance presents similar opportunities. Subway tunnels, underground utility corridors, and sewer systems require periodic communication network installation for inspection, maintenance, and emergency response operations. Autonomous cable deployment reduces worker exposure to confined spaces, toxic gases, electrical hazards, and structural collapse risks. Natural cave exploration and rescue operations, where communication with surface teams proves critical, could benefit from rapid autonomous cable deployment when time sensitive situations prevent safe manual installation.

Disaster response scenarios offer perhaps the most immediate civilian application. Following earthquakes, hurricanes, or other catastrophic events, communication infrastructure often suffers extensive damage precisely when coordination between rescue teams, medical facilities, and command centers becomes most critical. CIRCE adapted systems could rapidly establish hardwired communication networks through unstable debris fields, collapsed structures, or contaminated areas where personnel exposure must be minimized, enabling more effective disaster response while protecting rescue workers.

The societal acceptance of autonomous systems performing tasks traditionally requiring human judgment raises important questions. Public perception of military robotics remains mixed, with concerns about autonomous weapons and the ethics of removing humans from combat decision making. CIRCE's exclusive focus on communication infrastructure rather than combat operations may help demonstrate the positive potential of military autonomous systems, potentially influencing public discourse and policy regarding robotic systems in defense applications. Successfully deploying CIRCE could establish precedents for autonomous system reliability, safety standards, and human machine collaboration that benefit broader autonomous technology development.

Ethical Responsibilities:

The engineering team developing CIRCE bears profound ethical responsibilities, as the system's successful operation directly impacts personnel safety in combat environments. Lives may depend on CIRCE's ability to reliably establish communication links under hostile conditions. Mission critical communications enable commanders to direct forces, medical personnel to coordinate casualty evacuation, and isolated units to request support. Failure to establish these communications could result in preventable casualties, mission failure, or strategic disadvantages. This reality imposes an ethical obligation to pursue engineering excellence with unwavering commitment to reliability, thorough testing, and honest assessment of system capabilities and limitations.

Engineers developing autonomous systems that replace human workers in dangerous environments have a fundamental duty to ensure these systems genuinely reduce risk rather than merely redistributing it. CIRCE must not create new hazards. For example, an unpredictable autonomous rover that endangers nearby personnel or civilians presents an unacceptable tradeoff. The team must rigorously evaluate failure modes, implement appropriate safety mechanisms including emergency stop capabilities, and establish clear protocols for human oversight and intervention when system behavior deviates from expected parameters.

Transparency in communicating system capabilities and limitations represents another critical ethical responsibility. Military decision makers relying on CIRCE must understand its operational envelope about the conditions under which it can reliably perform versus scenarios where alternative approaches remain necessary. Overstating capabilities to secure funding or approval could lead commanders to deploy the system inappropriately, potentially causing mission failure or casualties. The engineering team must resist pressures to minimize acknowledged limitations and instead provide honest, comprehensive assessments of system readiness and appropriate use cases.

The development of CIRCE also requires consideration of dual use of implications and potential misuse. While designed exclusively for communication infrastructure, the autonomous navigation and path planning technologies developed for CIRCE could potentially be adapted for other purposes. The team should maintain awareness of how their technical innovations might be applied beyond the intended scope and engage appropriately with export control regulations and technology transfer policies. This responsibility extends to documentation practices, ensuring technical specifications receive appropriate handling while enabling legitimate collaboration and peer review.

Finally, engineers bear responsibility to the broader community of autonomous systems developers. Lessons learned from CIRCE's development, successful approaches, unexpected challenges, failure modes, and design decisions will contribute valuable knowledge to the field. Sharing these insights through appropriate channels, whether academic publications, industry conferences, or technical reports, advances the state of autonomous systems engineering and helps other teams avoid repeating mistakes or reinventing solutions. This commitment to collective advancement represents both an ethical obligation and a practical contribution to technological progress that ultimately benefits society.

The team's approach to CIRCE development will be guided by these ethical considerations, prioritizing safety, reliability, honesty, and responsible innovation throughout the design, implementation, testing, and deployment processes.

XIV. Statement of Contributions

Summer Morris: Contributed to the survey of existing resources, resources, personnel, and statement of contributions.

Brady Harkleroad: Contributed to background, personnel, resources, and constraints.

Sharif Zahra: Contributed to abstract, formulating the problem and budget.

Nick Romsdal: Contributed to Survey of Existing Resources, Personnel, Timeline, Statement of Contributions, and preliminary revisions to the proposal.

Daniel Davis: Contributed to Specific Implications, Personnel, Measures of Success, Formulating the Problem, and Statement of Contributions.

Gerardo Ramirez: Contributed to the Introduction, Formulating the Problem, Specifications, Personnel, Broader Implications, Statement of Contributions, and the Gantt chart.

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