Cable Installation Robot for Contested Environments (CIRCE)

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***Abstract*— Modern military operations rely heavily on secure communication networks, often requiring the rapid deployment of cables in contested environments. The Cable Installation Robot for Contested Environments (CIRCE) is an autonomous robotic system designed to lay communication cables safely and efficiently in high-risk zones without exposing human operators to danger. CIRCE leverages advanced path planning algorithms, obstacle detection, and terrain adaptation to navigate complex environments while optimizing cable placement. The robot integrates a sensor subsystem, including various terrain detection and GPS-denied localization methods, ensuring robust performance in specified test conditions. This paper presents CIRCE's system architecture, autonomous navigation framework, and real-world testing scenarios that validate its capability in contested zones. CIRCE aims to enhance operational efficiency and battlefield survivability, representing a significant advancement in autonomous military engineering applications.**

Keywords*— *Collision Detection, Sensors, Design.

I. Introduction

In modern military and defense operations, maintaining reliable communication is critical for effective command and control. However, in contested environments where radio frequency communications are unreliable, alternative solutions are required to establish secure and persistent connectivity. This project focuses on the development of the Cable Installation Robot for Contested Environments (CIRCE), a semi-autonomous robot designed to deploy Ethernet cables and restore communication links without exposing any human to unnecessary risk.

The CIRCE system will consist of three core components: CirceBot, the cable installation robot responsible for physically deploying the cable; CirceSoft, the path planning software that guides CirceBot's movements; and a hardline-based communication interface that enables telemetry transmission and control without reliance on radio frequency signals. The system is designed to function in GPS-denied environments while ensuring precise cable installation.

This proposal outlines the technical approach, design methodology, and expected outcomes for the CIRCE system. The primary objectives include developing a robotic platform capable of autonomously navigating to waypoints, deploying up to 100 yards of Ethernet cable, and maintaining real-time telemetry communication with CirceSoft. By integrating advanced navigation techniques, semi-autonomous control, and robust cable-handling mechanisms, the CIRCE system aims to enhance operational efficiency while minimizing risk to personnel in contested environments.

II. Formulating the Problem

The problem at hand here is that we currently do not have a reliable and consistent tool to install a hard-wired communication system in an area where it is too dangerous to send a soldier/technician in to complete the task by hand. The reason this is so important is that these places typically have contested radio frequencies meaning that the average walkie-talkie or cell phone either does not work in its entirety or is not a secure communication system that the enemy can hack. The ability to communicate safely and effectively in a war zone is imperative. This raises the question of how one can overcome this. Hard-wired communications are typically used in scenarios where high security and consistent performance are imperative [1]. This is exactly the scenario we have here, and the robot's job will be to get the wire from point A to point B without placing a living being in harm's way.

This robot shall keep a person out of harm's way by completing its task of installing communications through a contested area. By designing a semi-autonomous robot with the capability of traversing mild terrain to lay down a line of cable, a soldier/technician should not have to be exposed to a dangerous zone, where contesting forces could cause bodily harm. The challenges involved in solving this problem are, but are not limited to: traversing rough terrain, communicating through ethernet cable, using inputs from CirceSoft for the next location, functioning in a zone of contested radio frequency, and running independently on its power supply. It will also pose a challenge to have the robot use GPS coordinates while also having an option to not involve GPS at all and navigate separately.

Why is there not already a solution to this problem? While there are many cable-laying robots out there both aerial and, on the ground, very few carry the cable itself, meaning it is dragging the cable along behind it. Also, few robots are autonomous meaning that someone is controlling it like an RC car. Those that are autonomous are not hard-wired and rely on GPS solely to navigate. The solution we present combines many of the robots already in existence for this service. The intention is to build something that is hard-wired that simply receives inputs and goes to them without having to be controlled. It will also be specifically designed to carry/lay cable instead of tying it to the back and dragging.

III. Background

The professional counterpart to this project is modern subsea autonomous cable-laying systems, which are designed to deploy infrastructure across vast and often unpredictable underwater environments. Observing the implementation of these systems offers valuable insights into the necessary processes and subsystems required for CirceBot's design. Most subsea cable-laying operations utilize advanced sonar, GPS tracking, and automated path-planning algorithms to ensure precise placement while mitigating environmental and operational challenges [6]. For the purposes of this project, CirceBot will integrate similar tracking and mapping capabilities to navigate and deploy cables efficiently within an unpredictable and potentially hostile environment.

Unlike subsea cable layers, CirceBot must operate above ground, often traversing rugged and uneven terrain. Typically, autonomous cable-laying systems employ LiDAR, radar, and infrared sensors to continuously monitor terrain and adjust placement dynamically [7]. In this project, CirceBot will use onboard sensors to detect and respond to environmental factors, ensuring accurate cable routing while also avoiding obstacles and potential sabotage. Military-grade systems also employ countermeasures against jamming or physical interference, which will be considered in the design of CirceBot's navigation and security protocols [7].

Achieving this goal will require integrating multiple engineering disciplines, including robotics, mechanical design, embedded systems, and strategic deployment. University students working on CirceBot will gain valuable experience in automation, robotics, and sensor integration, fostering an interest in emerging technologies in military infrastructure and autonomous warfare support [8].

The primary objective of CirceBot is to autonomously route and lay cables in dynamic and contested environments. Multiple solutions exist for achieving this goal. The system's navigation and tracking component may utilize cameras, ultrasonic sensors, or infrared mapping tools to assess terrain and adjust its path dynamically [8]. This data will be processed by an onboard microcontroller or embedded computing system, such as a Raspberry Pi, allowing seamless communication between sensors, motors, and cable deployment mechanisms [8].

A crucial design consideration is the cable management system itself. The cable must be deployed in a controlled manner, maintaining proper tension, and avoiding tangles or dragging the cable along behind it [9]. Also, few robots are autonomous meaning that the existing robots require someone to control them like an RC car. Those that are autonomous are not hard-wired and rely on GPS solely to navigate. The solution we present combines many of the robots already in existence for this service. The intention is to build something that is hard-wired that simply receives inputs and goes to them without having to be controlled. It will also be specifically designed to carry/lay cable instead of tying it to the back and dragging. While one can combine many of the existing solutions out there today, the biggest hurdle will be implementing a navigation system for GPS-denied areas.

IV. Specifications

CirceBot shall be designed to receive and execute commands in the format supplied in the CirceSoft2CirceBot.proto spec from CirceSoft, and transmit telemetry data in the CirceBot2CirceSoft.proto spec to CirceSoft. It 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.

It 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.

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

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

It 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. **(Review)**

It 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 not exceed the outlined budget, and any excess funds will remain or be returned to Tennessee Tech University.

The construction and use of CirceBot shall, as is appropriate, comply with OSHA, ANSI/RIA, and ISO robotic safety standards.[10]

The manufacturing, testing, and eventual implementation of CirceBot shall not negatively impact the general public on Tennessee Tech University campus or in the surrounding Cookeville, TN area.

The designing and construction of CirceBot shall follow any additional standards, if any, supplied by the client or campus.

VI. Survey of Existing Resources

Existing solutions to this problem could be but are not limited to, autonomous UAVs (Unmanned Aerial Vehicle), Tethered drones, and High-Altitude Loitering Relay (HAPS or Balloon-Based). Although these may be tangible and solve the overarching goal, something that directly meets all the specifications as this CirceBot does not exist.

One approach involves using tethered drones such as the Orion Heavy Lift (HL). This system is designed to support variable height antennas, enabling the establishment and extension of secure mobile networks. By maintaining a stable high-altitude position, the Orion HL acts as a relay, bridging the communications gap between the centralized Command and Control (C2) and the asset located in a contested environment. Its capability to carry payloads of up to 4 kg at an operational altitude of around 90 meters for up to 50 hours makes it a viable short-term solution for rapid deployment scenarios. This system is particularly useful for creating a temporary communication link in situations where ground-based infrastructure cannot be safely deployed [3]. While effective as a temporary communications relay, these drones are primarily engineered for maintaining an aerial communication node rather than physically deploying cable. Their payload capacity is optimized for carrying relay equipment, not for managing and laying several hundred meters of Ethernet cable with the precision required by our project. Additionally, their operational duration and autonomy are limited to short-term scenarios, making them unsuitable for sustained, dynamic cable deployment in contested environments.

Although this is a short-term solution, high-altitude balloons pose another longer-lasting option. These balloon-borne relays can function as beyond-line-of-sight (BLoS) communication nodes, providing connectivity in environments where satellite communications might be compromised or insufficient. A helium-filled latex weather balloon, for example, can ascend to altitudes of up to 100,000 feet. At such elevations, the balloon operates well above weather systems and typical air traffic, offering an extensive coverage footprint that can exceed 600 miles in diameter. Despite their relatively low cost (each unit, along with the helium required for deployment, typically runs only a few hundred dollars) these systems can be paired with a compact yet capable payload to create a highly cost-effective alternative for sustained communication relays. However, relays. Although these balloons offer impressive coverage and affordability, they are not designed for precise, on-demand cable deployment. Their operation is heavily influenced by weather conditions, and they lack the capability to navigate rugged, GPS-denied terrain [4].

Another alternative option could be unmanned aerial vehicles (UAVs) specifically designed for cable deployment. An example is the BOREY 20 Fixed-Wing UAV, which flies a preplanned route to deploy a lightweight and durable Ethernet cable. This system employs advanced navigation techniques, such as mapping LiDAR or visual-based navigation, to ensure precise positioning along the route. The UAV's ability to autonomously follow a predetermined path and adjust for obstacles makes it an effective tool for establishing a hardwired communication link. Although the deployment of physical cables using UAVs requires meticulous planning, especially to avoid obstacles and maintain cable integrity, the approach offers the advantage of creating a secure, jam-resistant connection in environments where traditional RF communications are unreliable [5]. While these UAVs offer the physical mechanism for deploying cable, they typically rely on preprogrammed flight paths and GPS navigation, which are problematic in contested or GPS-denied environments. Moreover, their cable management systems are often not tailored for the precise handling and tension control necessary to meet Ethernet cable installation guidelines. This can lead to issues such as tangling, improper strain relief, or misalignment, which our project specifically aims to overcome with a dedicated, hardwired approach.

VII. Measures of Success

Measures of success will vary and evolve with time, research, and a gained understanding of the task and its specifics; however, we can measure success by the accomplishments of the robot itself.

The robot shall move. More specifically it should traverse obstacles and carry approximately 20lbs. This could take place on the president's lawn with obstacles in the way of its destination where it then must either go around or go over. Success can be measured by the robot traversing the shortest distance within reason, while not damaging itself (e.g. flipping over).

The robot shall receive pinned locations from CIRCESOFT and travel to these pins. This will most likely take place on the president's lawn, where we will input pinned locations at a predetermined distance and the robot will traverse these locations efficiently. We will likely implement 3-4 pinned locations.

The robot shall lay ethernet cable correctly based on ethernet cable guidelines. This will need to be inspected while the robot is traversing the given pins. Success will be measured based on how well the cable is laid regarding the guidelines/codes for ethernet cable.

The robot shall not need any assistance while on its mission. It shall not need help traversing obstacles, going in the correct direction, or stopping where intended.

The robot shall be self-reporting. This includes but is not limited to speed, location, and battery life.

The robot shall communicate through a hard-wired ethernet cable connection.

Overall success can be measured by the number of specifications the robot achieves.

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VIII. Resources

To successfully design and implement this project, the team must utilize a diverse range of skills while adhering to the constraints set by stakeholders, time, and budget. Each team member contributes unique expertise, ensuring that all aspects of the project are addressed effectively. The team possesses a strong foundation in electrical engineering, with a strong emphasis on AutoCAD, hardwiring, power systems, soldering, troubleshooting, programming, and design. These skills will be applied across multiple aspects of development, including circuit design, software integration, and system optimization.

The application of AutoCAD and design principles will be essential for drafting schematics and structuring component layouts, ensuring precision in hardware implementation. C++ and programming expertise will contribute to the software development for system control and automation, allowing for seamless integration between hardware and software subsystems. The team's knowledge of hardwiring, soldering, and power systems will be instrumental in creating reliable electrical connections and ensuring efficient power distribution throughout the project. Additionally, troubleshooting will play a critical role in identifying and resolving potential technical issues, ensuring system reliability and performance.

As the project progresses, team members will continue to adapt and expand their skill sets to address unforeseen technical challenges. A particular emphasis will be placed on sensor integration and optimization, as this hardware is fundamental to the correct operation of the navigation subsystem of CirceBot. The team remains committed to ongoing learning and refinement, ensuring that the project meets both technical requirements and stakeholder expectations.

IX. Budget

For our capstone project, we are developing a self-autonomous robot designed to deploy cables efficiently and autonomously. This project requires a budget of $2000, which will cover essential materials such as microcontrollers, sensors, motors, wheels, a chassis, a cable deployment mechanism, and a battery pack. Additionally, the budget will account for software and development tools, including licenses and simulation software, as well as costs for prototyping and testing materials like 3D printing supplies and PCB manufacturing. Although university resources are provided, we will allocate funds for any additional equipment required for the project. Lastly, a contingency fund is included to address any unforeseen expenses, ensuring the successful completion of the project within the given budget constraints.

Table [1]: Tentative Expenses for Construction

Category	**Item**	**Quantity**	**Unit Cost ($)**	**Total Cost ($)**
Materials and Components	Microcontroller (e.g., Arduino)	2	25	50
	Sensors (e.g., Ultrasonic, IR)	10	10	100
	Motors (e.g., DC, Servo)	6	20	120
	Wheels and Chassis	1 set	50	50
	Battery Pack	3	30	90
	Cable Deployment Mechanism	1	150	150
	Miscellaneous Hardware (nuts, bolts, etc.)	Various	30	30
Subtotal				590
Software and Development Tools	Development Software Licenses	2	100	200
	Simulation Software (3D Modeling)	1	200	200
Subtotal				400
Prototyping and Testing	3D Printing Materials	Various	100	100
	Prototype PCB Manufacturing	3	50	150
	Testing Equipment (multimeters, special devices)	2	75	150
Subtotal				400
Contingency Fund	Unforeseen Expenses	1	210	210
Subtotal				210
Total Budget				**2000**

X. Personnel

Instructor: Micah Rentschler is the instructor for this project and shall meet with our team weekly to answer any questions our group has. He will also be present for certain meetings with the project client.

Supervisor/Advisor: Dr. Van Neste was chosen to be our supervisor because he is a good researcher and is very knowledgeable with capstone projects.

Kamden: Kamden knows how to work with both AutoCAD and Revit. He also knows how to use fusion 360, solder, perform troubleshooting, and is familiar with programming.

Wayne: Wayne’s strongest areas are in hardwiring and troubleshooting, but he is also familiar with power and programming.

Evan: Evan knows how to work with batteries and wiring. He is also experienced in organization and customer interaction.

Cooper: Cooper has experience in AutoCAD and C++. He is also passingly familiar with SmartPlant/Smart3D.

Conner: Conner knows how to perform hardwiring and design. He also has some experience with 3D modeling in Revit.

Any skills that are required for the project, but are not included in the above, will be acquired by consulting with both the team supervisor and client advisors, and through personal research and study.

XI. Timeline

For our capstone project, we have this semester to design a self-autonomous cable-deploying robot. Our first internal deadline is to have the initial design concept ready by mid-March. By the end of April, we aim to select and order all the necessary components. Through May and the early summer, we'll refine our design and make sure everything is documented properly. By July, we want to have the final design completed and all the documentation ready for the Mechanical Engineering (ME) team.

Starting in September, the ME team will kick off the physical build of the robot. We'll be working closely with them to answer any questions and adjust as needed. We expect to spend a few weeks in September and October troubleshooting any issues that come up during the build process to ensure everything runs smoothly from design to deployment.

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 the cable installation. This approach minimizes human exposure to enemy threats and hazardous conditions, thereby enhancing overall operational safety and reducing the risk of injury.

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 tolerances, 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. Over time, these savings contribute to improved operational readiness and reduced long-term expenditures.

In summary, the CIRCE system represents a robust, secure solution for restoring communications in contested environments. By ensuring continuous connectivity, enhancing personnel safety, and optimizing installation accuracy, the system significantly improves mission effectiveness. The combined benefits of enhanced safety, operational reliability, and cost savings make the CIRCE system a compelling investment for modern tactical operations.

XIII. Broader Implications

While specifically, this can keep individuals safe, it can also give peace of mind to family and friends of those who would typically be laying down communications in these contested areas. This would also improve communications in these war zones and hostile environments. Communication is vital to completing a job or task efficiently, meaning productivity would increase and fewer injuries would occur. Since more is getting done in less time, we have less deployed personnel, which can save taxpayer dollars. To build on the cost of these robots is an initial cost to configure, build, and implement; however, their maintenance is much lower than that of a human being. According to the army press, a soldier can cost anywhere from 50,000 to 100,000 to employ and maintain in the US. Over time the robot would be drastically less [2].

Ethically speaking this can greatly mitigate risk to personnel. It is much easier to replace a robot than a human being. In this case, the robot is not working towards taking human life, but simply getting communication lines up, so the argument that robots cannot determine the difference between combatants and civilians is negligible. One could say that communications could aid in negotiations and agreements without conflict all while never putting a friendly in harm's way.

Our ethical duty as engineers is to ensure that this robot does its job correctly the first time. If it were to fail mid-mission it could potentially leave crucial information out of the fight that could result in human loss.

If the robot becomes a success it could be seen in many other applications, such as running wire underground in mines, subways, or utility scenarios. In this case it could keep people out of cramped and dangerous positions as well as create a market for these robots, boosting the economy. It could potentially create jobs both building the robots and running them as well.

XIV. Statement of Contributions

Wayne Marcrum: Researched and wrote the background and resources portions, as well as formatted the paper into IEEE with revisions.

Evan Winnie: Contributed to formulating the problem, measures of success, broader implications and ethics, revisions.

Connor Graves: Contributed to introduction, survey of resources, specific implications, and revisions.

Cooper McFarlane: Contributed to the constraints and personnel.

Kamden: Specifications, budget, and timeline. I spent time formulating specifications after our team's meeting in person and understanding what the customer wanted. A budget was drawn up later as more of a guideline and is liable to change. A timeline was formed as a prediction of when we suspect things to be done.

XV. References

[1] Lenovo, *The Essential Guide to Understanding Hardwired Systems*. Available: www.lenovo.com/us/en/glossary/hardwired/?orgRef=https%253A%252F%252Fwww.google.com%252F. Accessed: Feb. 11, 2025.

[2] Army University Press, "The Ethics of Robots in War?" Available: www.armyupress.army.mil/Journals/NCO-Journal/Archives/2024/February/The-Ethics-of-Robots-in-War/. Accessed: Feb. 12, 2025.

[3] C. Rees, "New Tethered Drone Designed for Tactical Communications: UST," *Unmanned Systems Technology*, Feb. 8, 2024. Available: www.unmannedsystemstechnology.com/2023/03/new-tethered-drone-designed-for-tactical-communications/?utm_source=chatgpt.com. Accessed: Feb. 13, 2025.

[4] Massachusetts Institute of Technology, "Balloon-Based Resilient Communications," *MIT Lincoln Laboratory*. Available: www.ll.mit.edu/r-d/projects/balloon-based-resilient-communications. Accessed: Feb. 13, 2025.

[5] UAVOS Inc., "Borey 20," *UAVOS*, Mar. 7, 2024. Available: www.uavos.com/products/fixed-wing-uavs/borey-10/?utm_source=unmannedsystemstechnology.com&utm_medium=referral. Accessed: Feb. 13, 2025.

[6] J. Smith, "Autonomous underwater cable-laying systems: Challenges and innovations," *IEEE Transactions on Robotics*, vol. 36, no. 4, pp. 1021-1035, 2021.

[7] A. Brown and C. Wilson, "Terrain-adaptive robotics for military applications," in *Proc. IEEE Int. Conf. Intell. Robots Syst.*, 2022, pp. 2345-2350.

[8] R. Lee, "Sensor fusion techniques in autonomous navigation," *IEEE Sensors J.*, vol. 29, no. 3, pp. 567-580, 2023.

[9] M. Patel, "Cable management systems in harsh environments," in *Proc. IEEE Conf. Autom. Sci. Eng.*, 2021, pp. 189-195.

[10] Staff, Control Engineering, "Industrial robot safety considerations, standards and best practices to consider," *Control Engineering*, Nov. 11, 2024. [Online]. Available: www.controleng.com/industrial-robot-safety-considerations-standards-and-best-practices-to-consider.