µSMET: A Lightweight Transport Robot

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ABSTRACT

Modern robotic technologies enable the development of semiautonomous ground robots capable of supporting military field operations. Particular attention has been devoted to the robotic mule concept, which aids soldiers in transporting loads over rugged terrain. While existing mule concepts are promising, current configurations are rated for payloads exceeding 1000 lbs., placing them in the size and weight class of small cars and ATVs. These large robots are conspicuous by nature and may not successfully carry out infantry resupply missions in an active combat zone. Conversations with soldiers and industry professionals have spotlighted a need for a compact, lightweight, and low-cost robotic mule. This platform would ensure reliable last-mile delivery of critical supplies to predetermined rally points. We present a design for such a compact robotic mule, the µSMET. This versatile platform will be integrated with the Squad Multipurpose Equipment Transport (SMET), to ferry supplies to soldiers in combat, evacuate the wounded, transport loads on a forced march, while having the ability to be carried by a soldier. The µSMET's variable geometry enhances mobility over challenging terrain: its rear wheel assembly can expand to increase its stability or contract to reduce its profile. This publication will describe the design and construction of a prototype µSMET.

Citation: K. Grenn, C. Adam, T. Kleinow, B. Mason, O. Sapunkov, P. Muench, S. Lakshmanan "µSMET: A Lightweight Transport Robot", in *Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium* (GVSETS), NDIA, Novi, MI, Aug. 10-12, 2021.

1. INTRODUCTION

1.1. Current Platforms

Early efforts at developing robotic ground systems for the US Army focused on lightweight, compact robots that could investigate areas too dangerous to send people. Portable robots such as the iRobot PackBot family carried cameras that could transmit images to an operator's controller. Simultaneously, a small robotic arm attachment could allow users to investigate suspected explosive devices or other threats. These small robots were not well suited to carry heavy payloads or travel at high speed, and were not capable of autonomous operation. Therefore, their primary use was to assist bomb disposal teams and search and rescue teams working in unstable or collapsed structures. The PackBot's modular design made it an excellent platform for specialized variants, including robots for detecting chemical and radiological warfare agents, in addition to having the functionality to detect enemy sniper fire using sensitive microphone arrays [1]. More recent developments focused on developing "robotic mules" for the Army to carry large numbers of backpacks and supply crates for soldiers, such as the HDT Hunter Wolf [2]. These robots are comparable in size to a small car and can weigh over a ton fully loaded, so they cannot remain practically concealed during operations near enemy forces. These robotic mules' size and limited engine power severely limit their speed and maneuverability, exacerbating their vulnerability to enemy fire following detection. Experimentation with walking robotic mules, such as Boston Dynamics' AlphaDog [3], has also been deemed unsatisfactory due to their low speed, lack of operational range and energy efficiency, and excessive acoustic signature in operation. Thus, the category of a compact, lightweight, inconspicuous cargo-carrying robot, which reliably resupplies troops in an active combat zone, is currently not fulfilled by available designs, so our µSMET proposal intends to fill that niche.

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Figure 1. Characteristic Examples of Typical Army Ground Robots [1] [2] [3]

1.2. Innovation Workshop

Available designs are limited to the current SMET configuration, which is a military battalion asset that squads, platoons, and companies can use [4]. Tests have shown, on multiple occasions that the SMET has problems in off-road environments that are too narrow to allow passage of its 5 ft. wide-body, while terrain with even a gentle slope can cause it to roll-over, and its top speed of 8 miles/hour is too limited for urban environments [5]. To counter this, the proposers of µSMET conducted a deep dive into the problem with military engineers, veterans, and instructing officers through innovation workshops in the community. A need became apparent – there was a gap in the military mobility space for an agile, small, and quiet robotic vehicle to accompany and assist soldiers between assembly areas and rally points, ensuring reliable last-mile delivery. The conversations brought to light the various engagement fields that the platform must perform when supplementing the SMET programs. As seen in Figure 2, the supplemental nature of µSMET comes into play in the transition from "friendly" to "hostile" terrain with the ever-increasing chance of enemy contact. The smaller platform is designed to carry smaller payloads and navigate more challenging terrain, ensuring success across the last 100 meters of the battlefield.

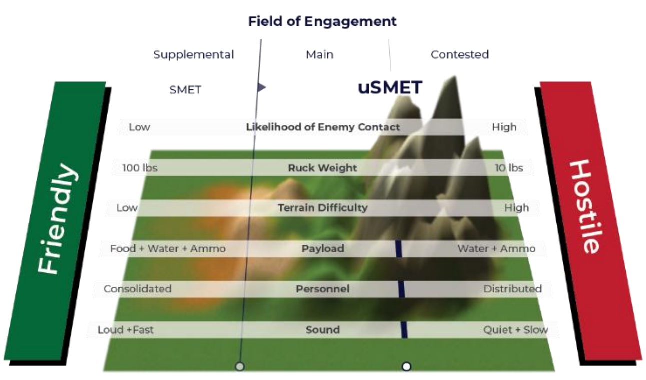

Figure 2. SMET and µSMET Operational Envelopes

In overcoming limitations that the SMET currently possesses, µSMET seeks to expand its operating terrain through unique platform implementation, based on a bicycle-to-tricycle form factor transition. This platform would strive to improve maneuverability in narrow spaces by having the ability to contract after delivering a payload and expanding to enhance transportability. Overall, advantages of the µSMET are given through its inherently compact size. They are not intended to replace the larger robotic pack mules, but rather to supplement their operations in challenging situations. The platform is intended to be small enough to hold a rucksack, ammunition, or a solider but not be excessively laden with gear. The reduced platform weight and carrying capacity allow for increased speed, as high as 15 miles/hour. Highlighting the variable geometry, the platform seeks to meet the apparent needs presented in the innovation workshop conversations. Figure 3 is a concept sketch that was developed based on the conversations. It highlights the need for adjustability and variable design, to allow for significant cargo capacity and the ability to collapse for a quick getaway on its return journey.

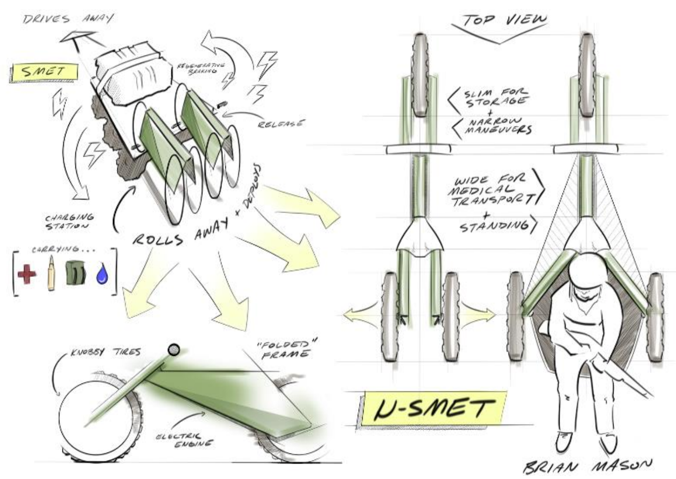

Figure 3. µSMET Preliminary Concept Design

1.3. Applications for µSMET

The proposed µSMET platform would be able to fulfill several major battlefield roles for the Army. Most importantly, it could provide reliable last-mile resupply for units in a combat zone, bringing ammunition, medical kits, and other urgently needed consumables to soldiers in action, without requiring soldiers to make the dangerous journey back to their supply base under enemy fire. Since the µSMET is a compact, high-speed platform, capable of autonomously navigating to a requested destination, it could easily travel concealed by local terrain - thus rendering itself less vulnerable to enemy fire even when traveling over open terrain with limited cover, compared to a more conventional car-sized robotic mule. Alternatively, swarms of µSMETs could be used to resupply artillery units with ammunition in situations where a traditional artillery resupply vehicle may be unable to navigate rugged terrain, find itself vulnerable to enemy fire, or may draw unwanted attention to a concealed artillery position. Robots returning from the combat zone, having delivered their supplies, could be used for medevac missions, evacuating individual wounded soldiers back to a secure position for immediate medical treatment. This basic concept was formerly explored with the DTV Shredder personal tracked vehicle, for instance, which can operate in robotic mode towing a man-sized cart [2]. However, the base vehicle is not itself designed to a secured payload.

Conversely, µSMET can carry a soldier. It would not have to rely on being paired with additional transport devices, reducing the logistical load on units that use it for medevac missions. We envision the µSMET to be compatible with a wide variety of payloads, as it can easily be modified to carry standard modular mounting systems, such as Picatinny rails, as well as custom mounting bracketry for types of cargo, such as artillery shells. The µSMET could be adapted to carry external attachments, including acoustic gunshot detection systems, sensors for detecting landmines and IEDs, CBRNE surveillance sensors, or infrared imaging equipment to detect approaching enemy vehicles at long range - thus serving as an effective early warning platform, informing soldiers of incoming threats, and enhancing their situational awareness on the battlefield. Suppose a fleet of µSMETs is equipped with portable radios. In that case, they could serve as nodes in a retransmission network, providing reliable communication for units deployed in dense urban or mountainous areas, where the complex environment limits radio communication range.

Figure 4. DTV Shredder Personal Tracked Vehicle in the Medical Evacuation Role [15]

2. Vehicle Design

2.1. Preliminary Concept Work

The µSMET robot derives its inspiration from an uncomplicated bicycle, a highly efficient energy efficient transporter of payload and personnel in narrow spaces and uneven terrain. There are ample examples in history of bicycles being used by the military, especially for medical evacuation of wounded soldiers from the battlefield [6]. There are also examples of the bicycle being used as a surrogate to a mule for transporting heavy payload – reconstituted bicycles have carried up to 1000 lbs. along forest trails [7].

The problem with the bicycle is that it is nominally/inherently unstable and requires to human in the loop to stabilize it, whether it be for driving it or pushing it. Drawing on a contemporary example of research conducted at the University of Michigan-Dearborn, there is the development of active steering stabilizable unmanned bicycle [8] [9]. Additional studies into unmanned stabilization can be seen through the works spanning the last ten years [10] [11] [12]. Those prior efforts directly lead to the concept of µSMET – a platform that inherits all the agility and versatility of a bicycle without its nominal/inherent instability. The other inspiration for µSMET is tricycles – an optimal transporter of heavy payloads or multiple persons in congested urban areas. The tricycle problem is that its wider wheel track has difficulty in narrow and uneven terrain when carrying a payload. Despite this limitation, there are several tricycles use examples seen in military history [13].

The combination of a tricycle and bicycle results in the premise of µSMET. Variable geometry is the highlight of this platform in that it combines the main objectives. Based on the innovation workshop conversations, the group compiled ideas and formulated sketches to help meet the newfound goals of supplementing the current SMET platforms. Additional ideas for capabilities brought up during those conversations, and brainstorming session, included moving cover, resupply, injury exfil, single transportation, high-speed retreat, and bushwhacking and clearing ability to aid soldier movement can be seen in Figure 6. These are all features but not the primary purpose of the design. The ideas were narrowed down based on practicality and needed to be focused on speed, carrying ability, and agility.

When going through the iterative design process, variations arose to meet the design criteria revolving around a bicycle-based platform. This manifested itself most heavily around the transition process in which the vehicle would expand and contract. Proposals ranged from expanding hammocks able to be lifted as a medical evacuation suspended between two individual bikes, a swinging rear fan spreading to carry a payload, and a foldable scorpion tail that would flip down to accommodate for diverse missions, as shown in Figure 5. The various features were weighed considering each configuration's advantages and disadvantages. Ultimately, a fan spread concept was ideal as it allowed for the most stable platform and versatile loading options that could be outfitted for diverse mission sets.

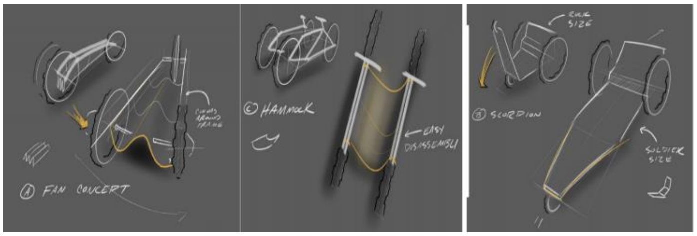

Figure 5. Folding Mechanism Configuration

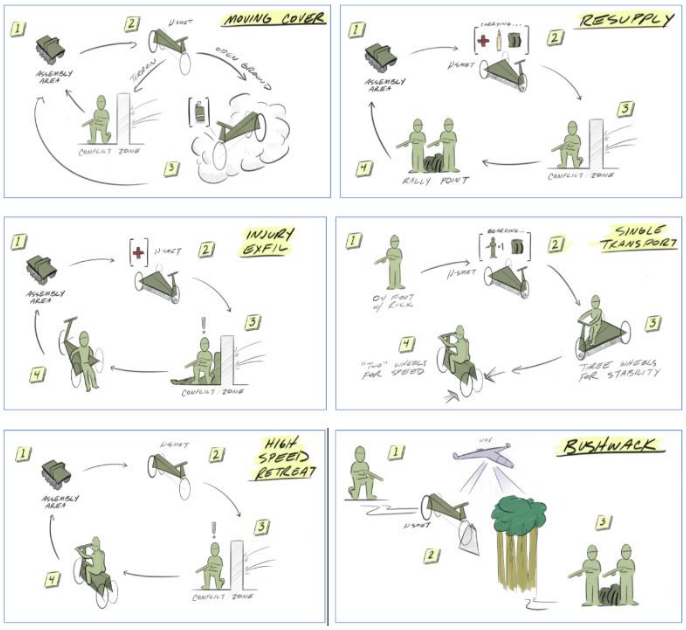

Figure 6. Proposed µSMET Applications.

2.2. Mechanical Design

Dismounted soldiers carry anywhere between 60-120 lbs. of water, food, ammunition, battery, fuel, and other equipment in their backpacks. This heavy payload limits their mobility and ultimately leads to soldier fatigue. To counter this fatigue, µSMET is designed to integrate with the current SMET programs and supplement soldier movements. This supplemental nature plays into mechanical design because it is imperative to accommodate for varied loads and adapt to the environment. The µSMET, weighing in at 40lbs, is currently built to carry a 100 lb. payload at a speed of 16 mph and pass through a 3-foot doorway with plans to exceed 100 lbs. The rear-wheel mechanism must articulate dynamically to balance the robot- to mechanically contract and expand its lateral distance between its rear wheelbases. Relying heavily on its crucial shape adaptive properties, the robot's narrow version will enable it to maneuver in tight spaces and travel at increased speed and maintain high rates and dynamic stability in its expanded configuration. When the µSMET is in its narrower shape, it is prone to roll-over, whereas it is more inherently stable when it is in the broader form. With its variable design highlight, the platform maintains dynamic stability via a combination of software and mechanical setup. The chassis is divided into two focus areas: steering apparatus and rear powertrain. Figure 7 offers an overall mechanical layout.


Figure 7. µSMET Platform Overview

The steering apparatus contains two high-torque motors independently connected to belt-driven systems—one motor act to control the rotational steering through a worm gear to a toothed platform. Designing a worm gear drive setup ensures that sufficient torque is present and prevents back-driving due to bumps from rugged terrain. The steering column consists of the toothed platform attached to two offset “lazy Susan” turntables constructed in double sheer to aid in turn movement. Situated on this platform is the second motor that translates motion into the wheelbase via gears and belts to drive the wheels. A rotational potentiometer monitors and provides active feedback to the control system to have accurate rotational position bearings. The front steering assembly can be seen in Figure 8.

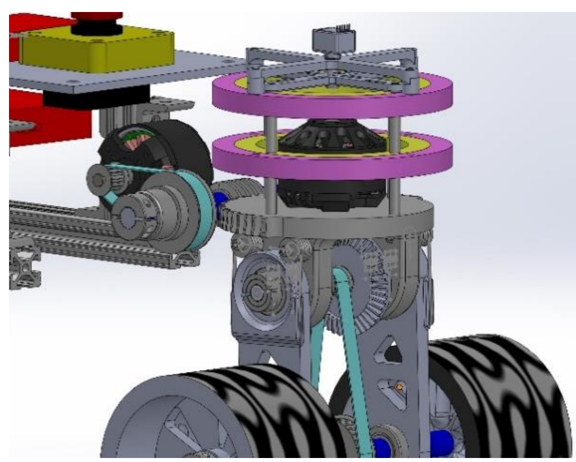
Figure 8. Front Steering Assembly

The rear powertrain consists of both the rear wheel track and the splits mechanism to produce the variable geometry. The powertrain system contains three high-torque motors power wheels independently to improve traction in off-road scenarios, as seen in Figure 11. Dynamic stability is gained in design by creating the rear track powered by a single motor mechanically linked to threaded rods for actuation. This single motor setup enables both rods to expand outwards and contract inwards in tandem on a geared ratio rather than at different rates. It is important to denote that it is in the intention in the future to split the geometry to result in independent variable control ultimately. Dual linear actuators monitor and provide electronic feedback to the control software to maintain the vehicle's desired position. Additionally, located within the powertrain system are two rear wheels. Two separate wheels on a belt are driven systems to translate the motor's rotation into wheel torque. These rear wheel setups contain suspension shocks to allow the vehicle to handle the various terrains the vehicle may encounter.

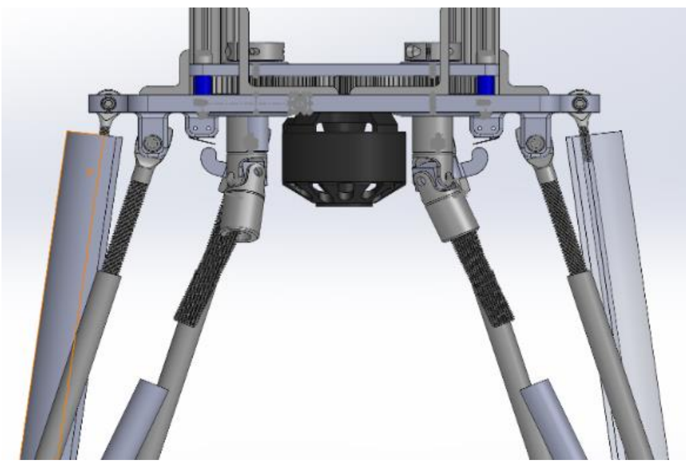

Figure 9. Splits Mechanism

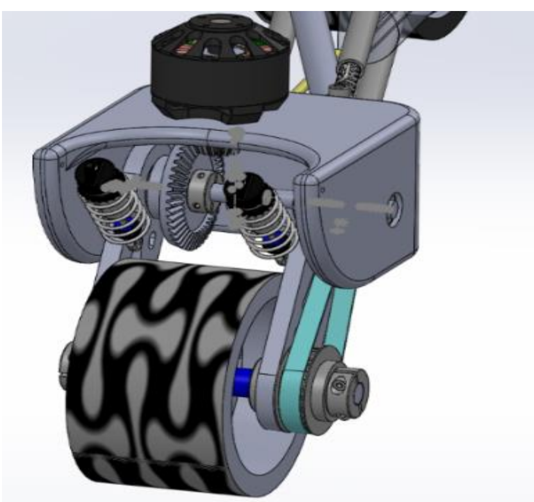

Figure 10. Rear Wheel Assembly with Suspension

Figure 11. Variable Geometry Mechanism driven by Motors and Dual Linear Actuators

2.3. Variable Geometry

The µSMET was initially inspired by earlier development efforts to design and prototype an autonomous robotic bicycle. Interest in this topic has been motivated by both the inherent mobility advantages that bicycles offer over other platforms of similar weight and the increased complexity of dynamic controls required for an autonomous bicycle. Unlike conventional robotic platforms, bicycles are not statically stable, and thus, must remain in a continuous motion to avoid falling over. This constraint necessitates a quick response from a control system that perpetually gathers data about its environment and makes intelligent path planning decisions that allow the bicycle to remain stable, just like a human bicycle operator. Once developed and successfully demonstrated, however, such a control system could easily be adapted to more conventional robotic platforms, enabling them to traverse rugged terrain faster without stopping and evaluating the next maneuver. As such, in its narrow configuration, the µSMET is intended as a testbed for dynamic bicycle control. Active balance stability control would be implemented to assist with cornering forces and dynamic roll centers.

The variable geometry of the µSMET allows it to shift from a statically unstable bicycle-like configuration to a statically stable tricycle configuration. As a technology demonstrator, this capability enables the µSMET to demonstrate dynamic bicycle stability and transport valuable payloads. The expanding splits could be adapted to various mounting systems, such as a simple net or canvas surface to hold bulky cargo or rigid mounts like Picatinny rails for more specialized cargo. In its transport configuration, the µSMET would be able to take advantage of the inherently more excellent stability of a wide-stance tricycle carriage while also benefiting from the fast dynamic controls developed for its narrow bicycle mode to ensure safe, reliable, and speedy transport of urgently needed supplies. These advantages make the µSMET an attractive option for last-mile autonomous delivery in active combat zones: perpetually remaining in motion and constantly maneuvering in its terrain will make the µSMET difficult for hostile forces to detect, track, and destroy.

2.4. Stability Analysis

The symmetric tip-over stability of the µSMET was evaluated through analysis of its support polygon in both the narrow and expanded configurations. First, we conducted a study of its tip-over angle in all tilt directions. Coordinates used in produced theoretical stability plots are described in Figure 12, and the resultant stability plots in the baseline configuration with vehicle overlay are represented in Figure 13. The evaluated tip-over stability data, represented by the blue outlines, is shown in the polar coordinate system, centered on the robot's center of mass, representing the angle at which the µSMET will tip if it is tilted downwards along that vector from the origin. The markings in black on Figure 12 denote the outside polar coordinates in which the vehicle is tilted. The markings in red denote the theoretical value of vehicle tip-over angle along a given vector of tilt.

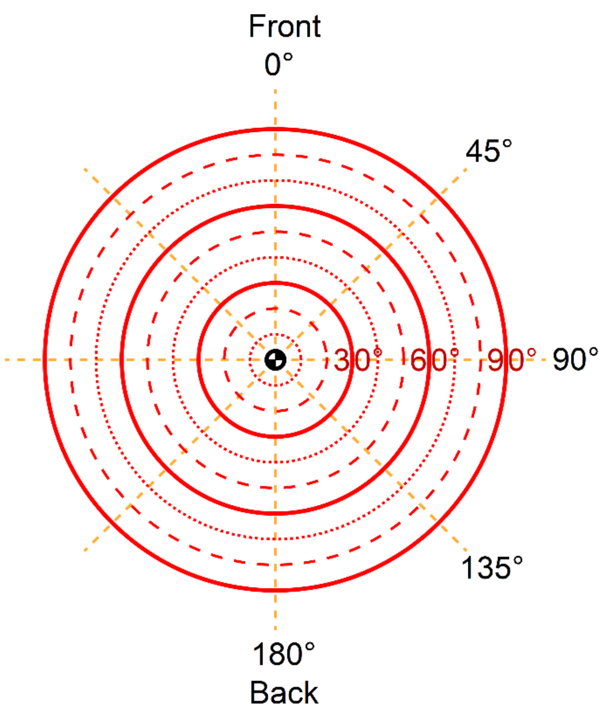

Figure 12: Stability Plot Key

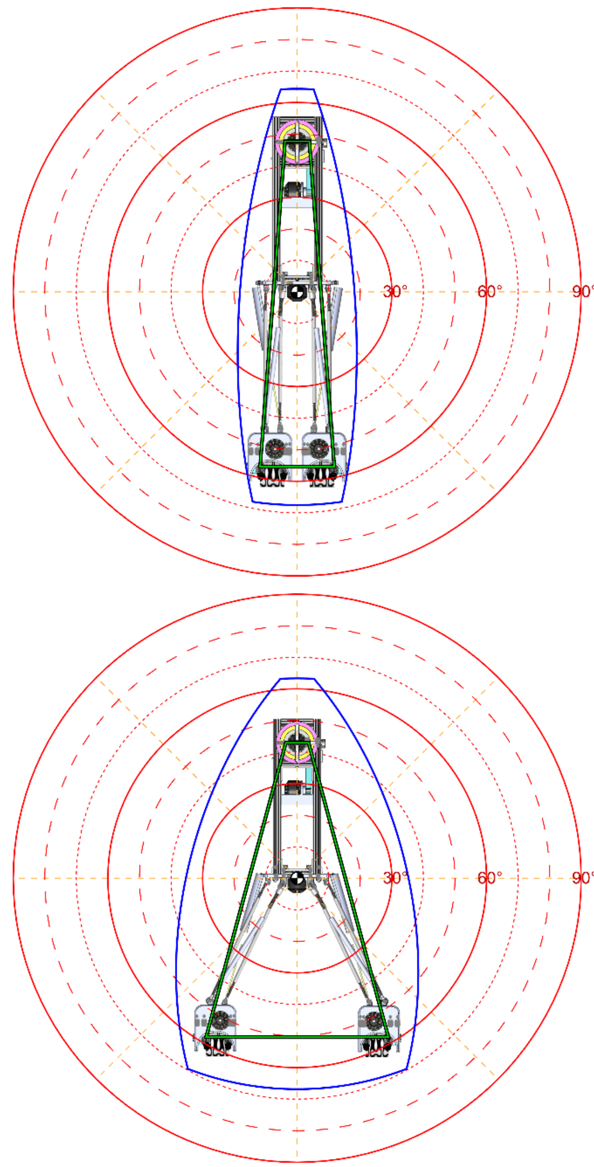

Figure 13: Stability plots of baseline Narrow and Expanded Unloaded Configurations with Vehicle Overlay

Vehicle evaluations occurred in six theoretical configurations, in which three of the six were evaluated experimentally. Of the six examined configurations, as seen in Figure 14, the plots are broadly arranged into narrow (A, C, E) and expanded configurations (B, D, F) read left to right in columns. Further subdivided in descending order, the top plots (A, B) are a front-loading condition, middle position (C, D) considered unloaded neutral, and finally, the rear loading configurations (E, F). Furthermore, positions C, D, and F tip-over stability zones were tested experimentally and test results are shown by purple dots.

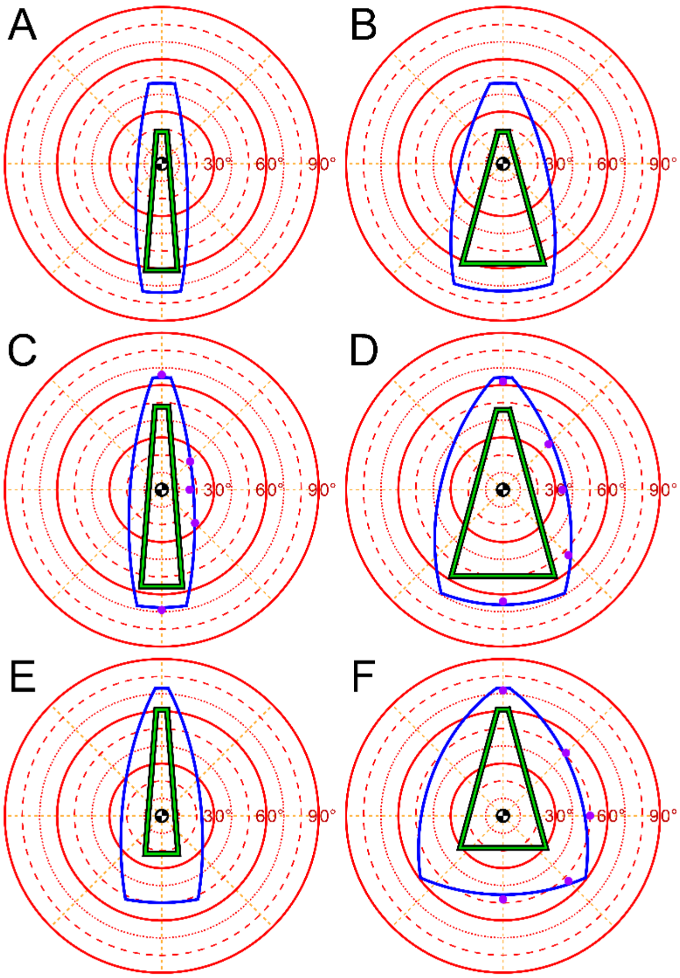

Figure 14: Six Vehicle Loading Configurations

Evaluated initially as a set of baseline narrow and expanded neutral configurations, the authors observed the generic stability profile of the vehicle. This offered insight on how to proceed with testing, as well as set the precedence for expected results. Thus, in the narrow configuration unloaded, the µSMET will tip on a slope of approximately 66 degrees at the 0-degree angle (parallel to the Y-axis), 23 degrees at the 45-degree angle, 16 degrees at the 90-degree angle (X-axis), 27 degrees at the 135-degree angle, and 69 degrees at the 180-degree angle (oriented uphill). In the expanded configuration following the same pattern of performed measurements, the µSMET will tip at 62 degrees, 37 degrees, 34 degrees, 53 degrees, and 64 degrees, respectively. These results were expected due to the inherent superior stability of a broader support base, and are reflected in the theoretical stability polygons.

Tip-over stability analysis of the µSMET was further evaluated through analysis of its support polygon in the expanded unloaded and heavily rear-loaded conditions, with a major shift of the center of mass. This is applicable in considering a heavy payload in the expanded configuration, such as a large artillery shell – the center of gravity shifts significantly to the rear from the robot's center split zone and results in modified increased tilt stability profile. The µSMET will then tip on slopes of 72 degrees, 51 degrees, 50 degrees, 53 degrees, and 48 degrees, respectively. It is important to note that this shift in stability will occur when there is significant enough mass to cause a center of gravity shift, creating an even more comprehensive support polygon of stability.

When testing the experimental results of the three configurations, the results gave comparable findings to that of the theoretical. This was found through using the above-stated testing criteria in the same simulation atmosphere. A standard tilt test was performed to collect experimental results, producing a quasi-static test scenario to determine vehicle stability and center of gravity location. When conducting the test, the robot was placed on a flat board and gradually angled until a shift started. The robot started to roll around 10 degrees in the narrow-unloaded configuration, as seen in Figure 15. This produced interesting real-world results that showed the designer that there was some chassis flex. Subsequently, this finding leads to reinforcements being placed within the robot, allowing the robot roll center to become consistent with the theoretical results. Implementing reinforced legs, the experimental results were consistent with the simulated findings. Both theoretical and experimental findings can be seen in Chart 1.

Figure 15: Experimental Tilt Test (Prior to Leg Reinforcement)

Case	Data	**0° Front**	**45°**	**90°**	**135°**	**180° Back**
Narrow	Theory	64.3	23.3	18.2	26.7	67.5
	Test	66	23	16	27	69
Wide	Theory	64.3	39.2	36.2	54.9	66.0
	Test	62	37	34	53	64
Wide Loaded	Theory	73.2	49.9	46.9	55.0	45.3
	Test	72	51	50	53	48

Table 1: Combined Theoretical and Experimental Values of Narrow, Expanded and Expanded Loaded Configuration with Resultant Tilt Points in Degrees

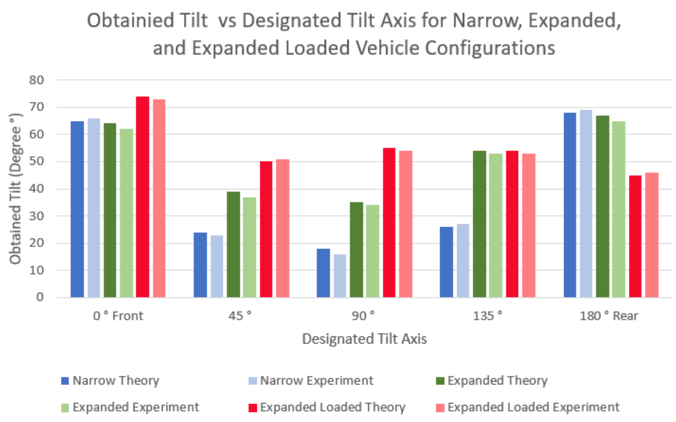

Chart 1: Tilt Orientation vs. Obtained Tilt Degree for Narrow, Expanded, and Expanded Loaded Configurations

Expanding upon the findings from Chart 1, the Loaded Expanded configuration is inherently the most stable in all situations except for uphill movement, in which the finding is consistent with classic Newtonian physics as it is rear loaded. The next aspect that should be looked at based on the findings would be where the payload is situated on the vehicle itself and how it shifts the roll center. It is beneficial to use the leg section as the primary cargo carrying area through purely theoretical simulation.

Calculated data on the µSMET's tip-over stability was then used to evaluate its stability on turning maneuvers conducted at some arbitrary velocity around an arbitrary turn radius. Figure 14 shows the equivalent side tilt experienced by a µSMET performing turns in a 1g gravitational field on flat, level ground, as determined by the robot's speed, turn radius, and the corresponding centripetal force. If the vehicle exceeds the max threshold of turn radius, it is likely to recover from moderate tip-over events in the expanded configuration. The data presented in Figure 16 is condensed and summarized in Figure 17 and reflected in the corresponding table, representing the minimum required turning radius for a µSMET attempting to conduct a turning maneuver on flat, level ground at an arbitrary velocity. The resultant curves follow a quadratic function. The minimum required turn radius in the narrow configuration roughly twice the magnitude of the turn radius in the expanded configuration, as expected from the known side slope tip-over angles. Turns attempted at excessively tight turn radii are expected to result in robot tip-over.

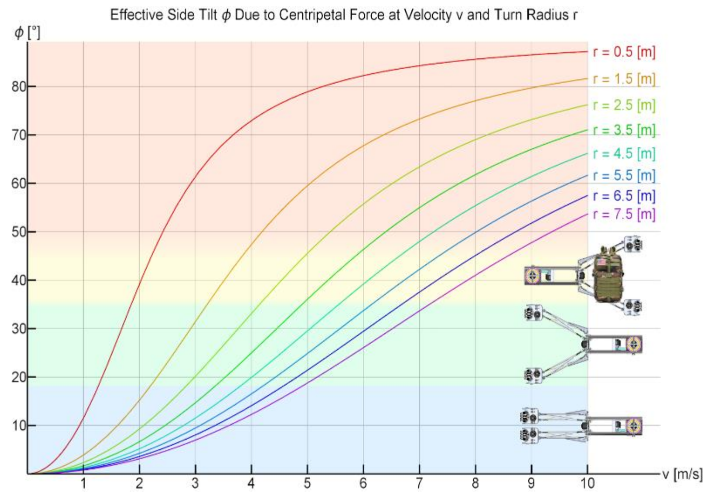

Figure 16: Effective Side Tilt Experienced During Turning Maneuvers

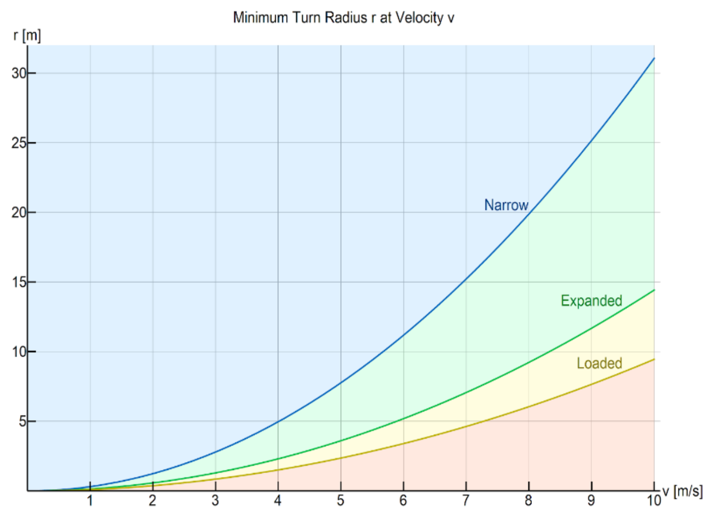

Figure 17: Minimum Required Turn Radius for Safe Turning Maneuvers

Effective Side Tilt Experienced During Turning Maneuvers		
Narrow	Blue	0-18 Degrees
Expanded	Green	18-35 Degrees
Expanded Loaded	Yellow	35-47 Degrees
Tip-Over Point	Red	47+ Degrees

Table 2: Effective Side Tilt Experienced During Turning Maneuvers Quantitative Results

Now that the physical payload mounting position has been determined in terms of being a payload being situation in the front, middle, or rear cargo net, payload height would be the next logical progression of features to look at. This was investigated through Lateral Tip over angle determining the CG point in terms of Distance **D** from the front of the vehicle concerning height **H** over the ground in the Narrow configuration (Figure 18) and Expanded configuration (Figure 19).

These figures communicate and reaffirm that the stability region is higher when the payload is set to pack on the robot within the rear cargo net. Applications are pertinent in that the user is informed that it would be more prudent to store a backpack in the cargo net rather than hang it off the vehicle's front. The second layer to this chart applies varying height by changing the payload height while keeping mass the same as the CG would change with the different weight distribution. The green zone represents feasible places as to where a payload could be packaged. The rainbow lines represent the new top height of the combined payload and vehicle spanning from 10 inches to 24 inches as the vehicle offers a 10-inch baseline height. The expanded configuration offers nearly double the lateral tip-over angle compared to that of the narrow configuration.

Combining Figure 18 and Figure 19 allows Figure 20 center of gravity position given Payload PL at Position PD from Vehicle Front to be visualized. The shifting center of gravity considers varying payload weight regarding the geographic location of the vehicle and obtainable Center of Gravity. The three aforementioned figures further support the notion and findings that the vehicle is more stable at varying weights, speeds, turn radii degrees, etc., when the payload is secured in the rear cargo net position.

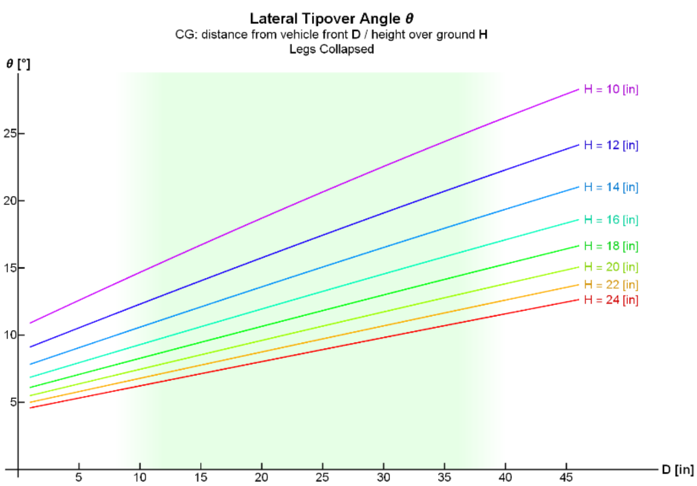

Figure 18: Lateral Tip over Angle Theta in terms of Distance **D** from Vehicle front over ground Height **H** Legs Narrow

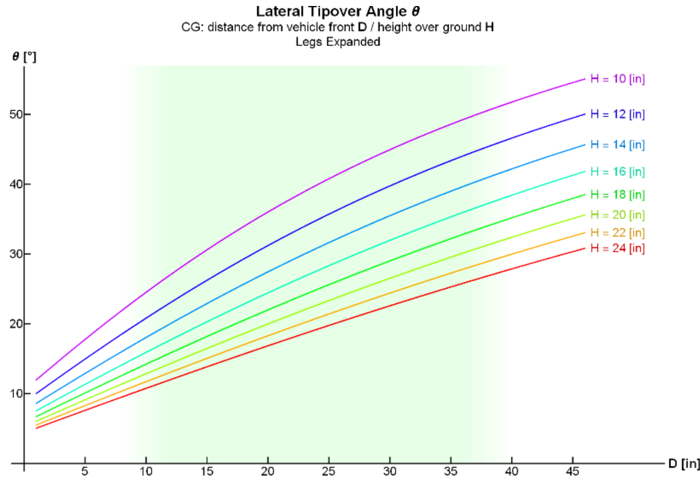

Figure 19: Lateral Tip over Angle Theta in terms of Distance **D** from Vehicle front over ground Height **H** Legs Expanded

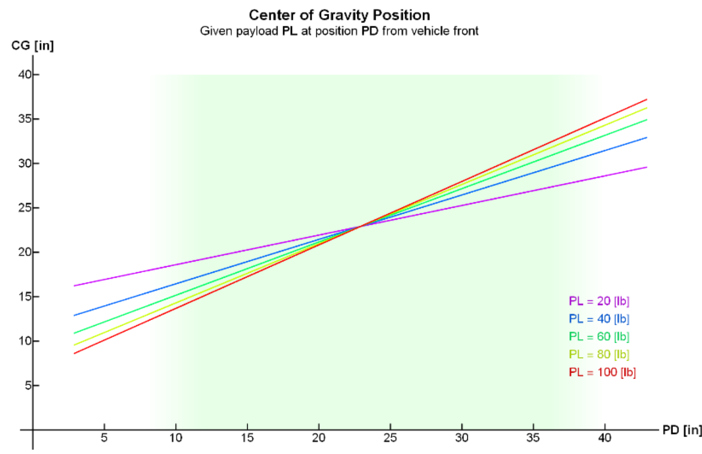

Figure 20: Center of Gravity Position given Payload PL at Position PD from Vehicle Front

2.5. Stability Control

The actuation of the splits mechanism, combined with throttle and steering control, will keep the robot upright while traversing irregular terrain. An Inertial Measurement Unit (IMU) will be used to keep track of yaw, pitch, and roll movements and be used as inputs to a PID controller that will maintain the net forces within its support polygon and adjust accordingly if it exceeds the safety performance envelope. The baseline control logic for this platform was developed by members of the University of Michigan-Dearborn [14]

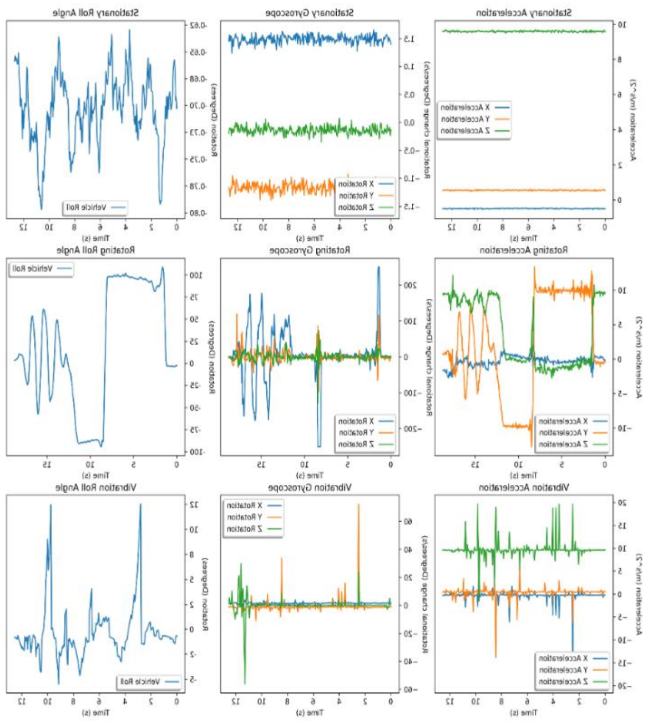

Figure 20: Yaw/Pitch/Roll Data for Steering Control

An Nvidia Jetson Nano controls this at a high level, with a Bluetooth connection to a phone control unit that will send high-level directions such as waypoint or target following or medium-level directions such as manual control of steering and throttle. Once these controls are received, they will be combined with sensor inputs from the camera, lidar, IMU, and wheel speed sensors. The controls, as mentioned above, will then implement low-level controls such as torque vectoring for improved traction, which will process on an embedded microcontroller for faster responses to changes in low-level sensor inputs. The stability control would take in known data values and active feedback to integrate with the variable geometry of the µSMET robot. As seen in Figure 21 various inputs from data tracking in Figure 20 flows into active feedback for the system

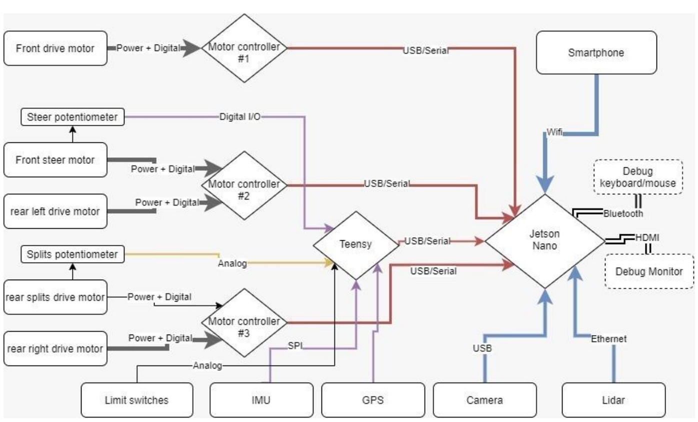

Figure 21: Control System Overview

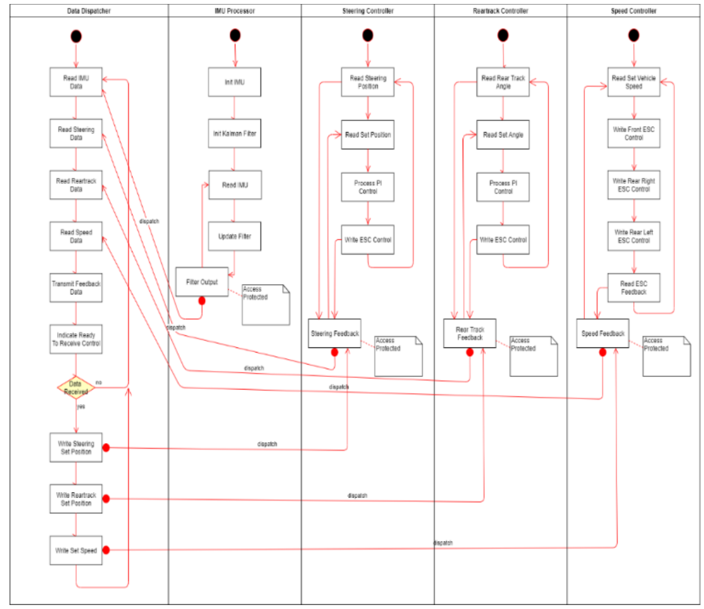

Figure 22: Control System

Going forth from the overall flow of Figure 21, Figure 22 gives a more in-depth look. The following feedback will be sent to the control unit to help the operator adjust their tactics and control if necessary:

1. Video stream
2. µSMET current state information including
    a. velocity/heading
    b. payload/splits angle
    c. GPS location
    d. Battery state of charge information
3. Operation mode
    a. Manual control
    b. Waypoint (progress to next waypoint, obstacle status)
    c. Tracking mode (distance to target, tracking confidence)

2.6. Sensor Controls

The µSMET's design enables the carrying of a suite of onboard sensors to enable autonomous mobility. At the most basic level, the robot's position and orientation are tracked using an onboard Inertial Measurement Unit (IMU). While IMUs are known for low fidelity over long distances and are subject to drift, they do not rely on any external systems and leave no evident signature, so they are an excellent type of baseline sensor to use in a radio-denied, GPS-denied, hostile environment. In addition to an IMU, the µSMET is intended to carry an array of cameras to use basic computer vision to help identify obstacles, decide on maneuvers, and gather data on potential threats in its environment.

If the µSMET is operating in a low-risk environment, or if enemy detection is not a major concern, the robot will also be operating a low-cost LIDAR, as this type of sensor is much more effective at identifying obstacles and mapping the topology of the µSMET's immediate surroundings than a simple camera array. Since LIDARs do have a significant near-IR signature when operating, which can easily be detected using basic night vision devices, the µSMET would have to operate without a LIDAR when conducting covert operations to avoid drawing enemy attention to its origin, path, or destination.

2.7. Vehicle Specifications

Wheel Diameter	5 [in]
Weight	40 [lb]
Cargo Capacity	100 [lb]
Dimensions (L x W x H)	Narrow Configuration: 36 [in] x 10 [in] x 12 [in]
	Expanded Configuration: 36 [in] x 24 [in] x 12 [in]
Range	2 [mi]
Vertical Obstacle	2.5 [in]

Table 3: Mechanical Specifications

Power	2 [hp]
Peak Voltage	42 [V]
Battery Capacity	10 [A∗h]

Table 4: Electrical Specifications

2.8. Human Interface

The second round of design research was conducted to discover the best methodology and hardware with which to control µSMET. Interviews with Army personnel indicated a desire to limit additional heavy equipment and that infantry soldiers were already starting to carry mobile devices, ranging in size from phone to tablet, in pouches on their plate carriers.

Figure 23: Army Ranger using the Nett Warrior [16]

As such, the controller we chose was a collapsible gaming controller that uses a USB-C connection to attach to an Android smartphone. Hard controls (rather than on-screen) are essential for steering a vehicle in the field, while the camera can act primarily as a camera feed with status messages regarding vehicle status. This allows the soldier to use a familiar mental model to control the µSMET while keeping costs down.

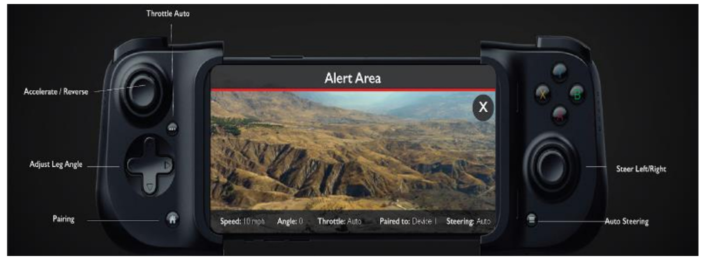

Figure 24: Controller Concept

The platform's physical Graphic User Interface GUI would give a live camera feed, speedometer reading, charge, turn position, inclination angle, and variable geometry spread.

Figure 25: Controller Concept GUI

3. Conclusion

3.1. Mechanics

Going forward, mechanically, the µSMET would aim to convert to a carbon fiber chassis from the prototype 80/20 stock aluminum that is currently implemented for the mainframe. This would allow both weight savings and more flexible design base to aid with rollovers. In addition to the chassis material change, the rear powertrain would change to include individual leg moments. Currently, the legs expand and contract in unison on a set motored gear ratio. To separate the leg movements allowing for independent articulation would result in enhanced cornering abilities. This could be used in both the expanded and contracted forms of the vehicle. Experimentation would be needed to accurately track the polygon of support to interact with the control algorithms. In addition to enhanced cornering ability, independent arm articulation could be used when traversing uneven terrain to enhance the vehicle dynamics when considering topological terrain mapping and lidar interaction.

Additionally, there is limited suspension currently included in the prototype. The suspension is limited mechanically to shocks in the rear wheel track mounted on each strut. Electronic suspension is to be integrated into both the front suspension and rear powertrain to aid in vehicle dynamics and payload protection. The electronic suspension would use a computer-controlled system that can adjust the overall vehicle's ride characteristics and performance. Unlike the current suspension system, an electronic suspension would modify the shocks and struts electronically to ensure a smooth ride in addition to adapting to changing road conditions for improved handling in all sorts of terrain.

3.2. Controls

One major area of further development for the µSMET is the implementation of more advanced autonomous navigation capabilities. Fully autonomous navigation to the desired destination would require integrating an onboard GPS system, as it is currently the best option for vehicle positioning in areas where auxiliary positioning systems, such as cell tower triangulation or tower-augmented GPS are not available. A µSMET equipped with a GPS tracker could be provided a GPS destination to arrive at a series of GPS breadcrumbs to follow a specific path used earlier by another vehicle or person. GPS enabled µSMETs could also make use of geofencing - the commanding unit may define a geographical area as a no-go zone - due to the presence of hostile forces or passive threats like landmines, and the µSMET would therefore find routes to its destination, avoiding the geofenced kill zone. GPS trackers on a fleet of µSMETs equipped with various threat sensors, such as gunshot locators or chemical agent sensors, as discussed in the introduction, would provide commanders real-time awareness of peripheral threats as they evolve on the virtual map and allow units to react before being ambushed by an unexpected attack.

If µSMETs are to be used in conjunction with other vehicles or soldiers, developing a leader-follower capability would significantly enhance the robots' utility to the Army. The forward-facing camera system could be trained on a standard fiducial marker, such as a QR code, so that the µSMET autonomously follows a leader vehicle or person, maintaining a fixed distance throughout the journey. This would reduce the need for soldiers to manually operate the µSMET, allowing them to focus on their environment and be alerted to approaching threats. Autonomous following of fiducial markers could also be used to string together small caravans of µSMETs, carrying substantial amounts of supplies to a forward position, though more advanced autonomy would be required to avoid fishtailing at the back of the caravan.

3.3. Data Collection

Since the µSMET is designed to be a lightweight, low-cost platform, fleets of these robots could be deployed to explore and map out potentially hazardous areas of interest, such as tunnels, caves, partially collapsed buildings, and other dense urban warfare zones that could either be used by militants as secure bases or could be the destinations of lifesaving search-and-rescue operations. While a single µSMET would have limited radio communication in such environments, a fleet of µSMETs could establish a radio network, piping the collected data up to the surface. Mapping could be conducted by a forward force of µSMETs equipped with low-cost LIDARs and cameras, with the supporting µSMETs behind this forward force used only for radio retransmission, reducing the overall amount of data flowing through the network. Real-time transmission of collected data would ensure that at least some of the information is captured and stored by the main receiving node if the mapping fleet is destroyed by enemy action or lost in a structural collapse.

While a GPS receiver would significantly expand the µSMET's navigation capabilities, the implied constraint of using such a GPS device is the combat environment itself. Operating in a zone controlled by hostile Electronic Warfare platforms, such as high-power radio jammers, or operating in rough mountainous terrain, the robot may not receive a GPS signal. It thus would rely on alternative means of localization, mapping, and route selection.

One such alternative method may involve the µSMET's IMU and camera. The µSMET can follow a path pre-traveled by another platform, which would have recorded its IMU data and taken photographs of specific landmarks along the route (for instance, distinctive-looking boulders). The µSMET can be provided this data before starting its journey and attempt to match the route extrapolated from the IMU data, correcting for drift in the IMU recording and the µSMET's own IMU drift by detecting the same landmarks using its camera feed and correcting its position estimate accordingly. If an actual thoroughfare exists along such a pre-planned route, such as a dust road or a forest footpath, which looks distinctive from its immediate surroundings, the µSMET's cameras can also help keep the µSMET traveling along the actual path, further correcting for IMU drift.

Another method for navigating a µSMET towards a destination in a GPS-denied environment is by using a directional radio antenna, ideally, one that is configured for an uncommon radiofrequency outside of the typical range interrupted by radio jammers. The deployed unit that needs to be resupplied could carry such a directional antenna and use it as a beacon visible to friendly forces (towards whom it would be pointed) while remaining undetectable to hostile forces. The µSMET could be equipped with a directional receiver set to the same frequency and home in on the source like an anti-radiation missile, using its onboard cameras to avoid obstacles along the way. While this system may be impractical for a small infantry squad, it could apply to concealed artillery emplacements in need of covert ammunition resupply.

3.4. Long-Term Vision

With further development, the µSMET could be adapted to more demanding roles as well. As a lightweight, low-cost platform, µSMETs could serve as an autonomous sentry or patrol robots, persistently circling and guarding a perimeter, and alerting friendly forces about the approach of potential threats. The low production and operation costs of the µSMET would make it well suited for this role, as it is more economical to replace than a full-size SMET if it were to be lost in an ambush, in addition to requiring considerably less financial investment in recharging or replacing its onboard batteries after persistent long-duration patrols. The modular design of the µSMET would allow it to easily carry a wide range of additional sensors for patrol missions, such as night-vision cameras and thermal imaging cameras for detecting approaching individuals or vehicles, sensitive acoustic sensors to detect abnormal sounds indicating potential threats, and radio spectrum analyzers for detecting enemy radio systems.

The µSMET's low cost allows for a configuration set as a semi-expendable ultralight combat platform. While the Army is extremely cautious about equipping autonomous systems with lethal weapons, the µSMET could play a key role in diversion operations, forcing enemy troops to respond to fake simulated attacks, drawing their attention away from the actual attacking force. In this role, the µSMET could be equipped with lightweight smoke generators and smoke grenades to obscure the diversion, and be "armed" with acoustic gunfire simulators, loudspeakers, flashbangs, and other nonlethal weapons, which could convince the enemy to direct part of its force to deal with this supposed threat. Swarms of µSMETs could be used to set up a single convincing diversion of a major assault operation or split up into groups to carry out several simultaneous diversions at distant locations, presenting the enemy with multiple dilemmas, overwhelming their command structure with their own conflicting reports about these simulated attacks. During nighttime diversion operations, µSMETs could intentionally use their LIDARs as a distraction, or even be armed with laser dazzlers, which could detect enemy electro-optical imaging systems (such as modern tank gunsights) and dazzle them with low-power laser beams which otherwise cause no permanent damage. The goal of the µSMET in these diversion operations would be to distract

he enemy long enough for the friendly attacking force to begin their own attack, after which the diversionary µSMETs could return to a safe staging area. However, since many µSMETs would be lost to enemy fire in these operations, the baseline platform's low cost makes it well-suited for such semi-expendable roles.

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