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Analysis of Army Doctrine Documents with Respect to Artificial Muscle and Robotic Mules

by David M Mackie

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14. ABSTRACT We analyze two unlimited distribution Training and Doctrine Command (TRADOC) documents with respect to the US Army Combat Capabilities Development Command Army Research Laboratory Director's Strategic Initiative entitled *Fermented Vegetation Efficiently Running Artificial Muscle (FeVERAM)* and its long-term goals. We start with brief introductions of the TRADOC documents, FeVERAM, and artificial muscles and robotic mules. The main section of this technical report utilizes a two-column table, with selected TRADOC document text on the left and our analysis on the right. We conclude with predictive descriptions of future infantry. An appendix briefly addresses energy concerns.		
15. SUBJECT TERMS Training and Doctrine Command, TRADOC, Army doctrine, Fermented Vegetation Efficiently Running Artificial Muscle, FeVERAM, fuel-powered artificial muscle, FPAM, movement, maneuver, observation, resupply, multi-domain, infantry, robot, exoskeleton, robotic mule, Director's Strategic Initiative, DSI, MDO, Multi-Domain Operations		

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1. Introduction

It is widely felt that infantry could be more effective carrying lighter loads. They would be more mobile, less fatigued, and less susceptible to stress injuries (of backs, knees, etc.) On the other hand, infantry are also continually being given more things to carry that help to make them more effective: heavier armor, more electronics, more batteries for those electronics, and so on. This dichotomy has led to the idea of reintroducing mules to the 21st century infantry—but robotic ones rather than the actual mules of the past. This technical report analyzes that dichotomy, arguing for robotic mules, and especially for legged robotic mules rather than small wheeled vehicles for that role. The report starts with brief introductions of two relevant official Army documents, the author's Director's Research Initiative (DSI) research program, and artificial muscles and robotic mules. The main section utilizes a two-column table, with the selected official Army text on the left and my analysis on the right. I conclude with predictive descriptions of future infantry, if practical artificial muscles can be developed, allowing the fielding of legged robotic mules and related advances.

1.1 TRADOC Documents

Two recent Training and Doctrine Command (TRADOC) unclassified pamphlets set out US Army principles for movement and maneuver on future battlefields. These are 525-3-6[1] and 525-3-1[2], released 24 February 2017 and 6 December 2018, respectively, and available at the following:

- https://adminpubs.tradoc.army.mil/pamphlets/TP525-3-6.pdf
- https://adminpubs.tradoc.army.mil/pamphlets/TP525-3-1.pdf

Lieutenant General HR McMaster, then-Director of the Army Capabilities Integration Center, TRADOC, introduces Pamphlet 525-3-6, *The U.S. Army Functional Concept for Movement and Maneuver (AFC-MM) 2020-2040*, (in part) as follows:

> Pamphlet 525-3-6…describes how Army maneuver forces generate overmatch across all domains, the electromagnetic spectrum, information environment, and human perception. The concept also describes how Army forces project power across strategic distances and then transition rapidly to cross-domain maneuver….
>
> Maneuver forces integrate reconnaissance and security operations, maneuver sensors and long-range capabilities into positions of advantage, integrate intelligence and operations, defeat enemy cross-

> domain capabilities, and transition from shaping operations to close combat. Maneuver forces…[a]ttacking from multiple directions and domains…compromises [the enemy's] defenses by reducing his ability to communicate, control direct fires and movement, and sustain the fight.

General Mark A Milley, Chief of Staff of the Army, introduces Pamphlet 525-3-1, *The U.S. Army in Multi-Domain Operations, 2028*, (in part) as follows:

> America's adversaries have studied [recent] US operations closely…. [W]e excel in a way of war that emphasizes joint and combined operations; technological dominance; global power projection; strategic, operational, and tactical maneuver; effective joint fires; sustainment at scale; and mission command initiative.
>
> Simultaneously, emerging technologies like artificial intelligence, hypersonics, machine learning, nanotechnology, and robotics are driving a fundamental change in the character of war. [They may] revolutionize battlefields unlike anything since the integration of machine guns, tanks, and aviation which began the era of combined arms warfare.
>
> Strategic competitors like Russia and China are synthesizing emerging technologies with their analysis of military doctrine and operations. They are deploying capabilities to fight the US through multiple layers of stand-off in all domains – space, cyber, air, sea, and land. The military problem we face is defeating multiple layers of stand-off in all domains in order to maintain the coherence of our operations.
>
> Therefore, the American way of war must evolve and adapt. [This pamphlet] describes how US Army forces, as part of the Joint Force, will militarily compete, penetrate, dis-integrate, and exploit our adversaries in the future.
>
> This product is not a final destination, but is intended to provide a foundation for continued discussion, analysis, and development. We must examine all aspects of our warfighting methods and understand how we enable the joint force on the future battlefield. We must challenge our underlying assumptions, and we must understand the capabilities and goals of our potential enemies. That is how we change our warfighting techniques and build the fighting forces we need in the future. It is also how we maximize deterrence and, if necessary, win future wars.

1.2 FeVERAM

Fermented Vegetation Efficiently Running Artificial Muscle (FeVERAM) is a joint project between the Sensors and Electron Devices Directorate and Vehicle Technology Directorate, directly funded by the Director of the US Army Combat Capabilities Development Command (CCDC) Army Research Laboratory (ARL) as a DSI program. FeVERAM began in April 2018 and is focused on developing fuel-powered artificial muscles (FPAMs), which convert the chemical energy stored in fuel directly into linear contractile movement similar to that provided by biological muscles. FPAMs are foundational to FeVERAM's ultimate aim of creating mule-sized robots to accompany infantry. FPAMs would also enable powered exoskeletons for Soldiers.

1.3 Robotic Mules for the Army (from FeVERAM's Perspective)

A "robotic mule" for 21st century US Army infantry would have the following attributes (which are supported by the analysis in Section 2):

1) A robotic mule must locomote using legs rather than wheels or tracks:

    a) This is necessary so that the robotic mule can accompany infantry forces through diverse terrains that range from high-density cities to the countryside, including rocky, heavily vegetated, and mountainous environments. (The combination of terrain and circumstance is known militarily as the operational environment [OE].)

    b) Falsely termed mules, robots that rely on wheels or tracks will limit the effectiveness of infantry forces due to their restricted ability to traverse difficult terrain. Enemies would be able to choose the OE to exploit this limitation to their advantage.

    c) The artificial intelligence (AI) to control the locomotion of robots using legs has been largely worked out by companies such as Boston Dynamics and Sony (often using Department of Defense [DOD] funding). Over the last 10 years, the CCDC Army Research Laboratory's Robotics Collaborative Technology Alliance has also conducted seminal research in this area.[3]

    d) The needed breakthrough is a way to actuate the legs that will work for the Army. We believe that FeVERAM's FPAMs will be that breakthrough.

2) The strength, speed, and travel of leg actuation for a robotic mule must be comparable to that of a real mule:

    a) This seemingly obvious requirement is often overlooked, especially by academic researchers developing artificial muscles. For example, of three recent (and otherwise excellent) artificial muscle papers published in *Science*'s July 2019 issue,[4–6] the largest load was 20 g and was only raised a few millimeters.

    b) Scale-up of FPAMs to "mule size" is an integral part of FeVERAM.

    c) Obtaining speed of contraction/relaxation sufficient to meet operational requirements is particularly challenging for mule-sized FPAMs.

3) A robotic mule must be quiet:

    a) In a small-scale wargame, regular infantry squads were pitted against otherwise-equal squads provided with (Defense Advanced Research Projects Agency–funded) legged robotic mules (from Boston Dynamics). The OE was hilly dense woods. The mules' legs were powered hydraulically from compressors that were driven by gasoline-powered, two-cylinder internal combustion engines (ICEs). Both the compressors and the ICEs were very noisy. (Operators needed ear protection.)

    b) Although the squads with ICE and compressor robotic mules were less encumbered and therefore significantly more mobile, especially over long distances, the lack of noise discipline allowed the "enemy" to identify and locate the infantry squad over a kilometer away. The ease of detection more than offset the mobility advantage.

    c) Legged robotic mules using battery-powered electric motors are much quieter and allow for improved noise discipline. In most models, a distinctive whine is audible nearby every time a leg is moved due to the high-speed motors and gears interacting to achieve the necessary torque. This can be mitigated with "custom, large diameter, low gear-ratio actuators that have no mechanical springs", according to Dr Larry Matthies, senior research scientist at the NASA Jet Propulsion Laboratory.[3]

    d) Legged robotic mules with FPAMs would operate as quietly as a Soldier.

4) A robotic mule must move its legs in an energy-efficient manner:

a) The most efficient walking cannot match the efficiency (or speed) of wheels/tracks over good roads or open and even terrain. It is assumed that, for rapid maneuvers over large distances, robotic mules would be moved the same way as Soldiers (i.e., by aircraft or vehicles).

b) Energy itself is weightless, but its carriers, like fuel and batteries, are not. The weight of carried energy decreases the weight that could be used to lighten the Soldiers' load (e.g., ammunition, weapons, sensors, radios, food, water, clothing, and medical supplies). Lightening the load for Soldiers to improve their survivability and lethality is the primary purpose of the robotic mule.

c) Energy carried as batteries is 1000 times heavier than energy carried as fuel. Thus, if leg actuation powered by fuel were only 1% energy-efficient, it would still be 10 times more weight-efficient than leg actuation powered by batteries—even if the latter were 100% energy-efficient (which is not possible).

d) A stack of fuel cells (FCs) to convert fuel to electricity may enable the use of electrically powered leg actuation. However, available FCs that would be portable on a robotic mule have energy efficiencies of 10% at best, and their weight must be factored into weight efficiency.

e) Small fuel-powered electrical generators have efficiencies roughly similar to FCs, are heavier, and are noisy.

f) Regenerating energy in the field is a possibility (see item 5), but it will be a slow process, whether biological, chemical, or solar. Since the robotic mule must not slow down the Soldiers, it must have energy-efficient leg actuation.

g) FPAMs are several orders of magnitude lighter than electric motors. Thus, unlike electric motors, FPAMs may be located at several points along each leg, and in particular near the "foot", without introducing extra significant weight that must be raised with each step. This would allow more biomimetic leg motion, which would increase movement efficiency, as well as agility.

h) Energy usage must be considered at a system level. Efficiencies and masses of all technologies/systems for energy storage, energy regeneration (if any), energy conversion (if any), leg actuation, and overall movement must all be taken into account. An appendix briefly addresses energy concerns.

5) Ideally, a robotic mule would have the option of self-refueling in the field:

   a) In concept, the robotic mule would ferment locally sourced vegetation (and carbohydrate-rich food sources) into a chemical fuel such as ethanol or hydrogen (which is the "fermenting vegetation" part of FeVERAM). This research is being conducted by the Biotechnology Branch of ARL, apart from FeVERAM.

   b) The robotic mule might alternatively self-refuel by conversion of any locally sourced dry organic material such as dead wood, paper, plastics, and so on. This research is being pursued with several projects at ARL.

   c) Solar recharging of batteries is not currently being considered for powering locomotion. The battery weight problem would be compounded by the solar array weight problem. More importantly, there is no combination of area and exposure time for foreseeable solar-cell arrays (even under ideal conditions) that would allow operation in infantry forces.

   d) Although self-refueling in the field would provide valuable additional options for use of robotic mules, it has the potential to complicate or sacrifice stealth and/or speed. Thus, fielded operation of robotic mules for 3 to 5 days at a time must not be *dependent* on self-refueling.

2. Analysis of TRADOC Documents

Tables 1 and 2 provide side-by-side analysis of the two TRADOC documents pertaining to FeVERAM. To reduce repetitiveness, we only analyze the Executive Summary of the second TRADOC document.

Table 1 ARL analysis of TRADOC document AFC-MM pertaining to FeVERAM

Quote from TRADOC Document	Analysis
1-4c: The Joint Force's ability to deploy large numbers of forces over extended distances rapidly, sustain them, and deliver precise, discriminate results provides a deterrent capability as well as the proper force required to defeat adversaries.	• Rapid deployability of large numbers: Limits the weight of all infantry support devices. • Sustainment: Easier if Soldiers do not have to carry everything; easier with self-refueling. • Precise, discriminate results: Implies close combat, which is especially dangerous.
1-5b(2): Future operating environments will consist of complex urban terrain and dense populations.	• Close combat; likely house-to-house. • Much of battlefield terrain will be impassable to wheeled or tracked vehicles.
1-5b(3): Future threats will become increasingly adaptive….	• Must assume threats will operate primarily where our infantry is most disadvantaged. • Turn current enemy refuges into traps.
1-5b(4): Future threats, with advanced technology, will degrade U.S. communications, observation, precision fires, and position, navigation, and timing (PNT), challenging U.S. forces across the breadth and depth of the battlefield.	• We will continue to need infantry assets close to the enemy (especially dangerous). Many battles will not be winnable with remote sensing and standoff weaponry. • Robotic mules could be periodically left behind in a trail to relay communications.
1-5b(5): Peer threats will exploit multi-domain anti-access and area denial capabilities….	• Deep penetration into enemy-controlled areas may be necessary, with concomitant high asset losses. Reconfigurable and reassignable swarms of weaponized robotic mules leading the way would minimize the losses of infantry Soldiers picking out the targets.

Table 1 ARL analysis of TRADOC document AFC-MM pertaining to FeVERAM (continued)

Quote from TRADOC Document	Analysis
1-5b(6): Lighter and smaller platforms and systems will increase strategic and tactical mobility for some formations, but U.S. armored brigade combat teams [BCTs] will remain the premier combined arms force with improved mobility, firepower, and protection capabilities. 1-5b(10): Armored, infantry, and Stryker BCTs will remain the Army's primary tactical fighting formations during 2020-2040.	• Robotic mules will need to be quickly reconfigurable, to suit the mission and unit. • Robotic mules will need to fit into and improve existing types of BCTs, not replace them. • We still need infantry. In many OEs, armored and Stryker BCTs will not be able to operate effectively. Plus, infantry BCTs, even with exoskeletons and legged robots, will be much lighter, and thus could be transported by a much wider range of aircraft.
1-5b(7) U.S. Army maneuver forces will become increasingly vulnerable over time as threat anti-tank, anti-personnel, and anti-air munitions continue to exceed protection. 1-5b(8) Active protection systems will mature, but will not protect against the full range [of] kinetic energy threats nor be fielded fully to the force during the 2020-2040 timeframe.	• Increasing the armor of infantry will decrease their ability to carry other materiel. Robotic pack mules could carry that materiel. • All maneuver forces would benefit from screening by weaponized robotic mules, which enemy units would be forced to engage, thus giving away their positions. • This strategy assumes the robots can go with the infantry and can go to the enemy.
1-5b(11) Enemy long range target acquisition and fires capabilities will increase the vulnerability of stationary light forces.	• Robotic mules must be fuel-efficient. Their squads may be on the move for days at a time.
1-5b(12) The Army will continue to rely on aerial maneuver when conducting air-ground operations and sustainment.	• Robotic "heliport" mules could extend the range of quadcopter unmanned aerial vehicles (UAVs), by refueling them repeatedly in advance of the forward line, and by relaying communications. • Sufficiently advanced FPAMs would enable flapping UAVs, hard to distinguish from birds.
2-2d: Unfortunately, enemies and hybrid threats will choose to live and operate in dense urban areas to mitigate U.S. capabilities due to the varying nature of the physical structures of a city, such as multi-story buildings, subterranean routes, bridges, and vast population centers.	• Enemies will hide among civilians in large cities, hoping to maximize collateral damage from air, artillery, and armored strikes. They will use this as propaganda against us. • We will need the ability to successfully attack enemies selectively from within buildings, rather than just blasting buildings from the streets outside.

Table 1 ARL analysis of TRADOC document AFC-MM pertaining to FeVERAM (continued)

Quote from TRADOC Document	Analysis
2-3b: Be mobile and maneuver dispersed.	• Spreading out reduces vulnerability to a single strike, but further increases the danger for point and flank positions. Give those to weaponized robotic mules. Force the enemy to waste their lives and assets on our robots.
2-3c: …the integration of intelligence and operations in close contact with enemies and civilian populations.	• Offloading carry weight and/or guard duty to robotic mules will keep Soldiers sharper and improve focus on human interactions.
3-4b: …defeat enemies by forcing them to fight against multiple types of attacks from multiple directions and domains, thus achieving surprise and gaining temporal advantage.	• Robotic mules can "rush" enemies on the ground, pinning them in place for air, artillery, and armored attacks. (Normally, this tactic would result in heavy casualties on both sides, which is a trade we do not want.) • You lose surprise if the enemy hears you coming or knows the path you must take.
3-4c(1): Ultimately, war is a brutal business that requires units to engage in close combat.	• Close combat, again. US strengths are technology, manufacturing, and economics. If we are trading lives for lives, we are ceding the advantage to the enemy.
3-4d(2): The capability to enter a theater at just about any point with combat configured, highly mobile, and lethal forces provides Joint Force commanders with options to surprise the enemy and present multiple dilemmas.	• Mobility, again. • Surprise, again: quiet; goes anywhere. • More lethal infantry will likely be carrying heavier materiel (weapons, ammunition, and air drones). Offload that onto robotic mules. • Robotic mules could be configured as any type of infantry weapon platform: rifle, grenade, mortar, UAV launcher, or spotter. • Robotic mules would think orders of magnitude faster than humans and could keep track of more things at once, more precisely. However, they would be hardware- and software-limited. Soldiers are more adaptable and better generalists.
3-4d(5): BCT success when operating semi-independently links critically to improved mobility, firepower, protection, and sustainment capabilities.	• Mobility: limits weight for infantry support vehicles/robots yet simultaneously requires them to operate in every infantry OE. • Firepower, protection, sustainment: All increase the (already large) carry weight for infantry.

Table 1 ARL analysis of TRADOC document AFC-MM pertaining to FeVERAM (continued)

Quote from TRADOC Document	Analysis
3-4d(8) Reduced logistic demands, organic power generation, autonomous resupply, additional medical capability and capacity, and extended reach improves BCT endurance enabling them to sustain a high tempo for sustained periods of up to seven days.	• A robotic mule that can self-refuel in the field can provide organic power generation. • Supply trains of semi-autonomous robotic mules could resupply from safe drop points. • Casualties could be conveyed to safe drop points by empty mules on the return trip. • Susceptible to enemy (and thieves) if traveling only on same predictable routes (i.e., roads).
2-3d: Decentralize operations.	• Platoons, and even squads, of infantry may need their own legged “mini-tanks”, to overmatch enemy infantry.
B-2a(2): Future maneuver forces require the capability to integrate and team air and ground manned and unmanned systems capabilities during cross-domain maneuver to seize and control terrain, including subterranean, destroy enemy forces, and protect populations, infrastructure and activities. (AFC-MM: 3-4.g.,h., 3-5.b.(2), (3), 3-5.e.(2)	• Requirement: We need unmanned ground systems that can seize/control (all) terrain and destroy enemy forces, while protecting (urban) noncombatants, buildings, and so on.
B-2a(4): Future maneuver forces require the capability to maneuver and survive in close combat against enemies with robotic and autonomous systems, unmanned aircraft systems, …. (AFC-MM: 2-2.a.(2), 3-4.e., 3-4.g.(6), 3-5.e.(2))	• The requirement implicitly acknowledges that the future enemy is likely to have weaponized robots. We cannot simply yield that advantage, sending our infantry Soldiers against the enemy unaccompanied. We must have robots, and they must be better.
B-2b(13): Future Army forces require the capability to employ remote and standoff CBRN detection and integrate disparate, non-CBRN detectors to enhance situational understanding of CBRN threats and hazards during joint combined arms operations. (AFC-MM: 3-6.e.(1))	• Robotic mules would be less susceptible than humans to chemical, biological, radiological and nuclear (CBRN), and exposure would not result in a long-term disability/casualty. • Robotic mules could act as data collection nodes, so that CBRN detectors would need much less power for transmission of data.
B-2b(15): Future Army forces require the capability to produce accurate firing data from the lowest echelon, transmit that information rapidly and accurately, de-conflict fires, and deliver precision fires on enemy formations to create the desired effects during joint combined arms operations. (AFC-MM: 3-5.b.(2), 3-6.d.)	• Human forward-observer spotters could determine the most important targets, then offload to robotic mules the most-dangerous duty of maintaining the “spot” on the chosen target as missiles/bombs/shells are incoming.

Table 1 ARL analysis of TRADOC document AFC-MM pertaining to FeVERAM (continued)

Quote from TRADOC Document	Analysis
C-1b: …autonomous robotic systems teamed with Soldiers enable integrated security operations allowing formations to conduct continuous reconnaissance, early warning and to maintain enemy contact….	• There is a temptation to "meet" this research requirement with wheeled robots, which will ultimately prove inadequate. • However, much of the control AI developed using wheeled robots will be useful for, and transferable to, robotic mules.
C-2a(4): Advanced sensor technologies will enable increased unmanned systems autonomy further enhancing maneuver and situational awareness.	• Increasing the autonomy of unmanned systems is actually more of an AI problem than a sensors problem.
C-2b(7): Combat vehicles will incorporate autonomous systems both on and off the vehicle. Autonomous systems assist in operating, targeting, protecting, and maintaining on-board systems. Off board systems will provide intelligence, surveillance, reconnaissance, protection, and additional lethality options to the manned combat vehicle.	• We believe the Soldiers in infantry units deserve the same consideration. • Robotic mules could serve the purpose for both infantry Soldiers and combat vehicles. • Infantry Soldiers with future exoskeletons would represent a new type of unit, a combination of human and vehicle.
C-2b(12): Remote and close proximity autonomous robotic unmanned ground and aerial systems that provide intuitive alert interfaces for danger awareness and avoidance, afford greater situational awareness.	• If the terrain accessibility of these planned autonomous ground scouts is limited, then the enemy will take advantage, and the autonomous ground scouts will be worse than useless, giving a false sense of safety.
C-2b(13): The small unit will have the lethality and survivability necessary to win the close fight…. Small units will mark autonomously, tag and track targets, recognize threats and automatically engage with lethal and nonlethal capabilities.	• Ideally, the Soldiers in small units would serve mostly to direct the overall actions of the unit, analyze the tactical situation, and be "humans-in-the-loop" (for targets that are not actively attacking the unit). Robots would do most direct engaging of the enemy.
C-2b(14): Each combat Soldier will operate from a protective ensemble that includes a helmet….	• Helmets are obviously the most important armor, but Soldiers are not just heads. • Unfortunately, full-body armor is *heavy*. It wears out and slows down infantry Soldiers, and reduces the amount of (also heavy) weapons and ammunition they can carry. • The answer is exoskeletons, *if* they can be done properly. The key technology is strong, fast, efficient, and silent artificial muscles.

Table 1 ARL analysis of TRADOC document AFC-MM pertaining to FeVERAM (continued)

Quote from TRADOC Document	Analysis
C-2b(16): Autonomous unmanned systems will have the capability to move over complex terrain and environments equal to or greater than will their human counterparts. These systems extend the reach of leaders while allowing formations to initiate contact under the most favorable conditions, and provide situational understanding.	• *Only* flying or legged systems meet this requirement. • The limited range of quadcopters can be extended with robotic mule "helipads." • However, quadcopters are nonstealthy. • Sufficiently advanced FPAMs would enable robotic birds with useful capabilities.
C-2b(17): Future technological advances in hemorrhage control, synthetic blood, virtual health, remote physiologic monitors, and human physiologic modulation will enhance Soldier survivability to prolonged combat field care.	• Many of these functions could be built into exoskeleton armors. • Robotic mules could be used to transport injured Soldiers rapidly and autonomously to combat field care. At present, doing so removes two more Soldiers from combat.
C-2c(6): Autonomous unmanned systems will respond to digital and verbal commands and act as members of the squad or crew. They will provide accurate verbal and written language translation unobtrusively. Autonomous unmanned systems will function as members of the formation executing tasks as well as providing oversight for subordinate systems. This capability will allow leaders to employ unmanned systems for critical and complex tasks such as establishing a mesh communication network, or reconnoitering and mapping subterranean infrastructures.	• Assuming we manage to develop such sophisticated autonomous unmanned systems (i.e., robots), it would be foolish to refuse to weaponize them due to concerns about losing the human-in-the-loop. For many decades, every military has had "fire and forget" bombs and missiles that carry out human-given kill orders on specified targets. Advanced sniper rifles now operate that way. Weaponized robots need be no different, morally. Our future adversaries will surely have them. • In any case, there are *many* dangerous roles that robots could fill, both military and civilian.
C-2d(2): Autonomous unmanned robotic systems integrated into combat formations allow the maneuver force from squad to the BCT to reduce force density in conditions of uncertainty, extend the area and time of the formation operational effectiveness, and enable freedom of movement and action. Future systems are capable of a high degree of autonomous operation including the decision analysis and execution of simple to advanced tasks without Soldier intervention.	• Integrating robotic mules (and other FPAM-driven robots, and FPAM-driven exoskeletons) throughout the Army, especially the infantry, would allow Soldiers at every level to concentrate on doing what humans do best: think, plan, and direct. • While our adversaries are kept busy concentrating on simply not dying, our Soldiers can be busy analyzing the situation. • Robot strengths: reacting to ambushes, aiming, shoot-and-move, no fear, no panic, no fatigue, and no loved ones at home.

Table 1 ARL analysis of TRADOC document AFC-MM pertaining to FeVERAM (continued)

Quote from TRADOC Document	Analysis
D-2(Areas of risk)(1): Insufficient funding and inadequate capacity. The Army requires an adequate budget to maintain force readiness, support warfighting functions, and fund future capabilities development simultaneously. E-1: The payoffs in speed, standoff, lethality, and manpower savings allow the Army to prioritize robotic technologies, operational concepts, and tactics, techniques, and procedures. E-2a: UGS already in use demonstrate small unit standoff from potentially lethal threats.	• Retirement and disability pensions plus lifelong health care are also military costs. Personnel are the Army's largest cost, by far. In 20 years, personnel will take up almost 100% of the anticipated DOD budget. • Reducing personnel and reducing injuries to personnel are the most effective ways to free up money, especially long term. • Robots and exoskeletons can be phased in to reduce and/or protect personnel, beginning at depots and progressing to the front lines and beyond, as FPAM and AI technologies mature.
Appendix E "Robotics Strategy" as a whole	• No mention is made of how the robots (unmanned ground systems) will locomote: wheels, tracks, or legs. Failure to address this basic issue is a weakness in the document, and may result in our troops being given what is currently available rather than what will be needed.

Table 2 ARL analysis of TRADOC document *The U.S. Army in Multi-Domain Operations* pertaining to FeVERAM

Quote from TRADOC Document	Analysis
2a: battlefield … is increasingly lethal and hyperactive	• Let the Soldiers use their brains: pick out targets, and give deployment and kill orders. • Let the robots do most of the fighting. They can aim faster and more accurately, with less ammo use. They have no fear. If a situation requires sacrifice of a squad member to take an objective, let it be a robot. • Things can be replaced; people cannot.
2a: Dramatically increasing rates of urbanization and the strategic importance of cities also ensure that operations will take place within dense urban terrain.	• In urban battles, we have often been left with a terrible choice between killing the civilians among whom enemy combatants are hiding, or taking many casualties as we go room to room trying to kill only combatants. Legged robots would give our infantry a (much better) third option.
2c: In armed conflict, China and Russia seek to achieve physical stand-off by employing layers of anti-access and area denial systems designed to rapidly inflict unacceptable losses on U.S. and partner military forces….	• China and Russia cannot compete with the United States industrially and economically. The only "unacceptable losses" they can inflict on the US Army are Soldier deaths. We can defeat them in a war of economic attrition.
2c: The Joint Force has not kept pace with these developments. It is still designed for operations in relatively uncontested environments….	• We're facing 21st century wars with 20th-century infantry.
2d(1): The demonstrated capability to prevail in armed conflict counters narratives by adversaries who portray the U.S. as a weak or irresolute partner.	• Often, US irresoluteness is due to the political cost of large numbers of casualties. By replacing some infantry Soldiers with legged robots (and using the robots as the shock troops, keeping the humans back from the heaviest fighting), our politicians are given more options for deterrence.
2d(2): Forward presence forces immediately contest an enemy attack in multiple domains.	• Infantry needs heavier weapons and better armor, while still maintaining mobility.
2d(2): …expeditionary capabilities able to deploy within strategically relevant time periods.	• Exoskeletons for humans, and legged robots ranging from dog- to draft-horse-sized, will be much easier to airlift into theater than the armored vehicles that are traditionally used to support infantry (and which cannot actually go everywhere that infantry needs to go).

Table 2 ARL analysis of TRADOC document *The U.S. Army in Multi-Domain Operations* pertaining to FeVERAM (continued)

Quote from TRADOC Document	Analysis
2d(5): …physically securing terrain and populations for sustainable outcomes	• Sustainable outcomes *require* "boots on the ground" over a long period, closely interacting with the populace. • We often take most of our casualties during this stage.
4a: Multi-domain formations provide the Joint Force with additional means to stimulate, see, and strike key components and vulnerabilities within enemy systems. Army forces also continue to conduct the traditional tasks of seizing terrain, destroying enemy forces, and securing friendly populations.	• In other words, we need infantry to get up close, into the enemy's stronghold areas, to force enemies out of hiding and to protect friendlies. • This is extremely dangerous. Use robots when possible to minimize our casualties.
4d: The Army must exercise careful talent management to make the most of these high-quality personnel….	• Highly trained troops should *not* be wasted like they are cannon fodder. • Do not use Soldiers as "red shirts" to break down doors, explore houses, villages, fields, and so on. Use FPAM-enabled robots for that.
4e(7): Improving the capability to conduct Multi-Domain Operations in dense urban terrain at all echelons through the development of tactics and capabilities to increase the accuracy, speed, and synchronization of lethal and nonlethal effects. (Supported by Army Materiel Modernization Priorities: Long-Range Precision Fires, Next Generation Combat Vehicle, Army Network, Soldier Lethality)	• Experience has repeatedly shown that dense urban areas can only be taken by infantry. • Long-Range Precision Fires are not useful for nonlethal effects, and only somewhat useful for selective lethality due to overkill. • Next Generation Combat Vehicle (NGCV) will not go inside buildings or through narrow roads/alleys. NGCVs may not get through regular streets filled with building rubble. • Exoskeleton enables Soldier lethality.

3. Future Scenarios for Applying FPAMs

We present here several potential battlefield scenarios of future Soldiers supported by robots and exoskeletons actuated by FPAMs.

3.1 Scenario #1: Not a Walk in the Park

SGT Rivera eased down the side of the ridge through the dense forest, its floor a tangle of vines, saplings, and half-rotted dead trees between the closely packed trunks of the live trees. Rivera was hiking comfortably under a 20-kg (44-lb) load. Near the bottom, Rivera paused, keeping a sharp eye and ear for any human contacts. A deep reconnaissance mission like this depends on avoiding detection. The locals were not necessarily unfriendly, but they might barter information. Rivera looked back at the recon squad: five Soldiers plus two small-sized robotic pack mules. The only noise was footsteps, human and robotic. At a slow pace, they could spook deer at 30 m.

Being a 15-year infantry, Rivera had doubted robotic mules when they had been introduced, but after one ruck march with the new legged versions through rough terrain, Rivera was a believer. The math was in the robots' favor: Each mule on this mission was carrying 30 kg (66 lb) for the Soldiers and 15 kg (33 lb) of recon equipment. If Rivera and the others Soldiers had to carry all that, they would each have a 35-kg load. That was 5 kg over the recommended maximum load, even for short trips on flat trails, and they were going 80 km in and 80 km out, in four days, cross-country.

Plus, tonight they planned to reapportion the loads. Each mule had started the morning with 45 kg (99 lb) of alane for fuel—plenty for *five* days. ("Plan for the unplanned".) The robotics tech said the alane turned into "rock powder", so it was safe to dump. That meant each Soldier could offload another 2 or 3 kg onto the mules every night. Since most of the recon equipment was not coming back, the tired Soldiers' loads on the return march would be gear-only.

The valley's bottom was a boulder field with a stream running through it. SPC Johnson, the robotics specialist, gave a low whistle. "Sure glad our mules have legs!" SGT Rivera nodded agreement. A few years ago the Army had tried out mules with wheels and tracks. Those had been great at carrying stuff—over easy terrain. The problem was, the enemy had figured that out. Soldiers had died because the Army's unlegged mules were forced along an obvious route.

Rivera led the legged mules confidently into the boulder field. The group had to slow the pace some to accommodate the increased demands on the mules' walking and pathfinding AIs, but they still made decent speed.

Johnson had run ahead to survey the ground and upon return reported an obstacle. "Hey, Sarge, the stream cuts a deep gully that's at least a meter wide, for as far up- and downstream as I can see." Rivera groaned. Water often meant people. Detouring would increase the risk of contact with locals. "Can the mules jump it?" Rivera asked. Johnson pondered that for a moment: "Yes, but not fully loaded like they are." When Rivera's groan turned into a growling objection, Johnson interrupted. "Sarge, I don't know about you, but I'm throwing my pack across before I jump. Shouldn't the mules get the same deal?" Rivera had to laugh. The Soldiers were getting attached to these legged robots. They'd be naming them next.

Unloading and loading was an annoying delay, but the mules jumped the gully like champs. Johnson bragged that "real mules wouldn't have done better". Rivera doubted that, but real mules brayed, ran off, bit, kicked, got sick, and left trails of dung, so they weren't asking for a trade.

3.2 Scenario #2: Spotter's Field

The wind was rolling an ominous cloud of white obscurant smoke toward the Soldiers. Nothing could be seen past the cloud's front, about a quarter-click away, but farther back they could hear the unmistakable clanking of armor, getting louder. "Coming slow, Sarge," said SPC Smith. The Soldiers' faces showed clearly that they suspected more than they were saying.

SGT Rivera shrugged, stalling for time. LT Franken's contingency plan might not be needed. "They don't want to outrun their cloud cover without air superiority. And we're entrenched in these rocky hills flanking the gap. We could enfilade the road four different ways and turn it into a killing zone." (In fact, that was their plan.)

Smith disagreed. "OK, they're slowed down off-road. But why aren't they right behind that smoke? I don't like it."

Rivera's heads-up display (HUD) lit up with an emergency alert from Franken. The mule they had sent out carrying a CBRN detector package had just signaled: the obscurant cloud was laced with nerve toxin. "You just got your answer, Smith." Rivera shouted instructions. "Gas, gas, gas!" Soldiers scrambled to put on CBRN gear and get into foxholes.

The enemy remained tightly buttoned-up in their armored vehicles. Spread out over a square kilometer, hidden in the smoke, near buildings and among trees, the adversaries felt safe from air and artillery attack. They idled their engines, waiting for the nerve toxin to take effect.

Meanwhile, nine robotic legged mules carrying robot spider payloads were silently moving down out of the rocky hills toward them. Spreading out and moving quickly from cover to cover, the mules found the enemy tanks and armored personnel carriers using a combination of AI and remote control. Once each find was designated “enemy” by a US Soldier, a small robotic spider emerged from the mules’ cargo, crept quickly to the vehicle, jumped up, and attached itself.

A quarter-hour later, US artillery salvos began taking out the enemy’s armor. The attack swept west to east in less than a minute, one round per vehicle. Before the enemy commander could finish swearing, shells had followed the radio beacons on the robotic spiders to every enemy vehicle.

3.3 Scenario #3: Cleaning House

SPCs Smith and Johnson tapped their feet and swore. How long was it going to take the lieutenant to get everyone in position? Apartment sweeps were dangerous enough, without giving so much time to any insurgents inside. Smith glanced at Johnson, 30 m to the right, stationed at the other front door of the 20-story building, with two robots keyed up ready to go.

Other than their temporary names —Lucy and Ethel—the two with Smith were just like the two under every Soldier’s control in this op, equipped for close assault. Both had tasers and armor-piercing guns, were fitted with heavy strap-on armor, and carried cargoes of soft robots. If they worked like they had in the wargames, the Soldiers would probably all survive this, as well as avoid shooting any civilians. Smith mouthed a few hopeful words and then the “GO!” signal came.

Smith remembered the rule to rein in one’s adrenalin, take time, and let the robots stay 10 steps ahead. A loud boom from the back of the building reinforced the rule’s wisdom. “I’m OK!” the radio yelled. It was SGT Rivera. “Damn IED took out my lead mule.” The radio crackled again. “Found another one,” said Johnson. “Taking it out.” There was a bang-boom. “All done. Watch yourselves!” Smith and the other Soldiers acknowledged grimly. Their intel had been correct about this place.

The lieutenant tersely ordered the deployment of their air support. They unpacked little quadcopters and sent them up the center shaft of the stairwells to do a recon. Quads were more expendable than mules, in case of IEDs, but would be easily destroyed by any enemies in such close quarters. Fortunately, there appeared to be no more IEDs in the stairwells, and no enemies either. That made life a bit easier.

Smith watched Lucy and Ethel easily and quickly climb the stairs. It was a sweet sight. (There were stories about having to carry robots up stairs. Unbelievable.) Moreover, the robots didn't stand around waiting for orders when they reached the top. Their AIs executed the next step in the operations plans, with Lucy positioning itself at 1A's door, while Ethel went down the hallway to secure the middle. Another robot appeared at the end, followed by a slightly shaken Rivera, who gave a thumbs-up and pointed at the doors. Smith nodded and told Lucy to proceed.

The robot rocked forward and gently bumped 1A's door. Knock, knock and a recorded greeting in the native language. It roughly translated to "US military here. Please excuse the intrusion. We're searching for insurgents. You have nothing to fear. Open this door or we'll send in the spiders."

The "spiders" were hand-sized, eight-legged, soft robots. They couldn't carry stuff like the mules, but they could squish under doors. Each had three fish-eye cameras, a microphone, a speaker, and a small explosive self-destruct. Their telemetry was sent to the mules, which passed it to a relay chain ending in remote human observers, who experienced and controlled the spiders in virtual reality. Initially, most noncombatants had grudgingly opened to the mules rather than experience the "horrors" of the "creepy-looking" spiders, but familiarity made the primal reaction fade with time. When Lucy's spiders found 1A's occupants, an old couple calmly washing up dishes at the sink, they harshly chided the spiders about invading their home. The civilians brushed off the relayed apology and warned of dire consequences if the robots made a mess. It was hard to tell if they were knowingly yelling at the remote-controlling US Soldiers or just personifying their little visitors.

The rest of the first floor and the next 13 floors were mostly the same mix of annoyed but nonthreatening reactions. A few people happily let Lucy in to look around. The children especially were fascinated by the "American mules". Smith used the opportunities for good-will chats using the Translate app. The searches never took long. "War makes us all paupers," thought Smith, making sure to leave much-needed gifts of friendship stowed in the mule's cargo. Apartment 8F was empty, with a rifle under the bed, technically illegal but not especially suspicious, given the circumstances. Rivera left a spider to guard it; they would deal with that on their way back.

As they progressed up the building, the calm interactions belied the ratcheting tension. Most likely, the Soldiers were driving any insurgents before them—and the occupants probably knew it. On the 14th floor, Smith texted this misgiving and spammed it to the squad. Rivera just said, "Yep." The sergeant never rebuked anyone for being Captain Obvious. The lieutenant cut in. "We've got six floors left, and intel says it's gonna get hot, so keep your minds on the op! I don't want to find out if a mule can carry an ass down 20 stories."

After clearing the nineteenth floor, they flew two "quads" out the windows. The roof was clear, so they dropped the cargo of four spiders, and set the empty quads to auto-surveillance.

As with all the other hallway doors, they opened the 20th floor with a standoff device. Unlike the other doors, this one exploded. "These guys want to do it the hard way," growled Rivera. Before the dust settled, they sent the quads in. The hallway was clear of booby-traps, and they sent in the mules and spiders. Three apartments were empty; the middle three had doors carefully sealed shut. "Get me a door-knocker," ordered the lieutenant. That was a telescoping pole for placing shaped charges. "Ready the mules for assault. Put Lucy and Ethel in front. I'm ordering them set to autoprotect." Smith inwardly whistled. Autoprotect would allow Lucy and Ethel to shoot any non-Soldier the AI determined was a threat, without waiting for further permission. It was a scary setting. The lieutenant would be held legally responsible for the AI's decisions. But the insurgents inside were clearly well armed. "Concurring with lieutenant's order for robot autoprotect," Smith yelled, loudly, so the insurgents could hear it through the door.

The end was swift. The door was breached; they lobbed stun grenades through. Lucy and Ethel ran inside and took out two insurgents shooting at them, who either hadn't understood "autoprotect" or didn't care about living. Fortunately the tasers were enough this time. Another 11 knelt in surrender. Some were mere children. Smith sighed with relief. Rivera nodded an amen. The lieutenant sent in the report: Operation complete. No casualties, on either side. Success.

3.4 Sniper in the City

Relying on a boost from an exoskeleton, SGT Rivera sprinted across the plaza at 30 mph. Sniper bullets whizzed past again as Rivera dove into the shelter of a mostly demolished apartment building. "You have arrived at your destination," intoned the helmet's nav unit calmly. Rivera was safe here, relatively speaking. There were no IEDs; the point robots had cleared it for use minutes before. But the place was still smoldering from an earlier artillery barrage—a reminder not to stay too long. The enemy had reduced much of the city's South Quarter to rubble. Rivera was proud of the US efforts to avoid such indiscriminate destruction.

Rivera snuck a peek toward the enemy. Three weaponized robotic mules (WRMs) from the squad that had taken point, checking for danger as they walked and climbed about, were 20 to 30 m away. Hewey, Dewey, and Lewey—as they'd been nicknamed—had automatically imitated the Soldiers' actions and taken cover. The squad's two other WRMs, Donald and Daisy, had cantered around the plaza, taking positions to cover the squad's flanks. Even though Rivera knew exactly where each WRM was, it was still hard to spot them due to their active camouflage. Fifty meters beyond Dewey was a hospital, clearly marked, easily the highest building remaining in the area. Sadly, the sniper was probably in there.

Rivera pulled up the tactical app on the HUD. SPC Smith, behind and across the plaza, had already confirmed the sniper's position. Smith's camera had noted a muzzle flash in a window and had sent a picture: third story from the top, sixth window from the left. Rivera sent orders. "Hooah," came the reply texts.

"Go!" signaled Rivera. The WRMs went into action first. Hewey and Lewey jumped out of cover and galloped toward the hospital, zig-zagging through debris like barrel-racing ponies. The sniper would be forced to respond to this threat. Once the WRMs got to the hospital, it was game over, because the legged mules could run up the stairs. Panicked shouts rang out from on high, followed by automatic gunfire. Bullets began to hail down on Hewey. There was more than one sniper; it was a trap!

But in less time than it took the humans to think that, Donald's and Daisy's audio sensors had triangulated on the gunshots behind them, without either turning its visual sensors from the flanks. These data, combined with Smith's camera footage and knowledge of each team member's location, fed into the targeting computers. There were six shooters, all shown in flashing red on Smith's and Rivera's HUDs. The US Soldiers' training kicked in. "Kill all bogies!" they ordered the WRMs.

The squad's firing solution seemed instantaneous. Dewey, already pre-positioned to attack, popped out of cover, and took out three shooters in rapid succession, while moving. Fifth floor balcony: #1 and #2, one round each. Eighth floor window: #3, one round. Smith's computer aimed carefully at #3, near the roof. It was a long shot. It took two entire seconds and two rounds. With the snipers distracted, Rivera stood and aimed in one fluid motion, taking out #5 and #6 with three-round bursts. Then it was over.

Rivera noticed Huey was down. "Oh, no." But the Team Health app assured Rivera that Huey only had a destroyed leg. It might be field-fixable. Relieved, Rivera quickly radioed the robotics specialist, who'd been guarding the rear with their two pack mule robots. "Johnson, get Ori and Nori up here with the spare parts. Time to earn your pay."

"Already on it," signaled Johnson, who had just transferred Ori and Nori to Smith's control. This being Day 4 of their mission, Johnson did not have all the parts anymore to fix Huey, but was busy making a swap with another squad's robotics tech. In a few minutes, a quadcopter was headed their way with an "organ donation" from an unsalvageable WRM. In return, Ori and Nori would fully recharge the quadcopter, and Johnson would send it back with the rest of their good-tasting MREs. Smith would gripe, but it had to be done. Mission first, and leave no Soldier, even a robotic one, behind.

4. Conclusion

A large gap remains between what the US Army needs robotic mules to be/do and the state of the art. Small wheeled vehicles acting as "mules" can provide a stopgap capability, but long term these will be limited by the terrains they can handle. Eventually, the US Army will need strong and efficient legged robotic mules. If such can be fielded, they will transform infantry warfare. We believe that the enabling technology for such legged robotic mules will be fuel-powered artificial muscles, such as those under development at ARL.

5. References

1. TRADOC. The US Army Functional Concept for Movement and Maneuver 2020-2040. Fort Eustis (VA): Training and Doctrine Command; 2017 Feb. https://adminpubs.tradoc.army.mil/pamphlets/TP525-3-6.pdf.

2. TRADOC. The US Army in Multi-Domain Operations, 2028. Fort Eustis (VA): Training and Doctrine Command; 2018 Dec 6. https://adminpubs.tradoc.army.mil/pamphlets/TP525-3-1.pdf.

3. Army research tackles tough terrain for Soldier-robot teams. Adelphi (MD): Public Affairs Office, CCDC Army Research Laboratory (US); 2019 Sep 11 [accessed 2020]. https://www.army.mil/article/226984/.

4. Tawfick S, Tang Y. Stronger artificial muscles, with a twist. Science. 2019 July 12:125–126.

5. Kanik M, Orguc S, Varnavides G, et al. Strain-programmable fiber-based artificial muscle. Science. 2019 July 12:145–150.

6. Mu J, Jung de Andrade M, Fang S, et al. Sheath-run artificial muscles. Science. 2019 July 12:150–155.

Appendix. Hydrogen Use in Robotic Mule with Fuel-Powered Artificial Muscle (FPAMs)

We begin by estimating the robotic mule's useful energy expenditure as approximately 1 horsepower for approximately 8 h/day. (So, ~16 h/day is nonwalking time.) That is [746 W × 8 h × 3600 s/h = 21.5 MJ] per day.

Hydrogen (H_2) ideally contains approximately 130 MJ/kg. If the robotic mule's FPAMs were 10% efficient running on H_2 (which would be about twice as good as any type of artificial muscle produced so far), then we would only get approximately 13 MJ/kg of useful energy.

So, we need roughly 1.6 kg of H_2 per day. That is 800 mole H_2/day (or 33 mole H_2/h).

A-1. Hydrogen Storage Example #1: H_2 from Aluminum Hydride (Alane) and then Aluminum Plus Water

The reactions are as follows:

- $2AlH_3$ + waste heat → $2Al + 3H_2$; then $2Al + 3H_2O$ → $Al_2O_3 + 3H_2$
- 30 g × 2 = 60 g of AlH_3 to make 6 moles of H_2; that is 60 g/6 mol=10g/mol. (MW AlH_3 = 30 g; MW H_2 = 2g.)

So aluminum hydride/alane (AlH_3) storage is 10 g AlH_3/mol H_2, or 2 g H_2/10 g AlH_3 = 20 wt%, which is amazing for H_2 storage. Note that aluminum oxide (Al_2O_3) is inert and safe to dispose anywhere, so the Al_2O_3 can be dumped as H_2 is produced.

The 1-hp robotic mule discussed previously would need (1.6 kg H_2) × (5 kg AlH_3/kg H_2) per day, which is 8 kg AlH_3/day. That would be an entirely reasonable weight of fuel to carry around, for normal missions of 5 days or less. Importantly, obtaining the H_2 from storage would be very simple, requiring no special hardware. (In contrast, releasing H_2 from hydrocarbons requires reformers, which reduce the useable weight percent, can be finicky, and only operate at high temperature so the efficiency is reduced and IR signature is increased.) Equally importantly, the reactions are fast, so the H_2 could be generated as needed. Also note that the reaction of aluminum (Al) with water does not require clean water, and in fact, works better with (fresh) urine. Assuming the accompanying infantry have access to potable water, the water needed by the robotic mule should not be a limiting factor.

A disadvantage of AlH_3 is that high H_2 pressures are needed to turn Al into AlH_3. This reduces its overall efficiency, making it a poor choice for a hydrogen economy. (In fact, it was abandoned by energy researchers for that reason.) However, this disadvantage (for economical civilian use) is not crucial to Army applications. Fuel efficiency at the rear base is not nearly as important as fuel efficiency and size, weight, and power during operations.

We note that US Army Combat Capabilities Development Command Army Research Laboratory researchers have already developed nanoparticle Al for H_2 production in the field. If only this were used, rather than AlH_3, the H_2 storage would be [20 /2 × 30/27 = 11] wt%, and the robotic mule would need [8 × 2 × 27/30 = 14] kg of Al per day. This is not particularly good H_2 storage. However, nanoparticle Al would allow for several-day missions, the reaction is fast and reliable, the technology is already available to the Army, and an upgrade later to AlH_3-based storage would be almost seamless.

A-2. Hydrogen Storage Example #2: H_2 from Starch and/or Cellulose

From Wikipedia article *Hydrogen Storage*[1]: "In May 2007 [researchers] announced a method of producing high-yield pure hydrogen from starch and water [plus a mixture of enzymes]. In 2009, they demonstrated … 12 moles of hydrogen per [mole of] glucose unit from cellulosic materials and water. Thanks to complete conversion and modest reaction conditions, they propose to use carbohydrate as a high energy density hydrogen carrier with a density of 14.8 wt%." That is a pretty good weight percent and would be sufficient for short missions. But the best thing about this technology is that additional fuel would usually be readily available in the field, making the supply of H_2 unlimited and the mission length unlimited.

Unfortunately, a critical problem with this technology is that, as of 2009, the researchers were only getting conversion rates of approximately 1 micromole (µmole) per hour per liter. Clearly, 1 µmole/h/L would require a ridiculously large volume. Even 1 mmole/h/L would require 33 kL, which is still ridiculous. Our volume needs to be closer to 33 L, so we need H_2 generation on the order of 1 mole/h/L. So this technology would need to be sped up by 6 orders of magnitude. That may not be an unachievable goal. The 2009 research was done entirely with nonoptimized, standard enzymes and at only 30 °C.

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[1]Wikipedia. Hydrogen storage. Wikimedia Foundation; 2020 Sep 19 [accessed 2020]. https://en.wikipedia.org/wiki/Hydrogen_storage.

List of Symbols, Abbreviations, and Acronyms

AFC-MM	US Army Functional Concept for Movement and Maneuver
Al	aluminum
AlH_3	aluminum hydride/alane
Al_2O_3	aluminum oxide
AI	artificial intelligence
ARL	Army Research Laboratory
CBRN	chemical, biological, radiological and nuclear
CCDC	US Army Combat Capabilities Development Command
DOD	Department of Defense
FC	fuel cell
FeVERAM	Fermented Vegetation Efficiently Running Artificial Muscle
FPAM	fuel-powered artificial muscle
H	hydrogen
HUD	heads-up display
ICE	internal combustion engine
IED	improvised explosive device
IR	infrared
MDO	Multi-Domain Operations
MRE	meal ready to eat
NGCV	Next Generation Combat Vehicle
OE	operational environment
TRADOC	Training and Doctrine Command
UAV	unmanned aerial vehicle
WRM	weaponized robotic mule
µmole	micromole

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