JANUARY 2015

20YY SERIES

Between Iron Man and Aqua Man

Exosuit Opportunities in Maritime Operations

By Andrew Herr and Lt. Scott Cheney-Peters

Center for a New American Security

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Cover Image

User demonstrates the ability to hold a heavy object using an exoskeleton designed for industrial applications.

(DAEWOO)

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EXECUTIVE SUMMARY

"We're building Iron Man. ... Not really. Maybe. It's classified."

PRESIDENT BARACK OBAMA, FEBRUARY 25, 2014[1]

By Andrew Herr and Lt. Scott Cheney-Peters

While the President jokingly made this remark at an event touting the promise of manufacturing innovation hubs, savvy observers noted that the U.S. government is in fact developing the technology popularized by *Iron Man* and other books and movies: *exosuits*. The government has also been open about this work, going so far as to post YouTube videos showing futuristic visions of exosuit-clad warriors.[2] Like almost all military exosuit efforts to date, these programs are intended to benefit the U.S. Army and special operations ground forces, but the potential military value of exosuits extends beyond the land environment, opportunities that analyses and programs have largely neglected to date. This paper focuses on one set of little-discussed applications – naval and maritime operations – and examines what is possible in the next five years.

The paper first provides a brief background, setting out definitions and a short history of exosuit development. It then looks at the current state of supporting technologies, demonstrating that unpowered exosuits can deliver immediate benefits and that powered exosuits that can provide major enhancements to human abilities are within reach in five years. The paper next outlines an array of maritime uses. It finds that damage control is the application with the greatest opportunity for capability enhancement and that use in deck operations and maintenance would provide major cost savings. Exosuits would also be valuable in humanitarian assistance/disaster response, construction, amphibious operations and medical care aboard small ships. Next follows an analysis of the value proposition compared with investing in robotics. It finds that exosuit-enabled humans have substantial advantages over remotely controlled robots, which are slow and do not give operators as much situational awareness, and that autonomy is not yet near the level of development required to handle the missions at which exosuits would excel.

We conclude by recommending that the Navy and seagoing elements of the other Services increase their investment, in time and funds, in exosuits for maritime operations. Yet while exosuits appear likely to offer benefits when compared to existing approaches, it is critical to deliver a cost-effective powered suit in a reasonable time frame. To ready exosuit technology for shipboard operational use while preventing cost and schedule creep, a Navy-led effort should:

- Identify prioritized missions, specific required capabilities, and a corresponding concrete list of technical specifications. These will facilitate focused research and informed choices about design trade-offs, as well as enabling effective cost-benefit analysis comparisons with non-exosuit solutions.
- Invest in the research required to optimize the design of exosuits to decrease power requirements so as to achieve two hours of energetic autonomy – the ability to operate powered, but untethered, such as on batteries.

Together with an intensive development program, these two steps will set the stage for a day in the next five years when exosuits take up a meaningful role in maritime operations.

I. EXOSUITS: A BRIEF BACKGROUND

So what exactly is an exosuit? For the purposes of this discussion, an exosuit is defined as a wearable technology that conforms to the human figure, enables relatively natural human movement and augments human abilities. It is composed of some combination of armor, mechanical systems, sensors, communications, interfaces, data displays, weapons, medical systems and power supplies. Exo*skeletons* are often a central feature of exosuits, bearing and transferring a load to the ground through a frame external to the user.[3]

As typically conceived, exosuits augment individuals' ability to carry out tasks: carrying heavier loads, moving faster and with improved dexterity, executing draining tasks with greater endurance and effectiveness, improving situational awareness and protecting the wearer from hazardous environments and enemy action. They can also enable new capabilities derived from integrated technologies, such as sensors and augmented reality. Design parameters, however, require trade-offs between the attributes a given exosuit can enhance.

This definition differentiates exosuits from robots and traditional vehicles. They are not robots because the human is present, allowing the user to leverage his or her senses and to provide on-site judgment, problem-solving and decision making, as well as to guide movement. They are not traditional vehicles because the user is not simply riding within a very different form-factor, but rather, the suit is roughly molded to the human body, maintaining aspects of human dexterity.

The idea that exosuits might serve practical military or emergency service applications is not new. The suits have long been a mainstay of science fiction, featured in books and movies since the early 20th century, while Robert Heinlein brought the concept to widespread prominence through his "powered armor" in 1959's *Starship Troopers*.[4]

Almost since that time, the U.S. military has been trying to bring the concept to the battlefield. By 1965, the U.S. Army and Navy were jointly trying to build what they termed a "powered exoskeleton." The program developed functional arm and leg components, but they were large, heavy, unwieldy and – indicative of one perennial challenge – required tethers to provide power. More recently, the U.S. Department of Defense has funded the development of a range of exosuits, bearing monikers such as HULC and XOS 2, and initiatives such as the Future Soldier program.[5]

Combat is not the only application of exosuits.

Throughout this history – and most of science fiction as well – developers have focused on ground-combat applications of the suits, enabling infantry or special operators in applications such as mobility, scouting and urban operations. Most current programs are no different. Warrior Web, a program run by the Defense Advanced Research Projects Agency (DARPA), is developing exosuit technology to increase mobility and decrease the likelihood of injuries for infantrymen.[6] The Tactical Assault Light Operator Suit (TALOS) program, the U.S. military's most forward-looking effort, is led by Special Operations Command and the Army's Research, Development and Engineering Command.[7] The project's goal is a suit that enables personnel to operate more effectively in the ground-combat environment; a promotional video shows an individual breaking down a door and withstanding a hail of AK-47 fire while staring down his adversaries.[8]

Combat is not the only application of exosuits. Maintenance is an emerging function the U.S. military is investigating. Even unpowered exoskeletons can help individuals hold moderately heavy tools

Ekso GT exoskeleton.
(EKSO BIONICS)

and perform jobs with repetitive motion faster and with less exertion. For example, Lockheed Martin's unpowered FORTIS exoskeleton enables an individual to use a tool weighing up to 36 pounds above his or her head as if it were nearly weightless. Beyond improving the speed of work by reducing fatigue and increasing endurance, U.S. military developers also expect that the suits will substantially decrease injuries – a benefit of interest well beyond military settings.[9]

In traditional industrial environments, exosuits could enable more dexterous operation than traditional tools, like forklifts. Panasonic is building a suit for industrial and emergency operations, echoing the one Sigourney Weaver donned in *Alien*, with a planned rollout in 2015.[10] Other companies, such as Ekso Bionics – with 91 units at hospitals in the United States and Europe – and ReWalk, are already selling exoskeletons commercially to medical providers as breakthrough tools for rehabilitation medicine, allowing recovering individuals to regain natural movement more quickly and complete some treatment at home.[11] These applications are already driving competition and innovation in the medical field, and to come full circle, Ekso Bionics has licensed its technology to Lockheed Martin for military applications and the HULC prototype.

II. THE STATE OF THE TECHNOLOGY

Developments in and around exosuit technology are moving the concept from science fiction toward deployable systems, although operational environments still pose important challenges. Relevant technologies are divided into two groups for the purpose of this paper: (1) those that are already demonstrated or likely achievable in the next five years and (2) future technologies with at least initial proofs of concept, but likely more than five years away. This paper focuses on near-term applications of exosuit technology, so the balance of the discussion explores the interplay between the first group and current challenges.

Militarily relevant exosuits already exist in two principal forms: higher-capability, powered versions and low-power or unpowered versions with limited but practical functionality. Adding power to an exosuit allows for motors and a variety of electronic systems, but at present, battery technology is insufficient to provide the energy required to operate freely – utilizing all of a suit's capabilities – for long periods. Raytheon's XOS 2 can operate for 20 to 30 minutes on a single battery charge, while Lockheed Martin reports that its HULC system has a five-hour battery life, but this is only when operating at the relatively slow speed of 2.5 mph on level terrain.[12]

In contrast, when tethered to a power supply, it's possible to extend total operating time and performance dramatically. Between the XOS 2 and HULC, this allows feats such as bursts of speed up to 10 mph; the ability to run, walk, kneel and even crawl; the strength to lift 200 pounds or more in awkward positions repetitively; and the ability to operate almost continuously. Interestingly, users are often able to control the suits effectively with a few hours or less of experience because they rely on human movement and human senses to guide them.[13]

Beyond batteries, there are other potential solutions to the power issue, such as using internal combustion engines and portable generator technology. Boston Dynamics is developing the Legged Squad Support System (LS3) robot for the U.S. Marine Corps with an engine that allows it to complete a 20-mile mission over a 24-hour period carrying 400 pounds of cargo. However, the engine is loud and causes substantial vibration. In addition, engines that spin cause gyroscopic resistance to motion, and the weight of the engine would affect the center of gravity of the suit. Altogether, these characteristics make present combustion engines unsuitable for attaching to a person's body through an exosuit in most environments.[14] Furthermore, LS3's performance characteristics are not necessarily sufficient for a unit relying on exosuits during high-intensity missions with the risk of being cut off or otherwise unable to return to a recharge or refuel point for more than a day.

While present power needs and power supplies do not allow for unconstrained operations, other areas of research may also decrease the challenge of power relative to extended missions. There is substantial work on efficient power plants for unmanned aerial systems, and existing powered exosuits have not been optimized to decrease power consumption, so focused efforts in this area may also provide important gains. Nonetheless, long mission times, uncertainty about availability of power or fuel and the implications of running out of either in a combat environment all underscore the power constraints that still exist for high-capability exoskeletons on the types of extended missions contemplated for ground-combat applications.

However, technology development is not the only path to enabling high-capability suits that can operate for extended periods. If, in contrast to the dismounted ground-combat environment, the operational environment allows for recharging or swapping of batteries, then this approach would allow for extended operations. The reliability of access to charging stations or replacement batteries and requirements for mission length will be key factors in the analysis, but different concepts of operations may enable users to circumvent the most challenging power requirements.

Exosuits can take advantage of advances in information display technology and human-machine interfaces to increase users' situational awareness.

On the other end of the spectrum, another option is simply to use no power or very little power. Companies have already demonstrated the value of unpowered suits. Two variants of Lockheed Martin's HULC, the Multi-Attachment Non-Tethered Industrial System (MANTIS) and the FORTIS, have stripped out the hydraulics to rely solely on the wearer for mobility. They leverage the passive exoskeleton system by transferring force to the ground, using counterweights to enable the wearer to hold heavy tools and supporting difficult body positions used in industrial and maintenance environments. A hybrid option is an exosuit with limited powered functionality. DARPA required the Warrior Web exosuit to draw less than 100 watts – much less than a microwave – enabling longer operational time, but restricting capabilities solely to assisted mobility. To maintain the low power level, Warrior Web stripped out the traditional exoskeleton, demonstrating the type of trade-off required to save energy and a different approach to augmenting human movement.[15]

Moving beyond power to other types of capability enhancements, exosuits can take advantage of advances in information display technology and human-machine interfaces to increase users' situational awareness. In the near term, exosuit heads-up displays are unlikely to use cameras to feed a display to the user, as opposed to the user viewing the world through his or her eyes. This is because even very responsive systems have a latency – the lag time between movement and an image's update – of 20 milliseconds or more that causes disorientation and sometimes nausea. Nonetheless, it is possible to overlie data on an individual's visual field, as demonstrated by Navy F/A-18 pilots' Joint Helmet Mounted Cueing System and commercial augmented reality systems, such as Google Glass.

Advances in related fields also offer the opportunity to customize suits to particular missions. Depending on design and mission requirements, exosuits could leverage small and low-power sensors and communications equipment developed for personal health monitoring and unmanned aerial systems to provide an internal view of the operator's mission, performance and health to commanders and doctors. Exosuits could also leverage personal protection technologies that provide improved individual survivability, such as the ceramic trauma plates used in Afghanistan and thermal protection suits, while negating the impact of their weight, a major drawback of most present protective equipment.

Looking beyond five years into the future, it may also be possible to outfit exosuits with a range of exotic technologies. DARPA's success using neural signals to control prosthetics demonstrates proof of concept, and liquid armor that solidifies only when impacted could ameliorate the loss of mobility that trauma plates cause.[16] According to a consultant working on the TALOS project, the program is seeking to integrate health monitoring technology and first-response medical treatment, such as automatic administration of a wound-sealing foam, which research funded by DARPA and others is bringing closer to fruition.[17]

Existing and near-term technology opens up the opportunity for a range of military applications when combined with well-thought-out concepts of operations.

Nonetheless, there are major developmental challenges to putting these futuristic technologies into service, and some are unnecessary. For example, while neural interfaces are powerful for paralyzed individuals, reading neural signals is very difficult, and losing track of the signal because of subtle sensor movement could be very dangerous, especially in operational conditions. Implants ameliorate this problem, but they open up the risk of infection and scar-tissue formation. In contrast, leveraging human movement and force feedback is natural to most humans and allows users to rely on their vestibular system to keep balance. As such, developmental timelines and potential drawbacks likely put this "further future" set of technologies out of reach for the next five years, but existing and near-term technologies already enable capable exosuits.

In summary, exosuit technology and related areas are moving forward, but there are remaining challenges; however, it is possible to circumvent many of these, such as power, by developing effective concepts of operations, as opposed to waiting for future technology development. Existing and near-term technology opens up the opportunity for a range of military applications when combined with well-thought-out concepts of operations. Using the first two sections as background, the balance of this paper examines use cases that would benefit naval and maritime operations and cost-benefit issues surrounding these applications of exosuit technology.

III. UNIQUE AND HIGH-VALUE MARITIME APPLICATIONS

Exosuits provide a mechanism for humans to perform more effectively in traditional environments and to operate in environments that would otherwise be too difficult. Of course, they are not the only technology that does this – tanks and ships allow humans speed, firepower and survivability that are well beyond what is available to dismounted infantry or swimmers. To identify and analyze where exosuits are particularly valuable, it is essential to distill their key characteristics. Exosuits are particularly suited to environments and tasks that benefit from all three of the following attributes:

- On-scene, human situational awareness
- Human dexterity and movement
- Beyond-human physical abilities

When situations only require two of the three, other technologies may be available. For example, when on-scene situational awareness and beyond-human physical attributes are required, but not human dexterity and movement, vehicles, forklifts or other systems may fit the bill. When beyond-human physical attributes and human movement may be required, but not on-scene situational awareness, as in highly predictable or controlled operations, remotely operated robotic systems may be sufficient.

We applied this rubric to military maritime missions and settings – which are relevant to the U.S. Navy, Coast Guard, the Marine Corps and Army sealift and vessels – and identified applications where exosuits present the potential for major improvements in effectiveness, as well as where they would provide evolutionary benefits combined with cost savings. Both are useful, as the business case for exosuit technology will benefit alike from a "killer app" (which may not involve combat at all) and the potential to generate cost savings. To maximize the value of this discussion for decision makers, we bound our analysis to cover areas (1) that are outside of the traditional ground-combat uses of the Army and special operations community and (2) for which the required technology appears possible to field within the next five years.

…damage control appears to be the highest-impact application for exosuits…

Damage Control

When examining the naval setting, damage control appears to be the highest-impact application for exosuits and one less encumbered by current technological hurdles. Rapid, effective reaction to damage can mean the difference between the survival and loss of a vessel, let alone its continued operational availability. The Oct. 12, 2000, al Qaeda attack on the USS *Cole* created a 40-by-60-foot hole at the ship's waterline and a mass of twisted steel, and the ship was almost lost.[18] In 2012, a blaze aboard the nuclear submarine USS *Miami,* during which "smoke was an impediment to locating the source of the fire," ultimately resulted in the Navy inactivating the vessel.[19]

In a damage control situation, the environmental protection, enhanced situational awareness and dexterity-strength combination promised by exosuits would better enable individuals to navigate confined "interrupted" environments, locate objectives, clear debris, carry the necessary equipment to quickly make repairs and endure some combination of heat, smoke, noxious chemicals and other hazards to save the ship. Tools, such as welding gear, might be integrated into the suits or available in damage control lockers for quick attachment. Lasers, inertial sensors and cameras can be integrated into a suit to enable wearers to better see through smoke-obscured environments and provide precise information about their own location without reliance on a network connection.[20] The specificity of this application highlights the importance of design choices for different missions and environments – in this case, less bulk to allow navigation of cramped spaces, integrated tools instead of weapons, and thermal protection from fire would all be especially valuable.

In the same vein, as shipboard environments differ between ship classes and vessel types, it may be preferable or necessary to tailor exosuits accordingly. For instance, exosuits aboard a submarine or those that are expected to operate in tight engineering spaces – a likely location of damage control efforts – would generally need to be more maneuverable and less cumbersome than those for use in less constrained quarters. Typically, the narrowest points of maneuver are a ship's watertight hatches and scuttles, so the main distinction might be between those operating inside the "skin" of a ship and those that remain in more open areas, such as topside, hangars, cargo bays and well decks.

Finding the threshold amounts of power and capability necessary to accomplish a mission will also require the development of concepts of operations and testing of equipment. For example, shoulder functionality requires especially large amounts of power and a complicated array of actuators to come close to human movement, so it will be important to ascertain the extent to which it is required in this application.

While posing some challenges, tailoring a design for damage control would also offer the opportunity to overcome one of the largest near-term technological hurdles to exosuits: power. There is a substantially greater likelihood of power availability on a friendly ship than there is in the middle of a hostile land-warfare environment. Furthermore, even if power is knocked out or it is impossible to run emergency power cables into the damaged section of a ship, extra batteries or other power sources could be stored in various locations on the ship, which is similar to how medical exosuits operate today. Exosuits could also be rotated and recharged as they run low on power, perhaps timed to the relief of individuals for exhaustion, although "hot-swapping" batteries – changing them while the suit is still powered-on and the user stays inside – is also technically feasible.

While damage control is a critical function aboard any ship, it is typically an infrequent activity. When not saving the ship, exosuits could benefit a range of other activities, improving the exosuits' total value.

Deck Operations

Ships are already mechanized to a large extent, from elevators to forklifts and even large cranes, depending on the class of ship. Nonetheless, the increased strength and dexterity of exosuits would likely enable faster, safer and less manpower-intensive deck operations. Flight decks and hangar bays are the scenes of some of the most dangerous and precise shipboard activity, such as loading sensitive missiles weighing hundreds of pounds into cramped internal bays that allow only a single person room to maneuver. These activities are difficult and time-consuming and cause a substantial number of injuries. Although there is already some protective equipment available, exosuits could make tasks easier and safer. Active or passive load-bearing could support an increase in the weight individuals can lift and carry, the precision of their movements and the amount of protection their gear provides, as well as additional benefits such as cooling or heating systems. In addition to acting as physical protection, suits could also mechanically or electrically maintain balance and warn the user before entry into dangerous areas on the flight deck.

Exosuits could also expedite port visits, particularly at underdeveloped ports, by accelerating line-handling, hooking up shore power cables and other ship-to-shore connections, on-loading and offloading stores and ammunition and especially by distributing those items to various departments throughout the ship by way of the cramped passageways where forklifts cannot tread. While these may seem like mundane tasks, they are also critical to the regular operations of a ship and absorb substantial time and effort. More importantly, the benefits from accelerating these functions would only increase during military operations, as getting ships back to the fight sooner is particularly valuable.

The exosuit design suggested by the damage control mission dovetails nicely into deck operations. Smaller size and a focus on dexterity would allow for nimble movement on deck and through corridors so as not to interfere with others' activities. Both damage control and deck operations would benefit from some degree of protection against hazardous environments, but neither requires armor, and deck operations could also leverage the battery swap-and-charge concept of operations described above, further allowing the suits to skirt the power challenges hampering models intended for ground combat.

Humanitarian Assistance / Disaster Response, Seabees and Amphibious Operations

The same versatility that would enable better damage control might also generate substantially better capabilities for humanitarian assistance/disaster response (HA/DR) missions. The U.S. Navy and Marine Corps are often the first responders for major catastrophes, and the overlapping requirements with damage control would allow for a relatively quick transition for operators and suits. If initial airlift, ship or port capacity is limited or degraded by the disaster, the value of having a versatile tool like a high-dexterity exosuit would be magnified because the range of specialized equipment normally used in such a situation would be unavailable.

Whether part of an HA/DR or combat operation, some of the Navy's first groups ashore are its Beachmaster Units, which "prepare the battlespace" by clearing obstacles before directing landings. Clearing a landing zone also presents a natural fit for exosuit operators, provided the suits are able to operate in sandy environments and the activity can be supported by extra battery packs rotated out from the ships. The same applications could benefit Navy Seabees (construction and engineering units). Of course, using exosuits ashore might pull them away from deck operations, as well as their power supplies, so it would be important to analyze the impact of their distribution between ship and shore and whether separate suits should be dedicated or tailored to expeditionary missions.

Maintenance

All military services face challenges maintaining their equipment. A prime difficulty for those operating in the maritime domain is the necessity of taking painted metal objects and using them in, on or above large bodies of saltwater. This results in a near-continuous fight against rust, in many cases requiring grinding to remove it, which is an arduous job performed by both shipyard workers and the ship's crew. The use of exoskeletons could greatly ease the burdens of this and many other taxing tasks requiring the use of heavy equipment for prolonged periods, especially overhead work.

In November 2012, the Navy tested prototypes of the unpowered MANTIS exoskeleton, combined with a spring-loaded, tool-holding device called the zeroG Arm, based on the Steadicam arm used by movie studios. Packaged together, the Navy terms this the Industrial Human Augmentation System (iHAS). The exosuit works by transferring whatever weight the arm holds to the ground, such as a tool weighing up to 50 pounds, and can do so effectively even when the user is moving over uneven terrain or up and down stairs. Initial results from two shipyards indicate "that human augmentation

FORTIS exoskeleton with the user holding a heavy grinding tool.
(LOCKHEED MARTIN)

enables improved productivity and product quality, while at the same time reducing worker strain and fatigue."[21] Providing powered exosuits would only increase the benefits seen in these trials.

Beyond enhancing endurance, exosuits can enable greater career longevity in naval maintenance. By dramatically reducing individuals' weight burden, especially in awkward positions, the suits can reduce the risk of injury and will even allow individuals with previous injuries to return to the job – a consideration especially pertinent to an aging shipyard workforce. Thus, in addition to immediate productivity and cost savings, exosuits used in maintenance can decrease many "hidden" costs, such as fatigue recovery time, injury compensation and the costs of training replacement workers.[22]

There are several design considerations that experience with the MANTIS and FORTIS highlights. For balance, they require the use of counterweights to prevent the load or tool from tipping the user over, and even then, if the tool gets more than approximately 18 inches away from the body, it will pull the person over. This highlights that gravity can still prevent certain maneuvers unless weight and balance are taken into account, although powered suits will also be able to mitigate this challenge, as they could prevent the arm from moving beyond a set limit, for example. And second, the suits highlight the potential benefits of modularity in several ways: in the ability to swap tools used with the zeroG Arm, the ability to detach the zeroG Arm and set it up in a space the full suit could not reach and the ability to augment the suit

"The Exosuit"
(AMERICAN MUSEUM OF NATURAL HISTORY)

with separately powered systems as required – such as with an augmented reality system, wireless communications or even something as simple as safety lights to indicate the wearer's presence in dark locations.

Medical Care

Highly dexterous suits combined with augmented reality might also enable substantially better medical care than is currently possible on small ships – which do not have onboard doctors – without a need for specialized surgical robots. Suits that could control their movement better than an untrained hand would allow corpsmen to provide the precise incisions and other actions necessary for surgery, either in cooperation with surgeons supporting remotely or by conducting surgeries based on guides overlaid on the patient through augmented reality. These systems might allow critical treatment in the "golden hour" – the first hour after injury, in which treatment often determines life or death – when it would otherwise be unavailable, thus making what at first glance might seem quite dangerous the only lifesaving emergency option.

If properly developed, this would provide much-improved emergency medical care on smaller ships, which now rely on evacuating seriously wounded personnel. Shipboard casualty evacuation operations are time-consuming, add delays before treatment and may be impractical during a mass casualty event or military operations, especially if U.S. forces are operating in contested environments. The helicopters that are normally used to evacuate the wounded are vulnerable to enemy action, and larger ships carrying out kinetic operations might not be able to receive casualties. While tele-operated medical robots could accomplish these missions in certain conditions, using exosuits already present for deck and damage control operations would obviate the need for additional, expensive, single-use systems, and exosuits could continue to operate when communications are limited, as might be the case during high-intensity operations or in a communications-denied environment. One challenge to this application is that there is often a trade-off between strength and speed on the one hand and precise dexterity on the other. Developers would have to examine how to best balance between these two needs when developing a suit.

Other Areas

While there would certainly be other naval applications that could benefit from exosuits – such as visit, board, search and seizure (VBSS) operations; force protection; and naval special warfare operations – these are much more similar to the ground-combat and special operations missions for which suits are currently proposed. They would also need substantially different design trade-offs than those favored by the important missions discussed above, with limited differentiation from ground-combat suits. Dive suits, in some ways a long-running example of exosuits, are another area of potential development. As exemplified by this year's testing of "The Exosuit," an atmospheric dive suit powered by thrusters, new prototypes have potential for special warfare use, but due to the major differences from the mission space this paper discusses, they are beyond the scope of this effort.[23] The use of exosuits for recuperative therapy or the mobility of injured sailors may also be an area of Department of Defense interest, but it is not a unique maritime opportunity or challenge.

IV. ASSESSING THE VALUE PROPOSITION

Why Not Robots?

Investment in the development of exosuit technology and concepts of operations needs to be weighed against devoting resources to the development of robotic systems, both remotely controlled and autonomous. The key factors in this analysis are the levels of readiness of the various technologies and the trade-offs between having a human present for situational awareness, decision making and skill application versus the limitations associated with human frailty and form.

Fully robotic systems are being developed for use in some of the cases described in the previous section. Most notably, DARPA recently held its *DARPA Robotics Challenge* to push forward and assess robots for use in disaster response, focusing on "executing complex tasks in dangerous, degraded, human-engineered environments." This program was partially spurred on by clear gaps in capabilities revealed by the Fukushima disaster.[24] While it has seen a range of successes, the limitations of even the advanced robots taking part in the DARPA event demonstrate the benefits of exosuits.

These robots rely on remote control because autonomous systems development is still at a relatively early stage, and unstructured, complex environments are particularly challenging. Although teams did successfully automate some tasks, they received descriptions of the tasks beforehand. Currently, autonomous perception and cognition are nowhere near as capable as a human. As Gill Pratt, the Program Manager in charge of the DARPA effort, noted about the robots, "Just because the body looks similar to a human being or an animal does not mean the brain of the robot is anywhere near as good."[25] Google's much-vaunted autonomous car has seen remarkable success, but it cannot even identify a stoplight unless it has precise maps in its system telling it where to look for one, let alone operate effectively.[26]

The use of remotely controlled systems tends to limit the situational awareness of the human directing the system and leads to slower operation. One observer described the DARPA competition as looking like "extremely slow tai chi."[27] Remote control also adds the requirement for reliable communications, which are a challenge on a ship and would only be exacerbated in a damage-control situation. Additionally, while network vulnerability will be of concern to both exosuit and robotic approaches, an exosuit-enabled human could be outfitted with the ability to physically sever any compromised connections and regain local control.

On the other hand, for activities such as firefighting and damage control, there are environments where humans cannot effectively operate. Robots are susceptible to some of the negative effects of fire, especially heat, but they are not as susceptible to the effects of smoke and toxic chemicals, which might be present in damage control and disaster response missions. However, it is worth noting that current damage control approaches rely on humans, demonstrating that technology exists that enables some human operation in many of these environments.

This mission-oriented protective posture (MOPP) gear – respirators, protective suits, gloves and the like – might also be less restrictive if integrated with an exosuit. For example, using the suit's power supply to cool the inside of the MOPP gear would enable longer periods of operation and better performance compared with today, when individuals get hot and tired very quickly. Thus, robots have an advantage over humans in operating in extreme environments, but there are some technological solutions that could mitigate this drawback to exosuit-enabled humans, and human dexterity, expertise and situational awareness appear to be major benefits that suggest exosuits would be the most effective option today and well into the near future.

While beyond the five-year scope of this analysis, looking much further into the future, ships may employ a complementary division of labor between exosuits and fully or semi-autonomous robots to achieve maximum effectiveness, for example by having humans in exosuits leading robotic teammates in on-scene damage control efforts. Exosuits might also eventually develop into "optionally manned" systems – able to operate in remote-control and autonomous modes, as well as with a human operator.

Cost-Effectiveness and Technical Requirements

While exosuits described in the applications discussed above appear likely to offer benefits compared to existing approaches, the question remains as to how to target a development program to deliver a cost-effective suit in a reasonable timeframe. It is hardly beneficial if exosuits prove a $100 million solution to a $1 million problem, especially if current equipment is already meeting basic needs. To achieve these dual goals, we see the development of one suit with versatility across the use cases described above as having the potential to offer substantial value.

To contain costs and develop this technology quickly, it will be critical to tailor this suit for maritime use. As we have described, effective operation on ships and especially in damaged areas will both require and allow for smaller suits. They do not need armor, which will keep the cost, weight and power needs down. Because a ship's crew can swap out battery packs, naval exosuits do not require the same degree of innovation in battery technology and power management that other suits would require. Maritime variants also will not need weapons systems and the associated sensors, further controlling costs. The Navy has already developed firefighting and other damage control sensors in hand-held forms, so designers can use these existing tools and integrate them into the suit if desired.

The unique needs and trade-offs of maritime exosuit applications argue for a Navy-owned development program, perhaps in collaboration with the U.S. Coast Guard.

Keeping costs down is especially important because suits will provide the greatest capability improvements only on rare occasions, such as during damage control efforts, while they will provide more modest benefits for everyday tasks. Yet even these benefits may provide a large return on investment, as people are expensive and injuries cause serious monetary and capability losses every year for the Department of Defense and other government agencies. Exosuits may allow for more efficient manning by enabling a broader range of individuals to perform any given task, such as individuals with less upper body strength but who are otherwise preferred candidates.

The unique needs and trade-offs of maritime exosuit applications argue for a Navy-owned development program, perhaps in collaboration with the U.S. Coast Guard. If the Navy tries to jointly develop a suit with the Army, it will likely be burdened with the cost of the requirements necessitated by operating in a land environment away from reliable power sources, almost certainly skewing the cost-benefit analysis against this promising technology for maritime applications. Beyond adding additional cost, bulking up the suit to meet ground-combat needs would also decrease its effectiveness in critical maritime missions because of space constraints.

This is not to say that maritime exosuits do not have additional costs and technical challenges associated with the unique operational environment. All operational environments have their extremes. The constant presence of seawater in the maritime environment is a major factor in the service life of equipment due to its corrosive nature and challenge to electrical systems. As such, naval exosuits would need special sealing, treatments and materials to ensure their durability, especially to operate in the damage control mission where water, fire, heat, smoke, gases and electricity all pose threats. The suits would also need a mechanism to release the wearer or stay afloat should they fall or be swept overboard, although a quick- or auto-release mechanism might in fact be a safety improvement for sailors compared to today, when those who fall overboard risk being dragged down by current equipment, even their boots.

Communications is another unique area. Although technology development is proceeding well for augmented reality and other situational awareness features – such as integrated communications with teammates or shipboard command-and-control locations – shipboard application will require specialized development to handle the complex electromagnetic environment onboard. Shipboard personal wireless, radio and cellular communications have difficulty penetrating the metal bulkheads and electromagnetic noise pollution aboard vessels. This is a challenge the U.S. Navy is attempting to tackle through a variety of efforts regardless of exosuit development, such as by installing Wi-Fi routers throughout the interior of vessels, but designers will need to take it into account when developing exosuits.[28]

In addition to tailoring suits to naval applications, it may eventually become worthwhile to subtly tailor ship design to improve exosuit effectiveness. Even if it could generate sufficient power, an exosuit that could lift 400 pounds would likely tip over without excessive counterweights or bracing. As such, it could be valuable to enable a suit to "clip in" to certain areas of the ship's structure to brace itself. Grounding straps and locations for those straps to fasten securely will also be necessary, especially in high-sea states. Additionally, passageways leading to priority or likely exosuit usage areas could be broadened to accommodate their movement. The question of the suits' storage may also recommend their usage to particular ship classes due to space restrictions or necessitate design changes. Of course, any major change to the design of ships is potentially disruptive and expensive, but depending on the capabilities first-generation exosuits bring, small changes may prove worthwhile in future ship designs.

V. CONCLUSION AND RECOMMENDATIONS

Future technology development and implementation are complicated by a range of issues: funding levels, the pace of technological development, the price of individual components and the prioritization of specific needs can all alter the cost-benefit calculus and attractiveness of options for tackling Navy, Coast Guard, Marine Corps and afloat Army requirements. Nonetheless, based on current technology development and missions, exosuits appear to be a valuable option to bolster the effectiveness and safety of maritime operations.

It is our assessment that the Navy and seagoing elements of the other Services should increase their attention to and investment in exosuits for maritime operations. While they should explore exosuits specifically tailored to their unique – and more limited – requirements, they should still connect with their counterparts in the Army, Special Operations Command and industry to leverage their research and development and to better understand costs and capabilities.

To push forward exosuit technology so it is ready to board ships in an operational role, the Navy should take two key steps:

- First, the Navy should develop a concrete list of technical specifications, especially size, strength, speed and special capabilities. Without this, it is nearly impossible to focus research effectively because, with changing targets, it is difficult to make informed choices about design trade-offs.
- Second, the Navy should invest in the research required to optimize the design of exosuits to decrease power requirements so as to achieve two hours of energetic autonomy – the ability to operate powered, but untethered, such as on batteries.

Taking these two steps will set the stage for the mission optimization necessary to provide high-functioning exosuits and should make it possible, with an intensive development program, to see a day in the next five years when exosuits take up a meaningful role in the operation of vessels.

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