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Defining Potential Market Growth of Innovative Applications for Military and Commercial Use in Soft Robotics

by Lillian S Olkkola, Vanessa M Townsend, and Claudia Quigley

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14. ABSTRACT Soft robotic technology, along with the advancements in its applications, has come a long way from its inception. By reviewing the fundamentals, potential market, and future of soft robotics, this research addresses clarity over the potential that some of these use cases have either separately or concurrently in military and commercial markets. Breaking down the potential applications given the current market provides an engineered prediction of how the industry will grow and how it will make a meaningful impact on robotic technology. Using the advantages and limitations named in this report can be used to advance the current methodology of soft robots, and can reduce the limitations in future research. This report discusses an overall review of soft robotics, as well as predictions for future applications that can be distributed for further research.						
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Contents

1. Introduction

The US Army Combat Capabilities Development Command Army Research Laboratory is actively developing soft robotics technology and would like to identify other military applications for this technology. These military applications could be medical, expeditionary, or logistical. Ideally, these applications would also fill a commercial need so they could potentially be dual-use applications. In identifying these applications, market research was performed to support material and performance parameters, manufacturing methods, and specific research gaps needed to make these applications a reality.

The emphasis on military and commercial applications keeps the Third Offset Strategy in line. This strategy seeks to outmaneuver advantages made by top adversaries primarily through technology that makes the industry able to innovate. Keeping the commercial markets technologically advanced will help with military advancements, which will deter any opposing powers.[1] Beyond the current capability of soft robotic systems, looking at the potential growth of the market and applications can be beneficial to the research conducted to advance these technologies.

2. What is Soft Robotics?

Soft robotics is a subset of robotics that focuses on the use of flexible and malleable materials, which draws from the way living organisms move and adapt to their surroundings. Most soft robotic systems have a set of key components that include actuators, sensors, and controllers. These include microcontrollers, power supplies, tethers, soft materials, and regulators within these three main categories. The easiest way to tell if a robot is a soft robot is whether or not it is resilient. Exploring the three key components of actuation, sensing, and control can unlock the potential growth in these areas that can lead to development and advancement in soft robotics.[2]

Sensors are used as windows from the robotic system into the environment. Sensors allow the physical measurement of geometric and physical properties. These may include velocity, force, position, distance, orientation, size, moment, weight, luminance, and so on. Sensors can be internal or external. Internal sensors tell information about the robot itself, while external sensors gather information about the surrounding environment.[3,4] The various properties used to describe a sensor's capabilities are sensitivity, linearity, accuracy, repeatability, response time, resolution, dynamic range, and bandwidth. There are common sensors used in robotic systems, which are now being manipulated into soft robotic systems (Table 1).

Table 1 Sensors used in robotic systems

Sensor type	Sensor name	Sensor application
Transducer	Light	Solar power, light resistance, power, camera operative systems
	Sound	Microphones, voice recognition
Proximity	Object detection	Collision avoidance, surrounding awareness
Tactile	Logistical	Obstacle avoidance, packaging processes
Temperature	Thermistor	Detect temperature changes as voltage output
Navigation	Accelerometer/rotation sensor	GPS

All of these sensors can be manipulated into soft robotic systems, either by changing the material composition of the sensor or its placement.[5] Soft robots have been limited due to their lack of good sensing capabilities, which is still a problem but researching material capabilities and manipulations of the sensor itself are bettering the industry as a whole.[6] If a robot cannot sense what is going on or what it is doing, then the system is not relevant to a purpose, which is why sensing research is so important.

Actuation is how the system moves and operates. There are many types of actuators, and each has its advantages and disadvantages depending on the application and system's purpose. Pneumatic artificial muscles (PAMs) or McKibben actuators are extensional devices operated by pressurized air filling a pneumatic bladder.[7] Fluidic elastomer actuators are actuators composed of low-durometer rubber and driven by relatively low-pressure fluid in the range of 3 to 8 psi.[8] There are also nontraditional methods of actuation for different uses. A good example of this is using rotating magnetic fields to guide ice-encapsulated origami soft robots to different stomach wounds.[9] Actuation in soft robotics is usually done through variable-length tendons or pneumatic actuation. Regardless of the actuation method, soft actuators are frequently arranged in a biologically inspired agonist–antagonist arrangement to allow bi-directional actuation.[3]

Soft robotics has a promising impact in a variety of fields. Specifically, control theory and control engineering with adaptive sensors, actuators, energy sources, and materials require new canonical plant models with complex spatiotemporal characteristics. Control has a large incentive on the production of soft robotics with the ability to tackle the challenges of control for high-degree-of-freedom dynamical systems.[10] Control modules are usually rigid, which is a limitation in soft systems due to their need for flexibility. Using inflation can allow a one-chambered robot to have multiple degrees of freedom with a rigid control panel.[11]

3. Material Composition

Robotic systems are considered soft robots mainly due to their material composition. The material composition can help a robot be classified as a soft robot, but a soft robot is not constrained by the typical Cartesian coordinate system and has numerous degrees of freedom. Unlike the control of rigid bodies, whose movements can be described by six degrees of freedom, the movements of soft bodies cannot be confined to planar motions. Soft materials are elastic and can bend, twist, stretch, compress, buckle, wrinkle, and so on. Such motion can be viewed as offering an infinite number of degrees of freedom—a fact that makes the control of soft robots very challenging. Controlling soft robots requires new approaches to modeling, control, dynamics, and high-level planning.[3] Material science is one of the key drivers in the soft robotics industry due to the capabilities of different materials. This includes the materials themselves as well as the different modeling software and ideologies used to plan the overall fabrication of a soft robot.[3,12]

In addition, having more advanced stretchable conductors would advance the soft robotics industry. Stretchable conductors are needed to make more sophisticated robots that are still entire soft-bodied systems.[13] In addition to the need for stretchable conductors, there is also a need for lighter-weight materials. This partially pertains to the electronics of soft robots as this would give more implementation of soft robots on a more nano-scale.[14] There is research that more soft robots can possess these qualities in the future by having self-regenerating or self-healing properties.[15] These properties are important for the future of soft robotics as they will allow dangerous and tedious tasks to be delegated away from Soldiers and can be fully automated, especially in times of war on the battlefield.[13]

4. Benefits and Limitations

Soft robotic systems have many benefits, but also some limitations. A benefit includes the capability to manipulate flexible materials. Some of these tasks include packaging fragile goods like eggs, fruits, and vegetables and being able to work alongside humans, unlike hard robots. The soft materials that "soft" robotics tend to center around opens up a plethora of new opportunities for robots to better integrate with human day-to-day activities.[16] This is what gives soft robotics an advantage and what most of the applications center around. Soft robots are also cheap to produce. Similar to the entire discipline of "hard" robotics, "soft" robotics has common characteristics, but depending on the use case and method of manufacturing this can vary greatly. With this in mind as a general commonality, the materials required for the makeup of the soft parts of a "soft" robot generally tend to be inexpensive.[17]

Cheap production comes at a cost, as these inexpensive materials generally are not developed with longevity in mind. So while the materials may not be costly to manufacture, they can be costly to maintain.[18] This can be deemed a potential limitation to the market applications to soft robotics as consumers do not want to constantly have to replace products. Though a consumer may have to replace parts, having soft and lightweight robots can be cheaper to produce, manufacture, and transport.[19] There will always be a trend toward innovation and adaptation both in the market and battlefield so in working with cheaper materials, and although complex in design, soft robotics has the potential to push robotics in a newer direction.[1]

Soft robotic system limitations include the inability of being precise due to pliable materials. Unlike "hard" robots, "soft" robots are not nearly as able to execute tasks with a similar precision or accuracy. The benefits of "soft" robotics are what inhibit its precision. The soft, flexible, and lightweight materials do not allow for easily planned or predictable movements. Along with this, tethers are necessary for larger applications. With the goal of soft robots being able to self-repair, and be flexible and lightweight, there is one thing that ties it down: the power source. The power source of a system that is not able to be on the body of the robot itself then leads to a tethered design for longer life capability and higher power output.[20] For more intricate applications that require an intensive amount of computing that the material's properties could not perform, having some sort of electrical or base station is necessary.

5. Applications

5.1 Military

Coming up with military applications for soft robotics is based on selecting tasks that are too redundant, too dangerous, and/or can enhance surveillance or troop performance. Something important to keep in mind is the overall goals for robotics in the US Army. One of the most prevalent strategies is the Robotics and Autonomous Systems (RAS) Strategy:[1]

The RAS Strategy established five priorities:

1) Increase situational awareness
2) Lighten Soldiers' physical and cognitive workloads
3) Sustain the force with increased distribution, throughput, and efficiency
4) Facilitate movement and maneuver
5) Protect the force

By developing a plethora of robots for the military, the Department of Defense has inadvertently caused an "Accidental Robot Evolution".[1] Brought on by the onset of wars in Afghanistan and Iraq, these robots were originally made for completing monotonous or dangerous tasks for our troops. Despite the still-large need and desire for these kinds of robots, there is a bigger trend toward ones that can work alongside humans to implement these tasks.[1] With this human–robot team trend there also comes a need for more information on the battlefield. This information acquisition is yet another task that can be taken away from troops and become almost fully automated. Soft robots can easily fulfill this need by their inherent environmental adaptability.[1] These same robots can also be used for search and rescue operations.

5.2 Medical

While the military use cases are more centered on removing the dangerous and monotonous aspects of service, applications that are deemed suitable for the commercial industry are based on human safety, enhancement, and demand.

End-of-life or beginning-of-life care is one of the few applications that could make a major impact on the future of medical care in the form of human enhancement; however, this vision is usually accompanied by a more humanoid-looking robot, similar to Baymax from Big Hero 6.[21] While the industry is seeing some humanoid robots today,[22,23] it is predicted that robots actually will not look like humans. This is due to the form factor of humans, which wastes a lot of energy to make simple movements that would otherwise be challenging or expends a lot of energy for a robot to be able to replicate. It makes more sense to take a task and then create a robot to be able to execute the task with as little energy expended and as efficiently as possible.[1]

While there is still a desire for humanoid robots, it is easy to foresee soft robots that are simple task-oriented robots. Non-humanoid task-oriented soft and hard robots already exist—like a robot assisting stair climbing in a wheelchair,[24] assisting with sit-to-stand motions,[25] assisting with walking,[26–28] and even small tasks such as putting on knit caps or hats,[29] all of which display an interest in end-of-life care in the robotics industry.

Similarly, there are even predictions that soft robotics will also make an appearance for beginning-of-life care as well. While there have been significant strides for how safe a soft robot can be working alongside humans,[30] there still is not enough research to truly be able to comment on the potential of end-of-life care robots being capable of beginning-of-life care.

5.3 Soft Machine Grippers

Soft machine gripper applications have the most longevity out of the rest of the soft robotic applications. However, most of the current manipulators are still in early research or struggling to get popularized in the commercial markets. Soft robotic manipulators are typically inspired by soft animals[31] or can take inspiration from the human hand,[32–34] octopi/squid,[3,31] and many other soft marine or land animals.[3,31]

Breaking it down further, soft manipulation can be defined into three different grasping categories: actuation, stiffness, and adhesion. Each has different object types/shapes they are best suited for, and most have a combination of the two methods.[35]

One of the primary challenges to making a soft manipulator is that there is no standardized software to project how the manipulator will interact with its desired pickup object.[3,32,34] While promising software solutions are out there, they either cannot predict micro-deformations of the system or have a limited amount of data overall of different materials.[32] Inability to properly predict the soft material's maneuverability is an overall problem of soft robotics;[3,32] however, this is particularly an issue for the control and sensor subsystem of the soft robotic manipulator application.[31,32] This is in part due to the issue of determining how rigid or soft the manipulator should be in addition to the number of degrees of freedom.[32] It is both a benefit of soft manipulators and also where its challenges show. The more degrees of freedom and softer the manipulator is, the less precision and ability to project the minute movements and load-bearing capabilities of the system.[3,33,35] Yet, it can handle more delicate materials due to less force being exerted on the object.[32,33,35] On the other hand, the more rigid the soft manipulator, the more force that can be exerted and more precision and ability to model and project the movements of the system.[32,33] Therefore, not only is it important to determine the desired application for the soft manipulator to determine how soft or rigid the manipulator should be, but to also determine the grasping method for each application.

Commercial Applications of Grippers

Speaking of applications, soft grippers have the opportunity to perpetuate the packaging and manufacturing industries in a way that has not been seen before. An example of this is quality control for the agricultural industry. Due to the delicate and pliable nature of soft manipulators, there is potential for a hand that could be used to determine whether or not foods are ripe enough to be packaged.[3,31–33,36] This can be similarly applied to automate the harvesting process too.[3,31–33,36] Another one of the primary reasons for the push of soft manipulators in the agricultural sector is that they can be made out of food-safe materials and easily sanitized to meet food-handling standards.[33,36] Lastly, soft grippers have a lot of versatility.[34] If a company changes its packaging or product the soft manipulator is handling, it is possible to reprogram the system to accommodate the new product.[36] There has even been a push toward biodegradable or even edible soft manipulators to further ensure food safety and to satiate environmental concerns.[33]

6. Dual-Use Applications for Military and Commercial Industries

The commercial market applications are important to explain, but the applications that are able to be dual-use are the ones that will continue to innovate and perpetuate soft robotics technology.

The medical industry is arguably the largest industry that will be impacted by these dual-use applications. Extremely niche problems can be addressed, like an ingestible stomach-wound patcher for when coin batteries or other hazardous-chemical-emitting substances[9] are accidentally swallowed or to magnetically control microbiological soft robots responsible for dispensing necessary chemicals internally with minimal invasiveness.[37] Both of these uses have the potential to address stomach issues or function as drug carriers for necessary internal medicinal treatments. Even so, the potential exists for more general first-aid administration that focuses on soft materials with atypical adhesion properties for "tissue regeneration and wound repair."[38] With its malleable, self-healing, and waterproof characteristics, hydrogel soft robotic first-aid technology could be extremely beneficial in an emergency or expeditionary situation for our troops.

7. Cyborg Industry

The soft robotic cyborg industry relates to the soft exoskeletons, muscle enhancement, and prosthetics currently in either the research or market stages. There are plenty of dual-use military and commercial applications that they could satiate.

In the case of the military, troops on expeditions or in the reserves doing repetitive tasks or carrying heavy gear (which could include ammunition, food/water, protective equipment, and any other necessary items) would be able to benefit from such a technology. There are already robots created specifically for more unstable environments, like the third generation of the Human Universal Load Carrier (HULC) exoskeleton.[39] Furthermore, the Berkeley Robotics & Human Engineering Laboratory (University of California Berkeley) has not neglected the commercial markets either with the creation of the eLEGs for those with mobility disorders and the prior generations of the HULC—the ExoHiker[40] and ExoClimber[41]—both aptly named for their target demographic. Another good example of a soft cyborg robot approaching the gap between research and becoming a commercially viable product, otherwise known as the "valley of death", would be XoSoft,[42] an exoskeleton that is more focused on the elderly and mobility disorders.[43]

There is plenty of research on and prototypes created for cyborgs. The current research for soft robotic cyborgs focuses on activities of daily living,[44–46] sensing and actuation innovation or issues relating to the implementation of soft cyborg robots,[47–53] and prototypes of soft cyborg robots[54–57] making a seamless transition toward robot–human interactions. What is needed for this application to flourish is either smaller integrations of human and soft robot interactions like ErgoTac,[58] or better simulation and modeling software. Testing soft cyborg robots, similar to soft manipulators, in a virtual environment would yield more statistics for reliability and manufacturability. However, unlike the soft manipulators, there is a greater need for soft robotic cyborg solutions for muscle optimization, elderly, or mobility disorders with a continually growing aging population. Research shows promising results in implementing software capable of properly forecasting robotic hand movements[59] as well as humanoid robot walking frameworks,[60,61] which could precipitate similar research and improvements for cyborg enhancements as a whole. It is important to stress the possible software development for modeling applications and designing soft robotic cyborg applications, as there is a good chance it would address the overall limitation of soft robotics being unreliable, which is important for the ability of soft robots working with or side by side with humans.

8. Market

The soft robotics' market is fairly new, since the industry just began increasing in the past 20 years. However, the soft robotic market was globally valued at $645.45 million in 2019 and is expected to reach $4.97 billion by 2025 at a compound annual growth rate of 40.5% over the forecast period (2020–2025).[1,62] Beyond the robotic market itself, robotic systems are only as capable as their computers. Artificial intelligence (AI) in robotics not only helps discover the model to perform certain tasks, but also makes machines more intelligent to act in several scenarios.[63] Currently, there is a $153 billion market for AI-enabled technology, with an estimated annual creative *disruption impact* of $14–33 trillion.[1] Since robotics has so many applications and industries, the market is usually broken up between industries. There are implications for the service robotics market size to double from 2021 to 2027.[64]

9. Soft Robotic Companies

Robotic companies that specialize in the innovation of soft robotics are impacting the market drastically. Most companies make soft grippers, which can vary in size, utility, and purpose. The most widely known soft robotics commercial company is Soft Robotics Inc. with 51–200 employees.[65] Even with the pandemic going on, they raised $10 million to meet pandemic food packaging demands caused by COVID-19.[66] Since the company's inception, its technology platform has experienced substantial customer validation and adoption with over 80% year-over-year revenue growth and production installations running 24/7 for Fortune 500 companies.[67] The company's technology is already installed in 30 facilities in Europe, North America, and Japan. Customers for the technology span across industries, such as e-commerce, advanced manufacturing, and food and beverage production.[67] As of FY 2019, Soft Robotics Inc has a revenue of $26.4 million, 75 employees, and its investors include FANUC Corp, Calibrate Ventures, and Material Impact.[67] mGrip and SuperPick are the two most commonly consumed products from Soft Robotics Inc. mGrip is an on-demand, soft robotic modular gripping system, and a SuperPick is designed specifically for e-commerce, grocery, retail, and logistics environments.[67] IAM Robotics is a competitor company to Soft Robotics Inc due to its focus on logistical problems and supply chain problems.[68] They were founded in 2012 and have 80 employees.[68] They have a product similar to the MGrip called I AM SWIFT, which has a soft robotics gripper that can also autonomously move about in addition to being able to pick up various-sized objects with its octopus biologically inspired vacuum gripper.[69] IAM Robotics has raised $21 million in venture capital funding.[70] Empire Robotics Inc used particle jamming as the primary gripping mechanism. It ultimately went out of business due to being unable to commercialize its own soft robotic gripper technology.[71] Despite its failure, they managed to raise substantial amounts of money for the startup—raising a total of $1.7 million—showing that there is still a desire to breach the valley of death.[72] Since there are not many current soft robotic consumer goods, it is difficult to make ample conjectures about the success of any future soft robotic goods. Having little to no media presence makes it difficult for the industry to make a meaningful impact. Big Hero 6[21] is an incredible depiction of soft robotics and the potential of the market, especially in the medical field; however, since it is a Disney animation movie, no one sees the reality of Baymax and the ideology in the movie.

10. The Future of Soft Robotics

After interviewing 16 industry professionals and researching their work, it is evident that the ability to develop future military and commercial applications is important for the prediction of the soft robotic industry's future. The goal of this research is to identify different use-case scenarios that will remove laborious or dangerous tasks from the troops.

Snake-like robots are a common research phenomenon for soft robotics. In an interview with military professional Brigadier General Peter Green, as well as PhD student John Garrett Williamson, snake-like robots were brought up as an ideal future application. Using the Stanford's Everting Tube Robot as an example, these robots can get into small and confined spaces like under doorways and around rocks.[73] They can be quiet, small, and squishy, which is important for search and rescue applications—especially in the military.[74,75] Being able to explore unknown spaces and not get stuck, flip over, and so on, is a potential benefit of the snake design.[76] These robots can also be used for more than search and rescue, such as cave exploration.[18,77] Snake-like robots can clean a skyscraper's windows, which is typically a laborious task. This specific idea came from interviewing Harvard fabrication specialist Christopher Hansen. The current methodology to clean a skyscraper's windows is very archaic; the cleaners have to go up on different lifting mechanisms and manually clean the windows themselves with safety tools, climbing tools, and cleaning supplies.[78] If soft-snake robots could be the "human" doing the dangerous task of being lifted hundreds of feet in the air cleaning windows, it could help mediate dangerous and laborious job risks.

There is a high demand for soft robots in the construction industry as they would significantly speed the timeframe to complete a job that would otherwise take much longer to do. Finishing a job more safely and timely can also help with the satisfaction of workers. This idea could be taken from the same arm idea used for the badminton robot with the potential control of a soft robot.[79] Soft robotics will be extremely beneficial to use on construction sites, as construction is one of the more predominant environments where humans work extremely closely with machines. There are roughly 150,000 construction-site-accident injuries each year according to the Bureau of Labor Statistics.[80] Installing drywall is just as laborious as cleaning a skyscraper's windows and could benefit from the integration of soft robotics. In interviews with Drs Michael Keller and Joshua Schultz of the University of Tulsa, the idea of installing drywall became apparent as a necessary advantage soft robotics could bring to the construction industry. The soft robotic system is capable of installing drywall as the task requires the installer to have both a degree of delicacy and precision.

Overall, soft robotics has too many denominations of impact to name in this report. Beyond what was mentioned previously, there are limitless possibilities for soft robots and surrounding industries. One notable impact for the industry would be more efficient 3-D printing for soft robots.[32,81] The 3-D printing market will grow with the acknowledgment of advancements in soft robots. The future is undetermined, but there are promising predictions for the capabilities of these systems.

11. Conclusion

The discussion of soft robotics, and the industry's potential, is a discussion for materials and robotics experts. This research is a review of information published, interviews conducted, and authentic ideas contributed by X-Force Fellows from the National Security Innovation Network. Defining gaps in the soft robotics industry can show the potential for market growth and applications in different industries. More research and testing needs to be conducted on potential applications to fully comprehend the abilities soft robotics can bring to both the military and commercial industries. Using marketing predictions and application ideas can narrow down the testing and manufacturing needed to deliver a prototype of these futuristic soft robotic systems.

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List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
AI	artificial intelligence
FY	fiscal year
GPS	Global Positioning System
HULC	Human Universal Load Carrier
PAMs	pneumatic artificial muscles
RAS	Robotics and Autonomous Systems

1 DEFENSE TECHNICAL
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DTIC OCA

1 DEVCOM ARL
(PDF) FCDD RLD DCI
TECH LIB

1 DEVCOM ARL
(PDF) FCDD RLD FR
C QUIGLEY

2 NATIONAL SECURITY INNOVATION NETWORK
(PDF) X-FORCE FELLOWS
LS OLKKOLA
VM TOWNSEND