Soft Robotics in Radiation Environments for Safeguard Applications

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Abstract

Oregon State University's School of Nuclear Science and Engineering (NSE) is partnering with our Robotics Program to investigate the suitability of soft robotics for nuclear safeguard applications. Robotics are particularly valuable for use in high radiation environments, access to areas not suitable for humans, redundant tasks, and areas that are difficult to reach. The soft robotics manipulators under investigation offer significant dexterity and mechanical compliance with high degrees-of-freedom, allowing for large contact-area, multi-point gripping, which is particularly advantageous for grasping and emplacing objects. OSU Robotics is focusing on designing a soft robotic arm that can operate under water with integrated touch and deformation sensors to enable closed-loop control of grasping and turning. Control software is also being developed to allow for remote operation of the system. The design goals for the robotic platform include the ability to grasp and turn knobs smaller than 20 cm with torques above 1 Nm, and to capture an image with an embedded optical sensor. Concurrent with the design of the soft robotic manipulator, the School of Nuclear Science and Engineering is examining the effects of high radiation environments on the system components, including impacts to system function, potential activation of the effector, material degradation with exposure to various radiation fields, and the potential for material reuse. Ultimately the research demonstration will provide a range of capabilities for deployment of this concept into areas that may benefit the IAEA and increase the efficiency or efficacy of safeguards measures.

Introduction

The nuclear industry has an established history of utilizing robotics in harsh environments. Robots have played an integral role as far back as atmospheric nuclear weapons testing and the cleanup of Three Mile Island [1] to access and perform sampling to characterize areas of high radiological hazard. More recently, robotic deployment following Fukushima has reinvigorated public interest as the press emphasizes 'dying' robots failing the cleanup effort, with headlines such as "Dying robots and failing hope" [2] and "Fukushima's Ground Zero – no place for man or robot" [3].

However, robots have demonstrated significant value in the U.S. DOE's cleanup efforts, particularly in handling legacy waste generated as a byproduct of the weapons program. Savannah River National Laboratory (SRNL) has led the effort in the DOE complex to design, fabricate, and deploy application-specific robotics for inspection and cleanup, including pipe and tank crawlers to enter areas inaccessible to humans. [4]

The DOE Environmental Management (DOE-EM) is continuing to invest in robotic system development, and consider robots essential to the safe and effective cleanup effort that is central to the DOE-EM mission. The theme of the upcoming 2018 Waste Management Symposia conference, *Nuclear and Industrial Robotics, Remote Systems and Other Emerging Technologies*, is indicative of the sustained need to reduce occupational exposure, and reduce risks associated with working in hazardous environments.

Many of the same concerns exist in field of nuclear safeguards. Inspectors often perform repetitive tasks in radiation environments in which robots could reduce risk or improve efficiency. Oregon State's School of Nuclear Science and Engineering (NSE) is partnering with the Robotics program to investigate new and novel materials for potential robotic applications in nuclear safeguards.

Potential Robotics Applications in Nuclear Safeguards

Harsh occupational environments and repetitive tasks are known to be a domain in which robots can enhance safety, and improve task efficiency and efficacy. The application of existing off the shelf robotics can be of value, as evidenced by the 2017 IAEA Robotics Challenge that is actively seeking solutions to "improve working conditions of the inspectors" and to "enhance the consistency of the IAEA measurements" [5]. Additionally, advanced soft robotics can further enhance characterization, inspection, and environmental sampling efforts in nuclear facilities that are inaccessible to workers, and which may potentially be under water.

The OSU Robotics team is addressing these real-world challenges by exploring the use of soft robotic manipulation, which utilizes novel soft materials that are dexterous and potentially well-suited for harsh radiological environments. Current robotic manipulators, even in a zero to low-dose area, are limited in dexterity due to the rigidity of materials and challenging operation. In contrast, the dexterity and mechanical compliance of high degree-of-freedom soft manipulators allows for large contact-area and multi-point gripping. This can be particularly advantageous for grasping objects delicately that may be slippery if attempting an underwater manipulation task. Soft materials also provide additional safety when operating around humans due to the passive mechanical compliance of the materials. For these reasons, OSU Robotics is currently examining new actuator morphologies, alternative fabrications techniques, and the use of novel integrated liquid metal sensors for use in nuclear environments.

While soft robotics can offer these advantages as well as new application spaces, there remain significant challenges in the motion planning of soft grippers. To address this challenge, the team is also developing a planning and control interface that is intuitive to learn, and could be used by site inspectors with little training. To simplify the control requires the integration of touch and deformation sensors into the soft gripper for managing grasps. This tight integration of sensors into the planning and control of soft grippers is a relatively new area of research.

The Current State of Soft Robotics Technologies

Soft robotics researchers propose building intelligent machines out of purely stretchable compressible soft materials [6]. As a field there have been several contributions already to the design of pre-programmed behavior in soft rubber-fiber composites [7], and there have been demonstrations of soft robotic devices as tools for novel sensing systems [8]. Soft robots require soft actuators, which in turn require appropriate material and power system development. The most popular mode of actuation in terrestrial soft robots is the use of pneumatic artificial muscles (PAM) [9] such as McKibben actuators [10] which contract with force and displacement characteristics similar to biological muscle. Patterning elastomer and inextensible fabric, it is possible to mechanically pre-program soft pneumatic actuators to bend, curl, twist, and extend [11, 12]. Figure 1 shows the time-evolution of a pneumatically actuated section of soft robotic material as it bends.

Figure 1: Time-evolution of bending behavior in section of a soft robot.

Unfortunately, pneumatic actuation is, by its nature, dependent on pressure differentials which are challenging under water. Hydraulic actuation is much less common in soft robotics, partially due to the challenge of high-speed valving and partially due to poor transmission efficiency. Tendon drive using servos [13] or shape memory alloy (SMA) [14] can provide muscle-like tensioning, but fabrication and biomimetic morphologies are especially challenging due to the requirement of manually weaving tendons into the robot limbs. Electroactive polymer actuators (EAPs) [15] such as dielectric elastomer actuators (DEAs) and ionic polymer metal composites (IPMCs) are conceptually exciting due to the possibility of purely soft actuation, but their power density is too low to use them directly as primary grasping and locomotion actuators in soft robots. In surveying options for soft actuation, it is clear that using commercially available hydraulic pumps will provide the highest performance mechanical heart of an underwater soft robot, but only as long as the power of the pump is appropriately transmitted to the numerous fluidic chambers within the soft robot.

Challenges for Soft Robotics Controls

The primary advantage of using robots in radiated environments is the potential to complete tasks without exposing a human to harm. In this particular application, their use can reduce or potentially eliminate the amount of time a human is exposed to radiation. In order for these robots to be useful, they must be able to perform the required tasks without the immediate presence of a human operator. This creates the requirement for an appropriate control system - either the robot must be able to perform the task on its own with no input from a human operator (full autonomy), the robot must be manually controlled over a wireless link by a human operator (full teleoperation), or some combination of the two must be used.

Each of these control strategies bring their own benefits and challenges. If the robot needs to be fully autonomous - capable of performing its tasks with no human intervention - there is a significant increase in the computational complexity of the system. The robot must have sufficient sensing capability to fully understand the world around it. In addition, the control software would have to be programmed to complete every task and react to every environment and possible error, and still be able to successfully complete its task. While not impossible, this is a fairly significant challenge which would require much time and effort for design, programming and testing.

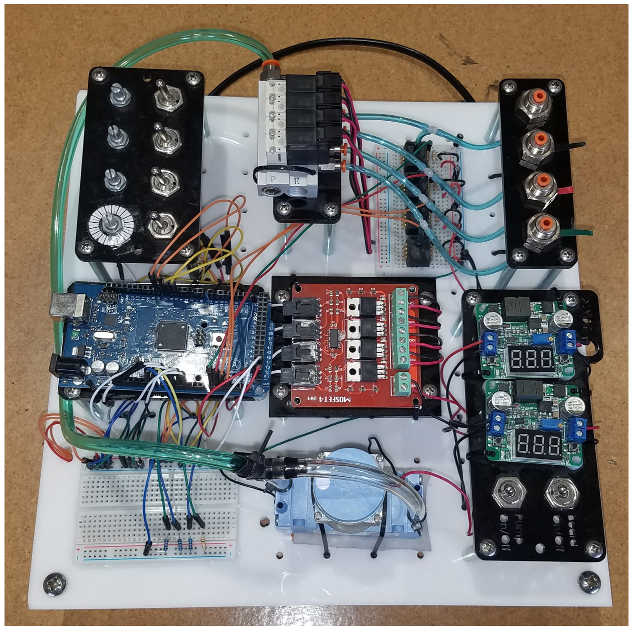

Figure 2: Manual control board for 2-axis soft robotic actuator

On the other end of the spectrum, a control system could be created in which a human operator teleoperates (remotely controls) the robot. They would have full manual control over each aspect of the robot. This control input would likely be sent over a wireless link from an operator in a safe location or 'control center' to the robot inside of the radiated environment. While this greatly simplifies the computation and processing required on the robot, it would likely be very difficult for a human operator. It would be necessary for the operator to undergo thorough training on use of the system, and would be difficult to transfer this knowledge to a new system or operator. A control board for a 2-axis (4 chamber) actuator can be seen in Figure 2. As the number of axes increases, this board would significantly increase in complexity. A continuous-curvature soft robotic actuator could have as many as 10 degrees of freedom (individual axes of rotation, bending, or elongation). With full manual teleoperation, a human operator would have to control each of these individually. If the goal required moving the end of the soft manipulator to a particular location, grasping an object such as a knob or valve, and then rotating it, it would likely be impossible for a human to figure out a plan and execute it correctly to control each of the 10 degrees of freedom.

It is on the continuum between these two extremes where a robot would provide the most benefit in a radiated environment. The goal is to create a system where a human operator can be trained to operate in a short period of time (1-2 hours), using a set of controls with which they are already familiar and/or are easy to use. The operator would perform high-level control actions, such as directing the position of the end-effector of a soft manipulator. These commands would be wirelessly transmitted to the robot, where the on-board control system would generate the low-level control actions for each of the 10 individual segments. Currently, we have demonstrated the control of a 4-chamber pneumatically actuated soft manipulator using an Xbox controller to direct the end-position of the manipulator.

Moving forward, we will utilize machine learning and other control methodologies to generate motion libraries capable of translating high level control inputs from a joystick or game controller into low-level commands capable of correctly positioning and manipulating a many-degree-of-freedom soft actuator. There are several methods for accomplishing this. One potential method would be to use real-time positional feedback from a vision system, as demonstrated by Katzschmann, Marchese, and Rus [16]. Another promising direction would be an extension of the work done with deformable objects by Lee et. al [17]. They demonstrated a method which combines geometric warping with statistical learning to generate control strategies from multiple human-controlled demonstrations.

Materials Characterization for Soft Robotics in Radiation Environments

To evaluate the potential effects of radiation on the soft robotic system, one must consider the components of that system. The actuator body of the soft robotic system is typically comprised of silicone polymers such as polydimethylsiloxane (PDMS) [see Figure 3], which can be fabricated by use of a mold or 3D-printed [see Figure 4]. Often, microchannels in the actuator arm contain liquid metals like Galinstan or EGain as a sensing and feedback mechanism. It is therefore important to understand the radiation effects on these components as an indication of the system level impact of radiation on the soft-robotic manipulator.

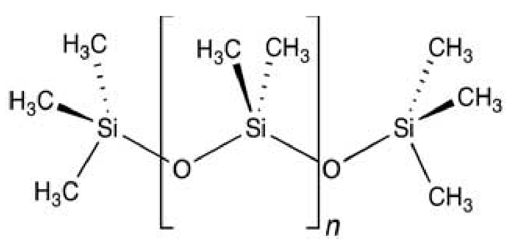

Figure 3: Chemical structure of silicone polydimethylsiloxane (PDMS)

PDMS is typically cured by an organometallic crosslinking reaction. If the ratio of curing agent-to-base is increased, a harder, more cross-linked elastomer results. By controlling the degree of this crosslinking, it is possible to customize properties such as the elastic modulus and/or tensile strength for soft actuation. However, radiation exposure is also known to alter the crossliking through secondary reactions of free radicals. These reactions include abstractions, double bond additions, decomposition, and chain scission/crosslinking of molecules. The reactions result in different molecular effects: chain crosslinking can cause embrittlement and an increase in molecular weight, chain scission can cause degradation and a decrease in molecular weight, and small

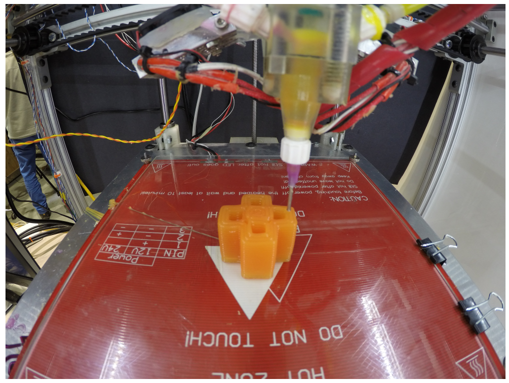

Figure 4: 3D printing a sample of soft robotic material.

molecule products can create trapped free radicals. The impact of these effects can then be assessed by measuring the properties such as embrittlement, durability, changes in molecular weight, and production of gaseous products [18].

Some of the earliest investigations of the effect of gamma radiation on PDMS were performed by Charlesby [19] and Miller [20]. It was determined that the degree of crosslinking induced by radiation is a function of dose and demonstrates a direct-response relationship. Charlesby calculated a 32 eV energy absorption requirement per crosslink and Miller calculated a crosslinking yield of 3.0% for irradiation by electrons. Notably, though, both studies were performed on a liquid form of PDMS with lower repeating unit number than seen in the solid considered in soft robotic applications. For solid polysiloxanes, an overview of the affected mechanical properties is provided in Tables 1 and 2.

Dose (Mrep)	Shore	Tensile (psi)	% Elongation
25	53	916	158
5	27	1180	750
1.25	18	135	550

Table 1: Effect of gamma radiation on silicone rubber [21]. [The rep was a unit of absorbed dose commonly used until the 1960s. 1 rep = 9.3 mGray.]

Dose (Mrep)	Shore	Tensile (psi)	% Elongation
2	15	153	780
6	26	742	605
10	29	876	580
20	43	679	250
40	52	561	117

Table 2: Effect of e-beam radiation on silicone rubber [21]

An example of the increase in "hardness" for various formulations of silicone as a function of dose is provided in Figure 5. Here, Basfar [22] quantified the Shore-A hardness of three different mixtures of cured silicone rubber, including 0.5/10 (Si-1), 0.25/10 (Si-2) and 1/10 (SiC) parts of curing agent/parts of silicone rubber. For reference, Figure 6 illustrates the Shore A hardness levels of flexible rubbers that can range from very soft to semi-rigid plastics [23].

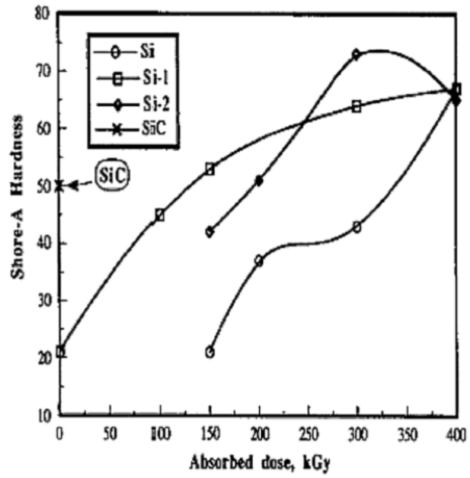

Figure 5: Shore A hardness measurements vs. dose for formulations of silicone rubber. [22]

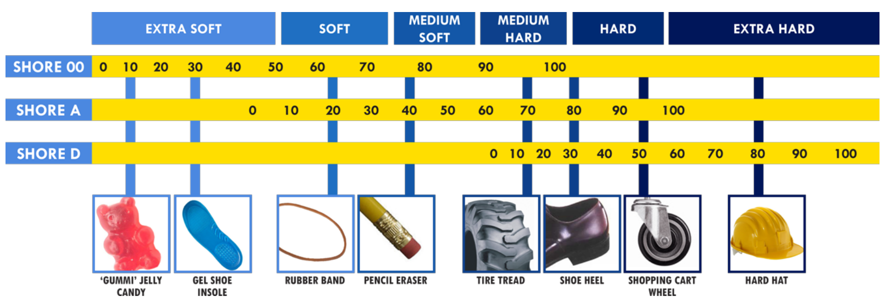

Figure 6: Shore hardness scales [23]

While direct high dose irradiation is known to alter the silicone properties, the extent to which low dose rate environments may impact the soft robotics is unclear. A more recent review [24] suggests that while crosslinking dominates the observed interactions following irradiation of PDMS, because scission and other bond breakage also occurs, the effects may compensate for each other and result in a negligible net response. Additionally little is known regarding the effects of neutron flux on either the soft silicone or liquid metal components. Therefore, the School of NSE and Robotics is evaluating the bulk effects of radiation on the soft robotic system. The initial step is to first observe the net, physical effects of various radiation conditions (including neutrons) on PDMS following chemical curing conditions that will be used for the soft robotic system. Figure 7 shows the OSU Robotics system used to measure the elastic modulus of a sample of PDMS. A potential extension of the assessment could include a molecular-level evaluation by quantifying changes in molecular weight (indicative of scission or crosslinking) and the production of small molecular products.

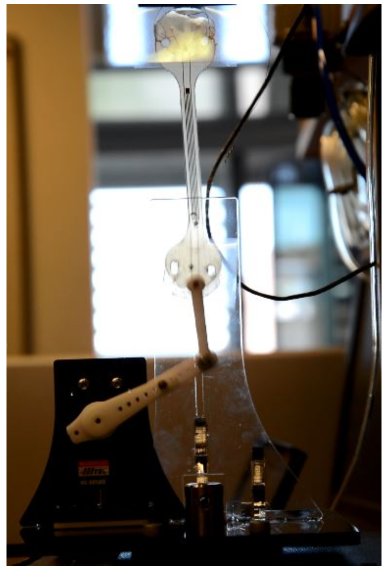

Figure 7: Measuring elastic properties of PDMS soft robotic material.

Conclusions

A promising modern soft-robotic technology is being evaluated for possible safeguard applications. The OSU School of NSE and Robotics Program is teaming with national lab partners to seek novel solutions by exploring safeguard tasks that are suitable for soft robotic technology. To do so, three areas of soft robotic development are being addressed, including fabrication of silicone materials for soft actuation in air and underwater, easy-to-use remote robotic control systems, and quantifying the radiation effects on the soft robotic components. The soft robotics manipulators under investigation offer significant dexterity, which is particularly advantageous for grasping and emplacing objects in hard to reach places, and can be deployed under water.

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