The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center ASEE
Portland, OR . June 23 - 26, 2024
Paper ID #43558

BYOE: McKibben Creature - A Low-Cost Robotic Simulation of A Biological Environment

Joseph Richard Midiri, Rowan University
Kathy Trieu, Rowan University

Kathy Trieu is an Undergraduate Mechanical Engineering student at Rowan University.

Wei Xue, Rowan University

Dr. Wei Xue is currently an associate professor in the Department of Mechanical Engineering at Rowan University. He received his B.S. and M.S. degrees in electrical engineering from Shandong University, China, and his Ph.D. degree in mechanical engineering from the University of Minnesota, Twin Cities. His research focuses on functional materials, soft robotics, and engineering education.

Dr. Mitja Trkov, Rowan University

Dr. Mitja Trkov is an assistant professor in the Department of Mechanical Engineering at Rowan University, NJ. His research interests include soft robotics, human-machine interactions, wearable system, ergonomics, and biomechanics. He received his Ph.D. degree in Mechanical and Aerospace Engineering from Rutgers University, New Brunswick in 2016 and his B.S. degree in Mechanical Engineering from the University of Ljubljana, Slovenia in 2007. Before joining Rowan, he was a postdoctoral fellow in the Department of Mechanical Engineering at the University of Utah in Salt Lake City, UT.

Dr. Cassandra Sue Ellen Jamison, Rowan University

Cassandra (Cassie) Jamison is an Assistant Professor in the Experiential Engineering Education Department at Rowan University (Glassboro, NJ). Her research interests focus on understanding and improving the learning that occurs in experiential, out-of-class activities for engineering students. Cassie previously received a B.A. in Engineering Sciences at Wartburg College (Waverly, IA) and her M.S. and Ph.D. degrees in BME from the University of Michigan (Ann Arbor, MI).

Dr. Smitesh Bakrania, Rowan University

Dr. Smitesh Bakrania is an associate professor in Mechanical Engineering at Rowan University. He received his Ph.D. from University of Michigan in 2008 and his B.S. from Union College in 2003. His research interests include combustion synthesis of nanoparticles and combustion catalysis using nanoparticles. He is also involved in developing educational apps for instructional and research purposes.

BYOE: McKibben Creature - A Low-Cost Robotic Simulation of A Biological Environment

Abstract

Developed by undergraduate mechanical engineering students, this BYOE paper presents a simple to construct, low-cost robot entirely actuated through the use of McKibben muscles. McKibben muscles are a type of pneumatic actuator commonly used in soft robot designs. As soft robotic designs and applications continue to grow in industry settings, this activity seeks to introduce students to soft robotics concepts early in their academic careers. With the primary construction materials being from readily available components and craft supplies, the project can easily be implemented in both college and high school learning environments with limited resources. The completed robot design involves three main functional challenges; maneuverability, ability to pick up small objects, and storage of the objects. Students' robots will then compete in a simulated biological environment, with small objects that can be placed at differing heights to vary the task difficulty and represent food sources at multiple elevations. Each team of students would be tasked to strategically design their robot to optimize performance in a competition for points. To optimize their robots, teams would have to make changes to their designs to specialize in different 'environmental niches' in order to outcompete others. As desired, the instructor can introduce several other gameplay mechanics that would increase the complexity of the students' design task and emulate other elements of the food web. This project can incorporate several key learning objectives, including implementing parametric design phases, enhancing an entrepreneurial mindset, optimizing product design, and applying knowledge of balancing forces to create motion. In this paper, the curricular context and classroom activity are thoroughly explained, as well as logistical aspects of implementation such as requirements, game ruleset, and set up environment. Additionally, the students who designed this project also developed a prototype McKibben Creature that adhered to the project scope. General manufacturing and design methodologies for that robot are provided.

Introduction

Soft robotics specialize in the use of flexible compliant materials to produce actuation as opposed to commonly used rigid links [1]. The use of these soft systems are particularly advantageous in prosthetics and surgical machinery but have the potential to evolve in a wide variety of fields [2]. The McKibben Creature project strives to introduce and familiarize students to soft robotic concepts, specifically pneumatic actuation. The goal is to expose students to this new growing field of engineering early in their academic careers to hopefully inspire a new generation of innovators.

The motivation behind this project is to teach important STEM-related skills to students in an engaging way. Using soft robotics specifically can offer a unique approach to learning as it encourages students to problem solve using a creative, adaptable, and entrepreneurial mindset. The project is also designed to integrate healthy competition among students which further encourages student involvement. Moreover, exposing students to soft robotics can provide a new perspective of problem-solving for the next generation of engineers.

The entirety of this module was developed as part of a design project completed by junior and senior mechanical engineering students which gives strengths to the feasibility of implementation in a classroom setting. Because this was developed by engineering students, it also gives validity that the project would appeal to the targeted audience of young STEM learners. As part of the design, the student designers were also tasked to develop learning outcomes that best suited this activity which were fine-tuned with engineering educators. The sample prototype was constructed by 3 student designers over the course of ~12 weeks, including failed iterations. During these 12 weeks, designers were given guidance in development of learning outcomes and overall scope of the project. The design and construction of the prototype robot itself was left up to the student designers. The curricular context and learning activity are discussed later on in the paper.

Project Overview

The participating students will be tasked to create an animal-like robot using only McKibben muscles to actuate it. The robot construction can be achieved using corrugated cardboard and other relatively inexpensive materials. At the end of the term, all students' robots will compete in a set up environment in order to forage for "food" items. Additionally, student learners will also deliver a design report of their developmental process with which a grading rubric can be found in Appendix D. The instructors can decide how the points contribute to the overall performance of the teams. With this method, student learners will still be encouraged to score as many points as they can while also not being extremely detrimental to their overall grade if their design does not perform as well. Educators can divide the design progress for students into 3 parametric design phases: Locomotion, Collection, and Storage. Table 1 below presents an overall scope of the project with phases in chronological order and general objectives to better demonstrate the scope of the project. Besides presenting the project requirements, we present our sample prototype as a creature model for example purposes.

Table 1: Schematic of the project with five phases and their corresponding objectives.

	Phase	Objective
1. Introductory	1.1 Introductory Stage	● Introduce the McKibben muscle and conduct a building workshop ● Introduce the project overview, end-of-term competition and robot challenges: Locomotion, Collection & Storage ● Ask student learners to begin their preliminary design for the robot
2. Challenge	2.1 Locomotion	● Student learners will address how to get their robot to move around
	2.2 Collection Mechanism	● Student learners will address how to collect tokens
	2.3 Storage and Improvement	● Student learners will address how items will be stored and make final improvements
3. Competition	3.1 Competition	● Student learners will all participate in the end-of-term competition

Curricular Context and Learning Outcomes

Because this project can be achieved with inexpensive materials and simple construction without using complicated manufacturing techniques, it can be implemented in almost any classroom setting. The module is targeted for students in first or second year engineering or STEM students involved in a classroom environment that is conducive to the level of dedication required. However, because of the project's simple nature, it can also be easily integrated into STEM courses within high school students.

Another reason the project is best suited for the recommended student group is that the learning outcomes align with that stage in engineering education. A major objective is to implement prototyping phases and narrow the variety of designs by testing parametrically. This is done throughout the entirety of the project, and due to the extreme variability and ease of construction of the materials being used, this aspect is especially pronounced. Another outcome that is especially relevant is to apply an entrepreneurial mindset to create a product that successfully fills a niche. In this case, the niche is not a term in relation to a market environment but a biological one, where instead of a product readily adapting to business competition and competing for monetary resources, the product must adapt to simulated physical competition and attain food resources. This and a plethora of connections can be made between the business world and the natural environment. Another major learning outcome is to optimize a product design by considering relationships between potentially competing constraints. These constraints include factors such as resource costs, limitations with the point system, and competition rules. As students are expected to produce a functional robot suitable for competition under all these constraints, they must conceptualize, evaluate, and optimize their design thoroughly. As a result, they are encouraged to apply their engineering knowledge throughout the iterative design process to create the final product. Analysis of all relevant factors will be considered and accounted for in order to create a successful design; because some of these factors are correlated to the progress of competing teams, this analysis will be dynamic. Of course, a fundamental learning outcome is to apply knowledge of how to balance mechanical forces and torques to enable motion. This is required for even the most basic iterations of this project, so it is woven into the entirety of the design and prototyping phases. An additional learning outcome is that by using McKibben muscles to create effective actuation students learn how actual biological muscles function to produce movement.

Requirements

The estimated timeline for this project is between 8-10 weeks. Team sizes are recommended to be between 3-4 students. The instructor must identify a space where the robots are able to roam easily around obstacles and other robots. The materials needed to create one McKibben muscle include a balloon, nylon braided sleeve and two zip ties. The number of muscles varies depending on the challenges discussed in next sections. Furthermore, the air source can be made with a silicone tube attached to plastic syringes. The creature assembly itself can be produced with mostly readily available materials such as cardboard, plywood, plastic sheets, etc. However, corrugated cardboard stands out as a suitable option given its cost-effectiveness and lightweight nature. Hot glue and tape may be used for creature construction but adhesive may need to vary depending on what is more suitable for the chosen material. Equipment may include box cutters, cutting boards, and scissors, pliers and an optional soldering gun. While the price for each McKibben creature will also vary depending on the bulk chosen material, the estimated average price for a McKibben creature based on the prototype we created is less than $25. An estimated bill of materials can be found in Appendix A. However, items such as silicone tubing and syringes can be reused for subsequent projects which reduces this cost long term.

1. Introductory Stage

For this stage, instructors must explain the basic principles of how a McKibben muscle is constructed with the available materials. For the next stage, a muscle can be incorporated into a mechanism to create motion which will lead student learners directly into the three challenges associated with the project: Locomotion, Collection Mechanism, and Storage and Improvements.

(a) Actuation Principle

The McKibben Muscle is an efficient and widely used pneumatic actuator patented by Richard H. Gaylord [3]. Conceptually, the muscle operates by inflating a balloon inside the nylon sleeve. When the balloon inflates, it is constrained by the sleeve and expands it. Because of the braided structure, when the sleeve is enlarged it contracts in length, causing linear actuation, as shown schematically in Figure 1 (a)-(c). This simple principle of linear contraction by the increase of air pressure is what students will be relying on to create motion in their robot. Its essential construction is quite simple and the exemplary one we demonstrate only requires a balloon, nylon braided sleeves, 2 zip ties, a section of silicone tubing, and a plastic syringe.

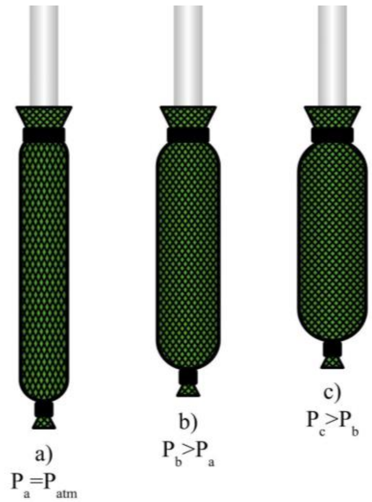

Figure 1: Illustration of McKibben muscle contraction process as pressure increases from stages (a) -(c). The relative pressure of the muscle is denoted at a given point in the schematic. An increase in pressure causes the muscle to contract linearly.

Educators should provide students with instructions on how to create the McKibben muscles and how best to utilize them. Students can explore various parameters that control the extension and contraction including muscle diameter, placement of zip ties, etc. It may also be beneficial to provide physical examples of an operating McKibben muscle so students have a clear understanding of how it should operate. Students can construct the McKibben muscle using the procedure provided in Appendix C while referring to Figure 2.

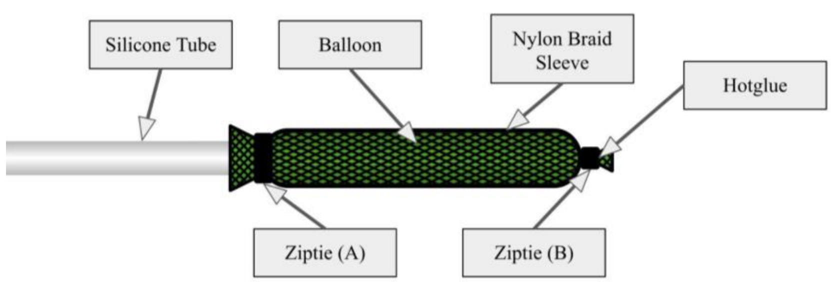

Figure 2: Illustration of McKibben muscles produced and its components. This figure can be used to aid in the construction process.

This pneumatic muscle system has several advantages and disadvantages. One key advantage is its simplicity which allows for ease of manufacturing and repair by student learners as well as a low unit cost. Also due to its simplicity, the muscle is intuitive to work with and students can easily understand its principles. There is a maximum limit to the amount of force the muscle can provide, as it can be returned to close to its original state by a strong pull. While not formally tested, the constructed muscles reliably actuated over the course of hundred cycles during the prototyping process without significant degrading. However, we noticed that leakage around the seal generated by zip tie A was a common failure mode. Once the muscles are compromised, the creature is challenging to control. As an example, the syringes had to be reset frequently on leaking muscles because the air volume in the system would slowly decrease. Furthermore, actuating the syringes rapidly can be fairly exhausting for the operator after a while due to the amount of friction caused by this. The silicone tubing also can cause issues, specifically with maneuverability, because the weight and elastic force caused by the tubes can affect the movement of the creature.

(b) Prototype Actuation

Before production of the McKibben creature, each team must first create an initial mechanism to explore methods to actuate. In this rapid prototyping phase, students should be encouraged to use easy-to-manipulate (e.g., cardboard, rubber bands) materials to develop multiple iterations of initial McKibben muscle mechanisms. Students should be encouraged to develop a design that addresses one of the three game challenges using a McKibben muscle. Another option is to assign students to produce a simple mechanism to complete a specified task that will sufficiently develop the student's understanding of the muscle actuation. Subsequently, students will be able to brainstorm various ways to address the remaining challenges not yet designed. Students should be given time to then sketch and plan for their preliminary designs for their robot. As groups begin to develop their designs, students have the opportunity to speak with one another and strategize to optimize their points. For example, if a majority of groups are developing designs to target the higher level points, a group may take advantage of that by targeting the ground level tokens with a lighter and simpler collection mechanism but an overall faster robot. Once a design is selected and drawn out, it can be submitted for review by the overseeing instructors. This ensures that each team has a design that can feasibly accomplish the three central goals. Once the design has been verified, this does not mean that modifications cannot be made to it. In fact, further modifications are expected and encouraged as building commences and new ideas are made.

Some simple force (F) and torque (T) analysis can be performed on each actuating member of the creature. This can be done by performing a summation of the forces in the x and y directions as shown in equations 1 and 2 respectively. This can be done, similarly, for the torques of the systems as shown in equation 3. By solving for the values in a static state, where the summations of all forces and torques are equal to 0, the performance capabilities of the creature can be evaluated outside of a testing environment and in the design phase.

$$\sum F_x = 0 \quad (1)$$

$$\sum F_y = 0 \quad (2)$$

$$\sum T = Fd = F \cdot r \cdot cos(\theta) = 0 \quad (3)$$

For equation 3, d is the distance between the line of action of the force and the center point, r is the distance between the point of application of the force, and θ is the angle between the direction of force and the line to the center point. Some of the values for forces can be directly measured, such as that of the rubber bands, McKibben muscles, and weights. Values for d, r, and θ can also be determined from measuring lengths and angles on the creature. If analysis of the leg pushing force is being done, both the static and kinetic friction of the creature can be measured using a small scale.

2.1 Locomotion

All robots should be capable of moving forward and changing direction from left to right. The degree at which these robots can change directions is up to the student's discretion and should be influenced by how the educator decides to set up their environment. Instructors may want to provide an example of Mckibben muscles being used to provide motion in a simple mechanism. By demonstrating an example, students can obtain better insight as to how the McKibben muscle can be implemented and how much force may be applied by the McKibben muscle.

For instance, 2 potential methods of locomotion can be seen in Figure 3 with labeled illustrations of designs on the left side and the sample-prototype on the right. The first method is a leg mechanism with the ability of single-direction locomotion in which the robot imitates an inch-worm-like motion using a single McKibben muscle seen in Figure 3 (b). The leg will extend when the muscle inflates and return back to its original position when the muscle is deflated. As the McKibben muscle contracts, the fore linkage (5) decreases in angle with the horizontal. Due to the friction at the surface (1), the base of the creature will slide forward. As the muscle extends, the fore linkage (5) will raise back up and the end linkage (2) will move back to the original position. The second potential design for others to attempt and modify is the mechanism shown in Figure 3c and d. This mechanism relates the alternating contraction of McKibben Muscles to the rotation of two axes back and forth, creating rolling motion.

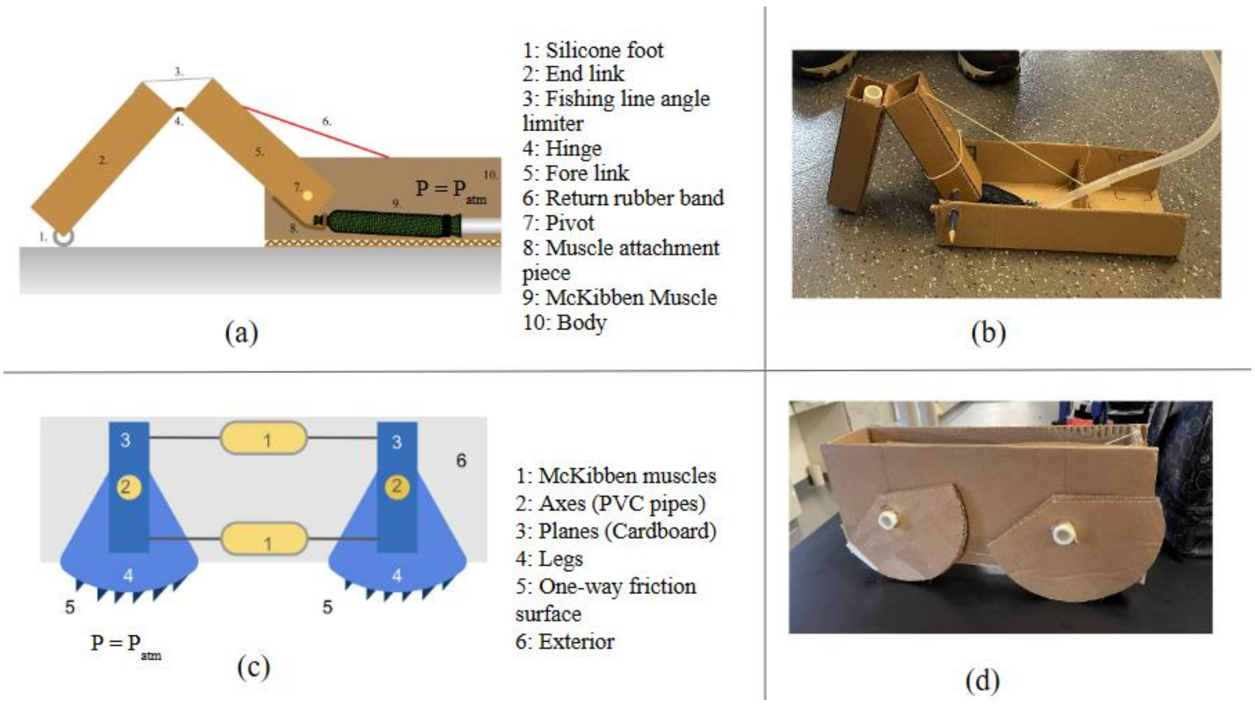

Figure 3: Diagrams and images of 2 potential locomotion mechanisms. (a) Design schematic and (b) attempted prototype of a leg mechanism. (c) Design schematic and (d) attempted prototype of a rotating mechanism.

In this stage, students should be encouraged to think about how the mechanical forces and torques drive the motion of their creatures, highlighting connections to these concepts for students during the project. As an example, Figure 4 shows the forces for the leg linkage that enable motion for the single leg mechanism we designed in our prototype. In propulsion, the McKibben muscle is inflated and causes force F_m on the base of the fore link. The force is large enough to overcome the torque caused by force F_b of the rubber band. This creates a counterclockwise torque, which causes a force at the foot, F_f. The force is oriented downward and back, propelling the creature forward. The downward force enables a high degree of adhesion by increasing the normal force at the foot, ensuring that slippage does not occur. In retraction, F_b creates a clockwise torque in the fore link. This has the opposite effect and reverses F_f to be upward and forward. The upward force substantially decreases the normal force, and thus the friction force, to such an extent that only slippage is possible. The foot drags on the ground until it has returned to its original position.

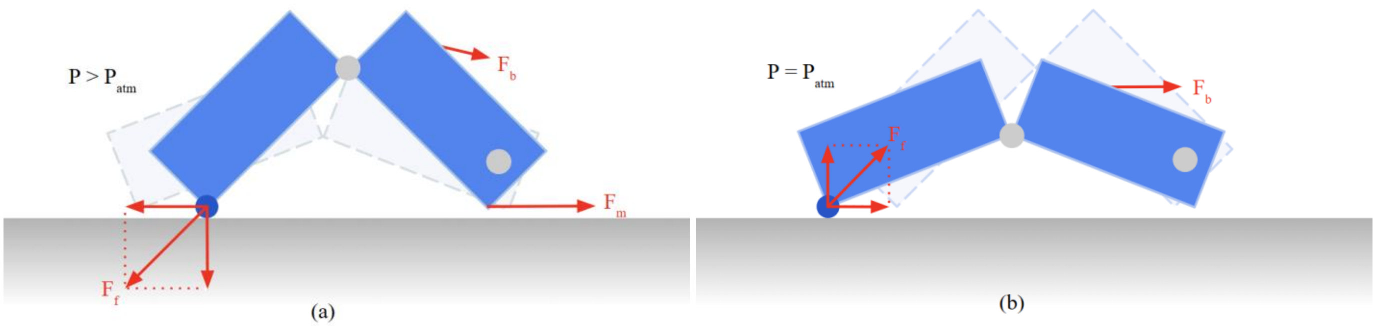

Figure 4: Diagram of force analysis in sample leg operation as pressure decreases in the McKibben muscle with the gray dots representing the pivot points. In (a), the muscle is contracted which causes the foot of the end linkage to sit closer to the creature. When the pressure in the muscles releases, in (b), the friction caused by the silicone foot allows the creature to propel itself forward.

Beyond this point, students will continue to develop and modify their designs. While students should work to complete each phase successfully before proceeding to the next one, they should be reminded to think about their design as a whole to avoid potential challenges. For example, students may choose to develop their locomotive mechanism for a robot that is small in space and lightweight for ease of maneuverability. However, this may present a challenge if they choose to add a complex collection mechanism if their locomotive mechanism cannot provide enough force to move the robot with its added weight. This can be avoided if students briefly test how much weight their robot can push before proceeding.

For the sample-prototype made, the locomotion mechanism simply duplicates the single-leg mechanism as shown previously. The robot includes 4 linkages, 2 McKibben muscles, and 2 sections of silicone tubing along with 2 plastic syringes, as can be seen in Figure 5. The benefit of this design is that the creature has a very high degree of maneuverability, albeit it lacks any reverse capabilities. Additionally, having a large base allowed for ample space for the collection mechanism.

There are numerous design ideas for the grasping mechanism with varying degrees of motion. The number of McKibben muscles in the design is directly proportional to the final range of the collection mechanism and the complexity of its construction. This means students would have to make key decisions in choosing their designs based on the needs of their individual McKibben creatures. The most simple configuration only uses one muscle, which would have the most limited range. This can be accomplished with an arm that sweeps and gathers up only food items that are on the ground, with the items being pushed into an entrance to the storage bin at ground level. More complex mechanisms that have more degrees of freedom and extended range but require more McKibben muscles to actuate and likely more weight to carry for the overall robot. Overall, the advantages and disadvantages must be weighed for in the selection process. The students must strategize their approach.

Figure 5: Images of sample-prototype iteration accomplishing locomotion from front and back view.

2.2 Collection Mechanism

One potential design for the collection may imitate an arm. Smaller, simple arms like the one developed for the sample-prototype that are capable of vertical grasping would be able to attain higher-level food resources, but would necessitate precise movements to maneuver the arm into the correct position. The particular one demonstrated uses 3 McKibben muscles for 3 degrees of motion. The elbow-linkage and the placement of the anchoring muscle is constructed similarly to the legs as can be seen in Figure 6.

The grasping claw is made of a flexible rectangular piece that is attached to another muscle placed inside the upper-linkage of the arm. As shown in Figure 8, when this muscle contracts, the flexible piece is pulled into the square hole created inside the upper arm linkage. The two sides of the flexible piece will fold to create a C-shape around the item. The rubber bands on the two sides of the gripper are used to increase friction.

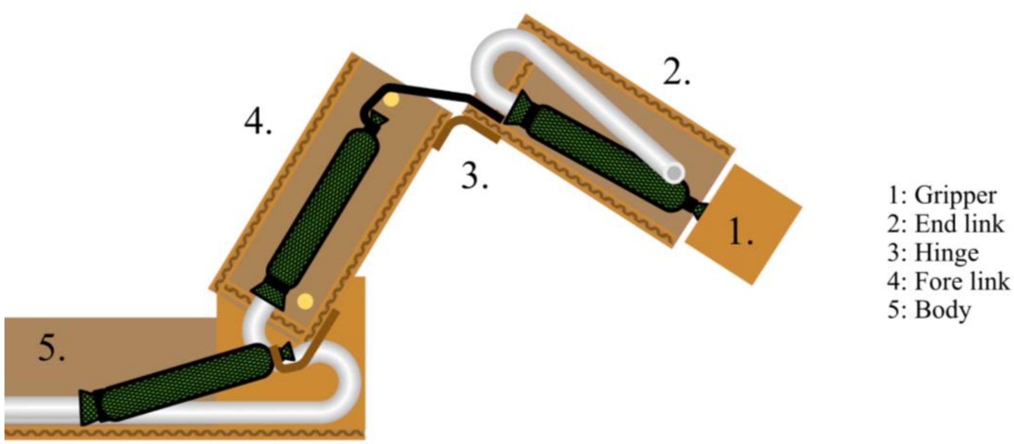

Figure 6: Illustration of side cutaway of the arm mechanism used for collection in the sample-prototype iteration.

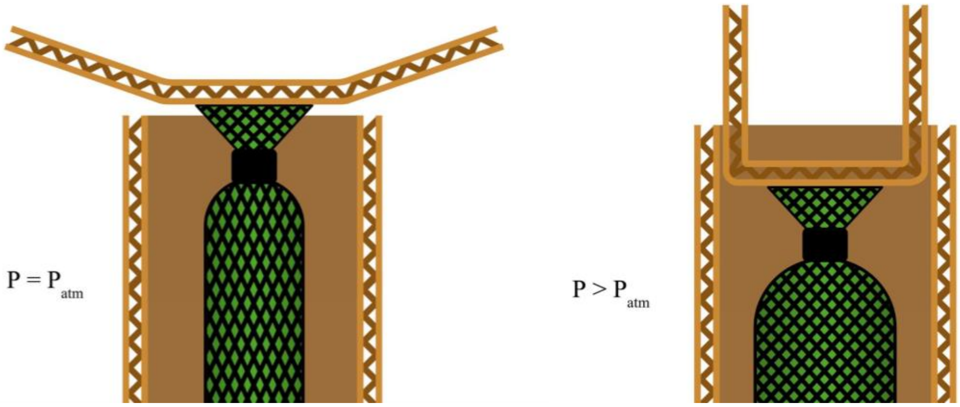

Figure 8: Illustration of grasping claw used in the sample-made prototype as pressure in muscle increases. P represents the relative pressure of the McKibben muscle. As the muscle contracts, the gripper folds in and closes as it is pulled into the arm.

2.3 Storage and Improvements

The storage section, although simple in construction, is essential for the proper operation of the McKibben creature. How student learners choose to go about storing their food tokens will be dependent on how their robot moves and collects items. This gives reason to why educators should emphasize thinking of the design as a whole rather than separate components.

To give an example, in the sample-prototype, due to the limited range and orientation of the arm mechanism, a container had to be added underneath the closest arm reach rather than utilizing the existing body itself. Because of this, the storage component also must not be inhibitive to the grasping reach of the arm, so it cannot be so large that the arm is barely able to reach past it and add too much weight that may hinder the robot’s ability to locomote. At the same time it must be large enough to be able to carry the items.

3. The Competition

The ultimate test of each created McKibben creature will be a competition. Each creature will be placed at different locations in a large classroom or other area filled with food resources. These food items, or tokens, can be any light, small object; however, the best item to use was found to be balls of paper towels held together with two rubber bands as can be seen in Figure 9 (a). This is a very inexpensive option, can be easily adjusted in size, and can roll when deposited in a McKibben creature without unintentionally rolling on the ground. The distribution of food tokens at various levels is up for the instructor to decide; however, having the food resources be placed at various levels, with equal amounts of food at each level, broadens the design space for student learners, enriches competition, and allows tailoring project’s complexity for targeted grade level. A simple method to elevate the food items is to place a rubber band around a taller object, such as a cardboard tube, and then thread the rubber band through one of the rubber bands holding the paper balls together which can be seen in Figure 9 (b). The final appearance that has been imitated using a water bottle can be seen in Figure 9 (c). This creates a connection that is able to hold the weight of the ball but can easily be released by a slight pull. During a set span of time the teams will be tasked with collecting as much food as possible from this environment and competing against other teams for resources. This essentially creates a simulation of a biological environment with lifeforms competing for energy. While this remains untested, an example of a game configuration can be 5 food tokens and 40 ft^2 of area size per each robot with a total game duration of 20 minutes. These parameters can vary at the instructor's discretion based on the number of teams, robot complexity, and time or space constraints.

a) b) c)

Figure 9: Demonstration of individual “food” item construction and placement with varying elevations. Food tokens are made using paper towels and held together using two rubber bands. The placement is also secured using rubber bands.

Alternative Gameplay Considerations

Since in this setup the creatures are collecting solely stationary objects, this is analogous to herbivorous animals. However, with some modification, carnivorous animals can be brought into the environment as well. This is a relatively simple change, as it requires that some of the teams specialize not in collecting food but in restraining other McKibben creatures. This can be done by moving the arm to the front (or making an alternative mechanism) to create a grasping mechanism sufficient enough to hold another creature from moving once caught. Once this event occurs, referees who would be monitoring the progress of the game would manually transfer all of the food items from the caught McKibben creature to the carnivorous one. The two would then be separated and could resume the game. Alternatively, omnivorous creatures could be allowed which would both be able to pick up food items and capture other creatures.

Final Results and Discussion

Though this project has not been implemented in a classroom, the team of 3 undergraduate student designers successfully developed a prototype that addresses all the challenges. In terms of performance, the prototype has a very high degree of maneuverability in terms of both locomotion and grasping. The turning radius is extremely tight, and much more so than expected, which is highly beneficial to navigating around objects and positioning the arm. The arm itself performs exceptionally well with high reliability. The range of the arm extends from the ground level up to items at an elevation of 10 inches. However, the maximum speed is relatively slow due to the limitations of the chosen moving method and its relative weight added to the robot. Videos of the final prototype locomoting as well as picking up items at 2 differing levels of elevation can be found in Appendix B. The final completed prototype can be seen in Figure 10. One can imagine that a variety of solutions are possible to complete the 3 challenges within the constraints.

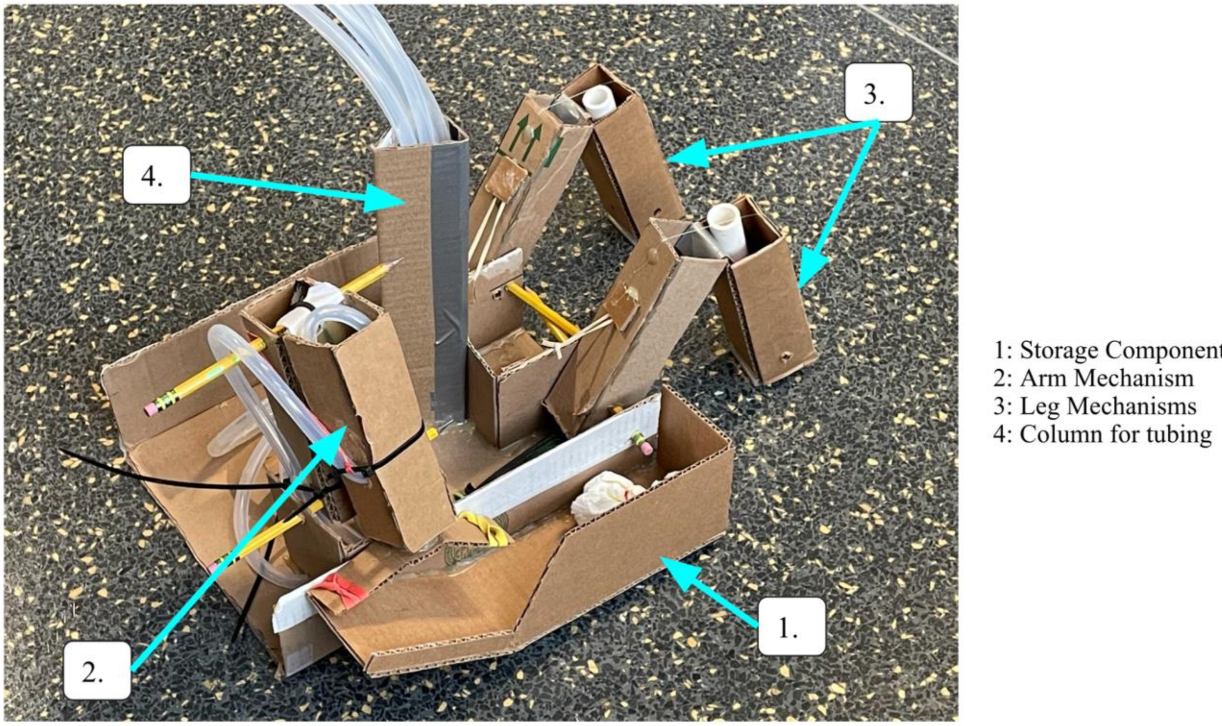

Figure 10: Images of final sample-prototype iteration with labeled components. The storage component can be seen under the arm mechanism.

Summary and Future Work

Overall, the developed project incorporated several beneficial learning outcomes for student learners and has proven to be more than feasible from the created prototype. By allowing for a degree of creative freedom and an edge of competition, we anticipate that the McKibben creature will be a highly enjoyable and educational project. Although implementation has not occurred yet into an active classroom environment, the fact that it was developed by students and for students is a testament to its ability to resonate with engineering learners. In addition, the simplicity of the project naturally yields the project to be used in a wide variety of learning environments and student learners. When implementation does occur, the generated results would need to be studied and further modifications would be made to the teaching approach. Eventually, the module and learning materials along with the project will be made highly accessible to educators through a centralized soft robotic teaching website being developed at Rowan University.

Acknowledgements

This material is based upon work partially supported by the National Science Foundation under Grant No. 2235647. Any opinions, findings, conclusions, and recommendations expressed in this material are those of the authors(s) and do not necessarily reflect the views of the National Science Foundation. We would like to acknowledge Douglas Snyder as part of the subgroup during the developmental process of the sample prototype for this project.

Appendix A - Bill of Materials

The following bill of materials is the cost estimate for the developed McKibben Creature as outlined by this paper. Since each McKibben creature will be entirely different, the cost and material used will be completely different for each. However, this table is meant to provide a guide on what is to be expected for the average creature to be built. Costs are based on an estimated average taken from reviewing listed internet prices. The table does not include the materials required for the game environment. This includes paper towels and rubber bands for the food items as well as whatever material is used to elevate the food.

Part	**Cost/Unit**	**Amount Used**	**Cost Used**
Cardboard	$0.00	$6ft^2$	$0.00
10” Hot Glue Sticks	$0.35/Stick	6 Sticks	$2.10
Duct Tape	$0.05/ft	1ft	$0.05
Plastic 60 mL Syringes	$0.60	5	$3.00
7.5” zip Ties	$0.05	13	$0.65
Barbecue Skewers/Pencils	$0.07	3	$0.21
½” Nylon Braided Cable Sleeve	$0.14/ft	2.5ft	$0.35
Rubber bands (variety of sizes)	$0.01/Band	8	$0.08
Fishing Line	$0.01/ft	1ft	$0.01
¼” Soft Silicone Tubing	$1.00/ft	15ft	$15.00
¾” PVC Pipes (or another means of adding weight)	$0.60/ft	12in	$0.60
12” Balloons	$0.01	5	$0.05
			$22.10

Appendix B - Video Demonstration

The following are links to videos of the McKibben creature sample prototype.

1. *Mckibben Creature Ground Elevation* - https://youtu.be/zyGcsCPP-0U?si=E0txQnEeV-F6G_HH

   This video demonstrates the locomotive capabilities of the developed McKibben creature and a successful capture of a food item located on the ground.

2. *High Elevation* - https://youtu.be/fy2qtum-Hvs?si=wus_u31SknkdK23n

   This video shows from multiple angles the action of the arm successfully taking an elevated food item.

Appendix C - McKibben Muscle Procedure

Instructions on how to create the McKibben muscle (refer to Figure 2):

1) Insert a rubber balloon through the nylon braided sleeve, ensuring the balloon is somewhat taut and that the open ends of the balloon and nylon sleeve are lined up
2) Cut off about ~3ft of silicone tubing and attach a plastic syringe to one end
3) Insert ~¼" of the open end of silicone tubing into the open end of the balloon and nylon sleeve
4) Seal the balloon, nylon sleeve, and silicone tube together with a zip tie (A)
5) Secure a zip tie (B) on the other end of the balloon and nylon sleeve
   a) Note: to ensure zip tie (B) is secured around the balloon and nylon sleeve, you can hold it into position while inflating the balloon and make sure they move in unison
6) Apply hot glue around the zip tie (B) to the nylon sleeve
   a) Note: Avoid applying the hot glue to the inflated side of the balloon
7) Cut the excess nylon braided sleeve
   a) Note: Alternatively, you can use a soldering gun to create a sealed or unfrayed end

Troubleshooting:
Students can identify leakages in the McKibben muscle when inflated. Students may need to further tighten zip ties to resolve leaks which can be aided with a pair of pliers. They may also be able to twist the open end of the balloon to close any gaps around zip tie (A).

Appendix D - Design Report Grading Rubric

Grade	*5*	*4*	*3*	*2*	*1*
Spelling, Grammar, ect.	There are no grammatical or spelling errors.	There are a few minor errors, but nothing significant.	Some major errors are present in the text.	Errors are scattered throughout and are highly noticeable to the reader.	Errors are prevalent and distract from the text material.
Text Language	Written in a concise and highly professional language that conveys information highly effectively.	Text is written well and material can be clearly understood by the reader	Paper reads fairly well, with some sections not being well understood by the reader.	Paper is disjointed and unprofessional. Material covered is not easily conveyed.	Unprofessionalism in the text is highly detrimental to the paper and concepts are very poorly conveyed.

Phase 0	Design process and progress made is effectively described and documented. Decisions during this phase as well as issues that arose are as very well explained.	Design process is documented well. Decisions and problems that occurred during are brought to attention.	Progression during this phase is described, although more detail is needed. Some of the decisions and issues are described.	Significant detail of the design process is lacking. Engineering decisions and issues that occurred are not well explained or left out.	Not enough documentation is present for the reader to understand the progression of the project. Major details are missing from this phase.
Phase 1	Design process and progress made is effectively described and documented. Decisions during this phase are justified as well as issues that arose are thoroughly explained.	Design process is documented well. Decisions and problems that occurred during are brought to attention.	Progression during this phase is described, although more detail is needed. Some of the decisions and issues are described.	Significant detail of the design process is lacking. Engineering decisions and issues that occurred are not well explained or left out.	Not enough documentation is present for the reader to understand the progression of the project. Major details are missing from this phase.
Phase 2	Design process and progress made is effectively described and documented. Decisions during this phase are justified as well as issues that arose are thoroughly explained.	Design process is documented well. Decisions and problems that occurred during are brought to attention.	Progression during this phase is described, although more detail is needed. Some of the decisions and issues are described.	Significant detail of the design process is lacking. Engineering decisions and issues that occurred are not well explained or left out.	Not enough documentation is present for the reader to understand the progression of the project. Major details are missing from this phase.
Phase 3	Design process and progress made is effectively described and documented. Decisions during this phase are justified as well as issues that arose are thoroughly explained.	Design process is documented well. Decisions and problems that occurred during are brought to attention.	Progression during this phase is described, although more detail is needed. Some of the decisions and issues are described.	Significant detail of the design process is lacking. Engineering decisions and issues that occurred are not well explained or left out.	Not enough documentation is present for the reader to understand the progression of the project. Major details are missing from this phase.
Evaluation	The paper clearly outlines key flaws and advantages of the design, as well as how these could be modified in the future. Performance is evaluated with substantial detail.	The paper presents some of the flaws and advantages of the design. Game performance is described with detail.	The paper presents flaws and advantages of the design, although more detail may be merited. Performance of the creature is discussed, but not thoroughly.	The paper presents flaws, advantages, and performance takeaways, though these need expanding upon.	The paper has inadequate detail on the flaws, advantages, and performance takeaways. This section cannot be taken as a proper evaluation.

References

[1] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots," *Nature*, vol. 521, no. 7553, pp. 467–475, May 2015, doi: 10.1038/nature14543.
[2] N. El-Atab *et al.*, "Soft Actuators for Soft Robotic Applications: A Review," *Adv. Intell. Syst.*, vol. 2, no. 10, Aug. 2020, doi: 10.1002/aisy.202000128.
[3] R. H. Gaylord, "Fluid actuated motor system and stroking device," 2844126, Jul. 22, 1958 [Online]. Available: https://patents.google.com/patent/US2844126A/en