Origami Robots for Explosive Ordnance Disposal

A Major Qualifying Project

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Abstract

The demining of landmines using drones is challenging; air-releasable payloads are typically non-intelligent (e.g., water balloons or explosives) and deploying them at even low altitudes (~6 meter) is inherently inaccurate due to complex deployment trajectories and constrained visual awareness by the drone pilot. Soft robotics offers a unique approach for aerial demining, namely due to the robust, low-cost, and lightweight designs of soft robots. Instead of non-intelligent payloads, here, we propose the use of air-releasable soft robots for demining. We developed a full system consisting of an unmanned aerial vehicle retrofitted to a soft robot carrier including a custom-made deployment mechanism, and air-releasable, lightweight, and untethered soft hybrid robots with integrated electronics that incorporate various pneumatic actuators. We demonstrate a deployment cycle in which the drone drops the soft robotic hybrid from an altitude of 2 m meters and after which the robot approaches a dummy landmine. By deploying soft robots at points of interest, we can transition soft robotic technologies from the laboratory to real-world environments.

Acknowledgements

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1. Introduction

Nearly one billion people are impacted by the remaining 100 million active landmines estimated to be undiscovered around the world. Each year there are approximately 7,000 casualties caused by these abandoned, unexploded landmines. In addition to the 100 million active landmines, 180 million anti-personnel landmines are being stockpiled by 54 countries. Each landmine costs between $5 and $30 to produce, whereas the cost of demining is anywhere between $300 and $1000 per landmine. Three of the most common demining methods include manual demining, animal demining, and machine demining (including aerial demining). Work conducted by the previous MQP team has shown that using a drone, for aerial demining, to drop water balloons onto a target is an ineffective means of demining, which was only able to hit the target 56% of the time. In this iteration of the project, we explore the use of soft robots as part of a larger robot ecosystem to address explosive ordnance disposal with intelligent payloads.

2. Background

2.1 Humanitarian Landmine Crisis

The lineage of landmines originates from spike traps and explosive powder trails used in 14th century Italy [1]. However, predecessors to the modern weapon were used in the 1800s during the American Civil War. Following the American Civil War, landmines were used extensively in World War II, the Vietnam War, the Korean War, the first Gulf War, and the Cold War [2]. Estimates show that 2.5% of the United States Army casualties and 20.7% of tank losses by 1945 were due to landmines. During the Vietnam War, approximately 65-70% of US Marine Corps casualties and 12% of Australian casualties were caused by landmines [3]. As landmine use became more normalized during times of war and the price of anti-personnel landmines decreased, war tactics shifted from strategically placing landmines to randomly deploying them in desired locations [1], [3]. This random dispersion of anti-personnel landmines has left an approximated 100 million active landmines scattered in areas of conflict, impacting the lives of nearly one billion people and causing an estimated 7,000 casualties every year [4]–[6].

2.2 Types of Landmines

Landmines are typically classified as anti-tank (AT) or anti-personnel (AP) landmines. AT landmines are larger and require more pressure to detonate in order to damage vehicles and their passengers [4]. AP landmines were initially developed with the intention of protecting AT landmines, but their purpose has since evolved to being weaponized to injure victims. In the economics of war, injuring victims, rather than killing, was developed as a strategy to deplete the enemy of their resources as it costs more to tend to the injured than to tend to the dead [5]. A subset of AP landmines, such as improvised explosive devices (IEDs), are not industrially manufactured and are more difficult to detect as they contain little to no metal parts [6].

2.3 Demining Methods

2.3.1 Manual Demining

Manual demining uses trained personnel to sweep a target area with metal detectors, radar, and/or probes to detect landmines. Once discovered, personnel must carefully uncover, defuse, or destroy the landmines [1], [7]. Approximately 1 in 1000 signals interpreted by demining personnel are landmines, while others are metal shrapnel, cans, or other metal objects.

This inaccuracy in detection combined with the need to mitigate risk of discovered landmines makes manual demining an extremely dangerous and slow process [5].

2.3.2 Animal Demining

Animal demining methods use animals such as dogs, rats, or bees, to locate landmines by using these animals' heightened sense of smell [6]–[8]. Animal demining is advantageous over manual demining because animals can detect non-metallic landmines based on odor and do not suffer from the same false positive signals that metal detectors are prone to. As such, animals are approximately five times faster at finding land mines than humans are [2], [6], [9].

2.3.3 Machine Demining

Machine demining can be broken into two subgroups: ground demining and aerial demining. Ground demining uses heavy machinery to locate and destroy landmines, using one of three main demining tools: flails, tillers, or excavators [2], [7]. While ground machine demining can be safer for human personnel, it significantly limits demining efforts to open terrains that heavy machinery is able to traverse. This prohibits demining efforts from reaching the 99.6% clearance guarantee that is required to deem a mine-ridden area safe [5]. In contrast, aerial demining uses unmanned aerial vehicles (UAVs) to locate or dispose of landmines. UAVs are typically equipped with magnetometers, ground penetrating radar, or chemical analysis devices to monitor progress in demining efforts by determining safe pathways through the terrain being surveyed. To remove mines, UAVs can drop heavy payloads or place remotely detonated explosives onto targets. UAVs prove advantageous over other methods of demining because they achieve a faster scanning speed of targeted areas and offer a significant increase in safety as they are remotely operated and do not contact the soil. However, UAVs are limited by small flight ranges due to their relatively short battery life, small payload carrying capacities (.5-3kg depending on the drone), as well as limited situational awareness of remote UAV pilots.

2.4 Previous Project Work

As aforementioned, previous Major Qualifying Projects (MQPs) have made progress in machine demining by using both a ground rover and an unmanned aerial vehicle to detect landmines and drop a payload for landmine detonation, respectively.

The 2019-20 demining team focused mainly on developing the autonomous capability of the rover as well as the landmine detonation system for the drone. Additionally, they produced a more robust rover for autonomous landmine detection than previous MQP attempts. The team also developed a software application for non-technical users to control and monitor the status of the rover and drone. The team showcased how they developed their detection method for the mine, followed by their aerial detonation technique, demonstrating the full integration of their rover and drone system. However, the team was hindered by a drone crash and the outbreak of the COVID-19 pandemic before they could finish their work. As such, the results they presented primarily highlighted their progress on their detection and detonation methods.

The demining MQP team for 2020-21 continued upon the previous project to create an operational autonomous demining system consisting of the rover, the drone, and a mobile base station: a computer communicating between the rover and drone. The project objective was to search a user-defined area for unexploded landmines, record their location, and return to safety. Once located, a drone could then fly to the identified landmine and drop a small payload to detonate them. The base station provides an accessible user interface for the operator to communicate with the rover and the drone. To facilitate detection of the landmines, the rover was fitted with a metal detector.

A Tarot T-18 heavy payload drone was used to carry the non-intelligent payloads (water balloons) for detonation. After testing, it was reported that only nine out of sixteen water balloons successfully hit the target mine when dropped from the drone hovering 20 ft above. This result alone showed insufficient promise to continue using non-intelligent payloads from a high altitude to detonate the mine, and it was concluded that a new approach must be investigated.

2.5 Soft Robotics

Soft robotics is a developing field in which robots use compliant materials in place of rigid links. Soft robotic actuators are durable and are often inexpensive as they are just the material cost. These soft materials are known for their safety and compatibility with humans and animals, low-cost, conformability to surroundings, high cycle-lifetimes, and damage resistance [10]. However, soft robots are often confined to lab research due to their slow speeds and limited range. To be able to use an untethered soft robot outside of the lab, it would have to be deployed near its objective. Given these strengths, designing a soft robot that can survive a free fall from a drone and potentially trigger explosions when detonating landmines is a promising possibility to explore.

3. Methodology

The primary goal of this project was to create a multi-robot system that combines the strengths of a land rover, a drone, and a soft robot, to improve the process of explosive ordnance disposal. This work is a logical extension of previous work conducted by prior MQP teams that implemented a two-robot system (rover and drone) to deploy unintelligent payloads, which was ultimately deemed inefficient and ineffective. We built upon the prior work with the rover and drone system by updating the rover and drone deployment mechanisms and introducing intelligent, soft robotic payloads. Multiple approaches to the design of the soft robotic payloads were explored and evaluated by their maneuverability, durability/robustness, simplicity, payload capacity, operability on different terrains, and the range they can traverse.

3.1 System Operations

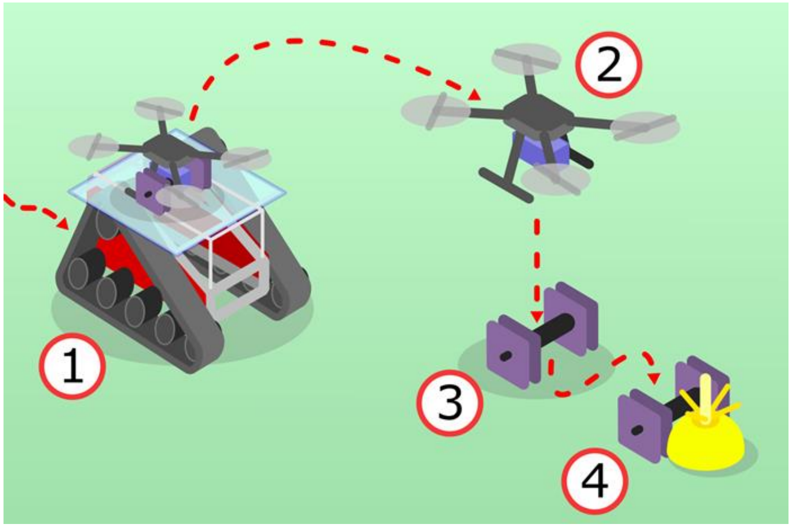

Figure 1: System Operations

A multi-robot system was designed that combined the range of a terrestrial rover, the speed and maneuverability of a drone, and the robustness of a soft robot. Rovers and drones facilitate long-range movement, while soft robots are expendable and can traverse the final leg to detonate a mine. As shown in *Figure 1: System O*, the rover is a mobile base station for our multi-robot system. The rover (1) can carry a 90 kg load for 40 minutes on battery power, which is useful for traversing long distances to a minefield and safely transporting our heavy-payload drone (2), which delivers our intelligent soft payload (3) to align itself more accurately over the landmine for demining (4). The drone's speed allows for rapid missions that involve deploying a demining robot and returning to the mobile base station before the demining robot detonates a landmine. The deployable, soft robot payload (3) then navigates to and detonates the targeted landmine (4). The soft robotic hybrid can account for errors in the previous MQP's work when deploying non-intelligent payloads. With this approach, we can protect and reuse our most valuable equipment by deploying a low-cost expendable soft robot.To determine if soft robots are a viable option for explosive ordnance disposal, we explored various soft actuator types for locomotion.

3.2 Soft Actuators

3.2.1 Artificial Origami Muscles

3.2.1.1 Kresling Pattern

The Kresling pattern is an origami pattern that forms a cylinder that easily compresses and expands. This pattern provides motion by using rows of triangles with their hypotenuses pointing in opposite directions such that each pair of rows compress linearly. A diagram of this pattern can be found in *Figure 2*.

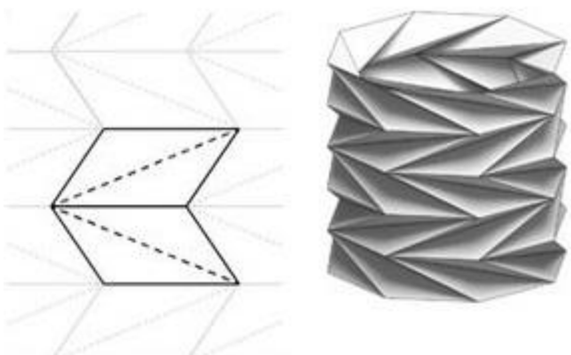

Figure 2: Kresling Origami Pattern

Using a set of Kresling origami structures, we developed an inchworm-type origami soft robot prototype. The structures were cut from a polyethylene sheet and folded according to the pattern in *Figure 2***.** Then the origami was encased within a heat sealable TPU film that, when a vacuum is applied, would cause actuation of the structure. We designed and printed end caps out of TPU that allow for stick-and-slip motion as the cylinder contracts and expands when vacuum is applied and released, respectively. Using two of these side by side allows for the robot to move forward (when both are actuated) and turn (when one side is actuated).

Figure 3: Inchworm Robot

3.2.1.2 Asymmetric Beam Pattern

The Asymmetric Beam structure, shown in *Figure 4*, is made of a series of triangular prisms arranged sequentially along a flat beam. Compressing this origami structure causes the structure to curve.

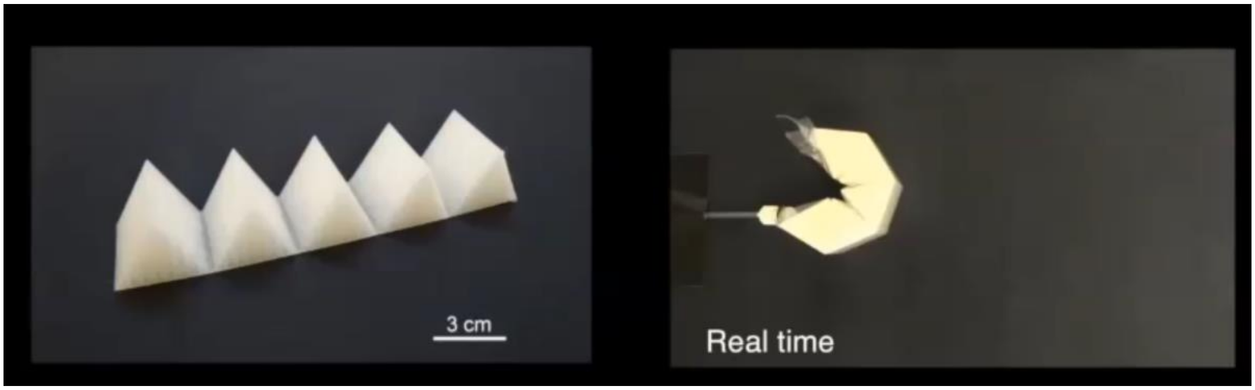

Figure 4: Asymmetric Beam Origami Structure

Using a set of Asymmetric Beam origami structures, we developed a hermit-crab-style origami soft robot prototype, shown in . The structures were cut from a polyethylene sheet and folded according to the pattern in *Figure 4***.** The origami was then encased within a heat sealable TPU film that a vacuum can be applied to, causing actuation. These Asymmetric Beams were attached to a cardboard body for prototyping. When a vacuum is applied, the structures bend and push against the ground to drag the body forward.

Figure 5: Hermit Crab Robot

3.2.1.3 Flasher Roller Pattern

The Flasher Roller pattern, shown in *Figure 6*, is a square pattern with fold lines moving radially outward from the center. This pattern produces rotational motion when contracted.

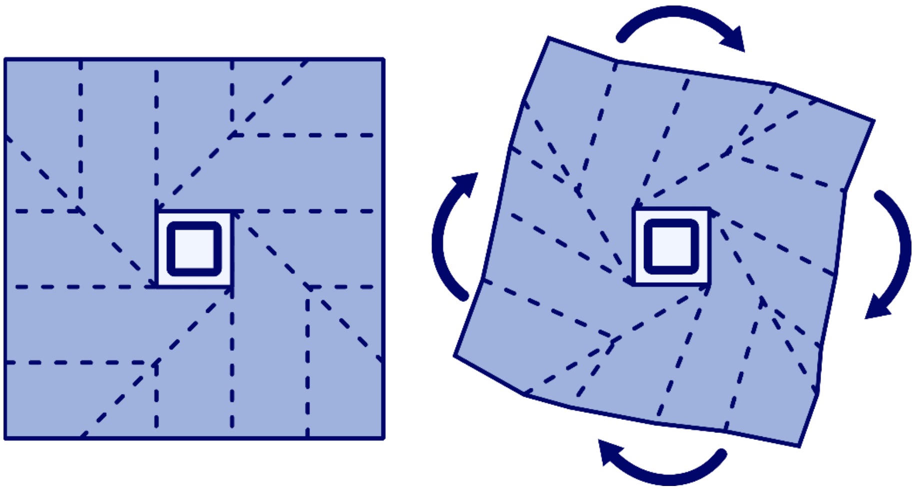

Figure 6: Flasher Roller Origami Pattern

Using four Flasher Roller origami structures, we developed a robot, shown in *Figure* 7, that is capable of moving forward and turning on hard floors and turf. The structures were cut from a polyethylene sheet and folded according to the pattern in *Figure 6*. The origami was then encased within a heat sealable TPU-coated textile bag that a vacuum can be applied to, generating the rotational motion. For more information about the robot we developed using the Flasher Roller pattern, please refer to Looney et al. [10] that we published in the IEEE RoboSoft 2022 Conference.

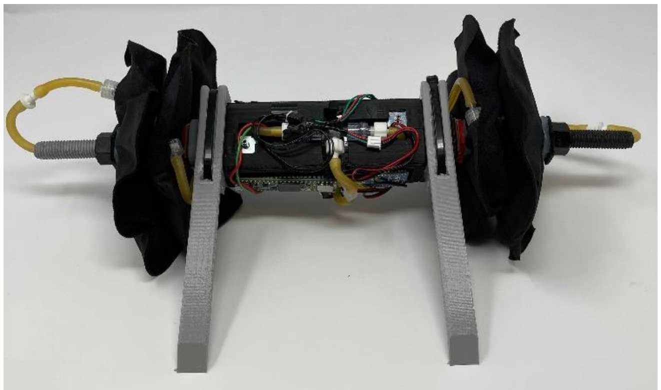

Figure 7: Flasher Roller Robot

3.2.2 3D Printed Actuators

3.2.2.1 Bellowed Actuators

The bellowed actuator is a simple linear actuator that is operated from a single vacuum source. This work was inspired primarily by the actuators presented by Tawk et al [11]. Linear motion is accomplished by compressing each bellow using negative vacuum pressure. This design was parameterized on the following: the wall thickness (t), the angle between Bellows (α), and the number of bellows as shown in *Figure 8*, which impact factors such as actuation length, curvature, required pressure, and more.

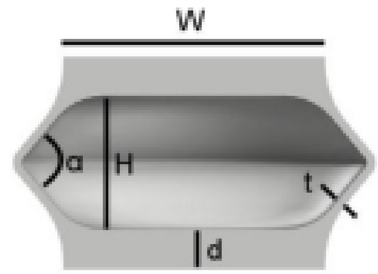

Figure 8: Parameters of a Bellowed Actuator

Our process for creating a **Bellowed Hexapod Soft Robot** is as follows:

1) Determine the optimal parameters of an actuator that provide the best compression time, actuation force, and actuation distance while maintaining ease of printing
2) Design and test a single leg that implements a bellowed actuator
3) Repeat step 2 and iterate to find a simple printable leg configuration
4) Construct a hexapod soft robot with the final leg design

Determine optimal parameters

Through a factorial design experiment of the three main parameters, we could characterize the actuator’s compression time, actuation force, and actuation distance, with respect to these parameters. All actuators were printed out of 1.75mm Ninjaflex with a shore hardness rating of 85A with a 15% gyroidal infill on a Prusa MINI+. Each actuator was tested under an internal vacuum of -40kPa and a flow rate of 85 liters per minute (LPM). Twenty different variations of the bellowed actuator were tested, with wall angles of 75, 90, 105, and 120 degrees, and wall thicknesses of 0.4mm, 0.6mm, 0.8mm, 1.0mm, and 1.2mm, shown in *Figure 9.* Actuators with 60 degree wall angles were printed, however, all 60 degree wall angle prints failed. Additionally many 75 degree prototypes failed or had holes in the walls which excluded these actuators from further testing. Prints were also tested by attempting to compress the actuators by hand, during which it was noted that the walls of both the 105 and 120 degree actuators buckled outwards rather than inwards. This severely impeded their compression and removed these actuators from further consideration and testing.

Figure 9: Factorial Experiment of Bellowed Actuator Parameters

Additionally, we include below our methods for gathering the data of the experiment as well as conclude which bellowed actuator parameters are best suited for the soft robot prototype.

To gather data on each actuator's compression time, we used a 240 FPS video of each actuator compressing 3 times and counting the number of frames it took to fully compress. It was observed that every actuator took less than 0.2s to compress.

To measure the actuation distance, a -40kPa vacuum was applied to each of the actuators and digital calipers measured the change in length of the actuator.

The actuation force was calculated by estimating the normal force of the actuator based upon the internal surface area of the bellows from the SolidWorks model, the vacuum pressure we were testing at, and the angle of each bellow using the formula:

$$F = \frac{P}{Internal\ Surface\ Area} * \cos\frac{bellow\ angle}{2}$$

Equation 1: Estimated Force Of Bellowed Actuator

	Wall Thickness(mm)	Wall Angle(deg)	Pressure(kPa)	Flow Rate (LPM)	Actuation Distance (mm)	Reaction time (seconds)	Compression Speed (mm/s)	Estimated Force (N)
1	0.4	75	-40	85	0	0.2501	0	160.08
2	0.4	90	-40	85	23	0.1389	165.6	133.98
3	0.4	105	-40	85	22.5	0.1458	154.2857143	109.39
4	0.4	120	-40	85	16.5	0.2139	77.14285714	85.72
5	0.6	75	-40	85	22	0.1417	155.2941176	152.21
6	0.6	90	-40	85	23	0.1042	220.8	127.89
7	0.6	105	-40	85	20	0.1556	128.5714286	104.84
8	0.6	120	-40	85	16.5	0.1625	101.5384615	82.50
9	0.8	75	-40	85	22	0.1347	163.2989691	144.52
10	0.8	90	-40	85	22	0.1139	193.1707317	121.93
11	0.8	105	-40	85	20.5	0.0931	220.2985075	100.38
12	0.8	120	-40	85	16	0.1431	111.8446602	79.35
13	1	75	-40	85	22	0.1778	123.75	137.00
14	1	90	-40	85	19	0.1111	171	116.10
15	1	105	-40	85	9	0.1319	68.21052632	96.02
16	1	120	-40	85	26	0.1611	161.3793103	76.25
17	1.2	75	-40	85	21	0.1917	109.5652174	129.66
18	1.2	90	-40	85	13.5	0.1236	109.2134831	110.40
19	1.2	105	-40	85	4	0.1514	26.42201835	91.75
20	1.2	120	-40	85	2	0.1583	12.63157895	73.22

Table 1: Bellowed Actuator Experimental Data

Based on the results in *Table 1: Bellowed Actuator Experimental Data***,** it was determined that the actuators with a 90-degree wall angle and either 0.6mm or 0.8mm walls performed the best. This determination was made on the basis that the actuators with these parameters were able to be consistently printed without issue, compressed cleanly with only inward buckling, and had sufficient compression speed and force.

Design and test a single leg

To facilitate locomotion using the bellowed actuator mentioned above, we designed a leg to convert the linear actuation of the bellows to the simplified 2-DOF model that mimics an insect leg. Two actuators were used per leg- one to move the leg laterally, and one to move the leg vertically as shown in *Figure 10: Single Bellowed Actuator Leg***.**

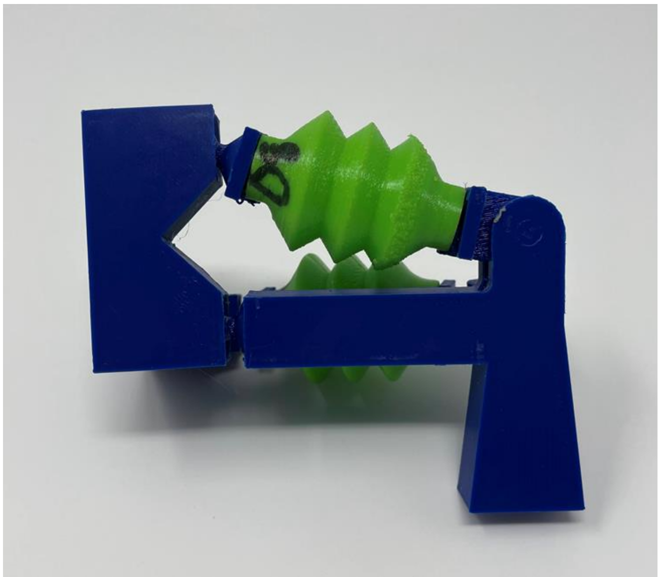

Figure 10: Single Bellowed Actuator Leg

To reduce the number of joints overall, ball joints were used where the leg connects to the body. In addition to reducing the number of joints, the ball joints allowed the leg model to be print-in-place which reduced the assembly time and increased the strength of the ball joints by avoiding two pieces that needed to be press fit together. To increase the overall strength of the legs, PETG was used due to its high strength, increasing the likelihood of the prototype surviving deployment from high altitudes. Additionally, the bellowed actuators were modeled to have a dovetail for attachment of the leg to the body. We found that the dovetail joint was not inherently secure and as a result, the actuators would pop off and render the leg immovable during testing.

Iterate Design

The redesign of the bellowed actuator reverses the pattern of the bellows and has the first bellow go inwards instead of outward, compare *Figure 10* to *Figure 11* for the difference.. This updated design simplifies the geometry of the actuator and makes it easier to print as it requires less curved geometry to be printed overall.

Additionally, the larger surface area on either end of the actuator allows for more options for means of attachment to hardware. Finally, this revision significantly decreases the footprint of the entire actuator which will allow us to shrink the body of the entire robot to a size that can safely fit under the Tarot 650 Drone.

The design of the 2-DOF leg linkages were also improved in two significant areas. While maintaining the “print-in-place” ideology, we expanded the design to incorporate both the left and right legs into the print-in-place module as shown in *Figure 11*. Additionally, we revised the attachment mechanism to be a barbed “push-to-connect” style fitting as shown in *Figure 11*. We also incorporated a dovetail joint connector between each printed-in-place component to allow us to expand the system to operate with any number of legs.

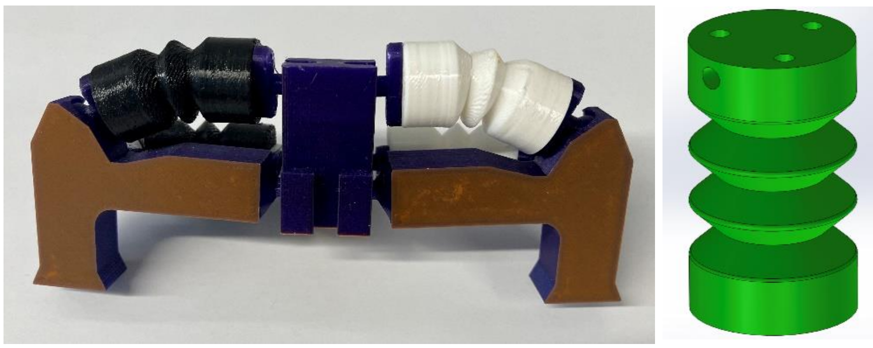

Figure 11: Updated Leg and Bellowed Actuator

Construct a hexapod soft robot with the final leg design

3D-Printing the entire Bellowed Hexapod design enabled rapid iteration of and refinement of the design. However, we noted that print quality of actuators was significantly impacted by inconsistencies in the filament and variations from printer to printer. These issues were harder to address than those present in casting silicone, as the manufacturing process is extremely automated with many parameters determining the quality of the product, not all of which were directly within the teams’ control.

Figure 12: Constructed Bellowed Actuator Robot

Additionally, a second prototype was created using bellowed actuators in an alternative fashion to the print-in-place revolute joints. This design, shown in *Figure 13,* focused on using the fewest number of bellowed actuators as possible to achieve all necessary motion. In order to achieve the desired linear motion, we used a simple linkage to gain a back-and-forth motion translated from the vacuumed actuators' linear motion. To allow the robot to reset its arms to reactuate we used two bellowed actuators underneath the robot to act as feet. When a vacuum is applied, the legs compress allowing the robot to rest on the arms. Once the arms reach the end of their motion, the feet are released, lifting the robot up and allowing the arms to reset. To turn the robot, one foot is actuated, making the robot balance on the other foot and the opposite arm. When the arm then actuates, it rotates the robot about the unactuated foot.

Originally, the bellowed actuator actuation distance was too large. This allowed the arms to reach a toggle point that caused the robot to fail. To address this, the pivot points on the arms were adjusted to create variable arcs with variable linear actuation distances. If the arms needed to stop before the bellow was fully compressed the bellow would disconnect. Additionally, the robot would move its center of mass past the points of contact and fall over if the arms moved too far forward or backward.

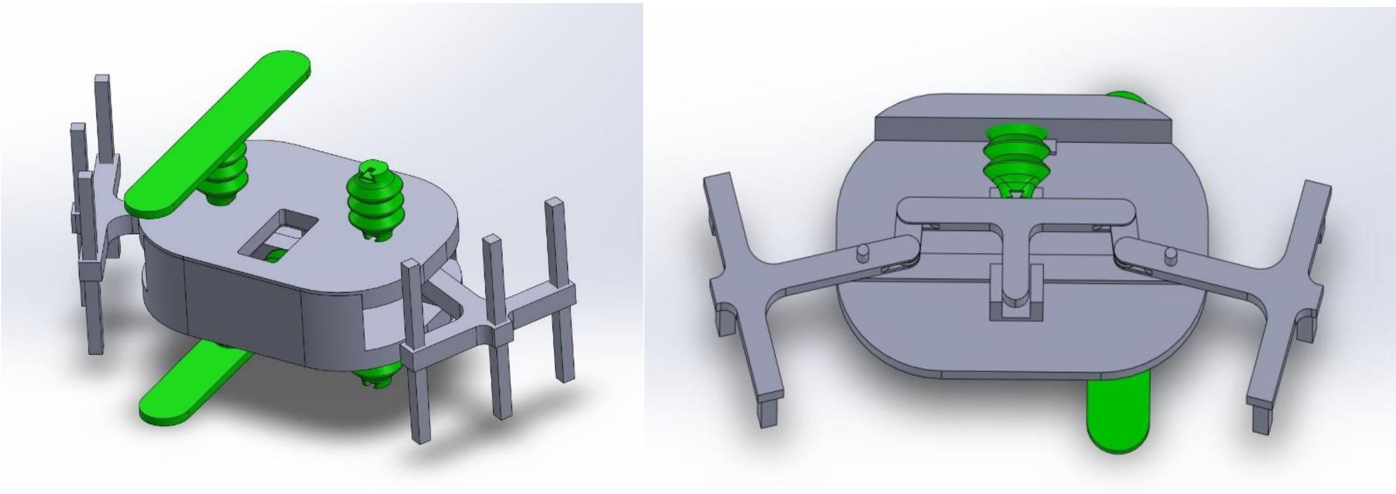

Figure 13: Pixar Bot Design

By extending the robot's fingers and adding feet to the top, the robot is able to walk and turn on both sides. The advantage of this design is that the arm actuation is still performed with one actuator. To increase stability, an additional linkage was added, as shown in *Figure 14*, allowing for a total of four arms to be actuated by a single actuator. With the added legs, the center of mass always stays between the contact points.

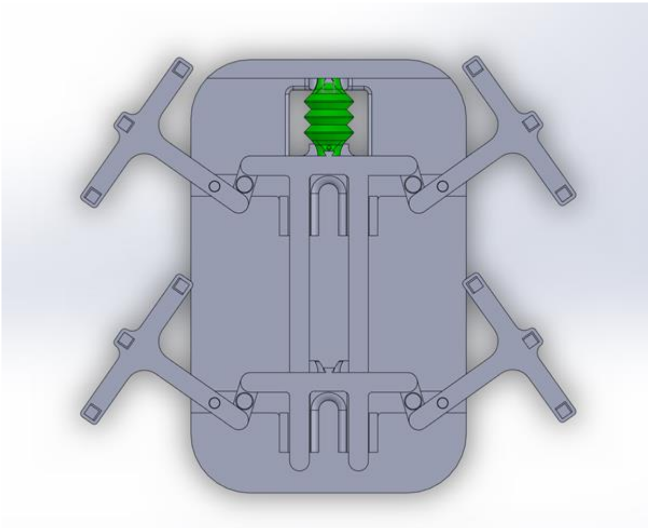

Figure 14: Final Pixar Bot Design

3.2.3 Silicone-Casted Actuators

3.2.3.1 Pneumatic Network

Pneumatic networks (PneuNets) are soft actuators that actuate via positive and negative pressure to create a bending motion.

To produce usable locomotion from the bending motion of a PneuNet, inspiration was taken from insect legs, which locomote in a similar fashion. We combined 6 legs, each operation in a cylindrical motion, to create a tripod walking gait motion. The motion of each leg required to produce this type of motion is as follows: each leg is first raised, pulled forward, lowered to contact the ground, and finally pushed backward to create forward thrust. To meet these parameters, we used a two-chambered actuator: one chamber dedicated to creating horizontal motion in series with a second chamber to generate vertical motion. We adhered the two chambers orthogonal to each other with a “pneumatic resistor” between them to create the sequence of motion desired when oscillating between motion created by positive and negative pressure.

Similar to the Bellowed Hexapod Robot, our methodology for designing and testing a PneuNet Hexapod Robot is as follows:

1) Review what parameters of a PneuNet actuator can be modified
2) Design and test a single leg that implements a PneuNet actuator
3) Repeat step 2 and iterate upon designs to find an leg with desired characteristics
4) Construct a hexapod soft robot with the final leg design

Review what parameters of a PneuNet actuator can be modified

The PneuNet actuator can be modified by altering a set of key parameters, as shown in *Figure* 15, that change the performance of the actuators. The parameters and their effects are summarized in *Table 2: PneuNet Parameter* Summaries with a visualization of the parameters on a PneuNet in *Figure 15: Parameters of a* PneuNet. The main effects of these parameters are the actuator bending angle and actuator integrity. When experimenting with these design parameters, we aimed to find the greatest bending angle without compromising the actuator integrity.

Parameter	Effect
Wall Thickness (t)	Inverse relationship with the bending angle of each fin and ballooning of chambers.
Number of Fins (n)	The number of chambers is linearly related to the total bending angle of the individual actuator.
Material Hardness	The material thickness drastically affects the actuator stiffness and functionality.
Actuator Width (w)	Our experiments did not alter wall thickness, but we predict that actuator width has a square relationship with actuator force, and a cubic relationship with actuation duration.
Pneumatic Resistance	Affects the propagation delay between the two chambers

Table 2: PneuNet Parameter Summaries

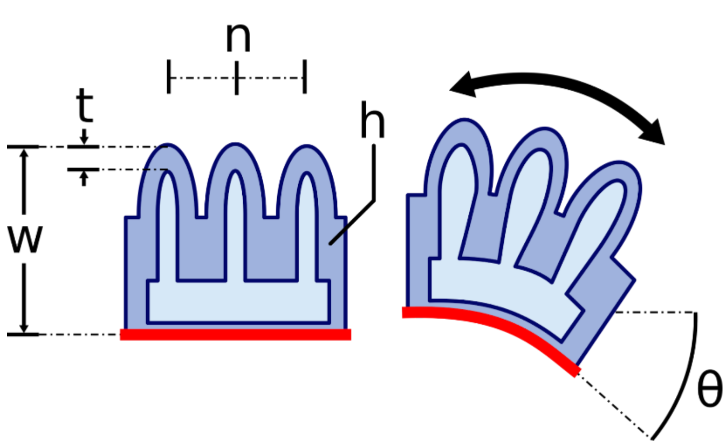

Figure 15: Parameters of a PneuNet

Wall Thickness (t)

Increasing wall thickness slightly increases the overall stiffness of the actuator and decreases the overall bending angle. The magnitude with which this parameter impacts the aforementioned characteristics is also dependent on the material hardness, as softer materials require thicker walls to withstand the applied pressures without ballooning or popping.

Number of Fins (n)

The number of fins in the actuator is linearly proportional to its overall bending angle and its overall length.

Material hardness

The actuator material hardness has a drastic effect on the functionality of the actuator due to its stiffness. For our project, we tested actuators made from Ecoflex 00-10, Dragonskin 10A, and Dragonskin 20A. Ecoflex 00-10 and Dragonskin 10A proved too soft, leading to ballooning and popping. However, Dragonskin 20A proved to be hard enough to resist ballooning and resisted popping over more actuation cycles.

Actuator Width (w)

The actuator width defines the short side length of the actuator cross section. In our experiments, we chose an actuator width of 25mm. While we have not experimented with varying this parameter, we predict that it affects the actuator force and actuation duration. Given that actuator force is based on pressure and area, increasing the actuator width will also increase the actuator force proportional to the change squared. Additionally, increasing the actuator width also increases the actuation duration as the parameter has a cubic relationship with the internal volume of the actuator.

Pneumatic Resistance

The pneumatic resistor is used to create a propagation delay between the two chambers. If the resistance of this part is lower, the two chambers actuate together and if the resistance is increased, there is a longer delay between the first and second chamber inflating.

To calculate the required pneumatic resistor, we determined a desired flowrate to achieve a reasonable actuation speed. Given a total actuator volume taken as 50mL and a desired actuation speed of 5 seconds, the desired flow rate was determined to be 10mL/s, (represented as the total volume of the actuator as 50mL over the desired propagation delay of 5s). We then found the length required for a given diameter tube in order to produce this desired flowrate by means of major losses. These calculations take into account the major losses of the system over the length of the tube based on a laminar flow scenario. To avoid the tube sealing its ends when a vacuum is applied, we routed two tubes, each of twice the calculated length to get an equivalent resistor with a lower probability of sealing.

Design and test a single leg that implements a PneuNet actuator

The soft actuators are made from a casted elastomeric silicone. The generic procedure for casting elastomeric silicone in a mold is as follows:

1. Pour Silicone (Ecoflex or Dragonskin) Part A and Silicone Part B by equal parts by weight into a mixing container
2. Mix two parts together thoroughly
3. Place mixed parts into a vacuum chamber until the mixture is completely clear and all air bubbles have escaped
4. Pour elastomer material into the molds until full
5. Seal molds if needed
6. Let mold sit for cure duration listed on the container

A single PneuNet actuator leg consists of an upper and lower section laminated together. To produce an actuator, we 3D-printed molds and casted the silicone molds in a three-step process:

1. Cast the molds of the upper and lower section of each chamber (*Figure 16*)
2. Seal the upper and lower sections together for each chamber (*Figure 17*)
3. Bind the two chambers together with a pneumatic resistor between them (*Figure 18*)

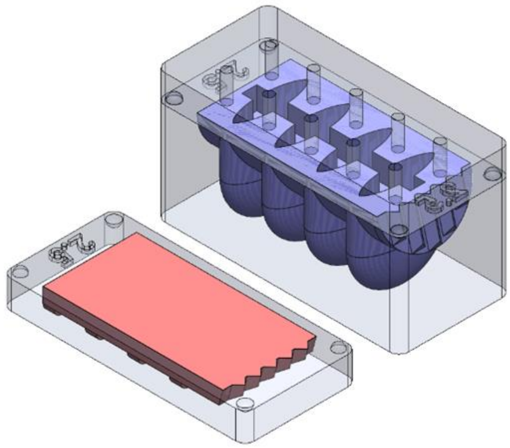

Figure 16: Casting Sections

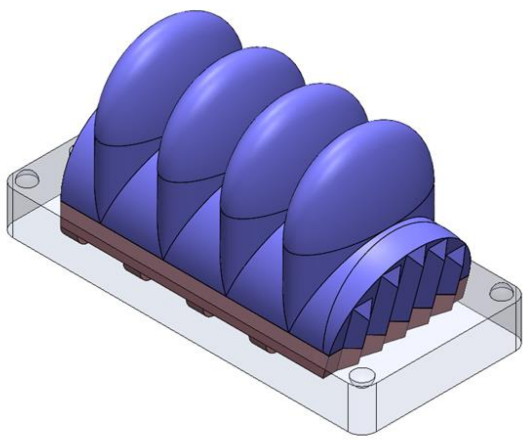

Figure 17: Combining Sections

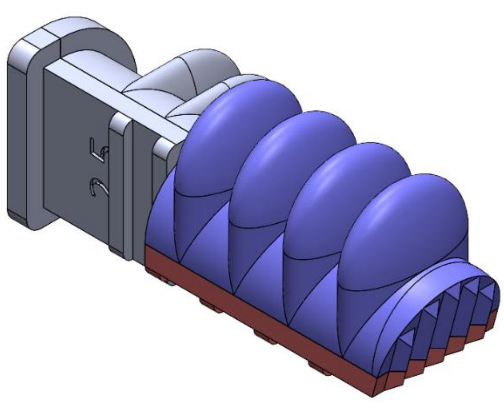

Figure 18: Attaching Two Units

Iterate over the leg designs (shown in *Figure 19*)

Our final actuator used Dragonskin 20A, which was determined to have an appropriate hardness for our leg design. We experimented with wall thicknesses between 1.5mm to 3.25mm and found that a wall thickness of 2.5 mm performed best for a material hardness of 20A silicone. Our final actuator had two fins on the hip joint and 4 fins on the knee joint, as this produced the best actuation motion for effective locomotion with multiple gaits.

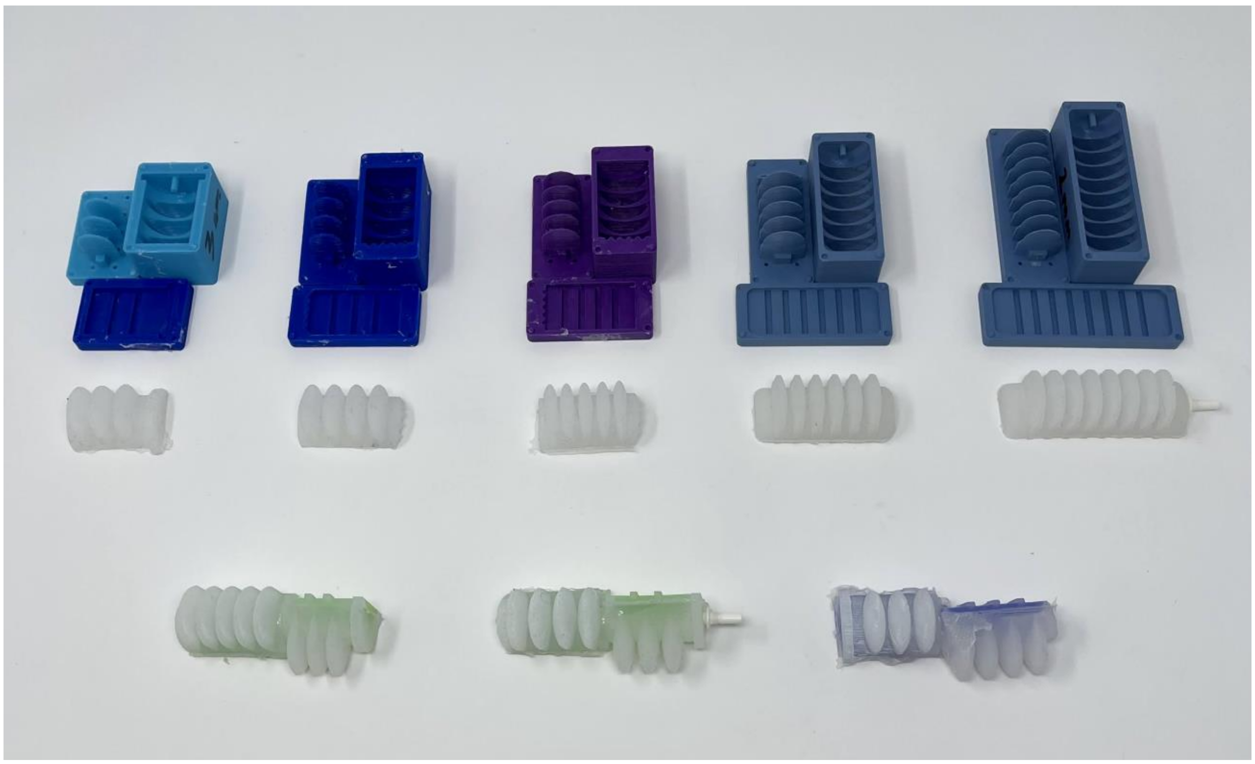

Figure 19: PneuNet Casting Iterations

Construct a hexapod soft robot with the final leg design

To attach several PneuNet actuator legs together to form a hexapod, we designed a body, shown in *Figure 20*, to host the legs and relevant electronics. The body holds the legs in place such that each leg is equidistant and angled away from its neighbors by 25°. Additionally, each leg mount is angled upward by 2.5° to avoid dragging the body on the ground. There is also a hole for a balloon to be mounted, that would inflate when the robot is deployed to prevent it from landing on its back. A rectangular inset in the base is sized to mount the controlling PCB.

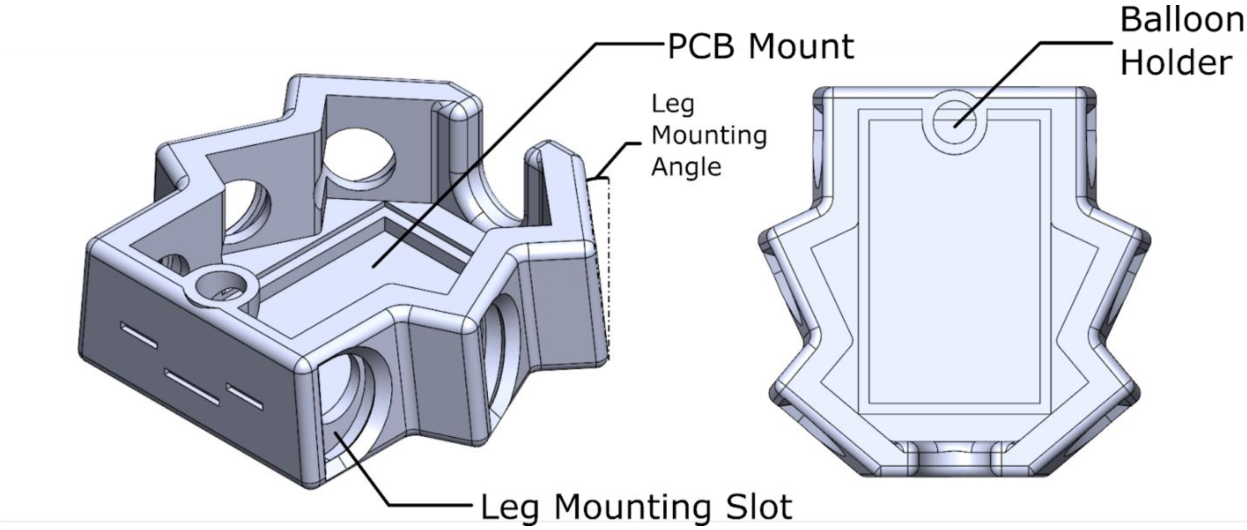

Figure 20: PneuNet Body

3.3 Software Control

The multi-robot system was teleoperated to provide the simplest control scheme and to ensure safety when deploying payloads and driving the rover, as the operator would be able to react real-time to any unexpected circumstances. The robots are controlled over radio with two separate controllers, one for the rover and one for the drone, and a laptop as seen in *Figure 21* and *Figure 22*. The drone launch remote control functionality is achieved using an XBee module. The launch platform then controls the servos with an Arduino Uno that interprets the commands from the Xbee. In addition to sending commands to open or close the launch platform drone, the user can also reprogram the servo values for the open and closed states of the launch platform. These servo values are stored in flash memory such that the optimal servo values persist after any system restarts once the user sets them.

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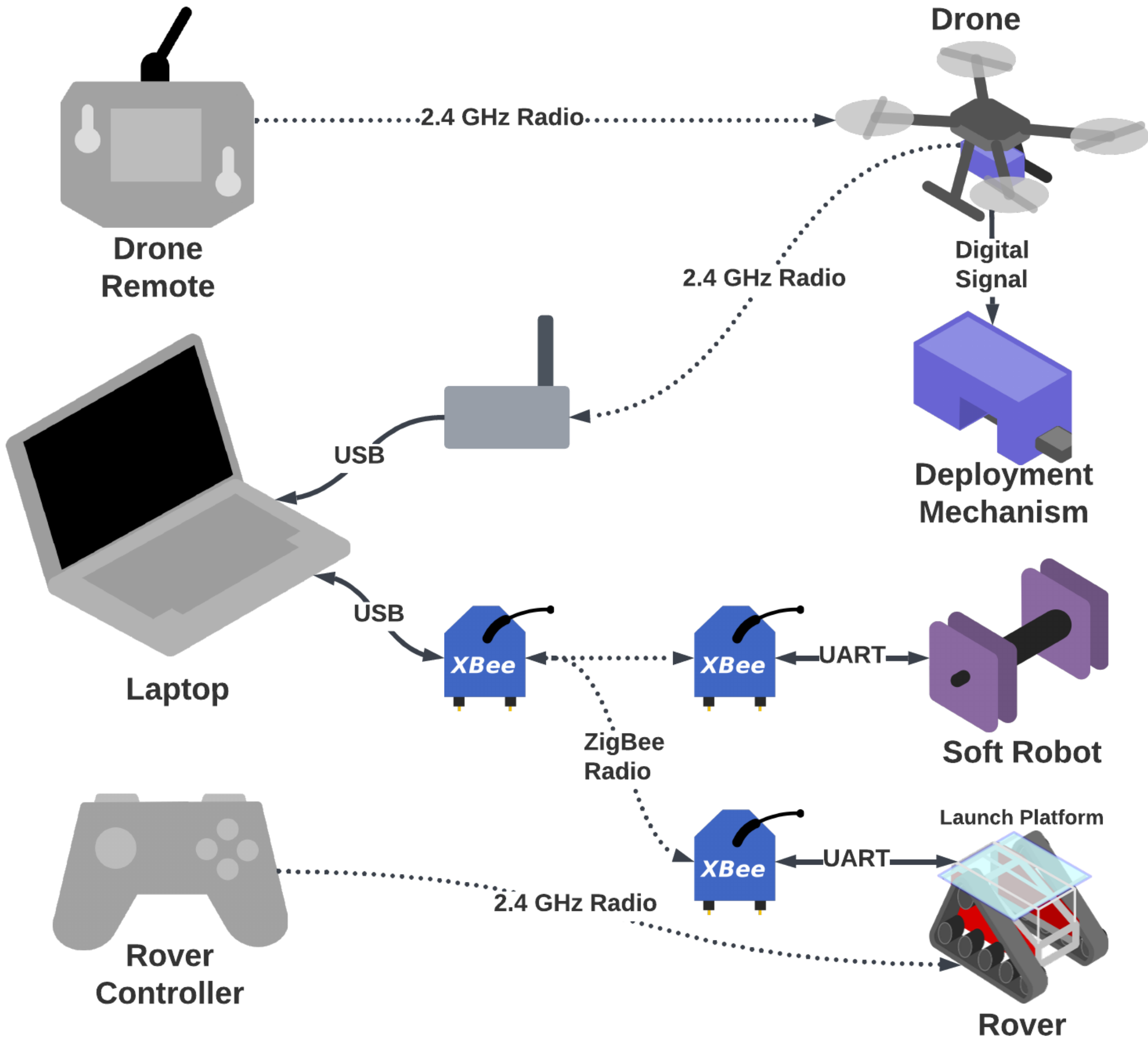

Figure 21: System Control Scheme

The Xbee modules for the launch platform and the demining robot are connected to their respective microcontrollers over UART. They communicate with a leader Xbee plugged into a USB explorer module on the laptop over the ZigBee radio communication protocol. The XBee modules allow us to control the launch platform and the demining robot remotely using a serial connection with the explorer Xbee using the XCTU software on the laptop.

We programmed the demining robot to have two-way communication with the laptop using the XBee modules. The demining robot could receive commands to perform motion patterns stored in lookup tables as well as receive commands to change its functionality. The demining robots have an Itsy Bitsy micro controller to interpret the commands as passed through the Xbee and perform the motion. The demining robot's motion patterns can modified remotely in real-time using the XBee communication with the laptop.

The Tarot 650 drone is controlled using its Taranis QX7 remote controller over 2.4GHz radio, and it communicates its state data to the laptop over 2.4GHz radio using the attached USB radio receiver. The drone runs the Arducopter flight control software on its mRo V2.1 flight controller which can be programmed and monitored by the Mission Planner ground control software on the laptop. We programmed the drone using Mission Planner to transmit a digital output controlled by a switch on the remote control unit to the deployment mechanism. This digital relay switch allows us to pass the message to deploy the robot from the remote controller through the drone to our deployment mechanism.

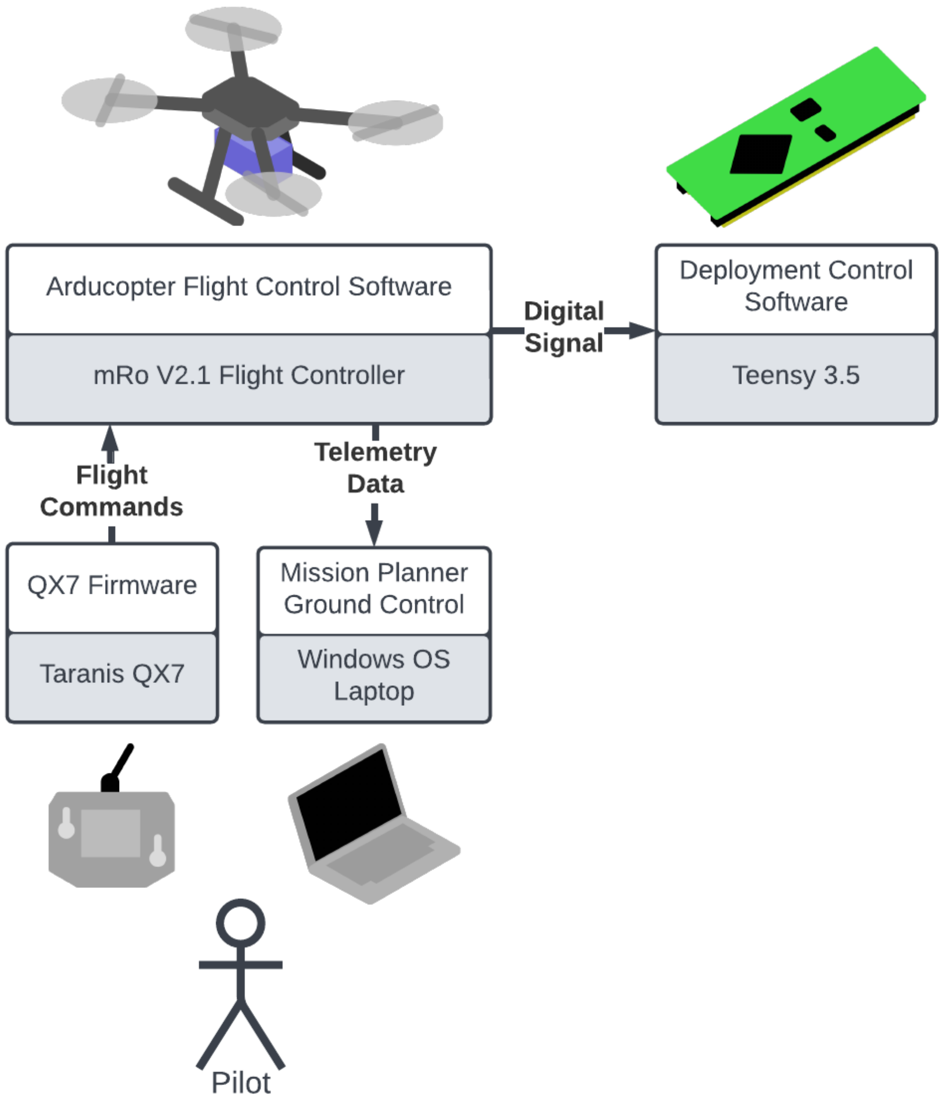

Figure 22: Flight Software Stack

4. Results

We used several pieces of criteria to evaluate the multiple types of actuators and robots that were developed over the course of the project, shown in Table 3: Evaluation criteria of each prototype *Table 3*:

	Maneuverability	Durability	Simplicity	Payload Capacity	Terrains	Range
Flasher Roller	Forward: 12 cm/min Turning: 70 deg/min	0-10m	# of actuators: 4 **Manufacturing time: 14 hours**	100 g	Floor Turf	~1 meter
"Pixar" Bot	Forward: 112.5 cm/min Turning: 700 deg/min	~1-2m	# of actuators: 3 **Manufacturing time: 14.5 hours**	200 g	Floor	~37 meters
PneuNet Hexapod	Forward: 27 cm/min **Turning:** N/A	~1-2m	# of actuators: 6 **Manufacturing time: 12.75 hours**	200 g	Floor	~1 meters
Bellowed Hexapod	Forward: 0 cm/min Turning: 0 deg/min	~1-2m	# of actuators: 12 **Manufacturing time: 18 hours**	4500g	N/A	N/A

Table 3: Evaluation criteria of each prototype

Maneuverability was evaluated by measuring the speed of each prototype moving forward (cm/min) and the speed of each prototype turning (deg/min). Out of the four pursued prototypes, three of them were able to move forward and turn. Of these three bots, the "Pixar" bot moves the fastest with a forward speed of 112.5 cm/min and a turning speed of 700 deg/min.

Durability/Robustness was evaluated by dropping the robot repeatedly from heights ranging from one to two meters, similar to the height that they would be dropped from a drone, and qualitatively reporting the results. All four of our robot prototypes survived repeated dropping, however, qualitative analysis of this testing ultimately ruled out some of the robots as an option, as the robots must be able to not only survive the drop, but also be able to either self-right or locomote on multiple sides. For example, the feet of the "Pixar" bot were printed out of PLA, they were more prone to breaking when dropped. Additionally, the "Pixar" bot most frequently landed in a configuration that was not capable of locomotion, and the robot had no system to right itself. Similarly, the Bellowed Hexapod experienced failures at the ball joints due to the rigidity of the PLA, despite the promising levels of robustness initially shown. The Flasher Roller also experienced failures within the rigid PLA structures (along its axles) after repeated dropping. In contrast, the PneuNet Hexapod is made from elastomeric materials and a sturdy thermoplastic body, making it highly impact resistant. Additionally, the PneuNet Hexapod can right itself with a ballooning mechanism on its back, allowing it to locomote after any drop. Given these results, the team believes the PneuNet Hexapod performs the best with respect to this particular parameter.

Simplicity was evaluated through the manufacturing time and the number of actuators used.

Payload Capacity was evaluated by adding weight to each prototype until the actutators could no longer actuate or until the rigid materials started to break. Although the Bellowed Hexapod could carry the heaviest payload, it was unable to locomote in any situation. Additionally, the Pixar Bot was able to carry the second heaviest payload with the PneuNet Hexapod able to support 50g less.

We also evaluated the performance of the moving prototypes on multiple **terrains** by observing if there was any net movement within a time frame of one minute. Of the three moving robots, they all were able to locomote on a lab floor/table, however, only the Flasher Roller was able to locomote on turf.

Range was evaluated through an estimated 2A current draw from a 1100 mAh battery and the different speeds of the robot. This estimate was based upon the identical electronics systems found in all untethered prototypes, and as we always ran the micro-pump at 100% power, the power consumption over time was almost identical from system to system. Due to the speed of the “Pixar” bot, it would be able to traverse approximately 37 meters as opposed to the Flasher Roller and PneuNet Hexapods that could only traverse approximately one meter.

5. Discussion

In this research-oriented MQP, we developed a set of soft deployable robots and different configurations of robot systems as explorations into addressing the problems associated with demining. In this section, we discuss the outcomes, comparisons, and processes of each to understand how this work can be interpreted to improve future work.

5.1 Flasher Roller Design Deficiencies and Impact

This MQP was a research-focused project which explored novel applications of robot teams and soft robots in the field of demining. Our first objective was to create a proof-of-concept robot. We accelerated our project timeline to produce the Flasher Roller robot to meet the deadline of the International Soft Robotics Conference. This methodology required us to bypass the traditional waterfall development process with a longer ideation phase and slower production in exchange for a more experimental agile development process. As a result of this rapid development process, the design had significant deficiencies in locomotive abilities that were noted during preliminary testing of the robot. However, the Flasher Roller still presented a novel origami actuation method that was robust enough to survive a drop and move regardless of the landing orientation during deployment. We found success in these characteristics, even though the Flasher Roller failed to create the rolling locomotion that was intended.

5.2 Difficulties With Untethering Flasher Roller Design

As with most soft robots, many difficulties arose when moving away from tethered testing to an untethered configuration. The Flasher Roller actuators found much greater success in motion when on a tethered prototyping system than when it was untethered. Once the robot was untethered and subjected to the weight of the electronic and mechanical components associated with operation, the actuators were unable to produce efficient motion. This does not mean the Flasher Roller is incapable of being used in this capacity, but this robot would require more investigation to overcome these difficulties posed by an untethered system. This could be mitigated in the future by designing better tests of the prototyped designs,which focus on the functional requirements of the actuators when put on an untethered body rather than the simple speed tests of the tethered actuators.

The Flasher Roller design and testing process provided significant learning opportunities and lessons that were carried into the design phases of the later soft actuators. We worked to improve our design criteria and testing methodology with our second wave of robots after experiencing the difficulties brought on by the Flasher Roller robot. We approached this by analyzing the flaws of the Flasher Roller system, and testing for performance under these niche conditions (e.g. testing with extra load of battery, testing motion on turf as well as tabletop).

5.3 Manufacturing Airtight Pneumatic Actuators

Maintaining airtight seals in our pneumatic system proved to be challenging when developing our actuators. During testing, all of our actuators suffered from leakages to varying degrees, with the Flasher Roller being especially susceptible to this failure mode. This is due to our fabrication process, which features several steps that are prone to error. First, we encased the origami pattern in a heat-sealable TPU-coated textile bag. Then we used a heat press to seal the bag along the edges before puncturing a hole in it to thread the axle through. The puncturing process creates a possibility for leakage because it would fray the textile bags and create openings for air to escape. Finally, silicone gaskets were fastened to seal the hole around the axle. If the silicone gaskets were not properly fastened, the potential for unwanted leaks increased. Due to this long manual process, there was a high failure rate, where more than half of our actuators leaked. In addition, repairing the actuators was nearly impossible and additional leak-prevention methods limited actuation distance. We considered this a fault of our manual manufacturing process, pushing us to investigate more automated solutions.

In contrast to the flasher muscles, the bellowed actuators are manufactured with little human interaction.As a result, they benefited from mass manufacturing capabilities, repeatable quality, and modular actuator products. However, this manufacturing method was prone to leaks due to 3D printer faults. Poor layer adhesion and under extrusion caused unrepairable leaks between the printed layers. Printing airtight bellows requires extensive tuning of 3D printing parameters, which was difficult to achieve given variations between filaments and printers. Fabricating Pneunet actuators was a middleground between the laborious manual construction of the flasher muscle and the automated bellowed actuator. This methodology used the 3D-printing process to create molds, with a manual step to cast the actuators. This process benefited from

3D-printed molds, which acted as a guide to avoid human error. The 20A DragonSkin silicone is a more resilient material than thermoplastic filament because it does not rely on layer adhesion. As a result, the actuators only exhibited occasional leaks from issues in sealing a seam or from an air bubble when casting. In addition, silicone is cohesive, allowing us to repair leaking modules by applying another layer. Therefore, the Pneunet actuators were the most reliable in airtightness of the three actuators.

Another key element of pneumatic actuator sealing is their connections. When creating a pneumatic system, the limiting factor is the flow rate of the pump. As such, it is important to use the correct fittings and tubings for chosen pressure and flow ratings. Small tubes restrict airflow and large tubes can create loose seals. This was a major issue in early renditions of the Flasher Roller, which forced us to reconstruct it many times. Flow can also be diverted to each leak in the system which reduces the overall performance of the robot. The more connections and actuators your system has, the more opportunities for leaks arise.

5.4 Deploying a Soft Robot

Deploying a soft robot was a major roadblock in the development of our robot system due the uncertainty surrounding it. When dropping a payload from a drone, there are several potential points of failure that can inhibit deployment and robot functionality, such as potential damage to the robot after dropping, landing in the wrong orientation, or even jamming of the payload in the deployment mechanism. After air deployment, the robot can be damaged by impact, such as the damage incurred by the fragile flasher muscles on the Flasher Roller. Disorientation is an issue to robots that have a need to land in a certain position or direction. The bellowed hexapod robot revealed issues with designs that must land in one orientation to operate.

Deployment can also fail when disengaging from the robot. During our experiments, we found that our original deployment mechanism failed due to its tight tolerancing and lack of adaptability to robot modifications. During experiments, we changed from our initial, larger deployment mechanism to a second, smaller deployment mechanism that relied on a tether system rather than a direct rigid interface. By implementing flexible components into the deployment mechanism, we could adapt the same system to multiple robots.

5.5 Discontinuities with Rover Progress

Since MQP projects only last for one year, information on the previous project is passed down to the next generation of students. This can be a difficult and frustrating process, especially when the project focus shifts between each year. When we started this project, the rover had been reverted to a previous state, without the autonomous navigation developed by prior teams. This forced us to use tele-operated travel instead of our anticipated autonomous mode. The rover was an instrumental tool in creating a long-range platform for our system, and we found success in the remote control of the rover across many surfaces. Unlike previous teams, we based our work around a fully-remote controlled system rather than prioritizing autonomous functionality. When working around landmines, our approach favored usage of a human operator in order to maintain safety of expensive equipment.

However, the rover could have its functionality expanded in the future to converge with the work done by the previous team, but that would require an overhaul of the electronics. The system is based on an old Hero board which lacks significant documentation and support abilities, and could benefit significantly from being streamlined by more commonly used and easier to interface systems, such as Arduino or ROS.

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5.6 Modeling Soft Robotic Actuators

In our MQP we did exploratory research into the use of soft robotics for demining through rapid prototyping. Our mechanical designs were created from an iterative approach, 3D printing and testing prototypes experimentally rather than simulating models of our actuators. Our approach focused on creating a breadth of ideas, each requiring us to quickly design, prototype, and manufacture various versions for use on our demining robots. This methodology created issues when extrapolating our experimental results beyond our initial tests. One example of this was our untethering process for our soft robots, where we first experimented with tethered prototypes. In these initial attempts, we analyzed the outcomes without creating simulated models for understanding the effects of untethering (increased weight, size, and a). Without modeling key characteristics such as actuator speed, force, and task space we were blind to potential pitfalls. We worked to reverse engineer our difficulties with the actuators to make new iterations rather than mathematically determining the improper characteristics. Because of this, we encourage future MQP and research teams creating soft robotics to use modeling tools such as SOFA (https://project.inria.fr/softrobot/) to characterize their actuators before moving forward with fabricating iteration after iteration of tweaks. In addition to professional modeling tools, pneumatic actuators could be modeled by comparing the fluidic circuit to an electronic circuit: actuators could be seen as capacitors with tubes between them as wires or resistors depending on their cross-section surface area. Proper characterization of actuators is an essential step to creating soft pneumatic actuators which will create significant locomotion.

5.7 Using a Drone on WPI Campus

As this project implicated the need to fly a drone, there were necessary prerequisites the team needed to gather in order to use the drone on WPI's campus. We have chosen to include the necessary steps to accomplish this in the case future MQP teams are also required to pilot the drone.

1. Obtain a Remote Pilot in Command (RPIC) license by taking the Unmanned Aircraft General Exam, commonly called the Part 107 certification after the legal section regarding drones that it covers. The exam costs $175 as of 2022.
2. Register the drone with the FAA. When flying, the WPI guidelines for drone use state that the RPIC must have their certification on hand.
3. Notify WPI police prior to flying. Usually during the booking process.

An important technical note is that WPI is within the Worcester Airport Class D restricted airspace, but drone missions are automatically approved within this airspace for missions under 200 ft of elevation. As such, the restricted airspace is not of concern, so long as the RPIC maintains flight below this height.

5.8 Robosoft Conference Submission and our MQP Direction

We successfully published a paper in the Robosoft 2022 IEEE Conference as part of our MQP, which was a benchmark set at the outset of the project that guided our decision process throughout the project. For example, the first term of the project was spent rapidly prototyping designs to quickly develop a minimally functional product, such that a paper could be written on the results of said testing. While the robot had significant deficiencies in ability, it served as an exploratory investigation of a novel actuation method. We believe that future MQP teams can continue this trend of submitting publications based on their work and benefit from some of the same lessons that our teams did, but also caution that it requires significant planning and is not necessarily completely compatible with the 4-term MQP setup that is traditional of WPI. This was due mostly to the fact that the publication submission was completed within the span of a single term, so careful thought had to be put into what work would be accomplished within the other 3 terms.We took away many lessons from our fall semester's work when it came to our second semester but we had little to carry over from our Flasher Roller robot used for our publication, as the work accomplished in the second semester was someone disjoint from the first semester work as it pursued entirely different actuation methods. However, the publication of our work in the Robosoft conference was certainly a highlight of our MQP.

5.9 Future Work

We encourage future teams to continue our work on solving real-world problems with heterogeneous robot teams using our equipment. We found that our soft robots were valuable tools to explore their application in demining, but future work should build upon these initial steps. There is much more research and exploration to be done for creating mobile, untethered soft robots. A challenge we encountered was that our actuators would show great promise in prototypes but were overburdened by the electro-pneumatic control system. The Arduino, Xbee, micro pumps, and solenoids needed to untether and remote control the actuators were heavy and relatively expensive. The actuators would be extremely low-cost, with the price point being close to the material cost. The electro-pneumatic control scheme we used could cost close to $50. It could be of great interest to future teams to investigate how these components could be replaced with lower-cost and lighter solutions to enable soft robots in the field.

We leave the rover and drone in a functional state that requires manual operation. The rover is solely equipped to drive and has no sensors nor further control. We found difficulty in programming the outdated Hero board on the rover and instead used an Arduino and Xbee setup, similar to our demining robot, to control the servos which held the drone in place. Future teams could choose to either use the rover as a manually-controlled mobile base station in this respect or could implement a further degree of autonomy.

The drone runs Ardupilot flight control software. This gives it the capability to run an entirely autonomous mission. We chose against this out of concerns for safety and for the simplicity of our project. Future teams could attempt these autonomous missions and can use the Mission Planner software to implement further functionality for the drone. We had used the Mission Planner software to program the drone to accept a switch from the remote control unit as a relay which toggled a digital output on the flight controller. We used this digital signal to indicate when it was time to release the demining robot to our deployment mechanism. This relay pin is merely one small example of the functionality that could be implemented on the drone with Ardupilot and Mission Planner software. Another example could be using IR to indicate to the drone the exact position of the Rover such that the drone could land on top of the Rover on top of the IR emitter on the base plate.

6. Conclusion

The OREO'd MQP was designed on the premise that a heterogeneous robot team with a soft robotic hybrid is a plausible and effective solution for demining. Our approach improves previous solutions by integrating a multi-robot system to highlight the strengths of both conventional and soft robots. The drone and the rover allow for long range movement and are capable of deploying the soft robotic hybrid at points of interest, which can then locomote to the detonation site. While the system presented within this paper could not detonate a landmine in its current state, our approach demonstrates significant promise as to how soft robotics can be used outside of the laboratory to solve real world problems.

The work that the team accomplished throughout the duration of this project leads the team to believe there is still room for exploration and improvement of the resulting system. As mentioned, the current soft robot could potentially locomote to a detonation site, but it would be unable to actually detonate a landmine. Future extensions of the work presented could investigate how small detonation sources could be added to the soft robot to demine. Additionally, more investigation could be performed into how to improve the locomotion speed and efficiency of the actuation methods presented herein.

Throughout the duration of this project, the team designed, built, tested, iterated upon, and reported on multiple novel soft robotic actuators, created multiple successful intelligent payload soft robots for deployment, and demonstrated that three heterogenous robots could be seamlessly integrated into a single robot team capable of accurate and efficient demining.

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