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Salamanderbot: A soft-rigid composite continuum mobile robot to traverse complex environments

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***Abstract*— Soft robots are theoretically well-suited to rescue and exploration applications where their flexibility allows for the traversal of highly cluttered environments. However, most existing mobile soft robots are not fast or powerful enough to effectively traverse three dimensional environments. In this paper, we introduce a new mobile robot with a continuously deformable slender body structure, the SalamanderBot, which combines the flexibility and maneuverability of soft robots, with the speed and power of traditional mobile robots. It consists of a cable-driven bellows-like origami module based on the Yoshimura crease pattern mounted between sets of powered wheels. The origami structure allows the body to deform as necessary to adapt to complex environments and terrains, while the wheels allow the robot to reach speeds of up to 303.1 mm/s (2.05 body-length/s). Salamanderbot can climb up to 60-degree slopes and perform sharp turns with a minimum turning radius of 79.9 mm (0.54 body-length).**

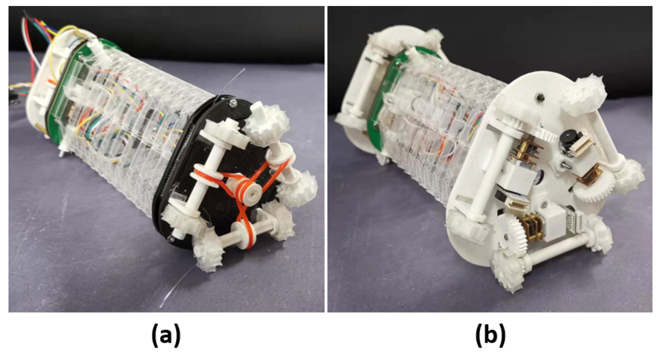

Fig. 1. (a) Salamanderbot with belt transmission design, (b) Salamanderbot with gear transmission design.

I. Introduction

Continuum manipulators present promising potential as robotic tools because of their ability to safely conform to the shape of the objects and environments they interact with. Traditional manipulators are usually rigid and heavy, with limited degrees of freedom, which reduce their dexterity in complicated, cluttered, or maze-like environments. Continuum manipulators are able to perform shape changing on their structure, such as length, bending angle, and bending direction continuously along their arc length, which makes them possible to negotiate much more complicated environments. Consequently, continuum manipulators are widely used in flexible arm research. However, considering their versatility continuum robots also offer great potential to be configured as mobile robots for search-and-rescue applications in unstructured environments. In this work, we introduce such a mobile robot, called Salamanderbot, consisting of an origami continuum robotic module and an active wheel system to offer flexibility and light weight to navigate cluttered environments.

Recent research developed continuum manipulators with pneumatic [1][2], [3], hydraulic [4], and cable-driven [5], [6] actuation. Pneumatic and hydraulic actuation methods are widely utilized to design and fabricate continuum manipulators. However, for these two actuation methods, a pressurized fluid source is needed, which means tubes, valves, and pumps are essential. Mobile robots, especially for search and rescue, can be much more efficient without a large cross-section, heavy payload, or external tethers. Thus, cable-driven actuation is a better choice since it can be readily operated with on-board electric motors powered by small rechargeable batteries. There exists a large body of research about cable-driven continuum manipulators, including design, fabrication and modeling. Because of the accuracy of motor driven system, forward kinematics, inverse kinematics and dynamics model of cable driven manipulators have been generated and validated [7].

Origami is known as the traditional art of folding a two-dimensional substrate, typically paper, in a crease pattern to create complex three-dimensional structures. Origami is considered as a promising technology to create light and deformable structures, with a large design space to generate active and passive degrees of freedom, and with considerable resistance to undesired deformations [8], [9]. Considering these unique features, origami is recently finding use to develop lightweight, low-cost, and deformable robots [10], [11], [12], [13].

This paper introduces the design, fabrication and experimental evaluation of a continuum origami mobile robot, called Salamanderbot. Based on our previous research [14], [15], a compact triangular-section cable-driven origami module is developed. The module is controlled by three miniature electric motors fixed on a custom control circuit. Each motor is connected to a cable embedded in the module, thus the module is capable of bending in 3-D and change its length. In addition, three sets of active wheels are distributed around the module on both ends to conduct locomotion. This design enables the locomotion to be decoupled from body

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deformation (used for steering and obstacle avoidance).

In our previous research [14], we used a similar origami-inspired approach to design and fabricate a mobile origami snake robot (OriSnake). Inspired by the biological snake, OriSnake can conduct snake locomotion following serpentine and sidewinding gaits. Because of the light weight, snake locomotion is not able to achieve high speeds. In fact, the highest speed we generated before with the origami snake robot is 40.5 mm/s limited by the friction between passive wheels and ground. Since snake locomotion need to follow certain gait patterns [16], [17], [18] in order to move the robots, propulsion and body deformation are inherently coupled. This limits their performance as mobile robots in narrow spaces, because there is not always enough space to execute snake-like locomotion gaits.

Similar to snakes, salamanders are also very flexible animals with long deformable slender bodies, while the limbs conduct locomotion instead of body undulation, so they do not have to generate certain pattern of deformation to move. Instead, the flexible body only helps to change direction to potentially traverse narrow paths when they move forward. Inspired by the unique physiological structure of salamander, we designed two groups of active wheels with different transmission systems to address the problem as shown in Fig 1. In this case, instead of generating locomotion, the continuum module is only used to deform the body for traversal, and the active wheels provide the locomotion. Consequently, unlike snake-like robots, the Salamanderbot does not need multiple continuum modules to move in coordination. In fact, a single module is as fast as any other number of modules, while keeping a smaller equivalent cross-section to navigate complex environments.

Experiments are conducted to test the performance of the robot. Our results show that, Salamanderbot can achieve a maximum speed of 226.4 mm/s, climb up to 60.3 deg slope, execute sharp turns with a minimum radius of 79.9 mm (0.54 body length), go through a maze which a 4-wheeled rigid mobile robot with the same length can not achieve, and keep operating even though it turns over or randomly tossed. Furthermore, with more modules connected in series, the assembled robot offers the potential to achieve better stability in climbing ramps or going over obstacles.

In summary, the contribution of this work is developing a flexibe origami mobile robot with the properties below:

- Light weight, low cost, and deformable;
- Relatively high maximum speed and climbing ability;
- Extremely fit for narrow and complicated maze-like terrain;
- Modular design, with the potential of completing more complicated tasks when serially assembled.

II. Design and Manufacturing

The Salamanderbot modules have two main actuation systems: an origami continuum bending actuator and a low-profile wheeled propulsion system. The origami continuum bending actuator, which can also extend and contract, allows the Salamanderbot to change its shape in order to wind its way through constrained environments. The wheeled propulsion system provides the Salamanderbot with a locomotion capability that will work even in the narrowest of environments, without needing the space to perform serpentine locomotion.

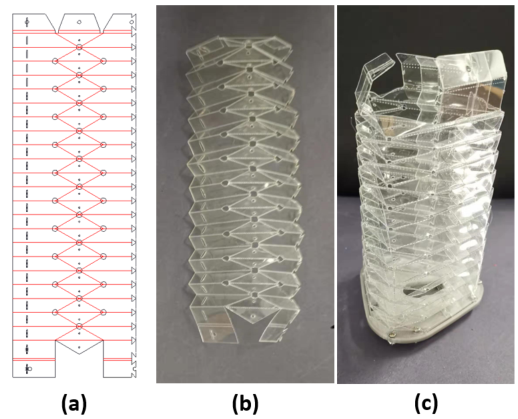

Fig. 2. (a) Yoshimura origami pattern, (b) Folded Yoshimura origami pattern with PET sheet, (c) Combine three pieces of (b) to get a triangular origami module.

A. Origami Module

The center of the Salamanderbot modules consists of a cable-driven origami bellows continuum bending actuator, which represents an improvement upon our previous work.[14] In the design and testing process of the OriSnake, the precursor of Salamanderbot, we encountered several problems. First, the motor ability of OriSnake depended entirely on extrusion between each other of the joints. Once, due to manufacturing error, the bottom side of a module warped, then the torsional rigidity of the module would be too high to make the next module fully touch the ground, which might end up block the snake's movement. Next, it was precisely because OriSnake consumed most of its energy on twisting, leading to an abbreviated available power , that finally made its velocity much slower than other snake robots. Besides, the snake's joints could not work independently, meant that they should be combined together and use a master board as main controller, which made the snake in a large scale. These two drawbacks determined that the snake was lack of practical value. Based on the shortages above, the main improvements we make to Salamanderbot's component modules are as follows: three pairs of active wheels are added to each module to directly drive the body forward and backward through gears and wheels, so that the motors originally used to simultaneously change the orientation and generate forward torque can be responsible for only controlling the direction now. Such a design solves the first and second defects at the same time. Also, the PCB layout is re-designed, and this version reduces the size by half and expanded more interfaces to facilitate the implementation of motion control, remote operation and other functions in the future.

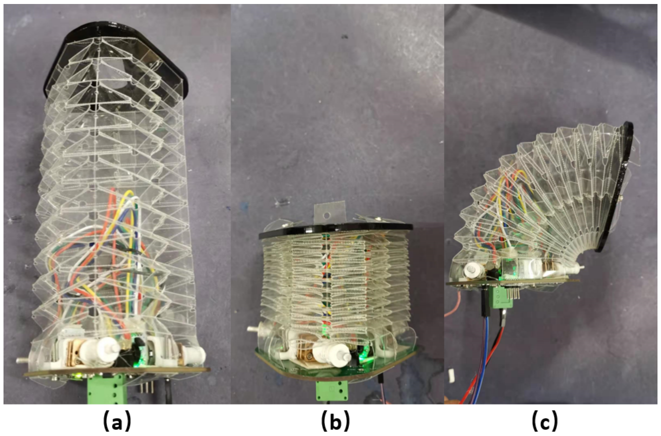

Fig. 3. (a) Fully stretched origami module, with the length of 148mm, (b) Fully compressed origami module, the length is 57mm, 38% of the maximum length, (c) Maximum bending angle of our origami module is 106 deg.

1) Mechanical design: Salamanderbot is made of a 3-DoF origami module. Each module is an independent joint, and when one end is fixed, the other side of the module has an approximately hemispherical workspace. It was constructed out of origami continuum bending modules based on our previous work [14]. The flexible mechanism of these modules consists of the Yoshimura pattern: a bellows-like origami crease pattern, as shown in Fig. 2. To establish such a mechanism, three pieces of 7-mil (178-μm) thick folded plastic (PET) (following our origami fabrication process [10], [15]) are assembled through tab and slot patterns. A sheet of 1/8" thick laser-cut acrylic and a module control circuit board are connected through the origami body. Three N20 gear DC motors (gear ratio 1:150) are bolted on the bottom side of the control circuit board to actuate each module. These motors have 3-D printed spools on their output shafts, which are connected to nylon fishing lines as cables. These cables are attached to the acrylic plate on the other end of the module. In addition, the cables are threaded through a series of holes in the origami body, ensuring that the cable always remains perpendicular to the control board and motors and maximizing the bending moment for the module. The 3-D origami module is shown in Fig. 3. The maximum length of the module is 148 mm. In our previous work [15], the axial and torsional stiffness are measured, also, the forward kinematic and inverse kinematic model of our cable driven continuum origami actuator is generated assuming the shape to be a circular arc in 3-D space. Some mechanical properties of the original module are listed here: the total weight is 110 g, integrated with actuation, sensing, and control systems. The origami structure has a 7.311 Nm/rad (0.128 Nm/degree) torsional stiffness while being capable of bending in two directions and changing arc-length down to a fully collapsed state. The module is capable of passively supporting a 1-kg mass at its tip, or 4 additional serially connected modules, bending approximately 6 degrees.

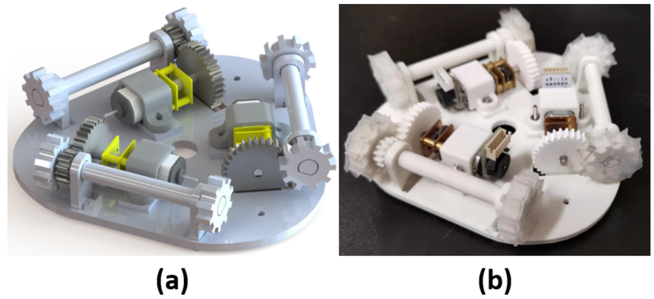

Fig. 4. (a) CAD rendering of gear transmission design, (b) Fabricated gear transmission design.

2) Electrical design: When a motor retracts its cable, while the other two keep still, the differences in cable length will clearly cause the origami module to bend towards the shorter cable. Identically, if all three motors retract their cables, the entire module will contract axially. The motors and cables are mounted in a triangular pattern, giving each module a full 3 degrees of freedom (DoF) in the form of bending curvature, bending direction, and segment length. More detail the kinematics of the module can be found in our prior work [15]. The controller board contains three channels of motor drivers, each of which being able to receive encoder data from the motor and implement low-level feedback control on the cable lengths.

Each separate module contains embedded electronic system, including a 32-bit ARM Cortex processor as the main controller and three sets of motor control chips. Salamanderbot's circuit boards have shrunk in size by nearly half compared with their predecessors, which makes the entire body smaller. Motor sets are placed triangulated on bottom side of the circuit board. By adjusting the motor to pull or release the cable, the module can bend in different directions, thus controlling the movement direction of the module. Specifically, the main controller reads the value of motor encoders, then calculates and outputs the corresponding PWM for the motors according to the codes. This low-level control mechanism has been illustrated in our prior work [15], either. In addition, a SPI interface is extended on the circuit board, which enables each module to be easily configured into slave mode and receive master board's instruction for high-level tasks.

B. Wheel System

We added low-profiled wheels to these origami bending actuators. These wheels would increase the speed of the robot, and allow it to continue moving in tight environments. They needed to be low-profile in order to limit the footprint of the robot and allow it to traverse narrow environments without catching on obstacles. In addition, we wanted these wheels to be on all three faces of the Salamanderbot, to reduce the chances of it from falling into a position where the wheels were not touching the ground, as well as allow it to use vertical surfaces to help propel itself. Powering these wheels without increasing the crosssection of the Salamderbot was a non-trivial engineering challenge.

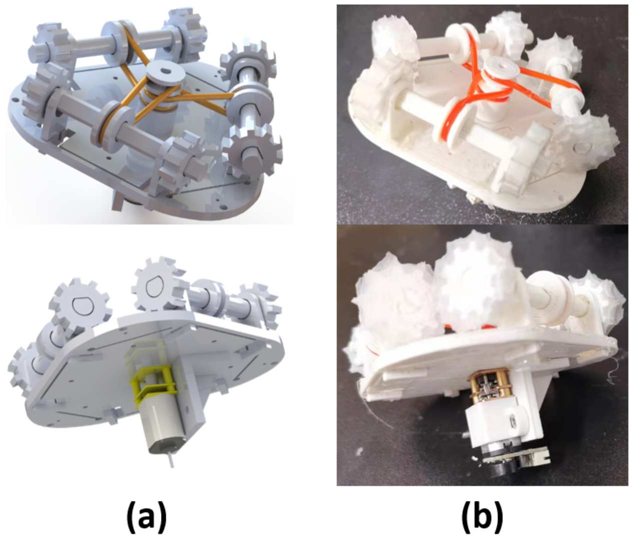

Fig. 5. (a) CAD rendering of belt transmission design, (b) Fabricated belt transmission design.

To solve it, we tested two possible mechanisms: a Gear Transmission method to provide higher speed and torque and a Belt Transmission method to lower the weight and energy consuming of the system.

1) Gear Transmission: One method we designed used three separate motors, each driving a pair of wheels. As shown in Fig. 4 in this system, there are three shafts placed on each side of the triangular section, with two wheels attached on each of them. Every shaft is driven by a DC motor parallel to the shaft through a gear transmission with gear ratio of 31:14. This gear ratio was chosen to increase the speed of the wheels but was limited by the need to limit the size of the driving gear. One problem with this method was the extra weight and power consumed by the three motors. We developed a method that would drive all 6 wheels using a single motor.

2) Belt Transmission: To minimize weight and required electrical power we developed another method to use a single propulsion motor that drives all wheels. To transmit the power of this motor placed vertically in the center of the section, we designed a system of belts transmitting to the wheel axes as shown in Fig. 5.

This system is composed of three shafts placed on the sides of the triangular section using shaft holders. A cylindrical part with three slots is placed on the top of the motor to convey each belt to its shaft. A pulley is placed on each shaft to hold the belt in place. Slots on the cylindrical part and pulley are designed with tread to increase the friction between belt and slot. Every part of this system is 3D printed with ABS (Acrylonitrile Butadiene Styrene) and meant to be easily replaced. The belts are made of Urethane. The solderable feature allowing us to modify the belt length as we required. All the parts fit together without glue or screws, except for the motor holder. The contact surface of the wheels are covered by silicon, producing more friction with the ground and improving the locomotion.

TABLE I
LINEAR SPEED WITH BELT OR GEAR TRANSMISSION SYSTEM ON DIFFERENT SURFACES

transmission / surface	belt [mm/s]	gear [mm/s]
tile	94.3	223.8
paper	91.0	303.1
rubber	85.4	242.3
carpet	80.7	278.8
grass	0.2	202.3

This method allowed us to drive all the wheels with a single motors, but we found that the urethane belts were unreliable, easily wearing out. In addition, they were prone to slippage, reducing the maximum power that could be applied to the wheels.

III. Experimental Results

We performed a range of experiments to test the capabilities of the Salamanderbot, comparing the performance of the two transmission methods against each other. We tested their speeds on a range of surfaces, as well as their ability to traverse a constrained environment, turn over, and climb up ramps of varying inclines.

A. Linear Locomotion Speed on Different Surfaces

Linear speed of the Salamanderbot is tested on five different surfaces, including tile, paper, rubber, carpet, and grass. The voltage of the motors is set at 11.9 V. Modules are tested with belt transmission system and gear transmission system separately, and are expected to go straight-line distance of 2 ft (609.6 mm). For each setting, we conducted the experiment for five times, and calculated the average speed. The result is shown in Table I. Modules assembled with gear transmission travels faster than modules assembled with belt transmission since the maximum load of the belt transmission is limited by the friction between the belts and pulley slots. Sliding between belts and slot will reduce the transmission efficiency. Under extreme conditions, for example on a grass surface, the transmission will not be able to propel the module since friction is too high, which is the reason that the the speed of the Salamanderbot on grass with belt transmission is close to zero. For gear transmission system, the transmission ratio is 14:31, and will stay still unless the gear teeth wear out.

B. Negotiating Narrow Passageways

In this test, a simplified maze is constructed, which is extremely difficult to traverse with a traditional rigid 4-wheel mobile robot. A data cable is connected from the control PCB to a computer through a tiny TTL-USB device, so that we can control the movement of the module from computer with UART to guide the module through the maze. As shown in Fig. 6, the module can successfully navigate the maze in 16 s. The maze is designed to be extremely narrow, that there would be no space for a similar snake robot to conduct serpentine locomotion to go forward. Meanwhile, the sharp

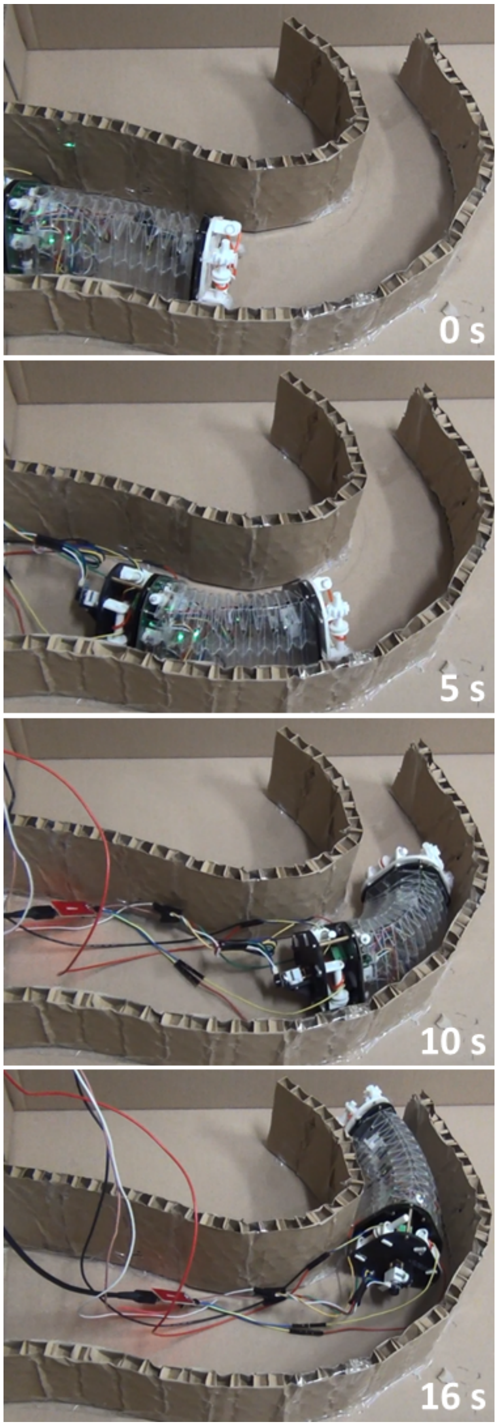

Fig. 6. Salamanderbot going through a maze.

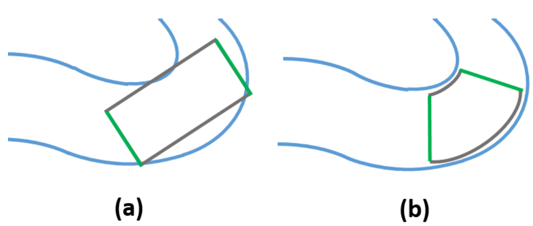

Fig. 7. (a) Overlapping between the traditional 4-wheel robot with the maze, (b) Salamanderbot with the same length can deform and go through the maze.

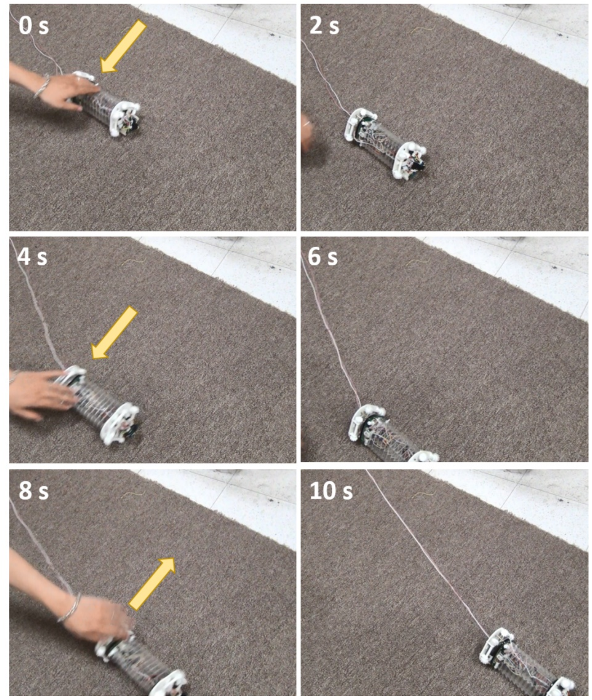

Fig. 8. During the experiment, Salamanderbot was turned over several times, while the velocity stayed the same. The yellow arrows show the turning over directions.

turn near the end of the maze would cause a traditional 4-wheel robot to get jammed as shown in Fig. 7. For such complex environments, which could be found in search-and-rescue or exploration tasks, Salamanderbot is a perfect agent.

Before the experiment, the module is programmed with basic motion primitives so that Salamanderbot can adjust its posture to achieve steering. Although primitives are already encoded, the robot is remote controlled. Thus, the reaction time of human being likely slows down the speed. In future work, tactile sensors and/or a camera can help the robot automatically analyse the environment and execute the proper motion. In this case, we believe that the traversal speed would be comparable to the characterized linear speed values.

C. Robustness through Radial Symmetry

Propulsion wheels distributed on the three surfaces on the module may be considered as a waste of energy when the Salamanderbot is moving on flat surfaces. However, this design makes it possible to overcome some extreme cases. To validate the robustness of the robot, we manually turned over the robot body, or randomly tossed it on the ground. It turns out that the Salamanderbot is still able to travel as usual as shown in Fig. 8. Also, if the three pairs of wheels touch the surface at the same time, which could be a tube or a narrow crack, the propulsion could be able to carry the module up a large incline.

D. Climbing on a Ramp

Light weight feature of origami structure could increase its performance in climbing. Thus we conducted the ex-

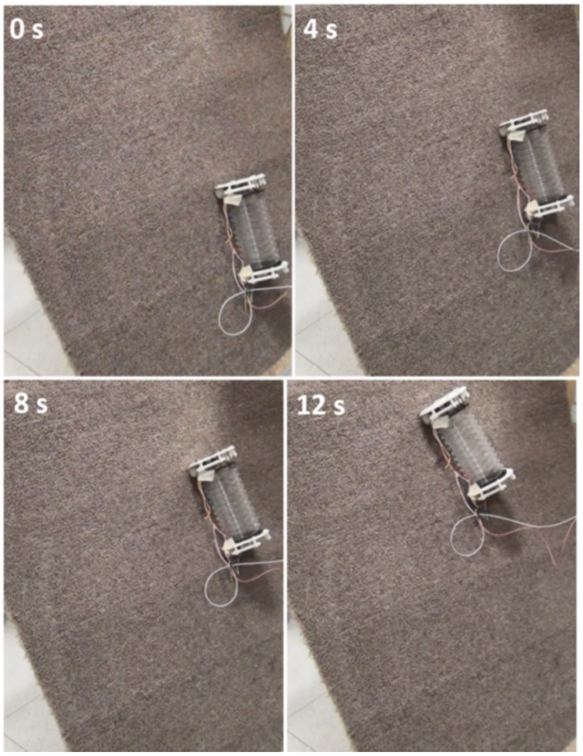

Fig. 9. Salamanderbot climbing on a 60 deg carpet surface slope.

TABLE II
MAXIMUM ANGLE OF CLIMB FOR MODULES WITH BELT OR GEAR TRANSMISSION SYSTEM ON DIFFERENT SURFACES

transmission / surface	belt [deg]	gear [deg]
rubber	18	39
carpet	36	60

periment to test the maximum incline angle of climb for the modules assembled with different transmission systems. In this experiment, a slope with changeable angle of climb is created. The surface of slope is covered with carpet or rubber to create different surfaces with different friction. We define the standard of ”climbability” as ”able to climb 1 ft forward in 30 s”. The result is shown in Table II. Modules assembled with belt transmission system are limited with the maximum load so the climbing ability is also lower than modules assembled with the gear transmission system. For gear transmission system, although it can provide enough force for propulsion, the climbing ability is still limited with the maximum friction between the wheel and surface. As for the gear transmission on rubber, unlike the other three conditions, the module fell off the slope instead of staying still. So technically, for gear transmission, if the friction coefficient of the wheel is higher, the climbing ability of the module will keep increasing. In addition, the stability of the robot could potentially be improved if more modules are connected in series, which is a subject of our future work.

IV. CONCLUSION AND FUTURE WORK

This paper introduced the Salamanderbot, a robot combining the morphological flexibility of a soft robot with the capabilities of traditional wheeled robots. The Salamanderbot combines a cable-driven origami continuum manipulator with 6 pairs of active wheels, which can drive it up inclines and through constrained environments. Salamanderbot can reach a maximum linear speed of 303.1 mm/s, and can travel up a 60 deg slope.

One weakness of the wheels of the Salamanderbot is their small size. While this was a result of the desire to minimize the profile of the robot, it also reduces their ability to effectively come in contact with the environment. We investigated ways of having flexible whegs (wheel-legs) attached to the wheels which could extend farther away from the body of the Salamanderbot while still being able to compress as the wheels turned around. The designs we tested could not find adequate purchase to increase robot performance, but this might be revisited as we seek to expand the environments the Salamanderbot is capable of traversing.

In addition, we plan to update the design of the single module to make it more compact, and redesign the PCB to integrate more function. For example, we will integrate a WiFi module for multiple Salamanderbots so that they can either be separately controlled or serially connected with each other, form a network, automatically assembled with nearby modules, and work together as a multi-segment robot. Considering the possible remote communication failure, we plan to generate connection between adjacent modules, so that the lost module could infer the expected command based on the command or locomotion of the other modules. As a mobile robot, Salamanderbot will also be mounted with sensors and cameras to conduct SLAM With the data from camera or radar and the position prediction from the forward kinematics calculation.

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