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# DESIGN AND MANUFACTURING OF A SIMPLE SOFT CATERPILLAR ROBOT

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## ABSTRACT

Soft robots are increasingly gaining attention not only within the scientific community, but also in various real-world applications, due to their inherent compliance, ease of manufacture and favourable mechanical properties. These robots can manipulate a wide range of objects without the need for precise feedback on position, orientation, force, and torque. Their low elastic moduli make them inherently safe. However, although the field of soft robotics has been well established now, there is still a significantly smaller number of successfully realized applications in the domain of mobile soft robotics.

This article presents a detailed development process of a tethered mobile caterpillar-like soft robot. A single part mould is designed and used to cast the silicone body of the robot with integrated four Shape Memory Alloy tendons, allowing generation of the inching motion pattern. The detailed analysis of the manufacturing process for robot fabrication, with the necessary hardware and software used for robot control is presented. Experimental verification shows usability of presented approach, but also reveals limitations mainly due to insufficient cooling of the Shape Memory Alloy tendons which limits the number of cycles per time.

## KEY WORDS

soft robot, shape memory alloy, biomimetic robot, soft robot manufacturing process

## CLASSIFICATION

JEL: L69

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## INTRODUCTION

Soft robotics is an increasingly growing interdisciplinary field that focuses on the design and manufacture of robots made from soft materials. The field is combining robotics, chemistry, and mechanics of materials to enable the preprogramming of the function – complex motion into flexible, soft materials [1, 2]. As the robot considered here is a mechatronic device, interdisciplinarity is understood, considering mechatronics itself consists of mechanics and electronics. Indeed, the article deals with both detailed mechanics (the movement of the robot) and electronics (through it circuits, relationship between electrical parameters and movement). Furthermore, the article deals with material science as well as one of the key considerations of a soft robot is its material (therefore "softness"), and a high degree of detail has been discussed. Lastly, as the manufacturing process is described in detail as well, the article includes considerations of manufacturing science.

Also, the article includes a detailed description of the manufacturing process of the robot, which can be reproduced, it can also be considered as part of citizen science. This allows the possibility for different volunteers all over the world to recreate the experiment. Citizen science can be used as a way to gather, where different volunteers can recreate the robot and perform experiments with different robot shapes or electrical parameters, and thus reporting it's influence on the results.

The term soft is related to materials with Young's modulus in the range ~ $[10^4 – 10^9]$ Pa, which is comparable to biological tissues such as skin, muscles, and to a lesser extent bone. Traditional robots made of metal alloys have elastic moduli in the range ~ $[10^9 – 10^{12}]$ Pa. Engineering materials such as silicones, hydrogels, rubber, thermoplastics, fit well into the range of soft materials which makes them suitable for soft robotics applications [3]. The actuation of these soft structures can be achieved by various stimuli, including pressure of fluids, both pneumatics and hydraulics, electrical charges, chemical reactions, shape memory alloys, and magnetic effects [4, 5].

Despite significant interest the field is gaining, there is still area for more theoretical studies and successful applications in the field of mobile soft robots. The main limiting factor for successful applications of mobile soft robots identified is low energy efficiency [6]. There are several applications indicating further limitations of current approaches in mobile soft robotics, as well as potential improvements, and research directions.

Trimmer et al. formulated the general principles of soft bodied robots inspired by motion of animals such as worms and caterpillars [7]. SMAs (Shape Memory Alloy) have been successfully applied to generate six gaits based on constraints imposed by the structure of the soft robots' body. Theoretical foundations for successful translation of locomotion patterns of animals to biomorphic robots have been proposed.

Seok et al. have explained the properties and production of NiTi (nickel-titanium) SMA actuators [8], which they have used in the soft robot with multiple contractile segments undergoing peristaltic crawling locomotion. They have proven their robot can withstand a hit with a rubber hammer without suffering any damage. Furthermore, Luo et al. have used fluidic elastomer actuators (FEA) to move their soft robot [9]. They have provided three distinct types of actuators, and whilst they have shown satisfactory results in controllability and speed, their disadvantage is a delay in response in release time (due to the fluid), which also varies with tube length. However, the main advantage is that they do not overheat (which is an issue soft robot with SMA actuators face) so they can work consistently for longer times.

Pfeil et al. used dielectric elastomer actuators (DEA) to create crawling motion in their soft robot [10]. Additionally, Munadi et al. have developed a motor-tendon actuator for their starfish-like soft robot [11], which achieves motion by a servo motor pulling a tendon. Chua and Yeow have used air propulsion to achieve locomotion in their air-driven soft robots [12]. Their robot can crawl, pinch, grasp and kick while powered from a pneumatic source.

Furthermore, one of the key issues soft robots face is storing power (to keep them autonomous), as conventional power sources which give autonomy such as batteries, pneumatic or hydraulic cylinders all bring rigidity, which will compromise the robot's softness. Mc Caffrey et al. offer a solution for the soft robot's autonomy by introducing magnetic coupled wireless power transfer on their caterpillar-based soft robot [13]. Their worm-like soft robot also utilizes SMA.

Regarding the topic of motion of soft robots, Calisti et al. give an overview of diverse types of soft robot locomotion (such as worm-like, serpentine, or peristaltic crawling and even swimming and flying for non-surface soft robots) [14], noting their pros and cons. All these types of locomotion draw their inspiration from nature. For example, Marchese et al. have developed a fish-like robot, with rapid body motions [15]. While their fish-like robot demonstrated impressive handling capability, part of its body is fully rigid, offering a place for conventional supporting rigid hardware, thus not being considered a fully soft robot. Furthermore, Joshi et al. designed a jellyfish-inspired soft robot [16]. The inflation of their robot alone was not enough to yield floating due to the weight it was carrying, so a swimming motion needed to be induced to move upwards. It would produce a swimming motion, actuated by fluidic actuators. Their robot was capable of manoeuvring in a water tank, although without full autonomy as it is powered by an external power supply. Zhang et at. have developed a worm-like soft robot capable of manoeuvring in complicated tubular environments [17], such as a pipeline with differing diameters. Their robot has shown strong environmental adaptability, being able to pass through complex constrained environments. A similar approach is presented in [18] by Lin et al., with a unidirectional soft robot based on a standard McKibben pneumatic actuator and custom 3D printed tentacles that enable very reliable motion in confined spaces like pipes with variable cross sections and curvatures. Wang et al. have incorporated rapidly exploring random-tree algorithm-based path planning [19], which makes the robot decide whether to continue forward or to back-up before manoeuvring.

Kandhari et al. have developed fabric-based soft robots [20], which have several advantages, mostly in the future development of wearable robotic devices (such as gloves). They have designed two robots, a larger one called "FabricWorm" which still has some rigid 3D printed parts and a smaller soft robot called "MiniFabricWorm", where the only rigid parts are conventional actuators which, by shortening or extending the cable, create the motion of the robot. They have compared their results to their previous, conventional non-fabric soft robot. Conventional actuators were used, meaning they do not face the time delay (as the FEA-based soft robots do) or the overheating issues (as the SMA-based soft robots do), however this means they do retain a degree of rigidity, which is not in perfect agreement with the idea of soft robotics. Additionally, the fabric-based robots have shown a large dependency on the surface (and the friction coefficient of the given surface). For example, when introduced to carpet the soft robot cannot effectively move. This could be addressed by adding small metal feet on the belly-side of a worm-like soft robot. Finally, the fabric-based soft robots have proven to be very costly to assemble. In contrary, Joyee et al. have designed a fully 3D printed soft robot [21], which does not require any assembly. However, the benefits of fully 3D printing are questionable for a larger production run, comparing the cost of 3D printing every single robot with the lower cost of a single 3D printed mould and subsequent silicone pouring.

Besides all the previously mentioned advances and limitations of different approaches used to materialize mobile soft robots, there is still a need for experimental verification of methods and materials used in their realization. If one wants to replicate a soft robot model, a concise and detailed process should be presented to allow for replication and comparison. In this article, a focus is set on availability of materials used to manufacture the robot. Detailed analysis of process variables (input voltage, temperature, elastic properties of materials used), and limitations they impose on motion behaviour is presented. A whole procedure from the mould design, SMA placement, silicon application, necessary hardware and software is given in details. This will allow simple replication and further development of similar applications and enable the usage in educational and research environments.

## MATERIALS AND DESIGN OF CATERPILLAR ROBOT

The focus of the proposed soft robot is on simplicity, as it is made with fewer elements than any other soft robot presented in the literature review. Also, it can be easily (re)produced in a shorter time with the straightforward and simple manufacturing process.

The choice of actuators is one of the defining features of a soft robot. Two different SMA wires were chosen as actuators, as shown in Table 1. NiTi SMA were chosen as actuators, with a 1:1 ratio of nickel and titanium. The ratio is particularly important, as a slight change in the ratio can move the temperature range by a considerable amount. They come from the factory in 10 mm length, fully compressed. When extended, it becomes 180 mm long. When in this extended shape, the actuators are cut in four equal parts and are used as such. This way four equal actuators are installed in the soft robot, working in two pairs.

**Table 1.** Specifications of SMA wires used in experiment.

| Kellog's Research labs SMA | | |
|---|---|---|
| **Property** | **NiTi SMA Wire** | |
| | **Specimen #1** | **Specimen #2** |
| Coil spring diameter, mm | 2,4 | 3,2 |
| Wire diameter, mm | 0,25 | 0,25 |
| Activation temperature, °C | 80 | 80 |
| Coil pitch, mm | 0,25 | 0,25 |
| Length, mm | 10 | 10 |

When an electrical current is introduced, the alloy is heated and its diameter increases, which results in a contraction in length. As the SMA contracts a force is generated, which lifts the body of the soft robot. This is the basic movement which this soft robot relies on. The soft body of the robot is made from silicone, which is poured into a 3D printed mould. The actuators are set in place and the silicone is poured over it, thus incorporating it into the body of the robot. A detailed description of the materials, production technique and the robot's performance are provided. The production process of the soft robot begins with the mould. The mould is designed as negative of desired robot shape. Catia V5 R20 is used as a CAD platform, since many previous designs of soft actuators are successfully modelled in this environment and transferred to Abaqus for hyperelastic material simulations [22].

Once the model is fully defined and finished, it is subtracted from a cuboid, which corresponds to the external dimensions of the mould. After the subtraction, the remaining part is finally the mould. One last operation is necessary, to add a small channel to hold the actuator wires during the pouring of the silicone.

The mould is 3D printed with Polyjet technology and presented in Figure 1. During research, different moulds were produced, to test and compare different sized robots. With the mould created, the next step is setting the actuators in place before pouring the silicone. This means preparing the electrical connections. The temperature at which the chosen NiTi SMA contracts is less than 100 °C, meaning they cannot be soldered due to even the lowest soldering temperatures being too high, thus highly likely to damage the SMA.

However, the connection still needs to be solid and to provide high electrical conductivity. Therefore, a mechanical connection was chosen. A custom-made connector solution is proposed, based on a M2 screw and the corresponding nut. A 0,7 mm hole was drilled close to the head of the screw, through which the SMAs are routed. They are then held in place by the M2 nut, and finally the electrical wires are soldered on the screw. With the 3D-printed mould ready, and the wiring completed, the pouring of the silicone into the mould can begin. The actuators are set into the mould, as shown in Figure 2. The choice of silicone is important, as it defines the mechanical properties of the soft robot's body, such as tensile strength and hardness.

a)

b)

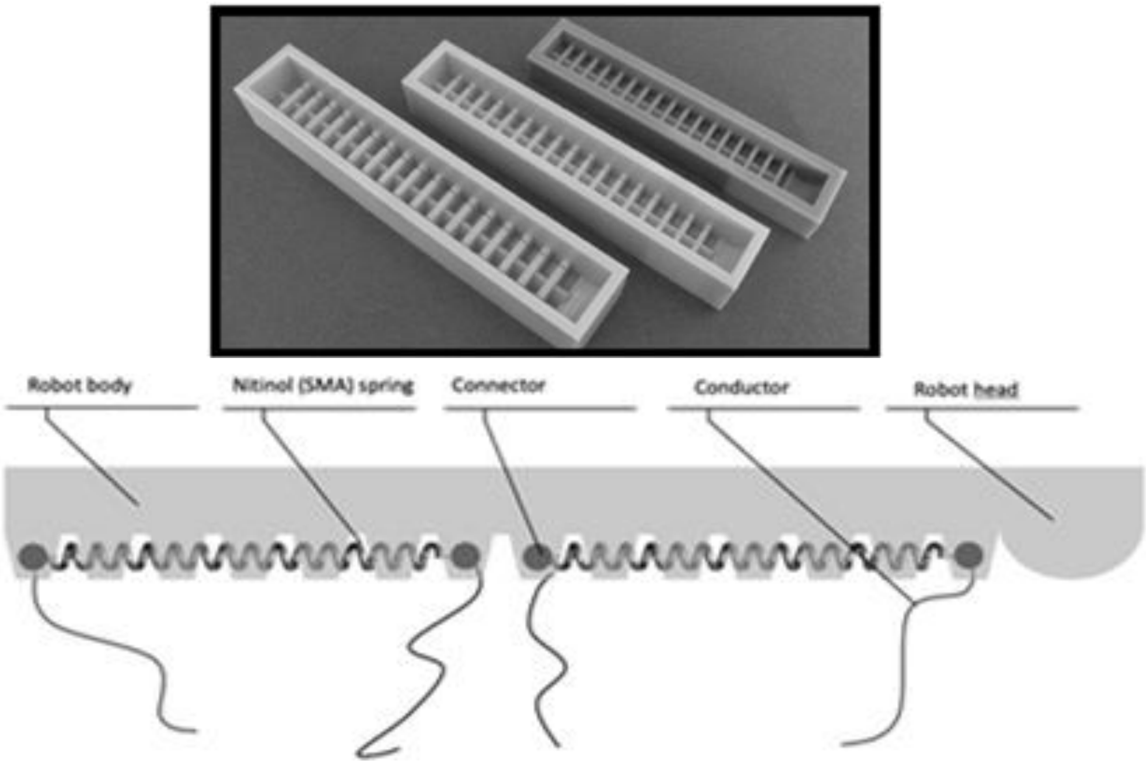


**Figure 1.** a) Different 3D printed moulds used for experiments, b) robot model with components.

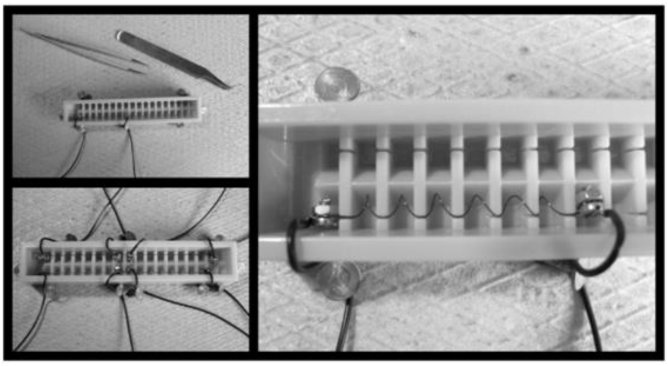

**Figure 2.** Actuators being set into the mould, before the pouring of the silicone mixture.

Research conducted in similar studies has shown similar robots were made from Ecoflex 00-30 or Ecoflex 00-35 two-part silicone. These products have proven popular due to their favourable mechanical properties – large elongation and low elastic modulus. The mechanical properties between the two products are similar, with the biggest difference being in cure time and pot life (the time from mixing the two components together to the point at which the mixed product is no longer usable).

In our study, upon evaluating several alternative but comparable silicone materials, an alternative silicon base has been selected. ALPA-SIL MF3 is comparable in terms of mechanical properties, with a clear advantage in terms of price. Table 2 shows the mechanical properties of the compared silicones, as per manufacturer.

As seen in Table 2, the chosen silicone alternative shows suitable properties. The significant difference between Ecoflex and ALPA SIL is in elongation and tensile strength. Alpa SIL is a material with higher elastic modulus compared to Ecoflex, and this has proven as a limiting factor. It limits the bendability of the robot, measured as the deformation of robot's body per force generated by the muscle wires. The consequence is reduced distance travelled per cycle. While it has a lesser maximum elongation, it shows better tensile strength and tear resistance.

**Table 2.** Comparison of silicone rubber options.

| Property | Ecoflex 00-30 | Ecoflex 00-35 | ALPA-SIL MF3 |
|---|---|---|---|
| Mix ratio by weight | 1A:1B | 1A:1B | 100A:10B |
| Specific gravity, g/cm$^3$ | 1,07 | 1,07 | 1,1 |
| Pot life, min | 45 | 2.5 | 60 |
| Cure time | 4 h | 5 min | 16 h |
| Hardness, Shore A | 30 | 35 | 28 |
| Mixed viscosity, Pa·s | 3 | 3,5 | 15 |
| Elongation, % | 900 | 900 | 600 |
| Tensile strength, MPa | 1,38 | 1,38 | 7,5 |
| Tear resistance, N/mm | 6,65 | 6,65 | 20 |

The A and B components of the silicone are mixed in the ratio of 1:10. The mixing is measured by weight, with 1 g of component A used with 10 g of component B. A thin nozzle is used to inject the mixture, with the use of a thin nozzle being especially important to fill the smallest gaps in the 3D printed mould.

The silicone then cures for 16 hours and can be extracted easily from the mould as illustrated in Figure 3. With the body separated and the actuators already in place, only one last step remains: the insertion of small metal legs or tail skids. The tail skids are used to give the robot support when lifting its body, as to successfully finish a meaningful movement. Without them, in many cases the robot did not actually move relative to the starting position at the end of a motion cycle. As the silicone is soft, the tail skids can easily be inserted in the body, even when the silicone is fully cured.

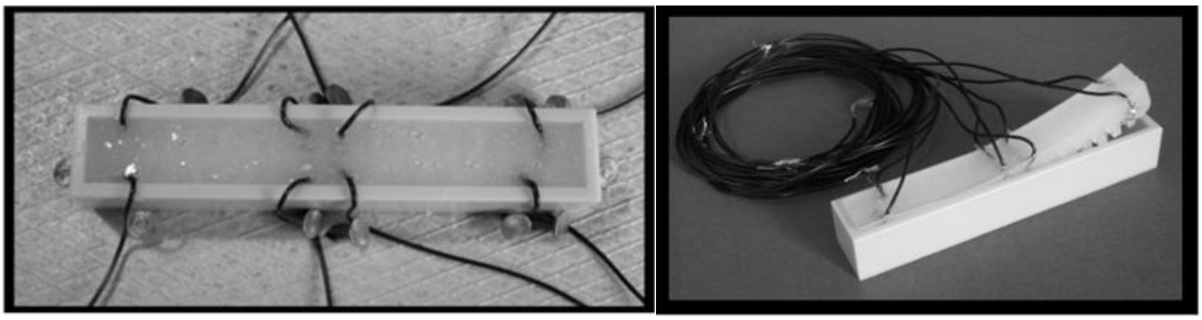

**Figure 3.** Curing of the silicone and the subsequent removal of the robot from the mould.

The robot is controlled using a microcontroller, connected to the robot by transistors, Figure 4. The microcontroller used is an Arduino Uno, connected to a PC via USB connection, whilst the chosen transistors are MOSFET IFR540. A KB817 optocoupler ($OC_1$) is utilized. The output from the microcontroller is limited to 5 mA current which is received by the optocoupler to separate positive side of the microcontroller from the power supply.

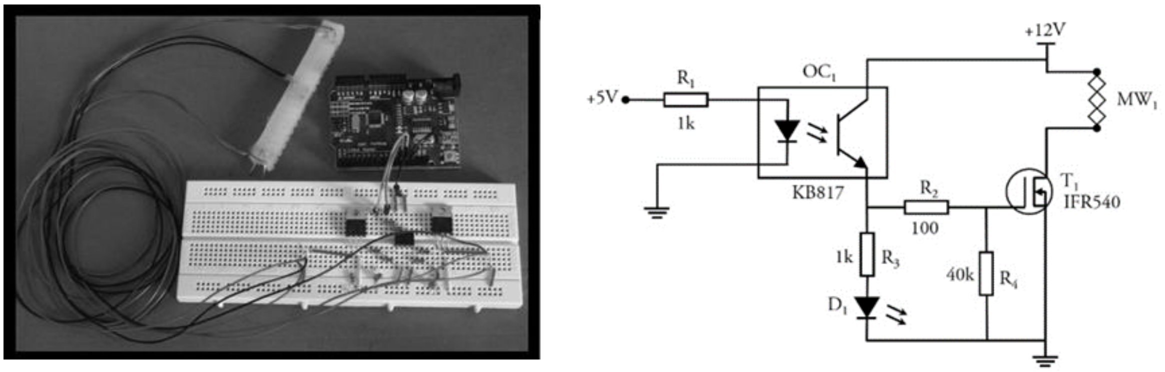


**Figure 4.** Equipment used for robot motion control.

The optocoupler is used as a means to protect the control electronics (the microcontroller and the PC) from an overvoltage coming from the robot, as the robot could be exposed to many different adverse operating conditions, such as proximity to active non-isolated electrical wires or strong electrical fields, it is important to protect the control electronics from any potential negative effects.

Digital signal from the optocoupler turns the transistor IFR540 ($T_1$) ON over the base where the transistor acts like a switch. Transistors are utilized as they use a small current or voltage source (the microcontroller) to control a larger current source needed to produce enough current to make the SMAs contract. The microcontroller turns ON the transistors with a few milliamperes which feed the current through the NiTi actuators. The intervals of conduction are predefined data in the microcontroller which instructs it on how to move the robot, what the conduction time of the SMA for a given flexion and thus movement is, stored in the memory of the microcontroller. Figure 4 gives components, layout and the electrical schematic of the SMA control circuit used for physical robot realization. Since there are four SMAs in the robots' body, working in pairs, the described scheme is implemented twice, once for each pair of SMAs.

## EXPERIMENTAL VERIFICATION

Different versions of a worm-like soft robot have been produced and their performance results compared. Body height has proven to have a considerable influence on the robot's performance. Figure 5 gives the comparison in lift between a robot with a 6 mm tall back height and a robot with a 9 mm tall back height. The robot with a smaller back height gives a larger deformation.

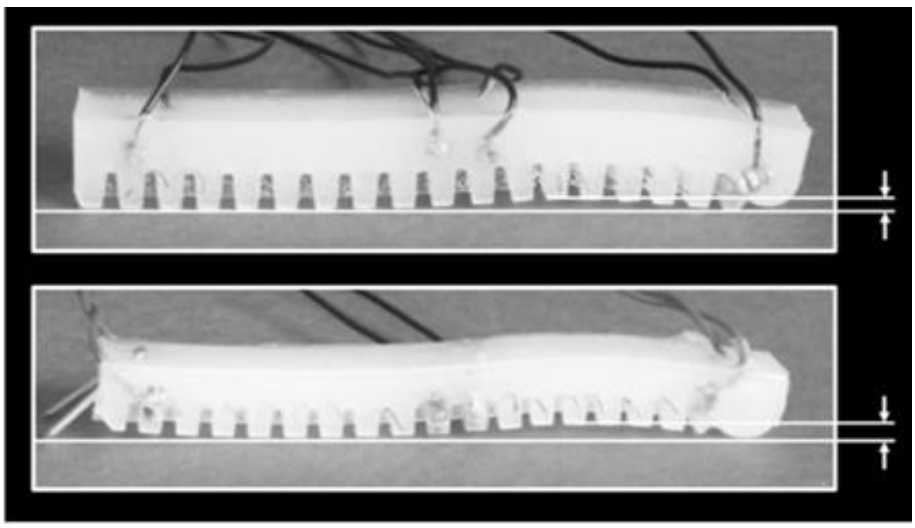

**Figure 5.** Comparison in achieved lift between robots with different cross sections (by height).

The difference is not only in the deformation absolute amplitude, but also in the speed of the deformation and its relation to the voltage applied. Deformation occurs faster in the robot with a smaller cross section and smaller voltage levels are required, but this is a trade off with the relaxation phase which is faster in the case of a larger cross section. This implies higher forces generated in elastic body of the robot which are used in the relaxation phase.

An experimental approach to determining the relation between increased stiffness for larger cross section and compliance for the smaller cross section is performed. Finally adopted height of the cross section is set to 6 mm.

One complete motion cycle is shown in Figure 6. At first, the rear actuators are electronically activated, lifting the rear half of the robot. This produces most of the movement, approximately 4 mm. As the rear part relaxes, simultaneously the first one is excited with electrical current and lifts. The lift of the front part of the body gives a smaller movement, usually pulling the robot 1 mm forward. At the end of one complete cycle, the robot has moved 5 mm. This depends on external factors, with surface being the most significant one.

Different surfaces were tried, with the best results achieved on soft surfaces such as linoleum, Styrofoam, and rubber. It is important to stress here that friction coefficients, and their ratios play a critical role in the forward motion cycle. In the active phase, the friction between the tail skids and the surface must be smaller than the friction between the front contact area and the surface.

This enables the back part of the body to be pulled in the desired – forward direction without simultaneous movement of the front part in the opposite direction. In the second phase, when the relaxation begins, the friction between the tail skids and the surface must be higher than the friction between the front contact part of the robot and the surface. Only this will enable a directional movement of the robot. This is a challenging design task that can be observed as a

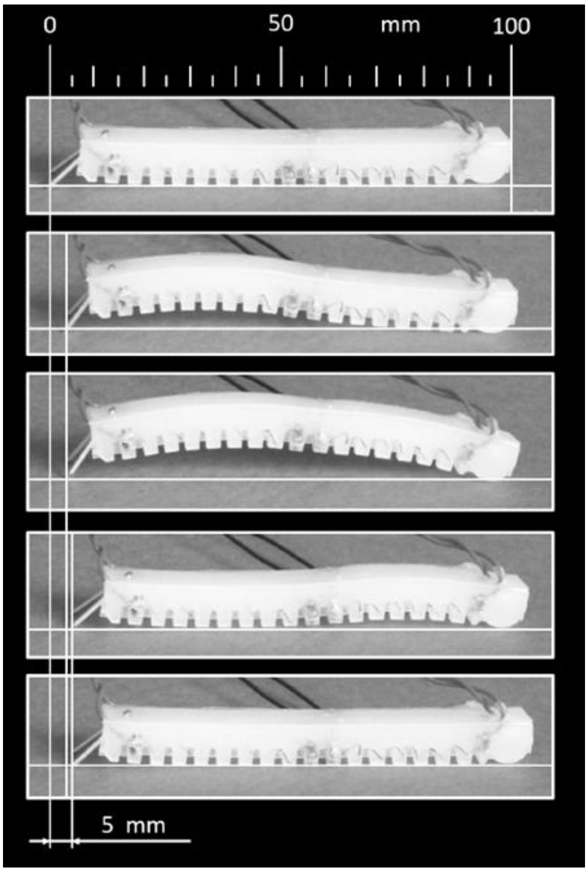


**Figure 6.** One complete motion cycle.

future improvement in applying directional friction surface to the contact region under the head of the robot. To break the coefficient of friction between these two phases, our approach utilizes the tail skids (to increase the back part friction) and a curved shape of the robot's head to decrease the friction of the front part in the relaxation phase.

In a step-cycle, the time, current, and voltage parameters need to be synchronized. The robot was tested at a voltage of 9 V, with the paired actuators drawing slightly less than 3 A of current, which is slightly above the recommended current which is 2,2 A. The duration of applying current to the actuators is one second, while the release time is three seconds. This time is sufficient for good deformation and relaxation, allowing the robot to fully settle on the surface it occupies. This is crucial because otherwise, the tail skids do not detach from the surface, causing the robot to get stuck and move in one place. For a detailed comparison between different approaches to realization of mobile soft robots, Table 3 is given. Parameters of interest are body material, actuation type, locomotion, and softness of the robot.

**Table 3**. Comparison of simple soft caterpillar robot with the other referenced soft robots.

| Robot | Material of body | Type of actuation | Type of motion | Softness |
|---|---|---|---|---|
| Ćurković and Mlivić | ALPA-SIL silicone | NiTi SMA actuators | Crawling (caterpillar) | Soft |
| Seok et al. [8] | Polyether ether ketone (PEEK) braided mesh tube | NiTi SMA actuators | Crawling (peristaltic) | Soft |
| Luo et al. [9] | Silicone rubber | Fluidic elastomer actuators (FEA) | Snake locomotion | Soft |
| Pfeil et al. [10] | Silicone strenghtened with textile | Dielectric elastomer actuator | Crawling | Soft |
| Munadi et al. [11] | Silicone rubber RTV-52 | motor-tendon actuator | Crawling (via limb bending) | Semi-rigid (soft arms connected to a rigid base) |
| Chua and Yeow [12] | Printed polyurethane | Air propulsion | Locomotion (via limb bending) | Semi-rigid (soft limbs connected to a rigid base) |
| Mc Caffrey et al. [13] | Composite of rubber-like material and rigid material (similar to ABS plastic) | SMA (wirelessly powered)? | Crawling (caterpillar) | Semi-rigid |
| Marchese et al. [15] | Silicone | FEA | Swimming | Semi-rigid fully rigid front body connected to a soft tail) |
| Joshi et al. [16] | Silicone | Fluidic actuator | Swimming | Soft |
| Zhang et al. [17] | Silicone body | Pneumatic | Locomotion | Soft |
| Lin et al. [18] | 3D printed elastic ribbon surrounding pneumatic artificial muscle | McKibben pneumatic actuator | Crawling | Semi-rigid |
| Kandahari et al. [20] | Fabric | Servomotor | Locomotion | Soft |
| Joyee et al. [21] | Soft polymer | Magnetic actuation | Crawling (caterpillar) | Semi-rigid (ends of robot are rigid actuators) |

Nitinol springs, used in the robot presented in this study, perform their function when they reach the required temperature. In this case, it does not matter whether the voltage is higher or lower; the change occurs with temperature. Current and voltage parameters only affect the speed of reaching the austenite to martensite transition temperature. Springs with smaller diameters, like those used in this study, have sufficient resistance, and additional connection with resistors to Nitinol springs is unnecessary. When heating the springs, the only important thing is not to overheat them, which means that the time of releasing the current through the spring must be limited. If the rated voltage is increased, the time to reach the transition temperature must be reduced, as with a higher voltage, the actuators will draw more current, and heating will occur more quickly.

However, when testing at such currents and voltage, the actuators quickly fail due to overheating, even though the heating time is short, just a few hundred milliseconds.

Although the time is restricted, the springs suddenly draw currents much higher than recommended, leading to failure because the springs cannot withstand such a large flow of energy passing through them. The recommended power is 20 W, which corresponds to a voltage of 9 V and a current of 3 A, the parameters for the proper operation of the actuators in the tested robot.

For the given parameters, a step of 5 mm was achieved in one cycle. The test results were compared with the theory of walking. The figure depicts a complete cycle of the robot's movement. It begins with the deformation of the rear segment, where most of the movement for one cycle is generated. The displacement of the rear segment during deformation is even 4 mm. It is followed by the phase of transferring the body to the first segment, where the rear segment relaxes simultaneously while the front segment deforms. The first segment creates a very small movement, usually a deformation of 2 mm, pulling the entire robot forward by 1 mm. With good adherence of the tail skids to the substrate, a movement of 5 mm is achieved in one cycle, as illustrated in Figure 6.

## CONCLUSIONS

In this study a complete process of designing a caterpillar-like soft robot is presented. Each phase in the process is reevaluated and compared to previously proposed designs. The focus set was the simplicity of the design, minimization of components used to generate motion and the ease of the manufacturing process of the robot.

The robot presented in the study has fewer components, materials used are readily available and more affordable comparing to those used in comparable studies. There are some limitations originating from this. In the first line, SMAs used in this study have a high activation temperature and their contraction is significantly smaller compared to the top of the market ones. However, they make up for smaller contractions and higher activation temperatures with their significantly lower price.

The SMAs which are lower on the price range have proved to be suitable for this application. They are a limiting factor in achieving a more pronounced deformation of the robots' body. This has been compensated by the design of the body to decrease the force needed to deform the upper body part, through the reduction of the robots' body height *h*.

The part of the robot which forms its back has a critical role, as it is used as an elastic spring which enables the relaxation and helps to bring the SMA back to the original shape after actuation. So, the balancing between the elastic constant of this flexural spring and force generated by the SMA used is required and performed experimentally.

Further analysis shall be performed based on hyperelastic material modelling of the robot's body which will enable the modelling of this parameter and its optimal selection. The next limitation which has proven critical is the heat generated by the SMA. This heat does not dissipate fast enough through the robot's body, and residual heat limits the SMA in austenite to martensite transition. The consequence is that after a small number of cycles the robot cannot generate forward motion. Designing more intense heat transfer from the silicone area in contact with SMA to the outer surface of the robot's body is the big challenge for further development of the soft robot. The silicone used in this study is also a limiting factor with ~ 35 % smaller elongation compared to silicones used in other studies. The silicone used for the robot presented in this study is perfectly safe for handling. It is also used for medical applications – dental and orthopedics, which makes the robot suitable for a broad range of research and educational purposes.

Future research will include modelling of the silicone used based on experimentally determined elastic constants of this material. This will enable the formulation of a realistic material model to be used in simulation and optimal design parameters selection for robots' body.

Additional effort will be made to model and realize more intense heat transfer from the SMA to the outer surface. A different wiring solution should also be considered, in which the wires would be routed together to the robot, in a single cable and then be moved to their connecting spot, either on the surface of the body or even through the silicone body. This can be compared to the current version, regarding possible problems with the robot's flexibility and movement or a possible impact on heat dissipation from the wires leading to the SMAs. In addition, there is room to improve the movement of the body through implementation of directional friction. This design exploits tail skids to ensure variable friction which enables the robot to propel forward. By combining tail skids with smart materials which can generate different frictions in principal axes, a reduction in sliding of the robot in the relaxing phase can be achieved which leads to increased distance travelled in a single power cycle through this difference.

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