DESIGN, IMPLEMENTATION, AND TESTING OF A 3D-PRINTED GRIPPER ACTUATED BY NITINOL SPRINGS

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DOI: 10.17973/MMSJ.2024_06_2024009

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This article explores the use of shape memory alloy (SMA) materials in the creation of robot effectors. Specifically, we focus on the design and implementation of a gripper powered by nitinol springs. Nitinol, an alloy of nickel and titanium, can return to a pre-set shape when heated - a phenomenon known as the shape memory effect - which we utilize to control the gripper. The article showcases the design, construction, and testing of the gripper, including its speed and reliability in grasping different objects. Our findings indicate that the gripper was reliable solution, but further research is necessary to optimize its functions and control for more efficient results in practical applications.

KEYWORDS

Nitinol Spring, Shape Memory Alloy, SMA Material, 3D Printing, Gripper

1 INTRODUCTION

Robotics is an interdisciplinary field that has proven to be immensely valuable in the manufacturing industry. Robotic devices possess the ability to manipulate a wide variety of objects, making them a primary advantage in manufacturing processes. However, to achieve this goal, robots need to be versatile. One possibility is the use of camera systems for better detection of objects with special algorithms. Another of the provided possibilities is the use of adaptive effectors [Kuznetsov 2020, Vagas 2022, Vagas 2023, Gavulova 2011].

Initially, grippers developed for industrial use were designed to securely grasp objects. Now, contemporary grippers are designed to handle soft materials, reduce noise during gripping, and facilitate the manipulation of objects with complex geometries [Kelemen 2022, Mikova 2015].

New approaches in robotics are emerging to exploit unconventional materials and physical principles to achieve revolutionary gripping properties. Among these are robotic grippers based on smart materials, such as grasping by particle jamming, electrorheological fluids, Giant ER Fluid, ER fluid with electro-adhesion, pneumatic actuators, and Shape Memory Alloy (SMA) grippers. Our research focuses on utilizing SMA materials and their actuation properties for various robotic applications [Varga 2023].

One of the most well-known shape memory alloys is Nitinol, an alloy of nickel and titanium that can return to its pre-trained shape upon heating. Nitinol comes in two primary forms: wire and springs. However, Nitinol wire only contracts by a few percent of its total length upon heating, making it less suitable for direct actuation. Therefore, spring-based configurations increasingly replace wire for actuation.

2 METHODICAL APPROACH

While spring-based configurations can achieve significantly larger strokes, controlling this material presents several significant challenges due to the nonlinearity of heating and cooling. This behavior can be characterized by a mathematical model described by the equation:

$$\frac{dR}{R} = \pi_e d\sigma + K_\varepsilon d\varepsilon + \alpha_{RT} dT \qquad (1)$$

where:

K_ε - coefficient of shape sensitivity
R - resistivity
σ - stress
α_{RT} - coefficient of thermal expansion
T- temperature
π_e - piezoelectric coefficient
ε - deformation.

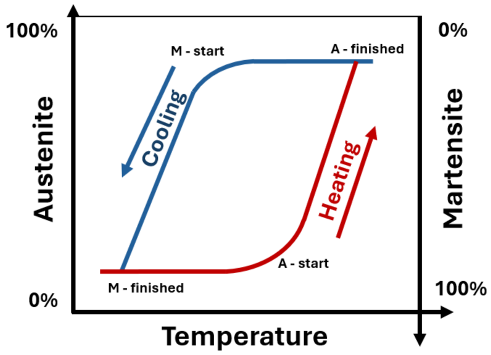

Figure 1. Diagram of transition of the SMA material structure from the atomic martensitic structure to the austenitic one

Also, we can describe it by using the hysteresis curve (Figure 1) of changes between austenite and martensite during temperature changes [Kelemen 2015, Kurylo 2017]. Nitinol is a unique material categorized as a Shape Memory Alloy (SMA). Its exceptional property lies in its ability to maintain a specific shape that it returns to upon being heated. This remarkable phenomenon, commonly referred to as the shape memory effect, is brought about by phase transitions between the austenitic and martensitic atomic arrangements of nickel and titanium atoms located within the lattice structure. This transition occurs as the material is heated:

- The most common method involves the application of electric current, also known as Joule heating. In this case, electric current passes directly through the material. This method will also be employed in our experiments.
- Another possible variation of heating using electric current involves utilizing high-resistance wire or tape around which the SMA material is wrapped. This method is most common for thicker springs.
- Nitinol can be heated using hot water or air flowing over the material.
- Alternatively, the material can be exposed to thermal radiation, which has found application in actuating Nitinol under the sun on other planets during space missions, or as waste heat when heating external devices, such as an internal combustion engine [Langbein 2011].

Regarding Nitinol springs as actuators, three fundamental utilization options are recognized:

- One-way actuator: At low temperatures, the spring is elongated by external forces (e.g., force exerted by a weight). Upon heating, the spring contracts and pulls the weight upward (Figure 2).

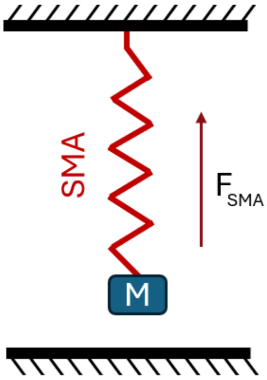

Figure 2. Principle operation of a one-way SMA actuator using mass

- Another method involves utilizing bias springs. From a theoretical standpoint, this method is like using weights; however, in this case, the force on Nitinol at lower temperatures is not generated by weight but by a spring acting in the opposite direction to the Nitinol spring during heating and contraction (Figure 3).

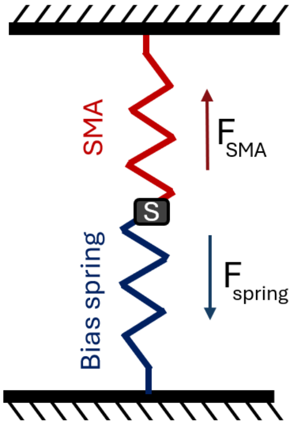

Figure 3. Principle operation of a one-way SMA actuator using bias spring

- The method we will employ in our experiment is the use of a two-way actuator, consisting of two one-way actuators. From a practical perspective, this constitutes a coupled system of two Nitinol springs independently. Movement occurs upon heating the first spring and cooling the second spring as the midpoint S moves upward. When the midpoint S moves downward, it is necessary to heat the second spring while the first spring is cooled by the environment (Figure 4) [Monteiro 2016].

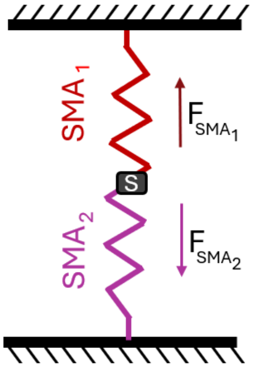

Figure 4. Principle operation of a two-way SMA actuator using two one-way SMA springs

3 DESIGN OF THE GRIPPER

The proposed gripper framework consists of several structural components (Figure 5), namely:

- Right and left fingers
- Holding
- Two simultaneously controlled Nitinol springs for finger closure
- One antagonistically controlled spring for finger opening.

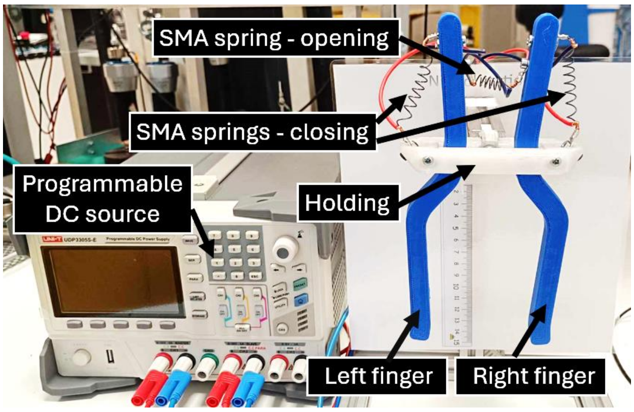

Figure 5. Schematic electrical connection of current sources and nitinol springs

The fingers and holding mechanism were designed within a 3D modeling environment, and subsequently, all components were fabricated using a 3D printer with PET-G (Polyethylene terephthalate glycol) material. PET-G is a durable thermoplastic polyester.

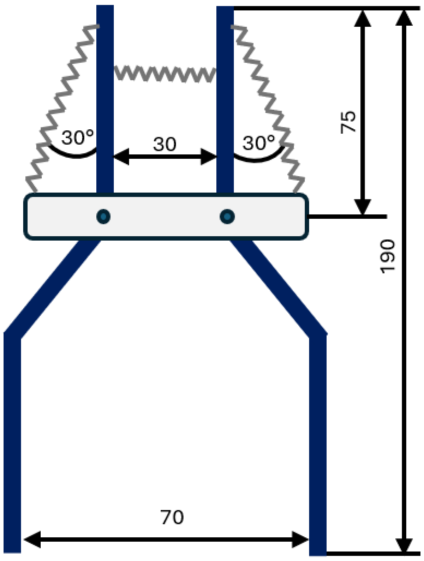

Figure 6. Dimensions of the proposed gripper

The overall length of the fingers is 190 mm. The rotation joint of the finger is located at 75 mm from the attachment point of the Nitinol spring. These springs maintain an equilibrium angle of 30° with the fingers. The distance between the fingers and the holding mechanism is 30 mm, while the distance below the holding mechanism is 70 mm (Figure 6). The fingers were designed with consideration for a wide range of objects, reflected in the final distance between them. In the equilibrium state of the fingers, depicted in the schematic diagram, the length of the springs is 55 mm, while the spring that opens the gripper has a length of 30 mm in this equilibrium position.

Naturally, during the closing and opening of the gripper during actuation, the springs significantly shorten or deform even further. However, the lengths of the springs were chosen empirically to achieve the most optimal result in opening and closing the gripper. The wire diameter from which the spring is made is 0.75 mm. For the actuation of the Nitinol springs, we employed Joule heating – using electric current. The springs were connected to a voltage source so that each spring carried an electric current of 2.6 A (Figure 7).

Based on our previous experiments, we determined this electric current level to be sufficient for inducing the necessary temperature change in the springs we used, to achieve the ideal mechanical displacement at the fingertips.

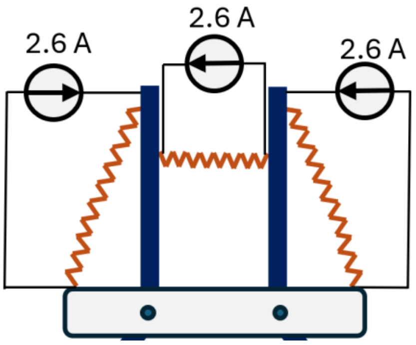

Figure 7. Schematic electrical connection of current sources and nitinol springs

The Nitinol springs were connected to a programmable DC power source for the application of electric current. The algorithm governing the entire device operates on a fundamentally simple principle. To initiate the gripping motion, an electric current must pass through two Nitinol springs positioned on the sides, which pull the upper part of the finger through their contraction (returning to their pre-trained shape). Based on the axis of finger rotation, this results in the approximation of the fingers, facilitating object grasping. No electric current flows through the antagonistically acting spring (Figure 8).

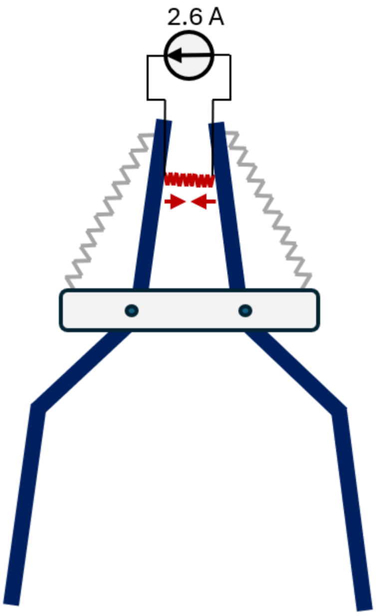

Figure 8. Actuation of the central spring to open the gripper with a current of 2.6 A

If we seek to open the gripper, thus initiating the release of the object, an electric current begins to flow through the horizontally positioned spring.

Through its expansion, the fingers commence to move apart. In this scenario, no electric current flows through the pair of springs (Figure 9).

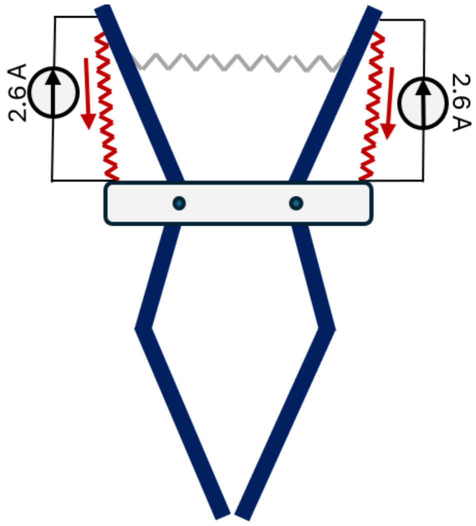

Figure 9. Actuation of the side springs for closing the gripper with a current of 2.6 A

The entire actuation mechanism of this device is predicated upon the transformation of the internal structure of Nitinol springs from a martensitic to an austenitic phase upon heating, and conversely, from austenitic to martensitic upon unrestricted cooling. This process occurs alternately for the outer springs and the central spring.

4 EXPERIMENTS AND RESULTS

The essence of our experiments lies in the evaluation of the gripper design propelled by Nitinol springs. In the initial phase, we assess the speed of gripper closure and opening without any grasped object. Subsequently, in the second phase, we examine its capability to grasp selected objects securely and reliably [Bozek 2021].

4.1 An experiment on the duration of the opening and closing of the gripper

This experiment scrutinizes the speed of opening and closing the fingers of our devised effector, one step at a time. This entails immediate opening of the gripper upon closure. We have chosen this experimental methodology as the least suitable for our effector, given that it does not allow for natural cooling of the springs, thus necessitating the continual overcoming of opposing forces within the antagonistically operating system. From a temporal perspective, this represents the least favorable scenario.

Throughout our experiments, we achieved a mean duration of gripper opening from the initial state (closed gripper) to the final state (open gripper) in 20 seconds (Figure 10).

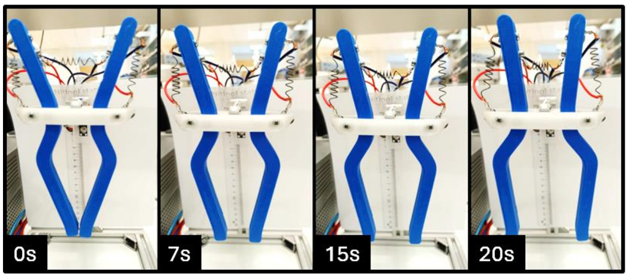

Figure 10. Gripper opening duration

Conversely, for gripper closure from the initial state (open gripper) to the final state (closed gripper), we recorded a mean duration of 30 seconds (Figure 11).

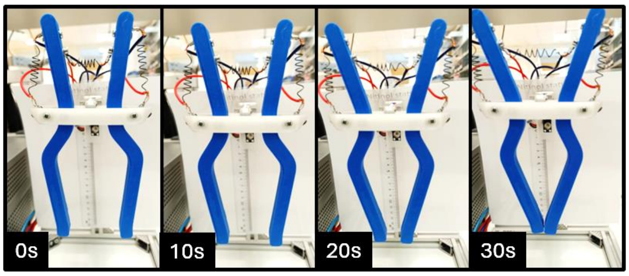

Figure 11. Gripper closing duration

From our experiment, we can conclude that despite our effector design utilizing two separate springs for each finger during closure, as opposed to a single spring initiating effector closure, their geometric arrangement is suboptimal. Ideally, positioning them as perpendicular to the finger as possible, akin to the central spring, would be optimal. However, this measure would significantly increase the dimensions of the entire effector.

4.2 An experiment on the reliability of grasping different objects

In this experiment, we focused on the grasping capabilities of our devised effector. The objects selected for testing included:

- An aluminum profile-40x40x240 mm, 700 g, smooth surface
- Candies-Φ40x20 mm, 100g, smooth surface
- Handkerchiefs-100x40x30 mm, 20g, soft object
- A bag of tea-40x50x2 mm, 5g, soft object
- A chocolate bar- 120x40x20 mm, 32g, soft object.

The outcome of our experiment yielded successful results for the selected objects. The designed gripper effectively grasped all mentioned objects with adequate force for secure and stable holding (Figure 12).

Figure 12. Tested objects held by a gripper

However, our effector was also subjected to further tests, such as grasping a soup spoon. In this instance, the surface was too smooth for the effector to securely grasp the object. Nevertheless, this deficiency could potentially be addressed by enhancing the grip of the fingertips.

5 CONCLUSION

This article addresses the design and construction of a gripper actuated by Nitinol springs. From our experiments, it is evident that we have succeeded in creating a gripper capable of reliably grasping selected objects. However, the time required for the gripper to open and close is substantial. Nonetheless, for the objects chosen in our study, it was unnecessary for the gripper to open and close to its maximum extent, significantly reducing the grasping time in practice. The next step in this research is to measure the force exerted at the fingertip over time throughout the entire grasping act. Also, this effector was tested in ideal conditions, i.e. without installation on the robotic arm. This could be the subject of further investigation - deploying the effector on a real device.

Further possible steps in this research could be monitoring the temperature and opening rate of the effector using remote access or connecting this gripper to a real robotic device [Galajdova 2020 and 2021, Kascak 2022].

ACKNOWLEDGMENTS

This article was created thanks to the funds provided by the Tatra Bank Foundation project - the digital grant program for university students 2023, to support education and finance the implementation of research "Research and development of an adaptive soft effector" and VEGA 1/0169/22 New methodics approaches to data from automated and robotized workplaces.

REFERENCES

[Bozek 2021] Bozek, P., Nikitin, Y., Krenicky, T. The Basics Characteristics of Elements Reliability. In: Diagnostics of Mechatronic Systems. Series: Studies in Systems, Decision and Control, 2021, Vol. 345, pp. 1–15. ISBN 978-3-030-67055-9.

[Galajdova 2020] Galajdova, A., et al. On local wireless remote control. MM Science Journal, 2020, pp. 4093-4096. ISSN 1805-0476.

[Galajdova 2021] Galajdova, A., Rakay, R. Long Range IoT Communication. MM Science Journal, 2021, Vol. October, pp. 4781-4785. ISSN 1805-0476.

[Gavulova 2011] Gavulova, A., Pirnik, R., Hudec, R. Modern transport telematics. In: 11th Int. Conf. on Transport Systems Telematics, TST 2011; Katowice-Ustron, Poland, October 2011. Communications in computer and information science, 2011, Vol. 239, pp. 382-391. ISSN 1865-0929.

[Kascak 2022] Kascak, J., Husar, J., Knapcikova, L., Trojanowska, J. Ivanov, V. Conceptual Use of Augmented Reality in the Maintenance of Manufacturing Facilities. In: 7th International Scientific-Technical Conference on Manufacturing, Manufacturing 2022. Advances in Manufacturing III, pp. 241-252.

[Kelemen 2015] Kelemen, M., et al. Experimental Verification of the Shape Memory Alloy (SMA) Spring Actuator for Application on In-Pipe Machine. Metalurgija, 2015, Vol. 54, No. 1, pp. 173-176. ISSN 0543-5846.

[Kelemen 2022] Kelemen, M., et al. Robotic gripper actuated using the shape memory alloy actuators. MM Science Journal, 2022, Vol. March, pp. 5539-5545. ISSN 1803-1269.

[Kurylo 2017] Kurylo, P. Shape Memory Alloy Actuators. Acta Mechatronica, 2017, Vol. 2, Issue 4, pp. 1-4. ISSN 2453-7306.

[Kuznetsov 2020] Kuznetsov, E., Nahornyi, V., Krenicky, T. Gas Flow Simulation in The Working Gap of Impulse Gas-barrier Face Seal. Management Systems in Production Engineering, 2020, Vol. 28, No. 4, pp. 298-303.

[Langbein 2011] Langbein, S., Czechowicz, A., Adaptive resetting of SMA actuators. Intelligent Material System and Structure, 2011, Vol. June, pp. 127-134.

[Mikova 2015] Mikova, L., et al. Application of Shape Memory Alloy (SMA) as Actuator. Metalurgija, 2015, Vol. 54, No. 1, pp. 169-172. ISSN 0543-5846.

[Monteiro 2016] Monteiro, C. et al. A comparative analysis of different shape memory alloy actuator configurations. Intelligent Material System and Structure, 2016, Vol. October, pp. 1-13.

[Vagas 2022] Vagas, M., Romancik, J. Testing of Ethernet-based communication between control PLC and collaborative mechatronic system. In: 20th Int. Conf. on Mechatronics, 2022. DOI: 10.1109/ME54704.2022.9983428.

[Vagas 2023] Vagas, M., Romancik, J. Calibration of an intuitive machine vision system based on an external high-performance image processing unit. In: 24th International Conference on Process Control (PC), Strbske Pleso, Slovakia, 2023, pp. 186-191. DOI: 10.1109/PC58330.2023.10217606.

[Varga 2023] Varga, M. et al. Calibration of Pressure Sensors. MM Science Journal, 2023, Vol. October, pp. 6699-6705. ISSN 1803-1269.

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