Soft Robotic Gripper using NiTi Coils

Shubham Gupta

Abstract—**This paper presents the development and analysis of a soft robotic platform that exhibits the grasping and release action similar to a human hand. The design of the gripper is basically based on a human hand except for the fact that all the joint to joint distances in a finger of the robotic gripper are equal. Each finger is composed of four sub-components and three fingers are joint together to a base to form the hand. Nickel titanium (NiTi) coils (also known as Shape Memory Alloys) are used as the actuating medium and are placed across the joints of the finger. The finger sub-components are made of PLA using a 3D printer. The actuation of the nickel titanium coils is controlled through a constant current supply, which in turn is controlled through a switching circuit and a microcontroller. This approach allows for a simple, low cost, energy efficient gripper. The paper further discusses the potential use and application of this platform.**

Index Terms—**Robotic gripper, nickel titanium (NiTi) coil actuators, PLA, soft robotics, shape memory alloys (SMA).**

I. Introduction

IN robotics, an end effector is a device at the end of a robotic arm, designed to interact with the environment. The exact nature of this device depends upon the application of the robot. In wider sense, an end effector can be seen as the part of the robot that interacts with the work environment. End effectors may consist of a gripper or a tool. When referring to robotic prehension there are four general categories of robot grippers, these are [1]:

- Impactive – jaws or claws which physically grasp by direct impact upon the object.
- Ingressive – pins, needles or hackles which physically penetrate the surface of the object.
- Astrictive – suction forces applied to the objects surface.
- Contigutive – requiring direct contact for adhesion to take place.

They are based on different physical effects used to guarantee a stable grasping between a gripper and the object to be grasped. [2] Industrial grippers can be mechanical, the most diffused in industry, but also based on suction or on the magnetic force. The type of gripper discussed in this paper exploits both friction and form closure and hence can be categorized under standard mechanical grippers. The most known mechanical gripper can be of two, three or even five fingers.

A common form of robotic grasping is force closure [3]. Generally, the gripping mechanism is done by the grippers or mechanical fingers. As in general only two or three finger grippers are used, as they are tend to be built for specific tasks and are less complex. In general the shape of the gripping surface of the fingers is chosen according to the shape of the objects that are to be manipulated. For example, if the robot is designed to lift a round object, the gripper surface can be a concave impression of it to make the grip efficient, or for a square shape the surface can be plane. The problem with such designs is that such gripper are not diverse in nature i.e. they are only limited to only certain tasks. Therefore, nowadays more focus is being laid on soft and under-actuated robotic hands [5]. Having proprioceptive soft hands enables exciting applications in robotic manipulation. In this paper we present a soft gripper platform that behaves similar to human hand during holding of objects of different sizes.

Usually in a robotic gripper, a finger of a human hand is represented through two series connected links. Since the movement to the links in the gripper is provided either through hydraulic, electric or pneumatic actuation, hence addition of links to the existing system is difficult and could produces complications in the system, thus making the system more complex. This is because in case of hydraulic and pneumatic actuation, addition of a link would require addition of companion parts and regulation of additional valves and regulators. Electrical actuation is generally provided with the help of servo motors, hence addition of a link would not only be complicated but will also require extensive manipulation in its control system.

In this paper we address the following issues and provide a solution for the same:

- We present a solution to the problem of limited links in the gripper, making the gripper an equivalent to a human hand with the advantage that the gripper can be either further expanded or reduced according to application.
- We present an approach to replicate the muscles of the human hand with the help of NiTi SMA Coils and use it for actuation of the fingers of the gripper through electrical impulses. Thus the gripper behaves as a human hand.
- We discuss the modelling, fabrication and development of a link structure, which can be merged with similar links to produce a finger similar to the bones in a human finger.

This work has been supported by Technology Information, Forecasting and Assessment Council (TIFAC Core), Ajay Kumar Garg Engineering College, Ghaziabad, India.

Shubham Gupta is an under-graduate in Electrical and Electronic Engineering, Ajay Kumar Garg Engineering College, Ghaziabad, 201009 India (email: shubhamgupta3121@gmail.com).

- The paper further explores and proposes potential development in the design for the application in the field of bio-sciences and prosthetics.

II. NiTi Coil Actuators As Micro artificial Muscle Fibers

Reference [4] shows that NiTi is one of the well-known SMA materials that generate mechanical work by phase change. Despite its low efficiency, it has a high energy density, which gives the ability to develop relative small scale actuators. In a solid state phase transformation, the crystal structure of the NiTi compound transforms from martensite to austenite states with up to 7% strain change [11].For larger displacements, coiled spring NiTi wires can be used.

Various NiTi model suggested, from the 1990s are discussed in [12]. These are mostly thermodynamic models of various forms of NiTi such as wires, tubes and sheets. Coiled spring NiTi models were discussed in [6], and [13]-[15]. These models, however are relatively incomplete. The previous models focused on the mechanical coiled spring equations using different shear moduli for the martensite and austenite phases, overlooking the change in the free length of the spring due to the phase transition. A more appropriate model, which is useful for a design of coiled spring NiTi is proposed in [4]. This model combines the mechanical and thermodynamic aspects of NiTi coil actuators to describe the overall martensite deformation and the geometrical spring effect together.

The paper named [4] Meshworm: A Peristaltic Soft Robot with Antagonistic Nickle Titanium Coil Actuators presented by Sangok Seok, Kyu-Jin Cho, Daniel Rus and other three members represent a remarkable work in the field of soft robotics using NiTi actuators. The paper represents the modelling, design, fabrication and evaluation of NiTi SMA Coils. I personally recommend the readers to go through their paper as it will help the readers in modelling and fabrication of customized NiTi coils.

This paper uses standard NiTi springs also known as Flexinol® springs manufactured by Dynalloy Inc. The various characteristics and guidelines associated with the Flexinol® springs used in the construction of the gripper has been discussed in the further sections of this paper.

A. Stretch Ratio

Reference [16] states that Flexinol® actuator springs can be an alternative to straight Flexinol® actuator wires for application with low force and high travel requirements. These springs can contract and relax multiples of their length. When Flexinol® actuator springs are used within the correct range obtaining repeatable motion from the springs for millions of cycle s is reasonable.

Stretch Ratio "SR" is defined as any length "L" over the solid length "SL", in any state, hot or cold. The hot and cold state refers to the austenite and martensite states of the NiTi actuators. For example a spring with a SR of 4 cold and 2 hot, assuming a solid length "SL" of 10mm would be 20mm hot and 40mm cold [See Fig. 1].

B. Spring Specifications

If Flexinol® actuator wire is used in appropriate conditions, then obtaining repeatable motion from the wire for tens of millions of cycles is reasonable. If higher stresses or strains are imposed, then the memory strain is likely to slowly decrease and good motion may be obtained for only hundreds or a few thousands of cycles. The permanent deformation that occurs in the wire during cycling is heavily a function of stress imposed and the temperature under which the actuator wire is operating.

Flexinol wire has been specially processed to minimize this straining, but if the stress is too great or the temperature too high, some permanent strain will occur. Since temperature is directly related to current density passing through the wire, care should be taken to heat, but not overheat, the actuator wire.

The Table I shows the specifications of the Flexinol® springs used in the robotic gripper. The specifications also give us a rough idea as to how much current and force to expect with spring of given diameter. The data has been taken from the technical datasheet provided by Dynalloy, Inc. [16]. We can calculate the number of turns of the spring using the following formula:

$$Number\, of\ coils * Wire\, diameter = Solid\, Length \tag{1}$$

Dynalloy, Inc. provides standard springs with three different wire diameters. The springs with the above described wire diameter (0.203mm) is best suited, as it fulfils the pull force required by the gripper to perform the grasp and release action. Secondly, the spring has the minimum cooling time of the three standard springs available at Dynalloy, Inc.

The contraction time is directly related to current input. The figures used here are only approximate since room temperatures, air current and heat sinking of specific devices vary.

C. Modelling of the Spring Actuators

According to [6], the muscles in the forearm and palm (thenar muscles) all work together to keep the wrist and hand moving, stable and aligned. The muscles that move the fingers and thumb are above the wrist in the forearm. Long flexor tendons extend from the forearm muscles through the wrist and attach to small bones of the fingers and thumb. When we bend or straighten our finger, these flexor tendon slide through a snug tunnel, called the tendon sheath that keeps that tendons in place next to the bones. When the muscles contract, they pull on the tendons to move the bone.

Here the NiTi coils are used to perform the functionality of the muscles and tendons. Two sets of springs of different turns are used. One set of springs represent the tendons on the forearm and the other represent the tendons on the palm side of the hand. Two different sets of springs of different turns are required because the springs counteract each other to produce the grasp and release action.

The solid length ("SL") of the spring is decided according to the length of the spring in its austenite phase. When the gripper performs the grasp action the springs attached on the palm surface gets actuated to its austenite phase. According to the finger model described in Section, the length of the spring in its various phases using the specifications defined in Section II, part B are given in Table II.

Similarly, when the gripper performs the release action, the springs on the forearm get actuated to its austenite phase. Hence the length for the second set of springs in their various phases, based on the specifications described in part B of this section, are defined in Table III.

III. Three Finger Robotic Gripper

Inspired by the skeletal structure of the human hand, we present an antagonistic actuation mechanism which utilizes the NiTi coils as muscle fibers and tendons as discussed in the previous section. This approach is used in the modelling, fabrication and development of a three finger gripper that behaves similar to human hand.

The three fingers are designed to represent the index finger, middle finger and the thumb of a human hand. The gripper produces a grasp and release action similar to a human hand on the passage of an electrical impulse. When an electrical impulse is passed, one set of the NiTi coil actuators contracts while the other set is relaxed. Depending upon which set of the actuators gets contracted the gripper performs the grasp or release action.

A. Modelling of the Finger Links

The human hand has a complex structure made up of 27 individual bones [7]: 8 carpal bones, 5 metacarpal bones and 14 finger bones (also called phalanges) are connected by joints and ligaments. The hand can be viewed in three sections by joint function:

- Carpus and wrist
- Metacarpus
- Fingers or phalanges

The links in the robotic gripper represent the phalanges and the metacarpus of a human hand. But, unlike the human hand in which the phalanges and the metacarpus are of different sizes, the links used in the robotic gripper are of same shape and size. This has been done to reduce complexity and introduce symmetry in the model. The link is modelled using SolidWorks. Fig. 2 shows a model of the link with all its dimensions.

The Fig.2 is a 2D representation of the link model. Fig.2 (a), describing the front view of the link has a hole with the radius of 0.14 cm is used to attach and hold the NiTi coil actuators mechanically through a screw. Mechanical joints are provided because soldering or welding damages the NiTi coils by changing its chemical properties. The sideways extrusion on the links [as seen in Fig.2 (c)] consists of holes of diameter 0.11 cm. These holes are used for easy passage of the wires required to complete the electrical circuit and prevent the wires from providing any hindrance during the release and grasp motion of the gripper.

The Fig.2 (b) describes the left view of the finger link. The holes at 0.40 cm from the bottom and with a radius of 0.16 cm, in this figure are used to attach the link to the next link through a wire and screws. In the same figure we can see an extrusion at the top end of the link where the other link gets attached. This extrusion is on the back side of the link and prevents the movement of the link in the backward direction when the NiTi coils present on the backside of the coil contracts.

B. Fabrication of the Links

The fabrication of the link includes the development of the link through a 3D printer. We used *Ultimaker2* for the purpose of 3D printing. *Ultimaker2* is the successor of *Ultimaker Original* which works on fused filament fabrication (FFF) printing technology. It uses a software *Cura,* which is the 3D model to toolpath Slicer. The material used to create the 3D model is PLA (Ploylactic acid). [8] PLA is a bio-degradable polymer that can be produced from lactic acid, which can be fermented from crops such as maize. PLA is harder than ABS, melts at a lower temperature (around 180°C to 220°C) and has a glass transition temperature between 60-65°C. It does have a slightly higher coefficient of friction in the drive and transport than ABS, but this is more compensated for by its lower viscosity when molten.

The NiTi springs during a phase transformation from martensite to austenite on actuation reach a temperature of around 70°C. At such a high temperature the model could rupture and break as PLA reaches its glass transition temperature. Thus to avoid this, the whole model is wrapped around with a high temperature tape. We used Kapton tape [9] which is made from Kapton® polyimide film with silicon adhesive. They are compatible with a wide range of temperatures as low as -269°C and as high as 260°C. Thus they act as thermal insulators and protect the model from the NiTi coils during its actuation.

C. Construction of the Fingers of the Gripper

The human hand consist of phalanges (fingers) and metacarpus. Each finger has three individual bones of different lengths. Construction of the fingers of the gripper in the similar fashion is a tough challenge, since links of different lengths would require springs of different number of coils. This increases the cost of the springs to a great extent. Hence a sustainable solution to the problem has been proposed. Unlike the bones of the human hand, all the links of the gripper will be of same shape and length. This helped in reducing the cost of the springs by a factor of approximately 80.

The finger of the gripper consists of four links. Three representing the phalanges and one the metacarpus. Fig.4 shows a fully constructed finger of the gripper. The links are connected to each other by attaching the extrusion, marked as (a) in the Fig. 3, of one link to the section marked as (b) of the other link. When the Hole 1 [See Fig.3] of one link is aligned in parallel with the Hole 2 of the other link, a wire is passed through these holes to provide movement to the link. Finally, the links are joined together through screws.

As discussed earlier in part C of section II, we require two sets of springs of different number of coils. The NiTi coils of solid length 4.4mm, are attached to the forearm side [See Fig.2 (b)] of the link while the coils of solid length 2mm are connected to palm side of the link. The NiTi coils are attached between two links. One end of the NiTi muscle coil is fixed in Hole 4 [See Fig. 3] of one link and the other end is fixed in the Hole 4 of the other link. The coils are held in their positions with the help of screws. Fig. 4 represents a finger of the gripper, formed through an assembly of four links. The extrusion on the forearm side of the assembled links [see Fig.4 (a)], helps the finger to stay in a straight alignment during the release action.

D. Design and Fabrication of the Gripper Base

In biology, [10] dactyly is the arrangement of digits (fingers and toes) on the hands, feet or sometimes on the wings of a tetrapod animal. Anisodactyl is the most common arrangement of digits in birds, with three toes forward and one back. This is most common in songbirds and other perching birds, as well as hunting birds like eagle, hawks and falcons.

The arrangement of fingers in the robotic gripper is inspired by those of anisodactyl. The only difference between them is that instead of three forward fingers, the robotic gripper has only two forward fingers with one at the back. To maintain symmetry in the design, the finger at the back is place opposite and in between the two forward fingers [See Fig.5]. This type of arrangement of the fingers provides a better grasp of the objects. The modelling of the base is done using SolidWorks and is fabricated using Ultimaker2.

The two extrusions present at the top of gripper base of 1cm height [See Fig.5 (b)] and 1 cm apart [See Fig.5 (c)] are used for connecting an external arm to the gripper. A hole [See Fig. 5 (b)] is provided to fix the gripper to the external arm through a M3 type screw.

E. Assembling of the Three Finger Gripper

The Fig. 6 (a) shows the fully connected fingers of the gripper. The finger links are wrapped in Kapton Tape to prevent any direct contact of the NiTi coils with the links. The NiTi coil actuators are joined on both sides of each fingers using screws and the links are connected to each other using a wire and screws (as discussed in Part C), which not only holds the links together but also provide easy movement to the links in the vertical direction.

The last link of every finger is permanently fixed to the base of the gripper using a hot glue gun. Fig. 6 (b) shows a completely assembled robotic gripper. Wires are connected to the fingers of the gripper to provide an electrical connection to the control circuit (discussed in section IV).

IV. Controller Design and Implementation

The working of the gripper is inspired by that of the human hand. To grasp and move objects, the hand has two different ways of gripping things [7]:

- Power Grip
- Precision Grip

The technique used depends on whether the object is very large and very heavy, and what sort of shape it has and how easy it is to handle. The power grip is better suited for large, heavy objects, and the precision grip is used for small, lighter objects. The proposed circuit design is used only for a power grip.

The SI unit for magnetic field strength H is A/m. However, if you wish to use units of T, either refer to magnetic flux density B or magnetic field strength symbolized as $\mu_0 H$. Use the center dot to separate compound units, e.g., "$\text{A}\cdot\text{m}^2$."

A. Control Circuit

A control circuit is required to control the grasp and release action of the robotic gripper. The control circuit basically controls the current through the NiTi coils, hence control their actuation. The control design uses an open loop control to control the grasp and release motion of the gripper. Fig. 7 represents the control circuit for the robotic gripper.

The control circuit consists of an 11.1 V Li-ion battery module represented by V1. It is further connected to a buck converter (represented by U1), which has an adjustable potentiometer (represented by R1). The value of R1 is adjusted so that the buck converter supplies a voltage of 9.5V. The output of the buck converter is connected to R2 and R3, which in turn are connected in parallel. R2 is connected to the NiTi coils on the forearm side of the gripper, while R3 is connected to the palm side of the gripper. Thus the NiTi coils on each side of the two resistors are connected in parallel to each other.

[See Fig. 7] The NiTi coils on the forearm and palm side are further connected to the collector of the NPN Darlington transistors Q1 and Q2 respectively. The emitter of the two transistors are connected to ground. The base of the two Darlington transistors Q1 and Q2 are connected to Port E pin 1 and Port E pin 2 of the microcontroller respectively. The switches SW1 and SW2 represent the Port F pin 0 and pin 4 respectively of the microcontroller. The switches SW1 and SW2 are tactile switches and are embedded on to the LaunchPad itself. The values of R2 and R3 are selected such when the switch SW1 or SW2 is pressed, the NiTi coils connected to the corresponding switch gets actuated through a current of 0.7A. The GND pin of the microcontroller provides the ground terminal to the circuit.

B. Power Grip

According to [7], the power grip is used to fro carrying heavy bags or for holding on to a handle. For example, in a power grip, the object is held in the palm of the hand, the long flexor tendons pull the fingers and the thumb so that they can tightly close around the object. This grip is made possible by the four other fingers flexing and, more importantly, the ability of the thumb to be positioned opposite the fingers. With the hand in this position, larger objects such as the stone or a heavy bottle can be held and moved in a controlled way. The greater the weight and the smoother the surface is, the more strength is needed for holding and moving the object.

The robotic gripper also uses the same technique for gripping of larger objects. The palm of the hand is represented by the base of the gripper and the tendons represent the NiTi coils. Since the robotic gripper is a three finger gripper, hence during the grasp motion, the two fingers flex together, with the third finger acting as the thumb, situated opposite to the two fingers [See Fig. 6 (b)], help in gripping an object similar to the human hand.

C. Implementation of the Control Circuit

The control circuit [See Fig. 7] is used to control the grasp and release motion of the gripper. With the current control circuit, the gripper can only perform a power grip. The grasp and release motion performed by the gripper is controlled using the two switches SW1 and SW2, embedded on the microcontroller [See Fig. 8]. The Fig. 8 (a), represents the control circuit during the grasp motion of the gripper. The functionality of the gripper is such that as long as the SW1 on the microcontroller is pressed, Port E pin 1 is open and a current flows through it.

This in turn activates the base of the NPN transistor Q2 and its collector and emitter are electrically connected. As a result NiTi coils on the palm side of the gripper gets connected to the ground and a current flows through them. A current of 0.7A flows through each finger of the gripper and as a result the NiTi coils get actuated through the structural transformation to its austenite state. As a result the finger links flexes towards each other, which in turn results in the gripping action of the robotic gripper. It should be noted that switch SW1 should be pressed for at least two seconds for the gripper to perform the gripping action. This is because the NiTi coils require a current of 0.7A for at least two seconds for complete phase transformation.

Similarly, when switch SW2 on the microcontroller is pressed, Port E pin 2 is opened [See Fig. 8 (b)] for a period of two seconds. This in turn activates the base of the transistor Q2 and its collector gets connected to its emitter. Hence the NiTi coils on the forearm side are connected to ground. This in turn circulates a current of 0.7A in each finger (on the forearm side) of the gripper. This results in flexing of the links away from each other and the gripper performs the release action.

There is also a three second delay after every grasp and release action of the gripper. This helps the NiTi coils to cool down from its austenite state to its martensite state after the current is removed. During this cooling deformation period, neither of the switches are operational. This helps in preventing any permanent deformation in the NiTi coils.

Demonstration of the gripping action of the gripper can be seen in Fig. 9. The figure shows different phases of the gripper during gripping of an object. As seen in Fig. 9 (c), the gripper uses an enveloping grasp to grip the object.

V. Conclusion and Future Work

This study demonstrates a three finger robotic gripper using NiTi coil actuators. It discusses the designing, modelling, fabrication and assembling of all the components of the robotic gripper. The robotic gripper is inspired by the structure and working of a human hand and is used to perform the grasp and release motion, similar to a human hand. A control circuit to control the grasp and release motion of the gripper has also been discussed.

The gripper uses the phase transformation property of NiTi coils for the movement of the links. When electric current is passed through the NiTi coils, they undergo a structural change from martensitic phase to austenitic phase. As a result, contraction of the NiTi coils takes place which in turn is used to produce a grasp or release action. The current control circuit can only actuate the gripper to produce an enveloping grasp.

Through addition of force sensors at the tip of the fingers of the gripper and using them as feedback to the control circuit, will allow us to develop a closed loop controller. This type of a control will thus help the gripper in adjusting better to the surface of objects and thus providing both, an envelope grip and a pinch grip.

Since each finger is an assembly of finger links, hence the length of the fingers can be increased or reduced by addition or removing of finger links respectively. Similarly, additional fingers could be added to the gripper by just modifying the design of the base of the gripper. Since the fingers are connected in parallel to each other, hence there is no change required in the control circuit. But care should be taken that the current drawn by the circuit lies within the operational limits of the components used in the circuit or else the components should be replace with those having higher current ratings.

Future work also includes increasing the number of fingers from three to five and restructuring of the base of the gripper to make the gripper more identical to a human hand. This kind of homogeneity along with a closed loop controller will enable the gripper perform more sophisticated operations of a human hand, such as different kinds of hand gestures.

Acknowledgment

This work has been done under the guidance of Mr. Vikash Kumar (Scientific Officer, TIFAC Core) and Mr. Rahul Dixit (Scientific Officer, TIFAC Core). I am grateful for the support and guidance provided by them. I would always be in debt to my friends Raghvendra Singh and Utkarsh Rastogi for their generous help and support.

References

[1] G. J. Monkman, S. Hesse, R. Steinmann and H. Schunk, “Gripper classification,” in *Robotic Grippers*. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA, Oct. 2006, pp. 62. ISBN 978-3-527-40619-7.

[2] G. Fantoni, M. Santochi, G. Dini, K. Tracht, B. Scholz-Reiter, J. Fleischer, T. K. Lien, G. Seliger, G. Reinhart, J. Franke, H. N. Hansen and A. Verl, (2014). Grasping devices and methods in automated production processes. *CIRP Annals – Manufacturing Technology* [Online]. 63(2), pp. 679-701. Available: http://dx.doi.org/10.1016/j.cirp.2014.05.006

[3] "Robotics Grasping and Force closure". FU Berlin. Retrieved 2014-03-20.

[4] S. Seok, C. D. Onal, K. Cho, R. J. Wood, D. Rus and S. Kim, “Meshworm: A Peristaltic Soft Robot With Antagonistic Nickel Titanium Coil Actuators,” *IEEE/ASME Trans Mechatron*, vol. 18, no. 5, pp. 1485-1497, Oct. 2013.

[5] B. S. Homberg, R. K. Katzschmann, M. R. Dogar and D. Rus, “Haptic identification of objects using modular soft robotic gripper,” in *IROS*, Hamburg, 2015, pp. 1698-1705.

[6] HealthPages.org. [Online]. Available: http://www.healthpages.org/anatomyfunction/anatomyhandwrist/

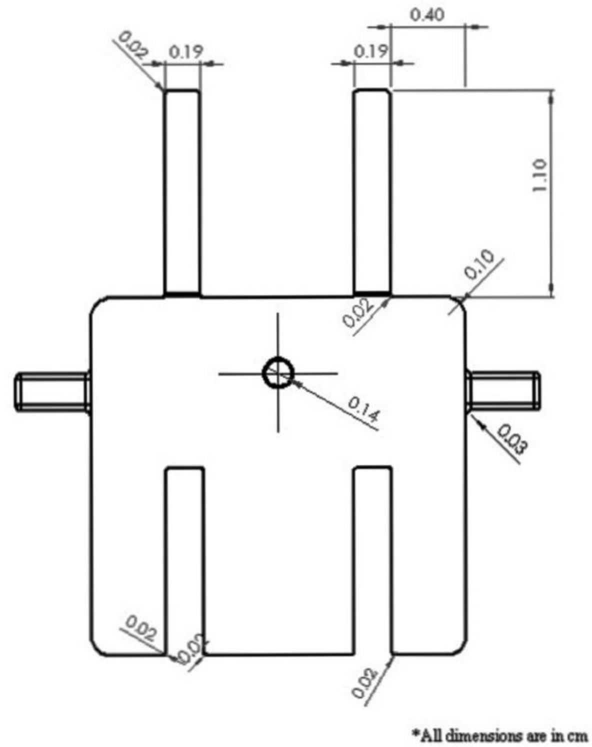
[7] National Library of Medicine PubMed Health. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmedhealth/PMH0072546/

[8] PLA RepRapWiki. [Online]. Available: http://reprap.org/wiki/PLA

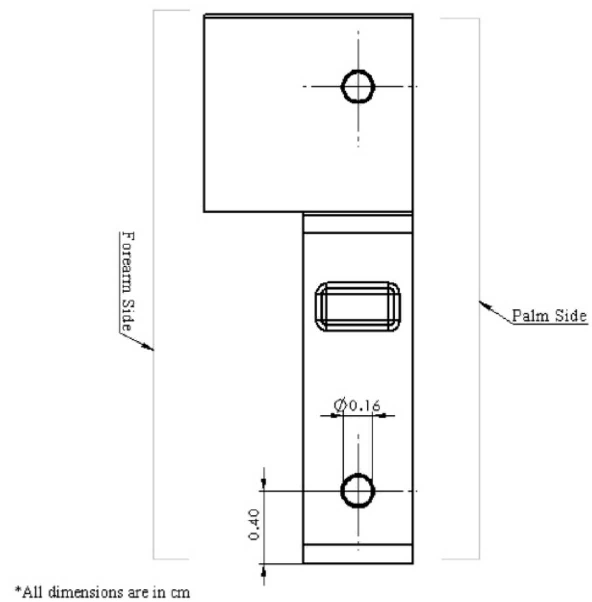
[9] "DuPont Circuit & Packaging Materials Awarded U.S. Patents for Matte Black Film and Coverlay". *November 15, 2013*. Retrieved 2015-05-28. "*DuPont invented Kapton® polyimide film over 45 years ago.*"
[10] Wikipedia, "Dactyly, the arrangement of fingers and toes". [Online]. Available: https://en.wikipedia.org/wiki/Dactyly.
[11] M. Dolce and D. Cardone, "Mechanical behaviour of shape memory alloys for seismic applications 1. Martensite and austenite NiTi bars subjected to torsion," *International Journal of Mechanical Sciences*, vol. 43(11), pp. 2631–2656, Nov. 2001.
[12] B. Chang, J. Shaw, and M. Iadicola, "Thermodynamics of shape memory alloy wire: Modeling, experiments, and application," *Continuum Mech Thermodyn,* vol. 18(1), no. 1, pp. 83–118, Jul. 2006.
[13] H. J. Lee and J. J. Lee, "Evaluation of the characteristics of a shape memory alloy spring actuator," *Smart Mater. Struct.* vol. 9, no. 6, pp. 817–823, Dec. 2000.
[14] Y. Dong, Z. Boming, and L. Jun, "A changeable aerofoil actuated by shape memory alloy springs," *Materials Science and Engineering A*, vol. 485, no. 1–2, pp. 243–250, Jun. 2008.
[15] K. Cho, E. Hawkes, C. Quinn, and R. Wood, "Design, fabrication and analysis of a body-caudal fin propulsion system for a microrobotic fish," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2008, pp. 706–711.
[16] FLEXINOL® Actuator Spring Technical and Design Data. [Online]. Available: http://www.dynalloy.com/tech_data_springs.php

Shubham Gupta was born in Lucknow, Uttar Pradesh, India on 9th March, 1994. He is currently working towards the B.Tech degree in electrical and electronic engineering, Ajay Kumar Garg Engineering College, Ghaziabad, Uttar Pradesh, India.

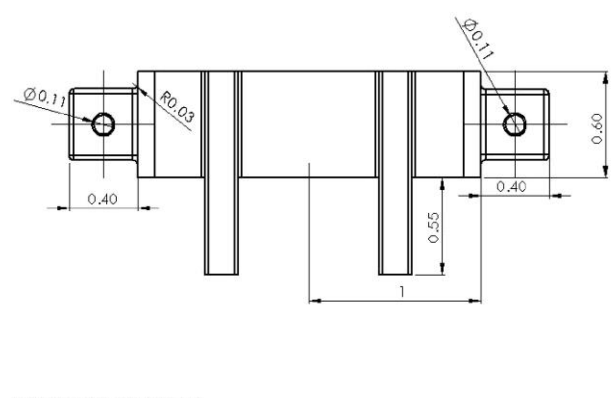
He completed his summer training from Hindustan Aeronautical Limited Lucknow, Uttar Pradesh, India. His research interests includes bio inspired robotics, micro-robotics and finding solutions to environment related problems.



(a)



(b)



(c)

Fig. 2. The following figure represent the three views of the finger link (a) Front view. (b) Left view. (c) Top view.

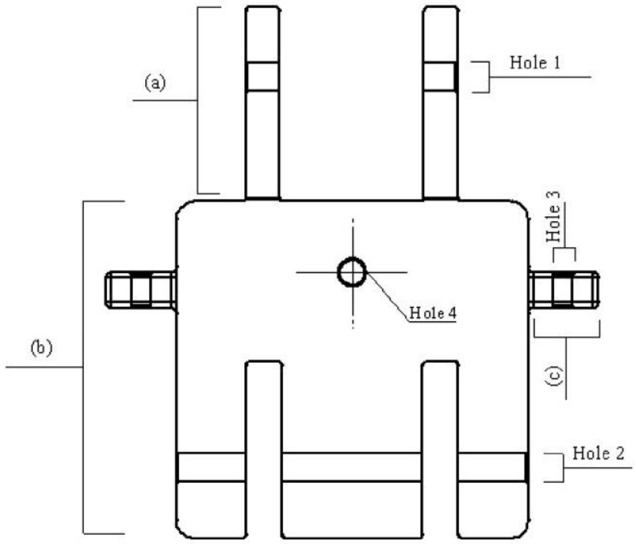


Fig. 3. Representation of the various components in the link model.

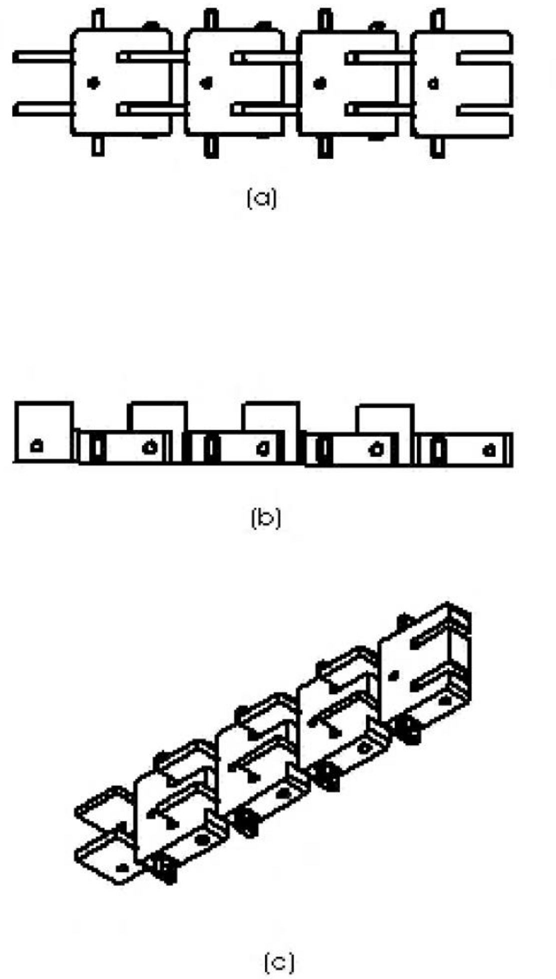


Fig. 4. Assembly of links to form a finger (a) Front view. (b) Left View. (c) Isometric View.

TABLE I
SPECIFICATIONS OF THE SPRING

Spring Wire Diameter	0.203 mm
Outer Diameter	1.37 mm
SR Cold, SR Hot	14,5
Displacement/ Coil	1.8 mm
Resistance on Straight Wire	29.13 Ω/m
*Heating Pull Force	39.3 g
*Cooling Deformation Force	15.94 g
Approximate Current for 2 s Contraction	0.7 A
**Cooling Time 90° C "HT" Wire	3.0 s

*The Heating pull force is based on ~ 25,000 psi, which for many applications is maximum safe stress for the wire. The cooling deformation force is based on ~ 10,000 psi, which is a good starting point in the design.

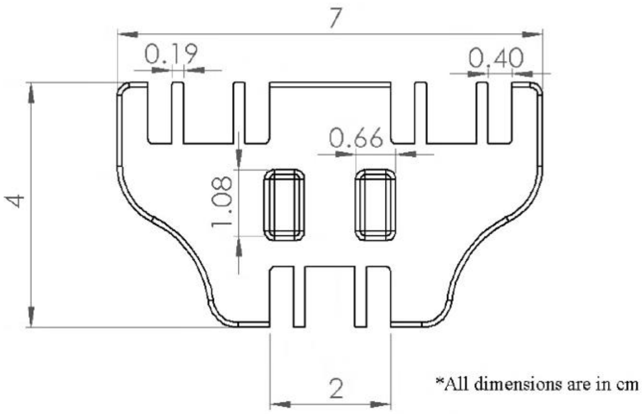
**Approximate cooling time is at room in static air, using a vertical spring. The last 0.5% of deformation is not used in these approximations. "HT" = High Temperature Flexinol® Actuator Spring.

TABLE II
SPECIFICATIONS OF THE SPRING ON THE PALM SIDE

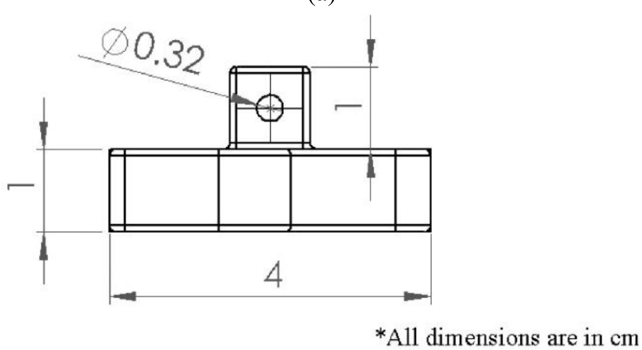
SR Cold, SR Hot	14,5
Length in Austenite Phase	10 mm
Solid Length	2 mm
Length in Martensite Phase	28 mm
Number of turns	10

TABLE III
SPECIFICATIONS OF THE SPRING ON THE FOREARM SIDE

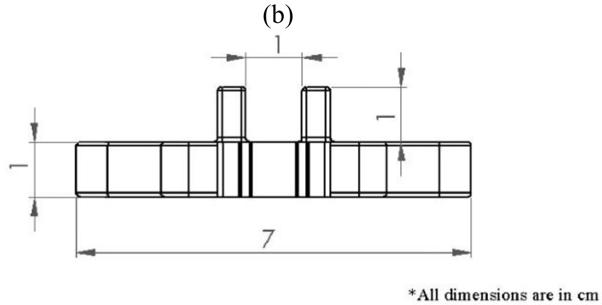
SR Cold, SR Hot	14,5
Length in Austenite Phase	22 mm
Solid Length	4.4 mm
Length in Martensite Phase	61.6 mm
Number of turns	21.67



(a)

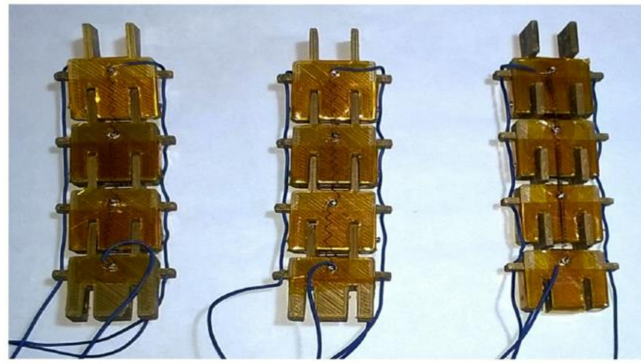


(b)

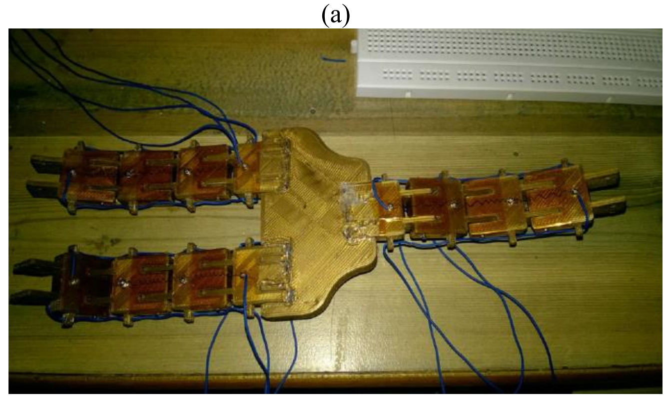


(c)

Fig. 5. Model of the base of the gripper. (a) Top View. (b) Left View. (c) Front View.



(a)



(b)

Fig. 6. (a) Three fingers of the grippers (b) Completely assembled gripper.

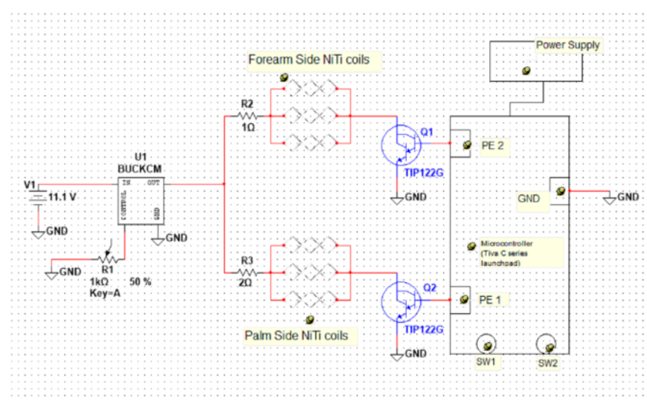
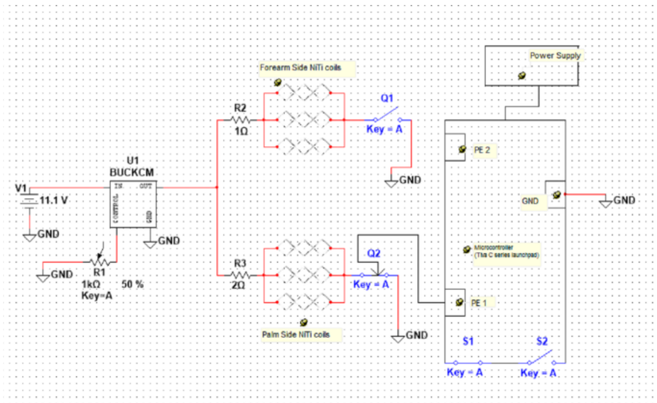
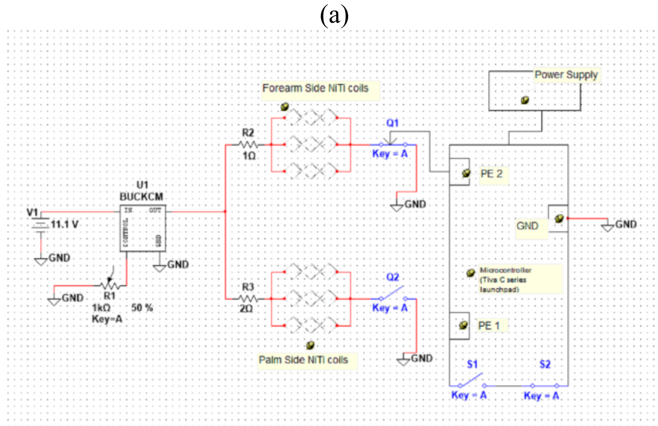


Fig. 7. Representation of Control circuit for the robotic gripper.

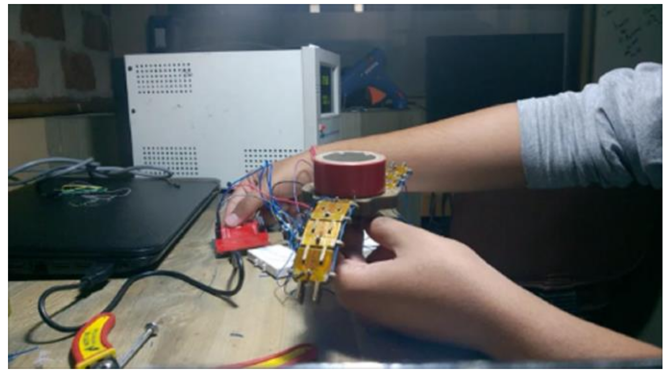


(a)

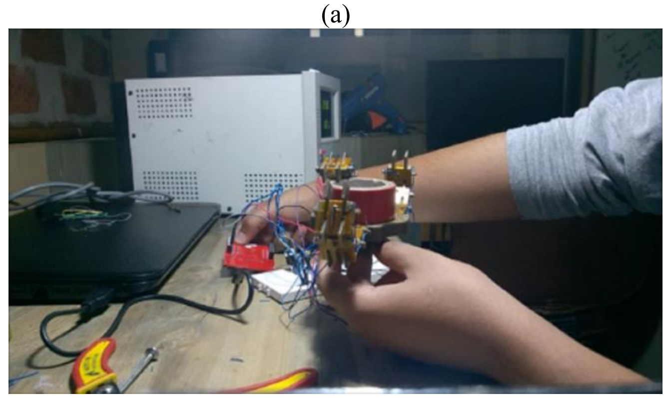


(b)

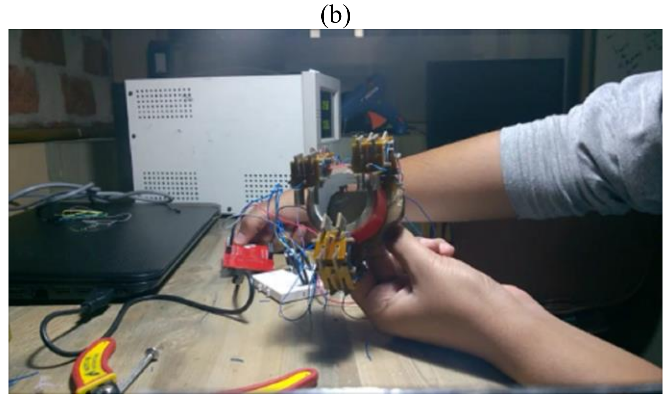
Fig. 8. (a) Control circuit during the grasp action of the gripper. (b) Control circuit during the release action of the gripper.



(a)



(b)



(c)

Fig. 9. (a) Gripper at rest. (b) Movement of fingers during gripping. (c) Full grip of the object.

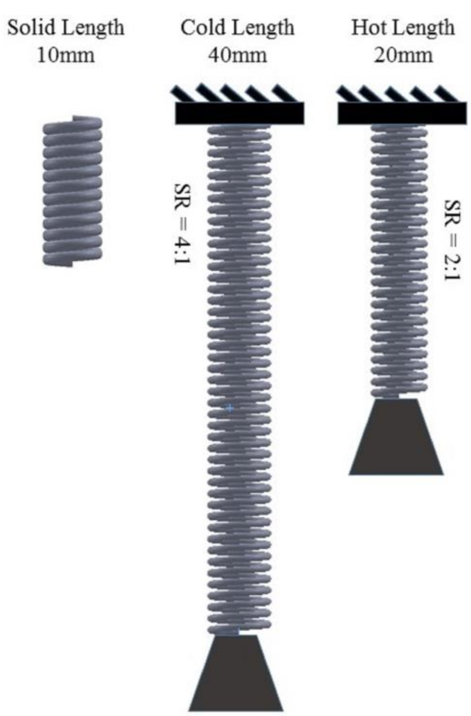


Fig. 1. Length of the spring in its various phases, under load, according to the stretch ratio of the spring.