Robotica (2002) volume 20, pp. 175–180. © 2002 Cambridge University Press
DOI: 10.1017/S0263574701003757 Printed in the United Kingdom

# Three-finger SMA robot hand and its practical analysis

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(Received in Final Form: September 8, 2001)

## SUMMARY

Gripping of different types of objects with a multi-finger robot hand is a vital task for robot arms. Grippers, which are end effector elements in robot applications, are employed in various industrial operations such as transferring, assembling, welding and painting. However, if a gripper is considered for handling different jobs or to carry different types of parts in an assembly line, a general-purpose robot hand is going to be required. There are various technological actuators of robot hands such as electrical, hydraulic and pneumatic motors, etc. Besides these conventional actuators, it is possible to include *Shape Memory Alloys* (SMA) in the category of technological actuators. The SMA can give materials motion by moving to a predetermined position, at a specific temperature. The conversion of this motion to a gripping action of the robot hand is the heart of the matter. In this study, a robot hand is developed using Ni-Ti SMA and a set of experiments were performed in order to check the compatibility of the system in an industrial environment.

KEYWORDS: Robot grippers; Robot hands, Shape memory alloys, Ni-Ti alloy.

## 1. INTRODUCTION

Recent studies regarding robot arms focus on configurations of multi finger robot hands that are capable of holding different objects as skillfully as possible. Robot hands have multi purpose holding features for accomplishing different tasks. Features and form of the human hand, which is the most skillful device, are taken as a model in configuring the functions of the present robot hand. Functionality, size, maintenance and working convenience are some of the important parameters that are considered in the design and manufacture of robot hands.

Three different types of gripping are considered when the gripping behaviour of the human hand is investigated. The first type is performed by the interior surfaces of the fingers, i.e. gripping performed by pressing a material in the palm is called strong gripping. The second type is the gripping of delicate pieces, i.e. gripping performed by using the fingertips. The last one is performed by using the sides of fingers.

Gripping area of fingers and determination of gripping action must be mutually taken into consideration when a gripping motion is considered. The gripping motion has three main restrictions. The first one is material (form, slipperiness, fragility); the second one is the gripping action (maximum motion area and maximum opening of fingers); and the third one is the gripping task (what will happen to the material). After considering these three restrictions, a possible gripping area can be formed.

The number of fingers of a robot hand was considered between three and five in previous studies.[1] The JPL/Stanford robot hand is an example of a three-finger robot hand (Figure 1a). Each finger has three degrees of freedom and four electrical motors. Its control system is very complicated and it is difficult to adjust the tension of four different cables of the fingers and to preserve the same tension for a long period of time. The Utah/MIT (Figure 1b) robot hand is constituted by a thumb and three fingers. Each finger has four joints. Additionally, each finger has four degrees of freedom, eight independent strings and pneumatic cylinders. The Belgrade/USC (Figure 1c) has a system of five fingers and four motors. Two of the motors are used for the thumb, and the other two for the other fingers.[1]

The Mat/METU is a pneumatic actuator type robot where a finger motion is obtained by a pulley-cord system.[2] Another robot hand produced at the Middle East Technical University is the METU-hand, which has nine step motors actuating its three fingers as each finger has three degrees of freedom. This hand is made of aluminium, and eighteen plastic coated steel cables are used as strings.[3]

An alternative robot hand is proposed in this study with the use of SMA technology. The main difference of the proposed SMA robot hand is the use of SMA materials as the driving mechanism.

The driving mechanism of the robot is a crucial step in the design of a robot. Appropriate positioning, reliability, the range of operation velocies, etc. are some of the factors evaluated while choosing the appropriate driving mechanism: Electrical motors, which are clean and can provide precise positioning; pneumatic drivers, which, cannot provide a precise positioning in the rotational path operations but are comparatively cheap; and hydraulic motors, which produce greater power in a smaller volume than the electrical motors, are some alternatives for driving units. By applying high-pressure oil to a simple hydraulic driver, one may produce high torque and rapid operation. The power needed to control an electro-hydraulic valve is small. The total power needed by a hydraulic pump can be provided by

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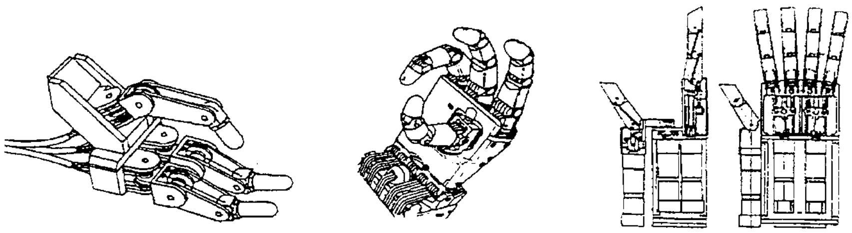


Fig. 1. Some robot hands examples.[1]

a powerful electrical motor. Power can be controlled by small electro-hydraulic valves. However, small electro-hydraulic valves with a high degree of precision are much more expensive and less reliable than powerful electrical amplifiers and controllers.

Briefly, hydraulic drivers are used if rapid motion is needed under a high torque or momentum; on the other hand, electrical drivers are used for less powerful tasks, and they are preferred in applications where explosive materials are not used.

Pneumatic systems are likely to be the cheapest choice if they can have enough features for practical use. The power/weight ratio of electrical motors is low and therefore, it is very easy to move them around. The reaction of pneumatic systems to a control signal is four times slower than that of hydraulic systems. Hydraulic systems can also be used as dampers. Oil used in hydraulic systems must be cleaned and filtered periodically. Otherwise, even very small particles could bring the system to a halt.[4]

Approximately half of the robots currently in use are controlled by electrical actuators. An improvement of the fixed magnet of electrical motors will increase the power/weight ratio. The most important advantage of this increase is to provide continuous speed control, which is needed by the robot's end effectors.[4] In fact, speed control could be done by simply adjusting the applied voltage between zero speed and the required speed. This control capability helps the robot to perform the required motion.

Hence, all three systems have their own advantages. Pneumatic actuators are preferred because of their natural simplicity, hydraulic actuators because of their power, and electrical actuators because of their improved control capacity and cleanliness.[5] The characteristics of some robot hands are given in Table I. The SMA robots will be compared with these conventional systems in order to show the applicability of the system.

When the SMA are exposed to plastic deformation at a specific temperature in the martensitic phase as a result of thermo-elastic martensite phase transformation, and are heated at a higher temperature, they are transformed into their initial shape. In other words, transformation from a martensitic phase to a beta phase (austenite phase, main phase) is completed without diffusion (without free motion of atoms) at a low temperature. Plastic deformation is, in fact, a thermo-elastic phase transformation.[6] The creation of martensite plaques started at a Ms (Martensite start) temperature is completed at a Mf (Martensite final) temperature. On the other hand, transition to main phase started by heating at As (Austenite start) is completed at Af (Austenite final). Some SMA compositions and their transformation temperature are given in Table II.[7]

Some characteristics of the nickel-titanium (Ni-Ti) alloy which is employed in this study are as follows:[8]

- Temperature of fusion : 1300°C
- Density : 6.45 g/cm$^3$
- Main resistance : 100 $\mu$ Ohm.cm (Austenite)
  - 70 $\mu$Ohm.cm (Martensite)
- Temperature of resistance : Between $-200$°C and 110°C
- Resistance to corrosion : Very high
- Gain of shape memory : At 550°C

The Alloy is heated until 550°C in order to form the SMA.

Table I. Characteristics of some robot hands.

| Characteristic/ Robot hand | Type of Actuator | Number of finger | Joint of thumb | Total Degree of freedom | Motion Transmission |
|---|---|---|---|---|---|
| UTAH/MIT | Pneumatic | 4 | 4 | 16 | Pulley-cord |
| Belgrade/USC model II | Electrical | 5 | 2 | 16 | Special mechanism |
| JPL Standford | Electrical | 3 | 3 | 9 | Pulley-cord |
| METUHAND | Electrical | 3 | 3 | 9 | Pulley-cord |
| MAT/METU | Pneumatic | 4 | 2 | 4 | Pulley-cord |
| SMA Hand* | Electrical | 3 | Effect of shape memory | Special Structure | Heating/cooling |

* The robot hand developed in this study.

Table II. Some of the SMA compositions and their transformation temperatures.

| Alloy | Composition | Transformation temperature |
|---|---|---|
| Ag-Cd | 44/49% Cd | Between −190°C and −50°C |
| Au-Cd | 46.5/50% Cd | Between 30°C and 100°C |
| Cu-Al-Ni | 14/14.5% Al<br>3/4.5% Ni | Between −140°C and 100°C |
| Cu-Zn | 38.5/41.5% Zn | Between −180°C and −10°C |
| Mn-Cu | 5/35% Cu | Between −250°C and 180°C |

This high temperature allows the nickel and titanium atoms, which form the alloy, to take an appropriate place according to their framework structure.[9]

The SMA technology is used in areas such as heat sensors, test valves of blood pressure in medicine, cooling fans in automobile industry, and multi mobile robots in robotics. The SMA was also used in the mobile robot of Pathfinder/Sojourner launched to the Planet Mars in 1994.

The actuator designed by Bergamasco et al.[10] is a good example of the use of the shape memory effect in actuator technology. Here, heating was achieved by an electric current, and cooling by liquid flow.

The most important advantage of the SMA is its simplicity. Another advantage is operation without noise and any harm to the environment. Because of these characteristics, its use in microelectronics, bio-technology and medicine is steadily increasing. The system can be used with a low voltage, like 3 or 12 volts. The operation of the actuators by an electric current gives the system the possibility of remote control. Actuators are required to be lighter and their power/weight ratio is required to be higher. As the power/weight ratio of nickel/titanium alloy is high, the gripping operation is more powerful. At the same time, a change of the alloy's resistance because of phase changes makes control of the system easier.

Advantages of the use of the SMA in robotics technology are as follows:[11]

- Simplicity of working mechanism
- High power/weight ratio
- Working without noise
- High resistance against corrosion
- Working clean without harming environment
- Facility of control with current.

A disadvantage of the system is the repetition life span (problem of getting tired). The repetition life span depends on the characteristics of the alloy and required ratio of shape memory change. Alloys whose Mf and Af temperatures are low have higher repetition life spans. In experiments made with nickel-titanium (Ni-Ti) alloys (if repeated more than 1000 000 times), it was shown that the shape memory capability drops to 1%. When experiment is repeated 10 000 times, the motion capability is around 2%.[11]

## SMA ROBOT HAND

Nickel-titanium alloys used in this study are obtained as rectangular sheets whose dimensions are $25 \times 75 \times 2$ mm, from Shape Memory Applications Inc. The size of the board was reduced to $25 \times 75 \times 2$ mm by means of cold cutting at the Izmir High Technology Institute Laboratory, Izmir (Turkey). Then, boards gained a double-sided shape memory effect which gives the robot the capability of gripping by the differential temperature analysis and processing at 550°C in the furnace.

Mf (50°C), Ms (70°C), As (90°C) and Af (100°C) values were determined as a result of experiments. The temperature/shape change for the Ni-Ti used in this study is given in Figure 2. A fiberboard is used as the hand palm of the SMA robot hand because of its resistance to heat and stroke, and insulation features. The sizes of the parts of the robot hand are determined by the solid modeling of the robot hand with Proengineer®. The Ni-Ti alloy fingers with double-sided shape memory that provide proper gripping motions are assembled over the fiberboard.

In this study, heating by means of a conducting current is preferred because of its suitability to our robot hand system and its capability of creating a database for a control system that will be formed in the future; a transformer whose output power is 300 W is used in this study. The design of the robot hand is shown in Figure 3. The SMA robot hand consists of three different subsystems, these are heating, control of pressure and cooling.

As soon as the gripping command is given, the electrical circuit is turned on in order to heat the Ni-Ti alloy. High resistance and high circuit features of the Ni-Ti alloy make the heating period comparatively short. As a result of a phase change of the Ni-Ti alloy, a change of shape in fingers (gripping motion) takes place. An increase or decrease in the power input will change the speed of finger motions.

Proper gripping of material is provided by means of a hydraulic balloon placed on the thumb. When the required pressure is obtained, a pressure switch linked to the

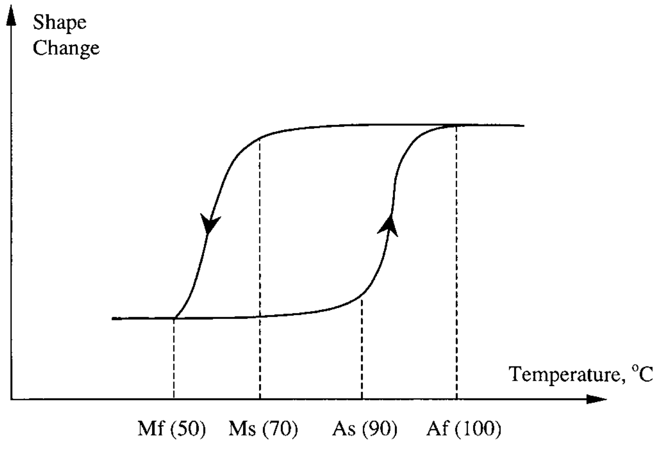


Fig. 2. Temperature/shape change in Ni-Ti used.

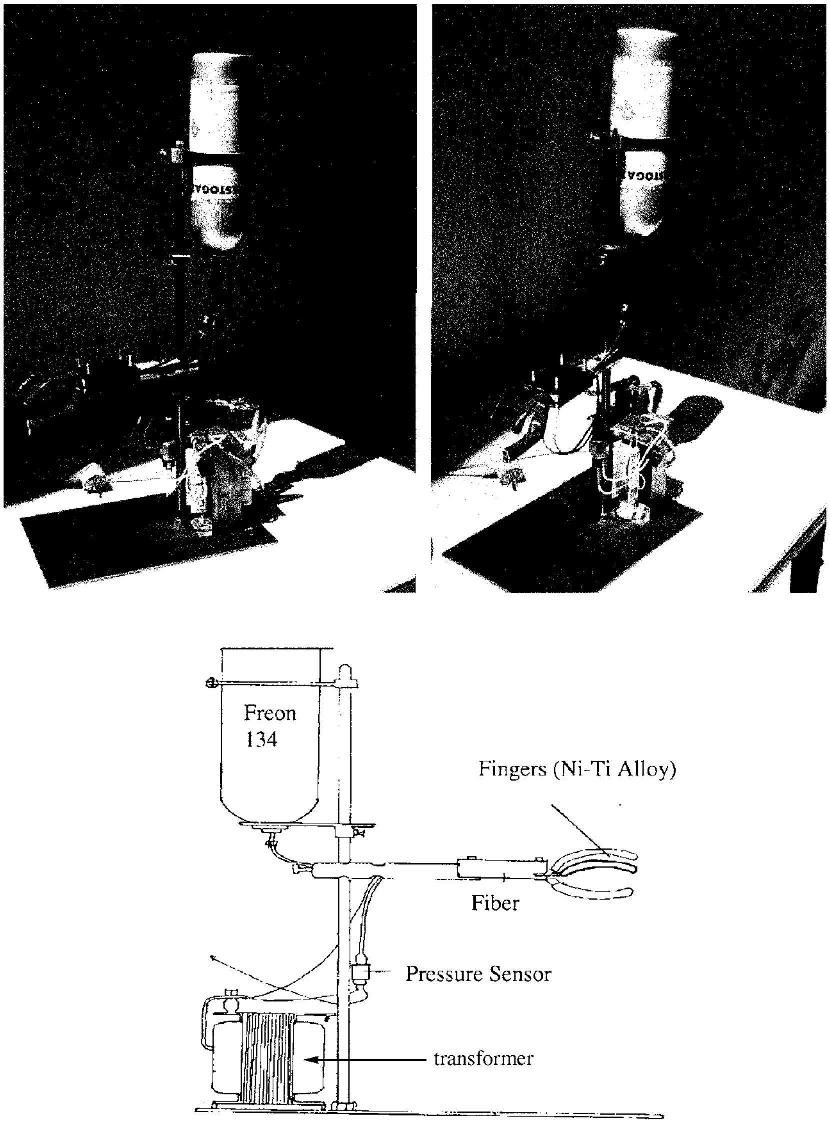


Fig. 3. The SMA Robot Hand with its warming/cooling systems.

hydraulic balloon cuts the circuit and stops the electric current. As a result, heating stops and the required gripping is realized. Heating of fingers is achieved by the use of a fire resistant cable and a suitable covering material.

During the cooling phase, Freon 134 R ($C_2H_2F_2$) gas is used for a faster cooling operation. The hot Ni-Ti alloy transforms into the martenisite phase by means of spraying freon gas over the fingers. As a consequence the material held by the robot hand is released. The cooling process occurs slowly if the system is inside an ambient temperature of below 40°C without any intervention. Moreover, the release motion of the fingers occurs at the same speed as the gripping motion. The algorithm explaining the working principle of the present system is shown in Figure 4.

## PERFORMANCE ANALYSIS OF A SMA ROBOT HAND

In order to determine the performance of the SMA robot hand a set of experiments on finger gripping time with respect to the applied power, gripping/releasing time analysis on the largest and smallest object dimensions that the robot hand can grip and the weight of the largest objects that can be carried by the robot hand, were performed. Experiments on the highest power rating that the fingers of

Table III. Ni-Ti fingers gripping time according to the number of fingers and to the power applied.

| | | Gripping time according to the number of fingers | | |
|---|---|---|---|---|
| | | 1 finger | 2 fingers | 3 fingers |
| Power | 100 watts | 38 seconds | 62 seconds | 92 seconds |
| Applied | 300 watts | 3.76 seconds | 6.34 seconds | 8.75 seconds |

Table IV. Releasing time in the SMA robot hand with different cooling systems.

| | Putting the object back | Fully opening |
|---|---|---|
| Freon Gas | 0.8 seconds | 3 seconds |
| Water at 15°C | 0.7 seconds | 4 seconds |
| 29°C room heat | 17 seconds | 397 seconds |

the robot hand can handle were also performed. All the results obtained are compared with the performance results of the METUhand.

*1. Gripping time of the Ni-Ti fingers according to power applied*

Two transformers 100 W and 300 W have been used in the experiments, which had been designed for measuring the gripping time of the SMA robot hand. The three fingers were in full gripping position in 92 s with the use of the 100 W transformer, while with the 300 W transformer this took 8.75 seconds. Table III shows the experimental results.

*2. Gripping-releasing time analysis in the SMA robot hand*

In this analysis, the time required to fulfil the full gripping motion has been observed. In addition, the time required to put back the objects has also been determined at a normal room temperature, with freon gas and water. Table IV shows the experimental results obtained. Note that the full gripping time for the robot hand was 8.75 seconds in the previous section.

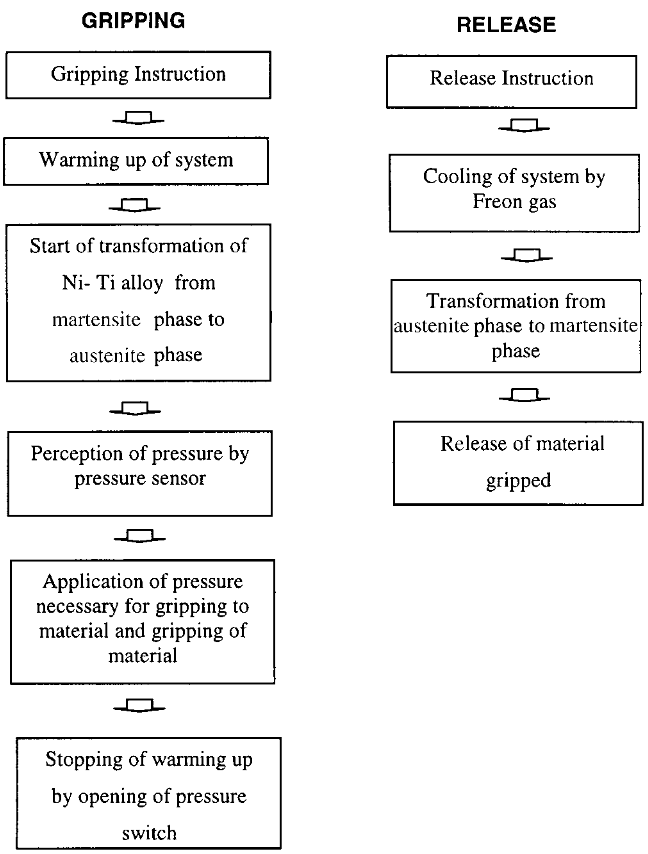


Fig. 4. Working algorithm of SMA Robot Hand.

*3. Largest and smallest objects that the SMA robot hand can grip*

In order to determine the range of the largest and the smallest object dimensions the dimensions of a prismatic object in three axes of the Cartesian coordinates are changed individually. Then the delicate gripping and strong gripping processes of the robot hand are tested within these dimensions. In the delicate gripping process, in gripping with fingertips, gripping action was observed for the objects which were as thin as a paper sheet and as thick as 4.5 cm. In the present design of the SMA robot hand, it has been observed that the robot hand can grip the smallest cylindrical object (2.5 cm in diameter) by using the inner face of the fingers (strong gripping). After increasing the object dimension step by step, the largest object diameter, which can be griped by the robot hand, has been determined to be 7.5 cm. In these delicate and strong gripping studies, the gripping range can be increased and decreased by changing the angles of finger roots, at the location where the fingers are fixed to the fiber frame.

*4. Weight of largest object that can be carried by the SMA robot hand*

In order to estimate the weight of the largest object that the SMA robot hand can carry, the robot hand fingers first handled the object with the delicate gripping style. After that other objects were added with a pulley and the maximum weight was measured. Later the position of the hand was changed in order to pull the object upwards. Beginning with 250 grams and increasing the weight step by step, the maximum weight that the robot hand can carry was observed to be 1750 grams. For greater weights, the objects between the fingers have started to slide.

*5. Maximum force that robot hand fingers can apply*

A range of experiments have been conducted by using one finger of the robot hand in order to determine the maximum force that the robot hand fingers can apply. For this experiment, first the spring constant, $k$, is determined and then the spring is attached to the bottom of the finger. The maximum force was measured while the finger was closing. It was observed that the finger can pull a weight of up to 2250 grams, when heated.

*6. A comparison of the SMA robot hand with the METUhand*

Experimental results of the present SMA robot hand have been compared with the performance results of the METU-hand. The analysis for the largest and the smallest object size that can be carried and for the maximum object weight to be lifted by the METUhand, and its repetition analysis have been made in parallel with the performance experiments for the SMA robot hand.

In the power analysis of the METUhand, a weight of 22 gram object was increased by 2 grams at each step up to 32

Table V. Repetition analysis of METUhand.[3]

| | Hook gripping | | Strong gripping | | Delicate gripping | |
|---|---|---|---|---|---|---|
| | First mistake | Shape deception | First mistake | Shape deception | First mistake | Shape deception |
| Unloaded hand | 6 | 8 | 5 | 7 | 5 | 6 |
| Carrying the cylindrical part | – | – | 3 | 4 | 3 | 4 |
| Carrying the prismatical part | – | – | 4 | 4 | 3 | 5 |

grams. It was possible for the METUhand to hold this weight without losing control.[3] In the same experiment performed with the present SMA robot hand, it was observed that it can carry objects as heavy as 1750 grams. In the tests designed to determine the smallest and the largest object volume to be carried by the METUhand, measurements were repeated by increasing the dimensions of a prismatic object ($3.5\times2\times5.5$ cm; $5\times2\times8$ cm; $2\times5\times10$ cm). It was observed that objects of dimensions $2\times5\times10$ cm and smaller objects could be gripped by the METUhand. In the same tests performed with the SMA robot hand, it was seen that objects smaller than 4.5 cm could be gripped with finger tips, and that objects between 2.5 cm and 7.5 cm in diameter could be gripped with the inner part of the fingers.

As a result of this performance analyses, it was observed that the METUhand and the SMA robot hand have almost the same gripping range. However, the object carrying capacity of the SMA robot hand was greater than that of the METUhand.

No errors were observed in the finger movement repetitions up to 1,000 times with the SMA robot hand. In the repetitions after that, a 1% memory loss in the finger gripping axis was observed. According to the repetition analysis positioning errors were observed to be too low to affect the appropriate gripping in the applications of the SMA robot hand up to 1,000 repetitions. Zengeroglu[3] reported the number of repetitions the METUhand robot hand would make to produce the first mistake during the hook holding, strong gripping and delicate gripping processes (see Table V).

The problem regarding the movement limitation for the fingers as a result of getting tired (after about 1,000 repetitions) in the Ni-Ti fingers of the SMA robot hand can be easily solved by changing the fingers at shorter intervals.

## CONCLUSIONS

The use of the SMA technology in robotics is quite new. Therefore, the SMA in conventional moving systems in robotics is very important, as it forms a basis for future studies.

This study proved that the SMA can be used effectively in a robot's end effector in versatile robot hand designs. The three-finger SMA robot hand can be used flexibly in various fields of industry.

The advantages of the SMA robot hand are as follows: The Ni-Ti alloys used in the robot hand fingers behave in the same way as the muscle structure of the human hand, hence it allows a more flexible movement. Therefore, the problem of increasing the degree of freedom in other robots is not applicable here. As the ratio between force and weight is higher, more active and stronger gripping can be obtained. The rate of errors in the object carrying-holding/releasing repetitions is low, up to 1,000 repetitions.

Developing the gripping ability of the prototype robot hand is possible by using the Ni-Ti alloy in alternative forms. The use of Ni-Ti alloys in the form of fibers instead of sheet form in the fingers of the robot hand will enable the system to operate more flexibly. In addition it will produce savings in energy consumption and will increase the working speed of the heating and cooling systems, which are the sub-systems of the robot hand.

Step motors occupy a part of the available space. The simplicity and smallness of the SMA robot hand system can be seen as another advantage of the SMA robot hand.

Furthermore, the systems made with the SMA are observed to be simple in mechanism; silent, light, clean and can be remotely controlled.

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