Journal of Ocean Engineering and Technology, Vol. 4, No. 2, pp. 191~197, December, 1990

⦿ Technical Paper

Submarine Robot Actuated by Shape Memory Alloy+

Heihachi Shimada*, Yasubumi Furuya*, Young-Chul Park** and Sae-Wook Oh**
(*Received November* 28, 1990)

形狀記憶合金에 의하여 驅動되어지는 海底로봇

島田平八*·古屋泰文*·朴榮哲**·吳世旭**

Key Words : Thermo-Mechanical Transformation (열기계변태), Shape Memory Alloy (형상기억합금), Submarine Robot (해저로봇), Submarine Resources (해저자원), Shape Memory Effect (형상기억효과)

抄 錄

최근 열에너지를 기계에너지로 변환이 가능한 신소재인 형상기억합금으로 제작된 새로운 형태의 actuator를 이용한 해저로봇의 개발에 관하여 많은 연구들이 행하고 있다. 저자들은 로봇의 모양을 실제 동물의 형태인 "게" 모양으로 하고, 로봇을 구동시키는 게의 다리의 모든 연결부분의 인공근육을 Ni-Ti계 형상기억합금 스프링 또는 와이어로 구성되어져 있으며, 마이크로 컴퓨터에 의하여 구동이 자유로이 조절이 가능한 게 형태의 모양 로봇을 실제의 1/20 크기로 제작하였다. 이 로봇의 특징은 구조가 간단하고, 고강도, 고내식성 그리고 부드럽고 자유롭게 3차원적 동작이 가능하다는 것을 들 수 있다. 해저 로봇의 최종목표는 심해자원의 탐사 및 채굴이 이용하는 것이다. 따라서 본 연구에서는 그 가능성 및 기술적 문제 그리고 미래의 이러한 형상기억합금 로봇에 의한 심해자원 탐사를 위한 국제적인 협력의 필요성에 대하여 연구 검토하고자 한다.

1. Introduction

Recently, the robot actuator worked by the driving recovery-force of the thermo-mechanical martensitic transformation of shape memory alloys (SMA) has been studied by a few reporter in these five years.[1~4]

This new type of SMA robot is simple in the structure, much more than other robots actuated by motor or hydraulic cylinders.

Especially, SMA actuator of Ni-Ti alloy is cha-

+ Reported at MRS. Int. I. Mtg. on AdV. Mats.(Tokyo, 1989)
* Tohoku University, Japan
** Member, Dept. of Mech. Eng., College of Eng., Dong-A University

racterized by high strength, high power/weight ratio, three dimensional free motions, high water-pressure and corrosion resistance etc, therefore, SMA robot has the possibility as one of the advanced extreme operation robots in the environment such as deep sea bottom, space and nuclear radiation etc. where the controls and maintenances of the robots operated in conventional systems with motors or hydraulics are very difficult because not only its structure would have to be excessively large but also its electrical and mechanical systems would be subject to very strong corrosive effects.

However, many technical problems lie before actual application of SMA robot such as responce speed in heating and cooling, precise control, fatigue and degradation of SMA and elevation of energy efficiency etc.[4~6]

Based on the above mentioned characteristics and advantages of SMA actuator, in this study, we have proposed and tried to developed an extreme operation SMA robot model which has a final aim to investigate and collect the very deep submarine resources by the remote control from mother ship.

2. Experimental Procedures

2. 1 Outline of SMA Mechanical Animal Robot

The outline of SMA mechanical animal robot first designed by the authors[3] is shown in Fig. 1. This "robot crab" employs springs or wires of shape memory Ni-Ti alloy in every joint just like a skeleton muscle of real crab. The "muscles" of this robot make use of the alloy's expansion and contraction with changes in temperature which are brought about by heating the alloy directly with electricity or allowing it to be cooled by the water itself. Using the direct current driving method under the micro-computer remote control

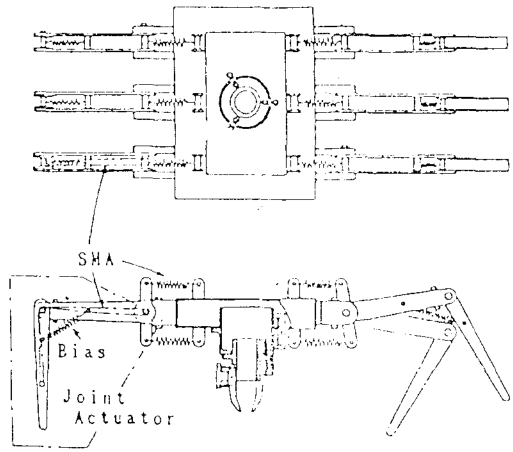


Fig. 1 Outline of SMA mechanical animal (mech-animal) robot (first trial)

from the mothership, the robot crab can move smoothly and investigate on the rugged bottom of the sea.

2. 2 SMA Joint Actuator Model of a Leg in Robot Crab

A model of leg in crab which is made to investigate the basic characteristics of dynamic motion of joint actuator with shape memory alloy is shown in Fig. 2 SMA, Ni-Ti wire(diametor $\phi = 0.4$ *mm*) is stretched from the root to another and of

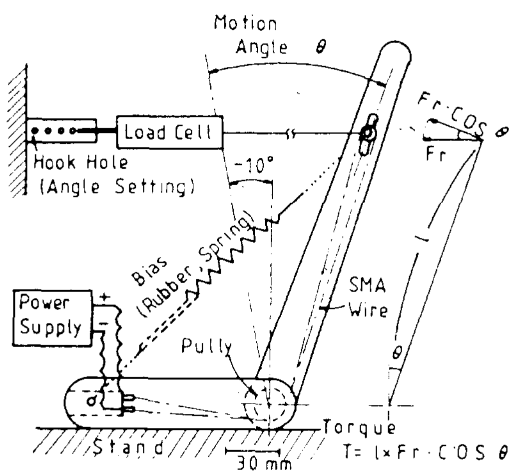


Fig. 2 SMA joint actuator

leg via a central pulley(diameter $\phi=20mm$), therefore, by this system, the rectilinear displacement of very small, a few percent(2~3%) in Ni-Ti wire can be transformed into considerably large angular displacement(i. e. rotation) of leg. The arm(i. e tip of the leg) opens towards the wider angle by the recovery force in accordance with the shrinkage of SMA wire(i. e. up to the length equal to memory state), which is brought about with the change of temperature in wire by direct pulse current from electric power supply, and on water-cooling process it closes by the tension force of bias spring or rubber less than the recovery force of SMA wire. Changing the location of hook-holes to set several angles of the arm, the generating torques(T) are measured by using recovery forces (Fr) at the tip of arm and the formula($T=\ell\times Fr\cos\theta$) in Fig. 2.

Dynamic motion and response speed of the SMA joint actuator are also investigated through the continuous photographs by full autocamera.

3. Results and Discussions

3.1 Selection and heat treatment of shape memory alloy(Changes of recovery force in SMA Ni-Ti wire with pre-strain)

In the SMA actuator in Fig. 2, Ni-Ti wire is always under pre-strained condition by the tensile force(Fb) of bias spring. Temperature change (20~80°C) of wire is obtained by direct current heating method and Fr value for each case is measured by tensile testing machine(Tensilon).

As a result, one can get the largest value of Fr under the pre-tensile strain(ε) of 3~5%.

3.2 Measurement of Torque of SMA joint arm(Effects of pre-strain, bias material on torque)

Relationship between the generating torque(T) of SMA joint arm and motion angle(θ) are shown in Fig. 3. Both of torque(T) and angle(θ) increase in proportion to the increase of pre-strain values. Also, torque(T) decreases inverse proportion to the value of the motion angle(θ) of the arm, and this means SMA actuator has inherently the capability of soft touches and actions just like the muscles of animals[4, 5]. It is also confirmed from the figure that nonlinear elastic material like a rubber is more effective for a bias material.

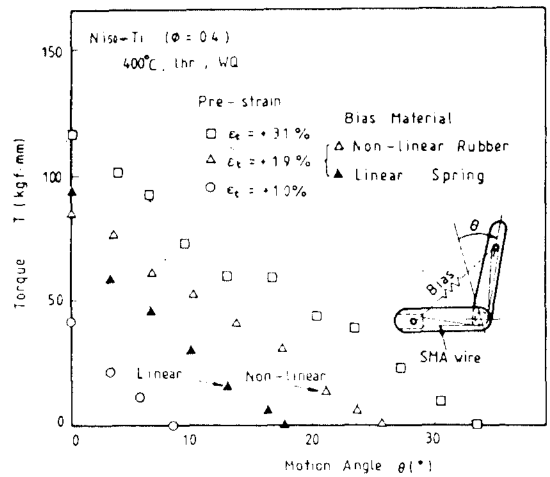


Fig. 3 Generating torque of SMA joint arm

3.3 Response speeds of SMA actuator in water

The speed up of dynamic motion of the actuator has been discussed as one of the most important technical problems in engineering use of SMA robot. So that we investigate the responses of SMA joint actuator in three cooling conditions (air, wind, water).

Relationships between the changes of motion angle($\triangle\theta$) and time laps in cooling process(t) are shown in Fig. 4.

The arm returns in a few seconds in water and its response speed is fast by about ten times that in air, however, electric power necessary for heating up the Ni-Ti SMA wire inevitably increases very much by about twenty times that in air.

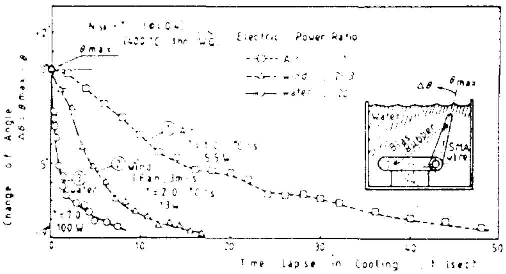


Fig. 4 Response speed of SMA joint actuator in three cooling conditions

This result indicates that a considerably large electric power will become necessary for driving the actual SMA submarine robot in open environment such as sea water, so that the more efficient construction and control system of SMA actuator will have to be discussed in making this SMA submarine robot fit for practical use for minimizing the electrical energy loss in sea water.

3.4 Changes of cyclic motions of SMA actuator(Fatigue and degradation of shape memory effect)

In general, SMA actuator necessitates a number of repeated motions, therefore, the investigation of the gradual decrease in recovery force(i. e. torque) with cyclic motion as well as the prevention measure of the degradation in shape memory effect(SME) are very important for the actual use of SMA robot actuator.

Fig. 5 shows the cyclic motion and degradation of SMA actuator.

From this figure, it is found that rapid decrease of cyclic motion range($\triangle$U) occurs in the early stage of about 10−20% in total life(Nf) and after this period $\triangle$U does not change so much and almost becomes saturated.

Failure of SMA wire occurs mostly at the part of pulley by plastically fatigue deformation. From these results, we can get the suggestions for more longer life of SMA actuator as follows.

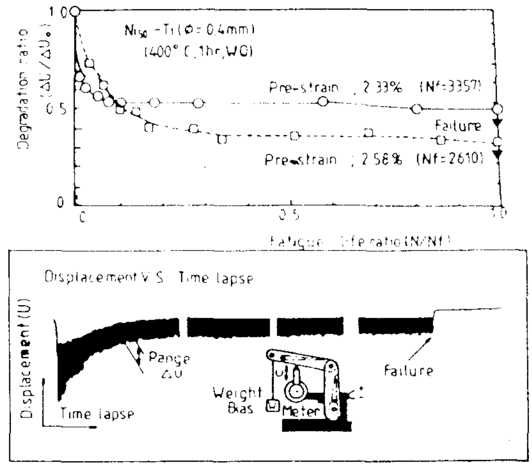


Fig. 5 Cyclic motion and degradation of SMA actuator

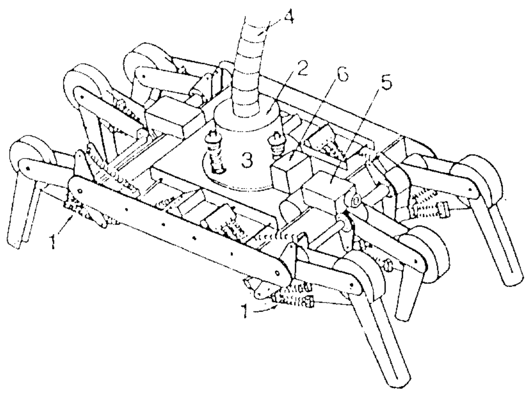
(1) Short period "training" before the actual use of SMA material or actuator will be efficient as one of the useful prevention measure for the degradation of shape memory effect.

(2) Mechanical construction of SMA actuator should be improved to decrease the prestrain value and avoid the plasic deformation of SMA material as much as possible.

3.5 Actual movement of SMA submarine mechanical animal "robot crab"

Since in 1985, we have been developing three trial models of robot-crab. First trial robot is constructed by SMA springs as shown in Fig. 1, second type by SMA wire and the latest model(i. e. third type) can be actuated by remote control by microcomputer. The outside appearance designed as a practical type of SMA robot crabs is shown in Fig. 6, however, at present, the third trial robot in our study does not yet have the machinery for collecting and sucking up the manganese nodules.

Joint part at the root of leg which is especially designed to minimize the reduction in the driving force(i. e. torque) of arm rotates semicircularly,



1. Shape Memory Alloy (Spring or Wire)
2. Collector of Nodules
3. Collecting claws
4. Suction Pipe
5. Ultrasonic Sensor
6. T.V. Camera

Fig. 6 Outside appearence of SMA submarine "Robot Crab" (in plan)

and each leg repeated up and down in turn by electric pulse current under micro-computer control.

This robot crab is arranged to move in the simple walking model of usual three standing pints. Every SMA Ni-Ti spring is enveloped by the fibre-glass pipes not only to avoid the excessive thermal exhalation from SMA materials but to decrease the amount of consumption of electric power. By the several technical improvements as indicated above, the third trial robot equipped with micro-video camera(see, Fig. 7) can move under remote micro-computer control and investigate on the bottom in water. The speed of its movement is about 15 cm(i. e. about 1/4 of total length) in 8 seconds(i. e. 1/2 peroid in one cycle) and the electrical power of consumption in this robot (i. e. about 1/20 in practical type) is improved toward the value of 10 *kW* in water. This electrical power value is about ten times as much as in air.

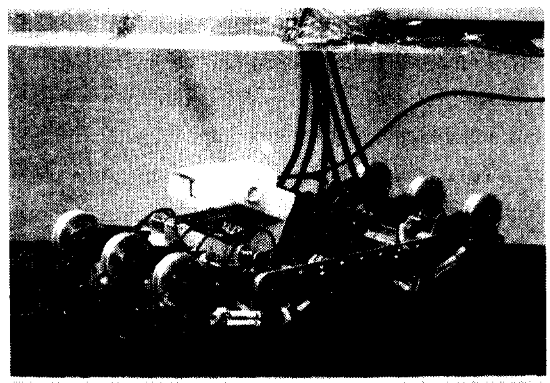


Fig. 7 Photograph of the developed SMA robot crab(about 1/20 in actual size)

3. 6 Features, technical problems and some opinions for developing SMA submarine robot

In the present projects for developing manganese nodules in advanced countries, the engineering systems by using the collecting machine(i. e. collector) towed by mother ship on the sea have been proposed[7]. However, this system inevitably necessiates very large-scaled, a whole controlling method through a ship to collector.

Therefore, in this system, it seems to be considerably difficult in total control and also is in danger of overturn of the collector on the rugged bottom of the sea.

Futhermore, in the extreme environment of deep sea bottom, the controls and maintenances of the robots operated in conventional systems with motors or hydraulics are very difficult because not only its structure would have to be exececessively large but its electrical and mechanical systems would be subject to very strong corrosive effects.

In contrast, SMA actuator of Ni-Ti material is especially characterized by high strength, high power/weight ratio,three dimensional free motions, high water-pressure and corrosion resistance etc., therefore, SMA robot has simple contruction as well as the possiblity to move smoothly without environmental pollutions in the ocean bottom.

Based on the above-mentioned characteristics and advantages of SMA actuator, we will probably be able to reduce the number of machinery components and weight in SMA robot much more than those in case of conventional actuation system by motors and hydraulics[8]. Therfore, in consequence, financial costs for the manufacture as well as maintenances could be reduced considerably in our proposing system of SMA submarine robot. Next, technical problems in developing SMA submarine robot are discussed.

As mentioned in the paragraph of 3.4 and 3.5, the main technical problems are thought to be summarized in next two factors. One of those is low energy efficiency in transforming the electric power into the motions of SMA acturator(i. e. torque of the arm). In general, the efficiency of energy transformation in case of a robot system by motors and cylinders is recognized in the order of 30~40%, on the other hand, that of SMA actuator is about 5~6% (i. e. about one tenth in the former case) at most due to the irreversible thermal exhalation from SMA material. It is one of the countermeasures for improving the energy efficiency that one adopts the thermally closed system by using a circulation of the hot and cold water alternately by small pump through the tubes which are connected with each SMA actuator. We might utilize the natural thermal energy source of the gap of temperature between sea surface (25℃) and deep sea bottom(4℃) by using of large scale circulation system in the sea water.

The second problms is thought to be the fatigue and degradation of shape memory effect with the long use of SMA actuator. As for this problem, short training as well as the improvement of mechanical design should be necessary, but it seems not to become so serious technical problem for the reason that SMA Ni-Ti material basically has very longer life about 10 cycles much more than the usually used engineering steels[6].

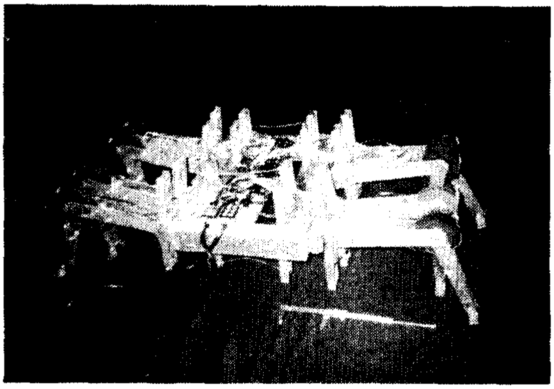
Another technical problem such as the precise control method for SMA robot and collecting system for manganese nodules from the ocean bottom in the depth of 5000*m* are still remain, however, in such an extreme environment, it is expected that the advantage of SMA robot system would surely increase more and more than in air due to the reasons mentioned in this paragraph of 3.6.

However, much more detalied technical improvements will become necessary by the time of actual application of this type SMA submarine robot. These problems with the development of SMA submarine robot are surely new, peculiar and not so easy to solve because the unkonwn factors and unique responses of SMA material still remain. From these reasons and the internationally common resources of manganese nodules in ocean bottom, the authors feel the necessity of international cooperation when our proposed idea of SMA submarine robot project would become worthy to be realized in the future.

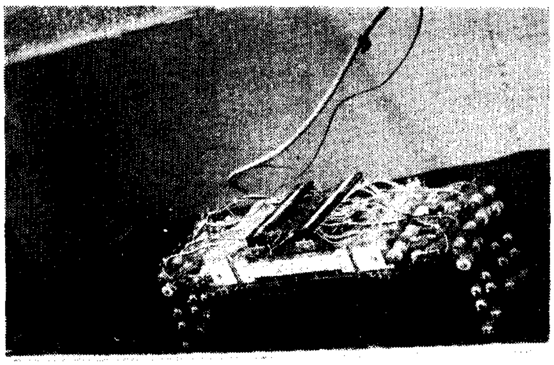
4. Conclusions

An advanced submarine robot model actuated by the driving force in thermo mechanical transformation of shape memory alloy(SMA) is developed. The manufactured model "robot crab" is constructed with the artificial muscles of Ni-Ti SMA spring or wires in the every joint part of moving legs, and it can move by electrical pulse current in micro-computor control.

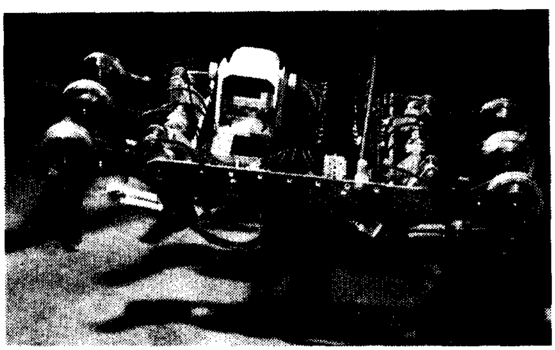
An summarized in the last Fig. 8, SMA robot is simple in the structure and also characterized by high strength, high water pressure and corrosion resistance as well as more rapid motion than in air due to the high cooling capacity of water. In the maunfacture of SMA submarine robot, main



First trial (SMA spring type)



Second trial (SMA wire type)



(TV Camera search in water)

Fig. 8 Our developed SMA "mechanical animal robot crab"

technical problems are thought to be summarized in the next two factors. One is very low energy efficiency(about 1/10 – 1/20) in transforming the electric power into the motion of SMA actuator. The second problem is the prevention measure of fatigue and degradation of shape memory effect with the long use of SMA actuator. Especially, the former, elevation of energy efficiency seems most essential problem.

Anyhow, much more detailed and systematic researches will become necessary for the actual application of this type SMA submarine robot. From these reasons and the internationally common resources of manganese nodules etc. in ocean bottom, the authors feel the necessity of international cooperation when our proposed idea of SMA submarine robot project become worthy to be realized in the future.

References

1) Miwa, K., D. Honma, Bull. Japan Inst. Metals, 14, p. 61, 1985
2) Kuribayashi, "System and Control (in Japanese)", 29, p. 288, 1985
3) Furuya, Y., H. Shimada, Y. Goto, R. Honda, 4th Japan Robot Sympo., p. 461, 1986
4) Hirose, S., K. Oita, M. Tsukamoto et al, 2nd Japan Robot Sympo., p. 123, 1984
5) Hosoda, Y., JSME Seminar No. 648, p. 53, 1987 – 7
6) McNichols, J. L., Jr., P. C. Brookes, J. S. Corny, J. Appl. Phys. 52, p. 7442, 1981
7) Manganese Nodules Mining System Projected by MITI, Rep. Tech. Res. Assoc. of MNMS, Japan, 1982
8) Ishibashi, T., Marine Museum in Tokai University, 13–2, 1983