A VIRTUAL TEACHING MODULE FOR LEARNING THE BASIC CONCEPTS OF SHAPE MEMORY ALLOYS

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Abstract - A shape memory alloy (SMA) is an alloy which can eliminate the deformation at lower temperatures and restore its original shape upon heated. The SMA has been receiving considerable attention in materials science, and its applications include robotics, automotive, aerospace and biomedical industries. Observing the shaping and restoration processes of an SMA is important for understanding its working principles and applications. However, the transformation of its nanostructure with temperatures can only be seen using special equipment such as the transmission electron microscope. In this study, a teaching module is designed using the virtual reality (VR) technology and the research results of SMA to show its shape memory properties, shaping and restoration processes as well as real-life applications in an immersive and interactive way. A teaching experiment has been conducted to investigate the learning effectiveness of students using the proposed teaching module in comparison with that of using real SMA materials as the teaching aids. The experimental results show that the virtual teaching module can enhance the learning effectiveness significantly, and the questionnaire results also reveal that most students held positive attitudes toward the teaching module. They believed it could increase their learning interest and help them understand the properties and applications of the SMA.

Index Terms - virtual reality, shape memory alloy, transmission electron microscope, shaping, restoration.

I. INTRODUCTION

The shape-memory alloy (SMA), also called smart metal or memory metal, is an alloy material which can fully eliminate the deformation at a lower temperature and restore its original shape when heated. In addition to the shape memory property, the SMA is lightweight and resistant to most chemicals. Some SMAs have the attractive features of super elasticity, damping capacity and biological compatibility, so they are widely applied in aviation, robotics and biomedical industries. The SMA products in real life include: self-adjusting dental braces, optical frames, vascular stents, and so on. The SMA can effectively reduce the cost of repeated shape adjustment as well as extend the lifetime of a product. The shape memory property was first discovered in the Au-Cd alloy by Chang and Read at the University of Illinois in 1951 [1]. A similar property had also been found in the Ni-Ti alloy at the U.S. Naval Ordnance Laboratory by Buehler et al. in 1963 [2]. Since then, the SMA began to receive the attention of researchers in materials science and the related industries. The applications of SMA grew extensively by the successive finding of the shape memory properties in other alloys such as Fe-Mn-Si, Cu-Zn-Al and Cu-Al-Ni [3-5]. More recent SMA applications include space antenna, military aircrafts, civil engineering and medical treatment [6-9]. The transition temperature for the transformation of an SMA's crystal structure can vary with its crystal size, applied stress, thermal cycling times and other factors [10], among which the proportion of the alloy ingredients has the major influence. Therefore, the applications of the SMA can be determined by controlling the proportion of its ingredients. In addition, the smelting during the manufacture of an SMA can be affected by the constituent elements. Some alloys can be directly smelted in the air, but others may react with oxygen and affect their properties. Taking the Ni-Ti alloy as an example, it must be hot rolled at 800-900°C by high-frequency vacuum induction melting, then forged at 700-850°C and finally crushed into the sheet or thread shape by processing in the cold room. This process can cause hardening, which is not favorable for many applications. Thus, the annealing process is often performed to eliminate the hardening effect. A simplified manufacturing process of the SMA proposed by Markopoulos et al. [11] is shown in Figure 1. To create the shape memory property, the SMA must be fixed to the required shape after the annealing process, then heated to about 400-500°C while maintaining the shape and then cooled down. If there is any deformation caused by external force at room temperature, the SMA will return to the memorized shape by simply heating it to the transition temperature.

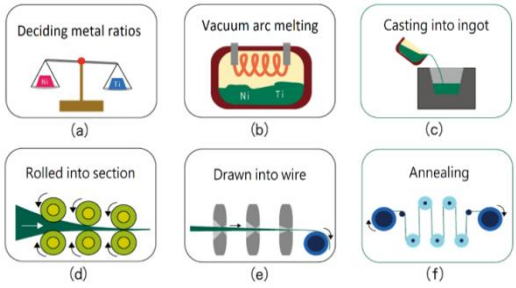


Figure1. A simplified manufacturing process of the SMA

The SMA is an important field of study in materials science. Observing the shaping and restoration processes of an SMA is essential for understanding its basic properties and applications. However, it is expensive to conduct the shaping experiment using real SMA materials, and the waste materials must be

disposed properly to avoid environmental pollution. Besides, the transformation of crystal structures must be observed using special equipment such as the transmission electron microscope (TEM) [12], which is an expensive apparatus such that many students do not have a chance to operate it personally. All these factors cause the difficulty of understanding the basic concepts and knowledge of the SMA. Virtual reality (VR) is a computer-generated virtual environment to simulate the realistic or imagined world, where the 3D visual effect and interaction can be achieved by wearing a head-mounted display and button-operated handsets. It can also be called immersive multimedia because one can see and hear as if situated in the real world, and even interact with other users manifested by avatars [13]. A virtual and realistic environment can reduce the cost and avoid the danger while satisfying the requirements in the experimental or training processes. VR has the sense of reality and high interactivity to enhance learning interest and motivation, so it is suitable for applications in science and engineering education [14-16]. In this study, a teaching module is designed using the VR technology and the research results of the SMA for learning its properties, shaping and restoration processes as well as real-life applications (e.g. the heat-driven motor and vascular stent) in an immersive and interactive way. The teaching module can be operated on mobile devices for students to conduct the virtual experiment of the SMA shaping and restoration. It can enhance the understanding of the basic SMA concepts through interactive operation and microscopic observation of the structural change with temperatures. A teaching experiment has been conducted to investigate the learning effectiveness and attitudes of students after using the teaching module. The experimental results can also be used as the reference for system improvement. The rest of this paper is organized as follows. Section 2 introduces the SMA properties and applications. Section 3 describes the design and operation of the teaching module. Section 4 reports the analytical results of the teaching experiment. Section 5 provides the conclusions.

II. SMA PROPERTIES AND APPLICATIONS

Pure metals contain the same kind of atoms which are closely stacked, while alloys are composed of different metal atoms and their crystal structures can be divided into the austenite phase and the martensite phase [17]. The SMA has both the austenite phase, which is high-temperature stable, and the martensite phase, which is low-temperature stable. When pure metals are deformed to exceed the elastic range by an external force, they cannot recover their original shapes by heating. In contrast, when the SMA is in the martensite phase and plastically deformed within the limited extent, it can be heated above the transition temperature to transform into the austenite phase, where the SMA will restore its original shape (Figure 2). When the SMA is cooled down to the normal temperature, it will remain the same shape. The shape memory property can be applied to develop a variety of intelligent products. Therefore, the SMA belongs to the intelligent materials.

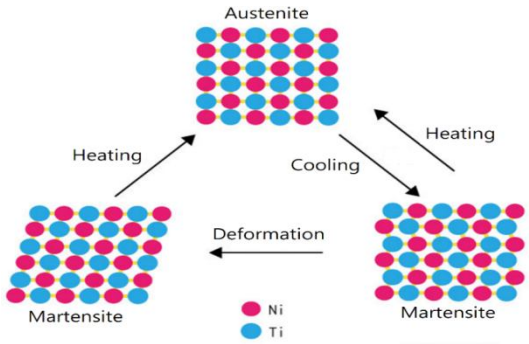


Figure 2. Transformation between martensite and austenite

The Ni-Ti alloy is the most important and widely used SMA due to its excellence in shape recovery, durability and corrosion resistance. Other attractive properties include high mechanical strength, super elasticity, biological compatibility and stable transition temperature, providing a high potential for engineering and medical applications. As a result, the Ni-Ti alloy is suitable for such industries as aviation, robotics and medical treatment. However, the Ni element, a toxic metal, may affect human health and increase the risk of cancer, so it is only used in the temporary appliances, such as dental braces and vascular stents. The Ni-Ti alloy is composed of about 50% Ni and 50% Ti, and the proportion can be adjusted according to the requirements of different applications, such as the range of transition temperature and the mechanical properties. In general, the transition temperature is lower if the content of Ni is higher [18]. For example, the transition temperature of the alloy with 50%Ni and 50%Ti is 40°C, and the alloy with 55%Ni and 45%Ti has the shape memory capability at room temperature. If the content of Ni is lower than Ti, the alloy's transition temperature can reach 120°C. Basically, the SMA shape memory effects can be divided into the following three types (Figure 3) [19]:

- **On-way shape memory effect**

When the SMA is in the martensite phase, it can be deformed and will remain this shape until heated above the transition temperature. Upon heating, the SMA transforms into the austenite phase and returns to its original shape. The SMA will remain in this shape after cooling until deformed again.

- **Two-way shape memory effect**

When the SMA is deformed with/without an external force and then heated above the transition temperature, the SMA will enter the austenite phase and return to its original shape. When the SMA is cooled down below the transition temperature, it will automatically return to the memorized shape in the martensite phase. It is called the intrinsic two-way effect.

● **All-round shape memory effect**

When there is more Ni in the Ni-Ti alloy, the SMA will have an abnormal memory effect similar to the two-way shape memory effect, but its deformation is more obvious and intense. Therefore, the SMA will automatically shrink when it is cooled down below the transition temperature. When the temperature is lower, it will change to the reverse direction of the deformation. The SMA will restore the memorized shape again if it is heated above the transition temperature of the austenite phase.

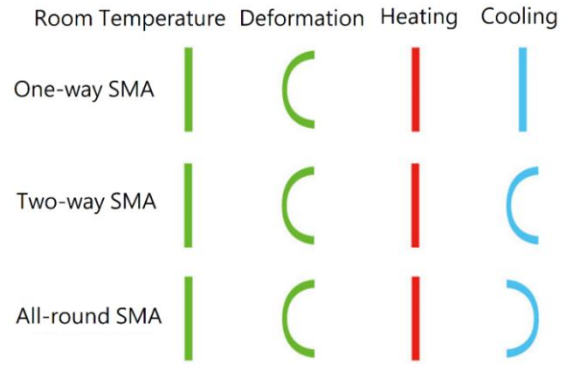


Figure 3. Different SMA shape memory effects

In the automotive industry, the SMA is a lightweight and solid-state alternative to conventional actuators such as hydraulic, pneumatic, and motor-based systems [20]. The heat conduction and shape memory properties of the SMA can be used to drive a heat engine to save electric power. For medical applications, the transition temperature can be set to the body temperature if the SMA is used for the production of biomedical devices. For example, it can be used to design fixation devices in orthopaedic surgery or dental braces in orthodontics to exert constant tooth-moving forces on the teeth [21]. There are some other real-life applications of SMA, which include:

● Vascular filter: When implanted into the vein vascular, it will gradually return to the net shape to prevent the sludged blood from flowing to the heart and the lung. It is effective for capturing and breaking apart particles in the blood.

● Vascular stent: After the implant surgery, the blood will flow through the vascular stent and increase the temperature to return to its original shape. It is used for treating the vascular sclerosis and angiemphraxis.

● Bone lamella: It is used in osteosynthesis to fix two pieces of broken bones, where the pressure generated by its shape memory effect can force the broken bones to heal faster.

● Fire alarm: At room temperature, its SMA connector is bending and has no contact with the power. When a fire occurs and the temperature rises, the SMA connector will stretch automatically and touch the power to send out the alarm signal.

● SMA-spring motor: The length of SMA spring can change with repeated heating and cooling by electric power to drive the motor and generate kinetic energy.When you submit your final version, after your paper has been accepted, prepare it in two-column format, including figures and tables.

III. SYSTEM DESIGN AND OPERATION

The learning contents of the teaching module are developed based on the research results of materials science and the SMA products on the market. The VR technology is used to design a virtual experiment for the users to experience the shaping process and observe the change of SMA crystal structures with temperatures through interactive operation. The teaching module is an application program developed under Microsoft Windows 10, with Unity3D as the system development tool (Figure 4).

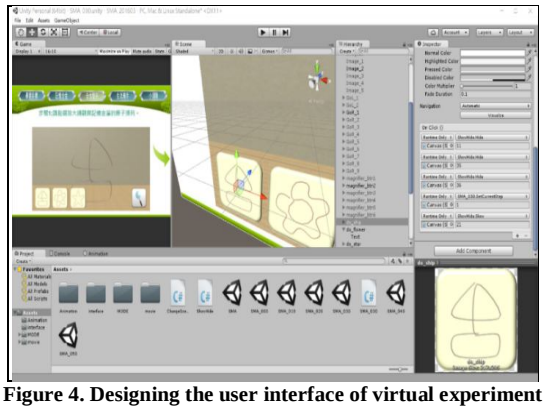


Figure 4. Designing the user interface of virtual experiment

The 3D objects and virtual scenes are designed using 3ds Max, where the completed 3D models and animations are exported to Unity3D to set up the interactive user interface with the programming languages of JavaScript and C#. Different behaviors for the same object can be set up during the script design to meet the requirements for different situations, e.g., the change of SMA shapes with temperatures. When the project is completed, it is converted into the installation file for execution on tablet PCs under the Android mobile operating system. The development of the teaching module includes three main parts (Figure 5). The first part is to create the 3D models of the objects in the virtual scene; the second part is to set up the properties of the objects; the third part is to design the interactive interface for the users to conduct the virtual experiment. To enable the easy cognition of the SMA basic concepts and knowledge, the teaching module contains three interactive mechanisms: (1) touchscreen control, (2) camera control, and (3) interactive user interface to support different learning activities: (4) SMA learning contents, (5) SMA shaping and manufacture, (6) SMA applications and (7) online test. The C# programming language and internal API functions of Unity3D are used to develop the user interface for conducting the SMA shaping experiment and observing the crystal structure during the phase transformation. When the user starts the teaching module, the system will

display the initial screen first. The user can click the button to enter the teaching module and begin with the introduction of learning objectives before conducting other learning activities.

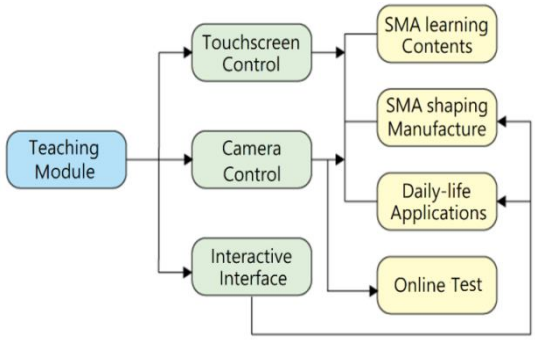


Figure 5. System architecture of the SMA teaching module

A. Learning Objectives

The teaching module developed in this study is focused on learning the SMA material properties, principles, shaping process and real-life applications. It is designed as an application program using the VR technology for execution on mobile devices such as smart phones and tablet PCs. The major purpose is to increase the learning interest and motivation of the users and help them understand the basic concepts of the SMA through interactive operation and observation. The learning objectives of the teaching module are: (1) understanding the material properties of SMA, (2) conducting the SMA shaping experiment, and (3) becoming familiar with the real-life applications of SMA.

B. System Architecture

The teaching module is designed for execution on mobile devices and its system architecture is shown in Figure 6. After entering the system, the verbal instruction will direct the users to go through each step for learning the basic concepts and knowledge of SMA. The user can read the learning objectives first by clicking the button in the upper left corner, and then followed by the introduction to SMA.

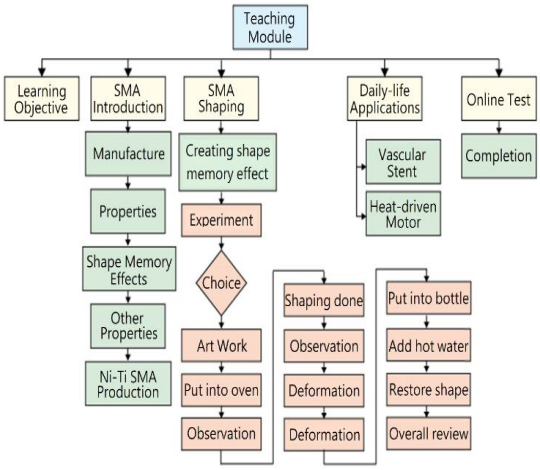


Figure 6. System architecture of the SMA teaching module

C. Designing 3D models

The 3D models and the virtual scenes in the virtual experiment are developed with 3ds Max (Figure 6). The textures were drawn with the image processing software and pasted to the 3D models by adjusting the luminance according to the environmental lights to make them look like real objects. After that, the 3D models were exported to Unity3D to set up the interactive user interface according to the script defining the operational procedure of the virtual experiment.

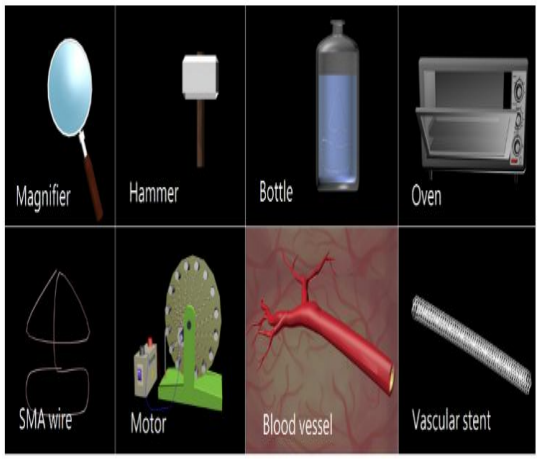


Figure 7. Designing the 3D objects in the virtual experiment

D. Initial Screen

When the user starts the application software, the teaching module will display the main screen first (Figure 8). The user can click the button to enter the system and perform the learning activities.

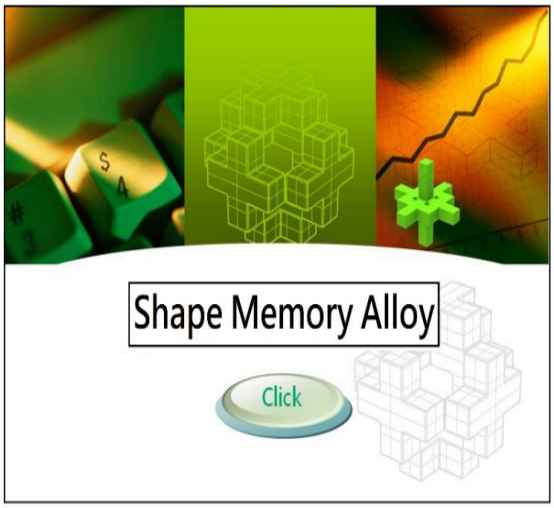


Figure 8. Initial screen of the SMA teaching module

E. Introduction to SMA

The user can learn the SMA properties and shape memory effects by entering the learning unit of 'Introduction to SMA', which includes the definition of SMA and its properties, shape memory effects, crystal structures, and manufacture of the Ni-Ti SMA (Figure 9).

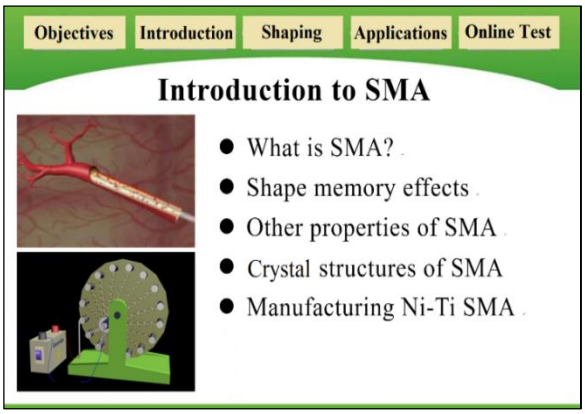


Figure 9. Learning the basic concepts of SMA

F. SMA shaping experiment

The user can experience the shape memory properties of the SMA by following the experimental procedure to observe the change of it crystal structure with temperatures (Figure 10). The purpose of this experiment is to design a ship in the bottle with the SMA wire. The user has to fold a piece of SMA wire into the shape of a ship and put it in the oven at 500 °C for 5 hours. After that, the ship is taken out of the oven for cooling down to room temperature. To check if the SMA wire has memorized the shape of a ship, the user hits the ship with a hammer and deforms it into a thinner piece such that it can be inserted into a narrow-mouth glass bottle. Then, the user pours hot water into the bottle to see if the deformed ship can recover its original shape. During the experiment, the user can observe the change of the SMA crystal structure between the martensite phase and austenite phase using the magnifier, a symbol of the microscopic view. Finally, the phase transformations for each step of the experiment is shown as a review of the whole shaping and restoration processes.

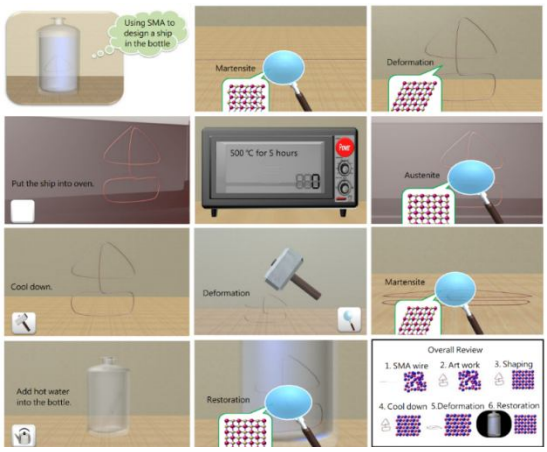


Figure 10. Designing a ship in the bottle using the SMA wire

G. SMA applications

The learning unit of 'SMA Applications' introduces two examples, i.e. the heat-driven motor and the vascular stent. The user can observe how the SMA material changes its shape and crystal structure with temperatures to understand the working principles. In the first example, the user can turn on the power supply to see the motor driven by the SMA spring, which is heated by the electric power and shrink to generate the tensile force (Figure 11).

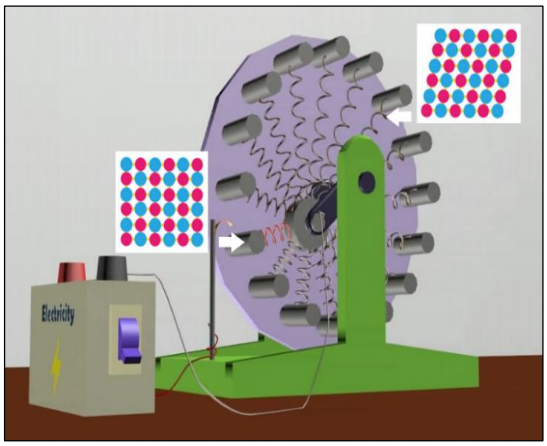


Figure 11. The heat-driven motor using SMA springs

After the rotation, the heated spring is disconnected from the power supply so it cools down and becomes loose. However, the succeeding SMA spring is connected with the power supply; it is heated and shrink to generate the tensile force for the motor to continue rotating.The second example shows the application of the SMA vascular stent for dilating the blood vessel. Before it is implanted into the blood vessel, the blood is stopped by clamps to keep the vascular at a lower temperature. The vascular stent is stretched into a thinner piece for easy injection into the blood vessel. After that, the clamps are removed and the blood is allowed to flow through the blood vessel. The blood temperature will trigger the phase transition and enable the vascular stent to restore its original shape for dilating the blood vessel (Figure 12).

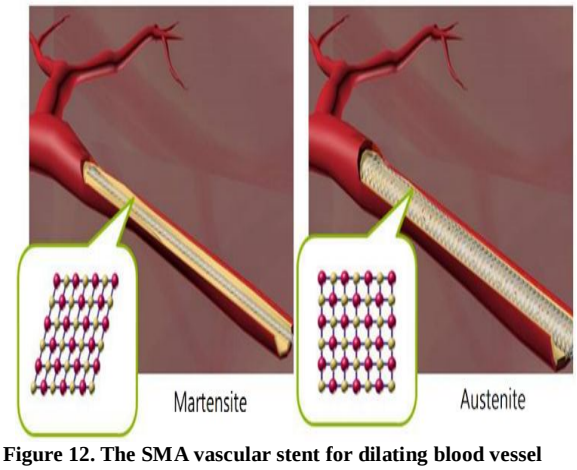


Figure 12. The SMA vascular stent for dilating blood vessel

H. Online test

When completing all learning activities, the teaching module will require the users to take the online test to evaluate their learning achievement. There are 10 multiple-choice questions designed based on the learning contents of the teaching module. By clicking

the 'Online Test' button, the system will display the test question one after another for the user to select the correct answer. For example, the first question in Figure 13 shows "Which of the following alloy is the most widely used SMA?" The user can select one of the four answers. If the user selects (D): "Ni-Ti", the system will reply "You are right." and move to the next question; if the user selects a wrong answer, the system will show the incorrect mark and and ask the user to answer again. The sceond question asks "Which is the structure of austenite phase?" The system will reply "You are right." and show a correct mark if the user selects (B).

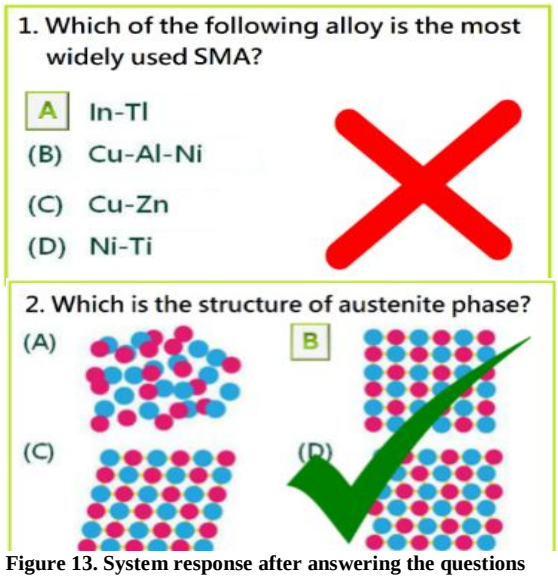


Figure 13. System response after answering the questions

IV. TEACHING EXPERIMENT

A teaching experiment has been conducted to evaluate the performance of the teaching module in learning the basic concepts of SMA. A questionnaire survey has been conducted to investigate the attitudes of students after using the teaching module. This study randomly selected two classes of students from the department of materials science and engineering at a university in northern Taiwan as the experimental samples, one class as the control group (70 students) and the other class as the experimental group (52 students). The control group was given a lecture and used the SMA wire as the teaching aids to conduct the real shaping experiment. The experimental group was given the same lecture and used the teaching module as the learning tool to conduct the virtual experiment. This study adopts a nonequivalent pretest-posttest design to investigate if a significant difference in learning effectiveness exists between the two groups. Before the teaching activities, the students in both groups took a pretest on their background knowledge about the SMA and its applications. After conducting the teaching activities, both groups took the posttest and the experimental group students also filled out a questionnaire. The questionnaire results can also be used as the reference for the system improvement. The flowchart of the teaching experiment is shown in Figure 14, and the variables in the teaching experiment are shown in Table 1.

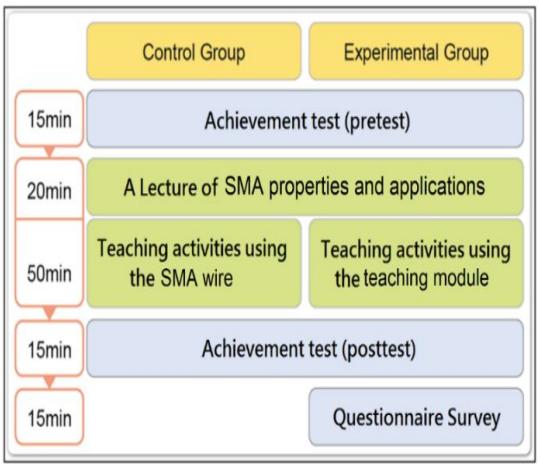


Figure 14. Flowchart of the teaching experiment

Table 1. The variables of teaching experiment

Independent variables	Control group	Conducting the real experiment
	Experimental group	Conducting the virtual experiment
Covariance		Achievementpretest
Dependent variable		Achievementposttest
Control variables		Teacher, teaching time, and learning contents

A. Research tools

The research tools in this study include the SMA wire, the teaching module, achievement test, and questionnaire survey, which are described as follows:

- **The teaching module**

The teaching module is an application program for execution on mobile devices. Its contents are based on the basic concepts and knowledge of SMA. The system was installed on tablet PCs and used by students in the experimental group (Figure 15).

- **SMA wire**

The SMA wire was used by the control group to conduct the real shaping experiment (Figure 16). After creating different shapes with the SMA wire, the students put their works into the oven where the temperature was set to increase 10°C per minute till 500°C. After cooling, the finished works were returned to students to check if they had shape memory effects.

● **Achievement test**

The achievement test (pretest and posttest) used in this study contains 20 test items, which were designed based on the research goal, teaching objectives and the SMA learning contents. They were revised according to the suggestions of two SMA experts and the science teacher.

● **Questionnaire survey**

The questionnaire is a system satisfaction survey and it was designed based on the discussion with two SMA experts and the science teacher. The questionnaire contains 17 questions (5 questions on learning contents, 5 questions on user interface, and 7 questions on operational experiences). This study adopts a 5-point Likert-type scale (scoring: 5=strongly agree; 4=agree; 3=neutral; 2=disagree; 1=strongly disagree) [22] to measure the attitudes of students after using the teaching module. The statistical software SPSS is used to perform a reliability analysis and the value of Cronbach's alpha is 0.95, showing the results have met the standard of high reliability.

B. Learning achievement analysis

In the teaching experiment, an analysis of covariance (ANCOVA) has been conducted to investigate if a significant difference in learning effectiveness exists between the control group and the experimental group. The statistical software SPSS is used to analyze the test results (Table 2). For the control group, the average scores of the pretest and the posttest are 55.22 and 60.29 respectively. For the experimental group, the average scores of the pretest and the posttest are 54.90 and 67.69 respectively. The progress made by the experimental group (12.79) is higher than the progress made by the control group (5.07).

Table 2. Descriptive statistics of achievement test

	Achievement test	Students Number	Average score	Standard error	Standard deviation
Control group	Pretest	70	55.22	1.58	13.23
	Posttest	70	60.29	1.54	12.85
Experimental Group	Pretest	52	54.90	1.59	11.48
	Posttest	52	67.69	2.10	15.13

This study uses the Levene test to compare the pretest results to see if any significant difference about the background knowledge of SMA exists between the two groups. The results show that F=1.93 and P=0.17>0.05, indicating no significant difference and therefore their SMA knowledge is about the same. To investigate if students made significant progress after learning, this study uses a paired sample T-test to perform a statistical analysis on the pretest and posttest for both groups. For the control group, the T value is 2.98 and the significance P=0.004<0.01, indicating the real SMA experiment is effective to enhance the learning achievement of control group. For the experimental group, the T value is 6.55 and the significance P <0.001, indicating the virtual experiment can also enhance their learning achievements.

Table 3. Statistical results of paired sample T-test

	Mean ofprogress	Standard deviation	T	Significance (P)
Control group	5.07	14.26	2.98	P=0.004<0.01*
Experimentalgroup	12.79	14.09	6.55	P<0.001**

P<0.01*, P<0.001**

Before performing the ANCOVA to compare the learning effectiveness between two groups, the assumptions for the homogeneity of variance and within-group regression coefficients have to be satisfied. The statistical results for these two analyses are described in the following:

● **Homogeneity of variance**

This study used the Levene test to verify if there is homogeneity of variance between the two groups. The results show that F=0.7 and P=0.4>0.05, indicating the variance has not achieved the standard of significance and thus the assumption for the homogeneity of variance is satisfied.

● **Homogeneity of within-group regression coefficients**

Before performing the ANCOVA, the test for the homogeneity of within-group regression coefficients has to be conducted for the two groups. The results show that F=1.37 and P=0.24>0.05, also without achieving the standard of significance. The covariance and dependent variable are not influenced by the independent variable and therefore the assumption is satisfied, so the ANCOVA can be continued.

● **ANCOVA results**

This study uses an ANCOVA to compare the difference in learning achievements between the control group and the experimental group. After excluding the effect of covariance and dependent variable, the impact of independent variable (the teaching method) is obtained as F=10.72 and P=0.001.

A significant difference exists between the control group and experimental group, and the learning achievement of the latter is higher than that of the former. In other words, the virtual experiment is more effective than the real experiment for enhancing the learning achievement of students.

C. Questionnaire results

A statistical analysis is performed on the questionnaire results by the experimental group. The student number and percentage in each selected item as well as the average score are calculated for each question to understand the attitudes of students after using the teaching module.

- **Learning contents**

Most students thought the contents of the teaching module is easy to understand and enables them to learn the principles and applications of SMA. They agreed that the teaching module could be used to learn the related knowledge and basic concepts of SMA and it enabled them to understand the crystal structure of an SMA may change with the temperature. The statistical results reveal that the scores in this category are between 4.27 and 4.40, and the overall average score is 4.33, indicating most students gave positive feedback on the learning contents of the teaching module.

- **Interface design**

Most students considered the operation of the teaching module is easy and the simulation of the SMA applications is close to the real situations. They thought the teaching module provides friendly user interface as well as proper font sizes and clear images.However, the score for the operational speed is slightly lower because the tablet PC needs more computation time in processing the 3D interaction. The statistical results reveal that the scores in this category are between 3.63 and 4.37, and the overall average score is 4.12, showing students were satisfied with the interface design of the teaching module.

- **Learning experience**

Most students could actively complete learning activities by following the system instructions. They felt the teaching module could help them understand the principles and the shaping process of SMA, and they could also understand that the crystal structure of an SMA may change with temperatures. They thought the teaching module could increase their learning interest and they would like to use it for learning the related knowledge and basic concepts of SMA.The statistical results reveal that the scores in this category are between 3.94 and 4.25, and the overall average score is 4.1, indicating the students were satisfied with their learning experience after using the teaching module.

D. Observation Records

The teaching experiment was conducted in the class of a material science course at a university in northern Taiwan. The students in both groups took the pretest before the lecture of teaching the SMA properties and applications. Then the control group used the SMA wire while the experimental group used the teaching module for conducting the SMA shaping experiment respectively. Due to the limited number of tablet PCs, 3 to 4 students in the experimental group shared a tablet PC in the teaching experiment. The instructor first explained the operation procedure and then let the students started conduct the learning activities. Because the SMA wire is expensive, 3 to 4 students in the control group shared a piece of SMA wire when conducting the shaping experiment. There were 5 teaching assistants on site to help with the teaching activities and answer the questions.

During the teaching activity, students in the experimental group were curious about the virtual experiment in the teaching module and they were focused on learning the SMA knowledge. Most students had the ability to operate the tablet PCs while using the teaching module and they discussed the learning contents with the group members actively. They considered the teaching module useful in learning the SMA properties and applications because it was easy to operate and thus could save a lot of time as well as incurred no danger or environmental pollution. For the control group, the teaching assistants first demonstrated the shaping process of SMA and then provided students with 15cm SMA wire. The students had to be careful about the strength used when developing different samples with the SMA wire. The works of different shapes made by the students during the class had no shape memory effect yet. The teaching assistants had to put them into the oven for the shaping process, which took about five hours. To save the shaping time, this study prepared some wire samples with shape memory for the students to continue the deformation and restoration process. The students stretched and twisted the wire samples and they were surprised to see the immediate restoration of their original shapes when put into hot water.

CONCLUSIONS

In this study, a teaching module is developed using the VR technology and the research results of the SMA products as the learning contentsto show the SMA properties, shaping and restoration processes, as well as real-life applications in an immersive and interactive way to enhance the understanding of SMA knowledge. A teaching experiment has been conducted to investigate the learning effectiveness and the attitudes of students after using the teaching module. The experimental results show that:

- **The teaching module is effective in improving the learning achievement.**

Both the control group and the experimental group made significant improvement after the teaching experiment, indicating the experiment using SMA wire as well as the teaching module are both effective for improving the learning achievement.

However, the ANCOVA results show that the learning effectiveness using the teaching module is significantly higher than that of using the SMA wire to conduct the shaping experiment.

- **The students held positive attitudes toward the teaching module.**

The questionnaire results show that most students were satisfied with the learning contents, interface design, and system operation of the teaching module. The students held positive attitudes toward the teaching module and they considered it easy to operate, useful in increasing their learning interest, and effective to help them understand the properties and applications of SMA.

- The teaching module can save the cost and time of conducting real experiments.

Using the teaching module, there is no need to use the TEM to observe the crystal structure of SMA. Besides, a high-temperature oven up to 500 °C is required in the shaping experiment and it takes more than 5 hours for the shaping process to complete. Therefore, the teaching module can be used as a useful tool in learning the basic concepts and knowledge of SMA for educational purposes.

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REFERENCES

[1] Chang, L.C., Read, T.A.: Plastic deformation and diffusionless phase changes in metals – the gold-cadmium beta phase. Transactions of the AIME, 189, 47–52 (1951).

[2] Buehler, W.J, Gilfrich, J.V., Wiley, R.C.: Effect of low temperature phase changes on the mechanical properties of alloys near composition TiNi. Journal of Applied Physics, 34(5), 1475–1477 (1963).

[3] Krishnan, R.V., Brown, L.C.: Pseudoelasticity and the strain-memory effect in an Ag-45 At. Pct Cd alloy. Metallurgical Transactions, 4(2), 423–429 (1973).

[4] Si, N.C., Sun, K.Q., Sun, S.C., Liu, H.X.: Damping performance of Cu-Zn-Al shape memory alloys in engineering structures. Journal of Central South University of Technology, 11, 246–251 (2004).

[5] Lojen, G., Anzel, I., Kneißl, A., Krizman, A., Unterweger, E., Kosec, B., Bizjak, M.: Microstructure of rapid solidified Cu-Al-Ni shape memory alloy ribbons. Journal of Materials Processing Technology, 162-163, 220–229 (2005).

[6] Mabe, J.H., Calkins, F.T., Alkislar, M.B.: Variable area jet nozzle using shape memory alloy actuators in an antagonistic design. Industrial and Commercial Applications of Smart Structures Technologies 2008,10-11 March 2008, San Diego, California, USA.

[7] Lagoudas, D.C., Hartl, D.J.: Aerospace applications of shape memory alloys. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 221 (4), 535–552 (2007).

[8] Song, G., Ma, N., and Li, H.N.: Applications of shape memory alloys in civil structures. Engineering Structures, 28 (9), 1266–1274 (2006).

[9] Machado, L.G., Savi, M.A.: Medical applications of shape memory alloys, Brazilian Journal of Medical and Biological Research, 36(6), 683–691 (2003).

[10] Alaneme, K.K. Okotete, E.A.: Reconciling viability and cost-effective shape memory alloy options – A review of copper and iron based shape memory metallic systems, Engineering Science and Technology, 19(3), 1582–1592 (2016).

[11] Markopoulos, A.P., Pressas, I.S., Manolakos, D.E.: A review on the machining of nickel-titanium shape memory alloys. Reviews on Advanced Materials Science, 42, 28–35 (2015).

[12] Neogy, S., Savalia, R.T., Tewari, R., Srivastava, D., Dey, G.K.: Transmission electron microscopy of nanomaterials. Indian Journal of Pure and Applied Physics, 44(2), 119–124 (2006).

[13] Kim, G.: Designing virtual reality systems: the structured approach, Springer, Heidelberg (2005).

[14] Tarng, W. Tsai, C.F., Lin, C.M. Lee, C.Y., Liou, H.H.: Development of an educational virtual transmission electron microscope laboratory, Virtual Reality. 19, 33–44 (2015).

[15] Tarng W., Ou, K.L., Yu, C.S., Liou, F.L., Liou, H.H.: Development of a virtual butterfly ecological system based on augmented reality and mobile learning technologies, Virtual Reality. 19, 253–266 (2015).

[16] Hou, L., Chi, H.L., Tarng, W., Chai, J., Panuwatwanich, K., Wang, X.: A framework of innovative learning for skill development in complex operational tasks, Automation in Construction. 83, 29–40 (2017).

[17] Lei, C.H., Li, L.J., Shu, Y.C., Li, J.Y.: Austenite–martensite interface in shape memory alloys. Applied Physics Letters, 96, 141910 (2010).

[18] Spini, T.S., Valarelli, F.P., Cançado, R.H., Freitas, K.M.S., Villarinho, D.J.: Transition temperature range of thermally activated nickel-titanium archwires. Journal of Applied Oral Science, 22(2): 109–117 (2014).

[19] Ryklina, E.P., Prokoshkin, S.D., Yu, I, Khmelevskaya, A.A., Shakhmina: One-way and two-way shape memory effect in

[20] thermomechanically treated TiNi-based alloys. Materials Science and Engineering A, 481482(1):134–137 (2008).

[21] Jani, J.M., Leary, M., Subic, A.: Shape Memory Alloys in Automotive Applications. Applied Mechanics and Materials, 663, 248–253 (2014).

[22] Andreasen, G.F., Hilleman, T.B.: An evaluation of 55 cobalt substituted Nitinol wire for use in orthodontics, Journal of the American Dental Association, 82, 1373–13 (1971).

[23] Allen, I.E., Seaman, C.A.: Likert scales and data analyses, Quality Progress, 40, 64–65 (2007).

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